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CFD-Wind Tunnel Aerodynamics Correlation Study

DrivAer Car Model

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Objectives

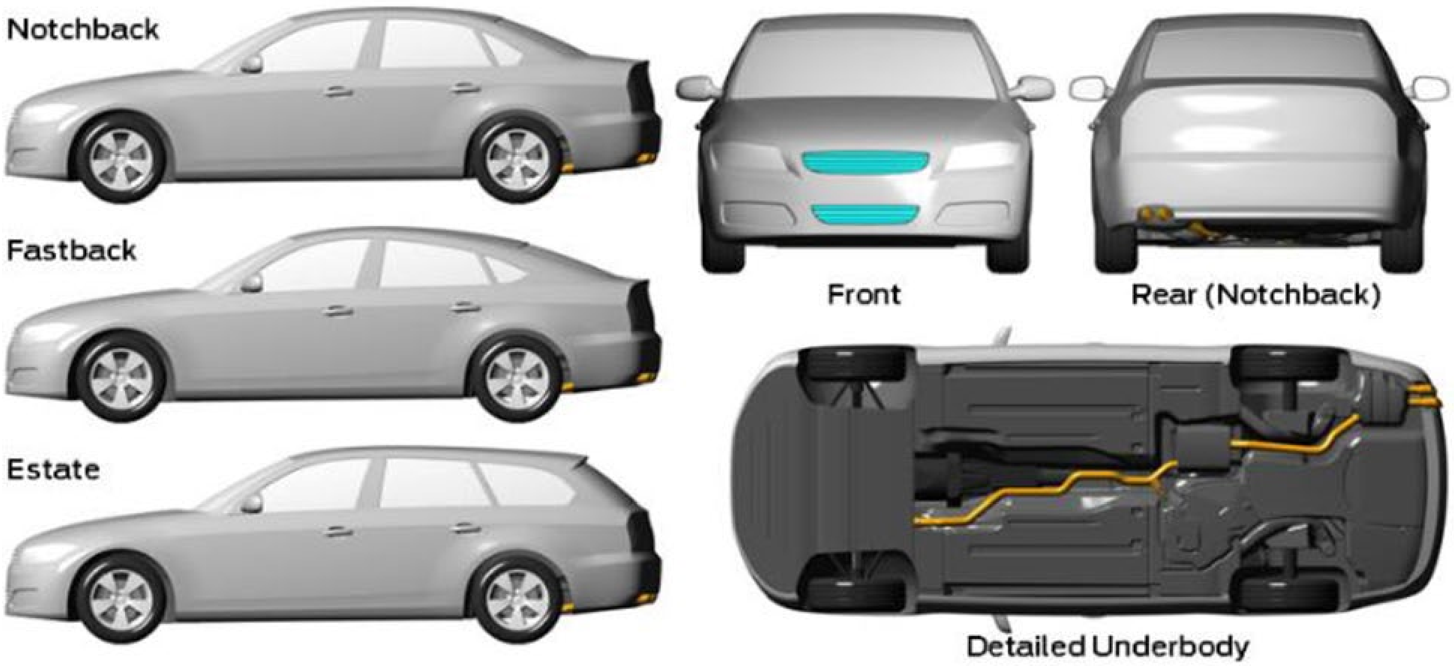
- To demonstrate SABE's CFD methodology capability in predicting aerodynamic characteristics of road vehicles.
- Review of the latest WT validation experiments and correlation studies.
- Analysis and report of CFD-WT correlation and related intricacies and issues:
  - WT-related
  - CFD-related

Geometry (1)

- The geometry chosen for this study consisted of the well-known DrivAer car model.
- This was selected for the following reasons:
  - Realistic geometry representative of real passenger roadcars
  - Sufficient geometry detail that produces flow characteristics representative of realcars
  - Accepted standard for automotive aerodynamic experiment-CFD correlation verification
  - Availability of WT data: forces, surface pressure and flowfield measurements

Geometry (2)

- Convenient modularity of the model:
  - Fastback, notchback, or estate
  - Smooth vs detailed underbody
  - Closed vs open cooling flow paths
  - Static vs moving ground
  - Fixed vs rotating wheels
    - Rigid vs soft tyres
  - Slick vs grooved tyres
  - Sealed vs detailed rims
- Two variants of the DrivAer model:
  - Original by Heft et al. as a collaboration between TUM, Audi AG and BMW AG
  - Modified by Hupertz et al.; Ford Motor Company.



Heft, A., Indinger, T., and Adams, N., "Introduction of a New Realistic Generic Car Model for Aerodynamic Investigations," SAE Technical Paper 2012-01-0168, 2012, doi:10.4271/2012-01-0168.
Hupertz, B., Krüger, L., Chalupa, K. et al., "Introduction of a new Open Cooling Version of the DrivAer Generic Car Model" 11th FKFS Conference "Progress in Vehicle Aerodynamics and Thermal Management", Stuttgart, 2017.

Existing experimental Data (1)

- A number of experimental studies and CFD-WT correlation work have been carried out on different DrivAer model variants, including on both original Heft's and modified Hupertz's models
- Various combinations of modules as described earlier (car rear-end type, underbody, tyres, cooling, ...etc)
- Different scales of WT models; namely 25%, 40% and full scale
- Various WT freestream conditions => Reynolds number Re_L (L is total length of model)
- Diverse WT types; open-jet, closed-loop, ...etc

Existing experimental Data (2)

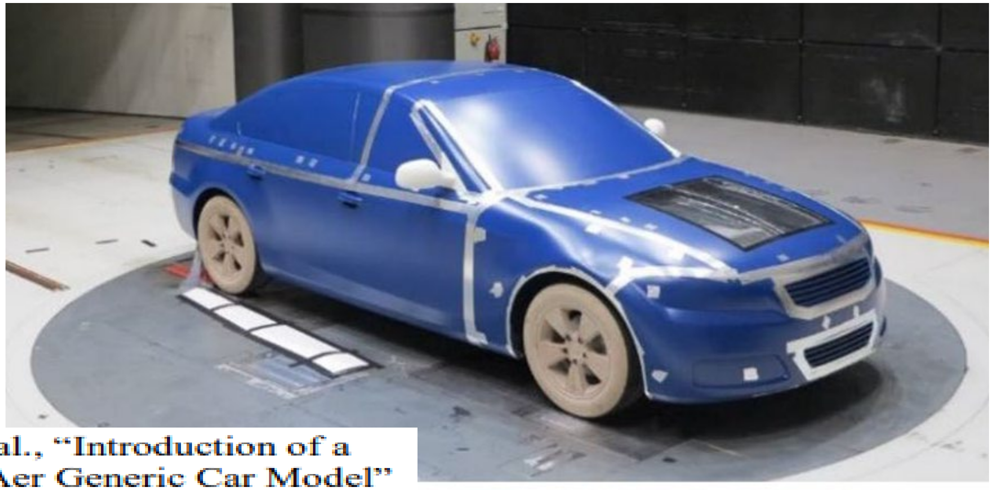
- WT data were evaluated and filtered in terms of:
  - Model scale/geometry fidelity
  - Model specific setup in WT test section;
    - Car front and rear ride heights
    - Model positioning wrt:
      - Tunnel nozzle exit,
      - Test section exit plenum,
      - Rolling belt,
      - Boundary layer suction/bleeding system
      - Boundary layer inception point
  - WT type (open-jet, closed-loop, …etc) and geometry detail
  - WT operating and test conditions
  - Measurements errors and uncertainties
  - Quality and variety of experimental data made available.

CFD-WT correlation related uncertainties

- Correlation studies generally consider the wind tunnel as the absolute truth
- Experimental errors and uncertainties around the test itself, data acquisition and post-processing are often neglected from literature reporting
- Furthermore, another type of uncertainty in any experiment is what we call the “model characterisation uncertainty”. This refers to deviations and assumptions in the modelling compared to the real-life application.
- For this study, our CFD model replicated the wind tunnel domain, conditions and setup with the goal of minimising this type of uncertainty.

WT influencing parameters (1)

- Test section size => blockage ratio
- Nozzle exit free shear flow interference
- Streamwise pressure gradient
- Test section exit collector
- Boundary layer suction/scooping/bleeding
- Boundary layer inception point
- Belt surface state, size and positioning wrt model
- Wheel-ground contact detail;
  - Soft vs rigid tyres
  - Static vs rolling belt with balance rods
- Top and wheel Struts interferences



Hupertz, B., Krüger, L., Chalupa, K. et al., "Introduction of a new Open Cooling Version of the DrivAer Generic Car Model" 11th FKFS Conference "Progress in Vehicle Aerodynamics and Thermal Management", Stuttgart, 2017.

WT testing parameters (2)

- Wind tunnel to tunnel variation
- WT test to test repeatability
- Measurement dependency on WT
  - Nozzle and collector interference, including nozzle wall free shear layer interference
  - Streamwise pressure gradient
  - Top and wheel Struts interference
- Model manufactured geometry fidelity to CAD

CFD methodology affecting parameters

- Surface mesh resolution and quality for model geometry fidelity
- Volume mesh resolution and quality for flow field resolution
- Far field domain size and boundary conditions in relation to actual WT
- Blockage effect consideration
- WT ground boundary layer accurate capturing/simulation
- Tyre and ground roughness specification
- Tyre shape and tyre-ground contact representation
- Turbulence modelling
  - RANS
  - URANS
  - Scale-resolving; such as DES, LES, …etc
- Numerics

Correlation Set 1

Peichl - 2019 (see ref. below)

- TUM + AUDI WT experiments:
  - 40% model scale
  - Notchback + detailed underbody
  - Closed cooling
  - Sealed rims
  - Slick tyres
  - Rotating wheels + moving ground
  - Top strut and 4 wheel struts
  - V_{∞} = 43.57 m/s => Re_L = 5.2 million.
- Data: C_D, $C_{L\text{-body}}$, C_p (y=0 & z=cst).

Peichl M.A., *Investigation of Coherent Structures in Unsteady Car Aerodynamics*, Dr.-Ing. Dissertation, Technical University of Munich, 2019.

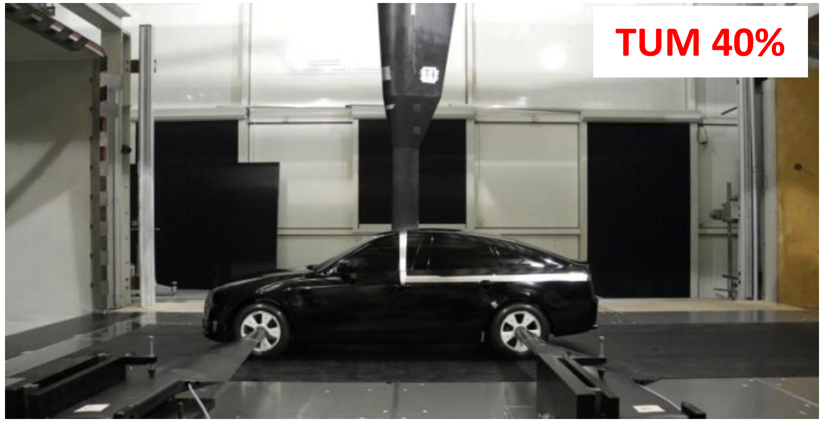
Set 1: Force Coefficients

- Difference between TUM and Audi WT forces due to differences in the facilities, test sections and model setup (see Collin et al. for more details)
- 40% DrivAer model used in both facilities

	SABE CFD	TUM WT	AUDI WT	SABE CFD (MSS correction)
C_D	0.283	0.279	0.289	0.289 to 0.292
$C_{L,Body}$	0.123	0.032	0.073	-

- CFD simulation does not include MSS (Model Support System = top and wheel struts)
- Very good agreement between CFD and Audi WT drag force prediction
- +0.006 to 0.009 drag correction for MSS (as reported in Peichl's ref)

- Overprediction of lift in CFD
- Lift correction for MSS is unknown.



Collin, C. et al., *A Numerical and Experimental Evaluation of Open Jet Wind Tunnel Interferences using the DrivAer Reference Model*, SAE Int. J. Passeng. Cars - Mech. Syst. 9(2):2016, doi:10.4271/2016-01-1597.

Set 1: Cp – Upperbody Centreline

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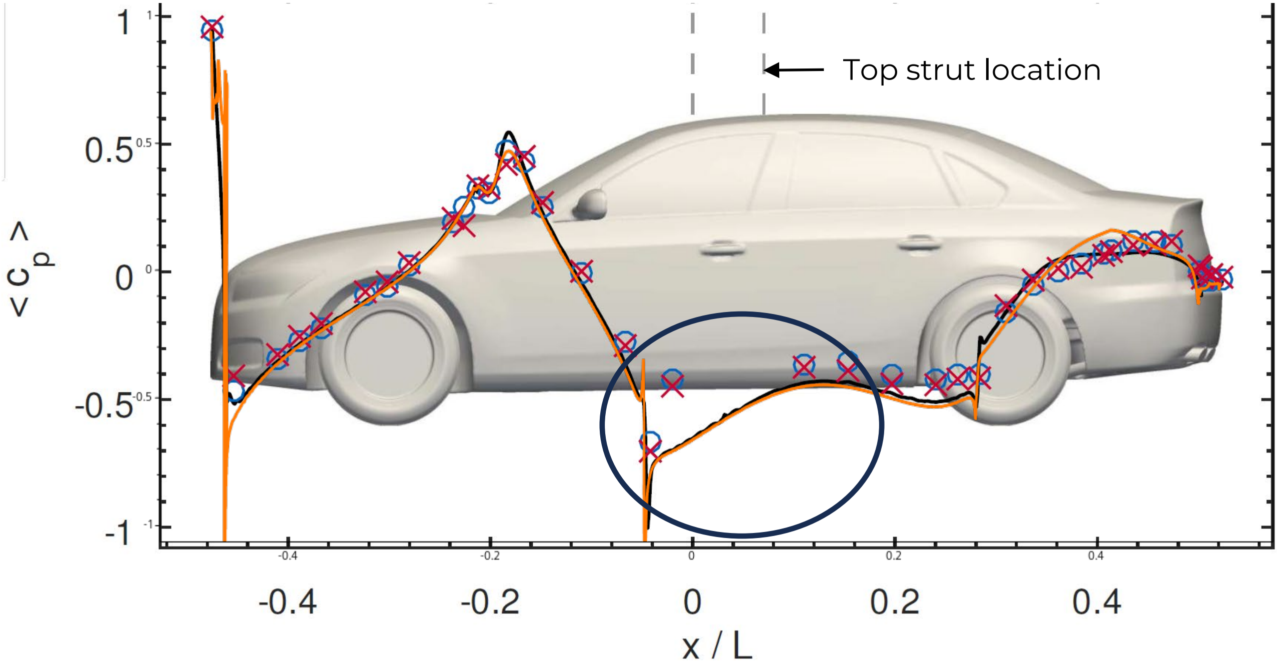
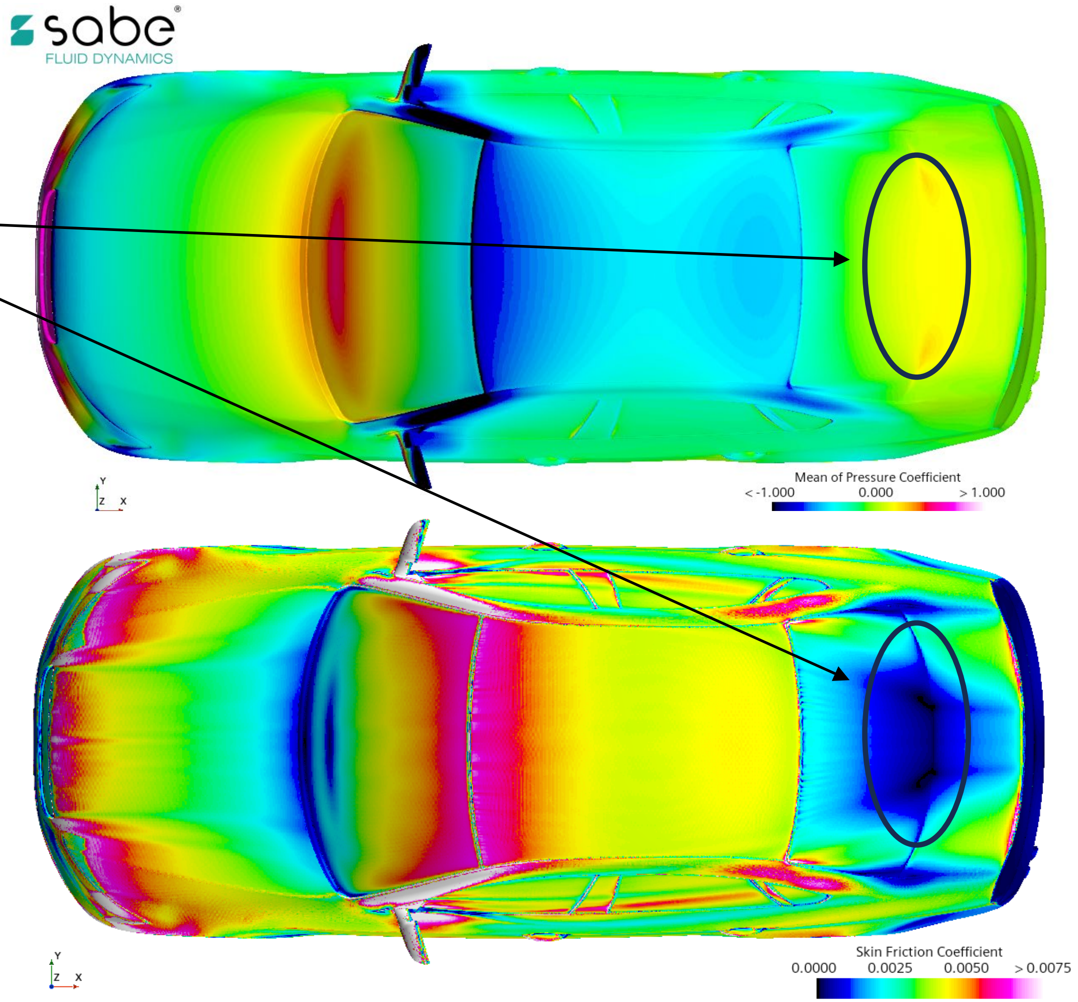
- Good agreement between CFD and WT data
- Under-prediction of pressure around the top Strut location due its absence in the simulation
- Slight over-prediction of pressure in rear window back, a well-known sensitive area of the car

(orange: SABE CFD, blue circles: TUM WT, red crosses: Audi WT, black line: Peichl's SA-DES)

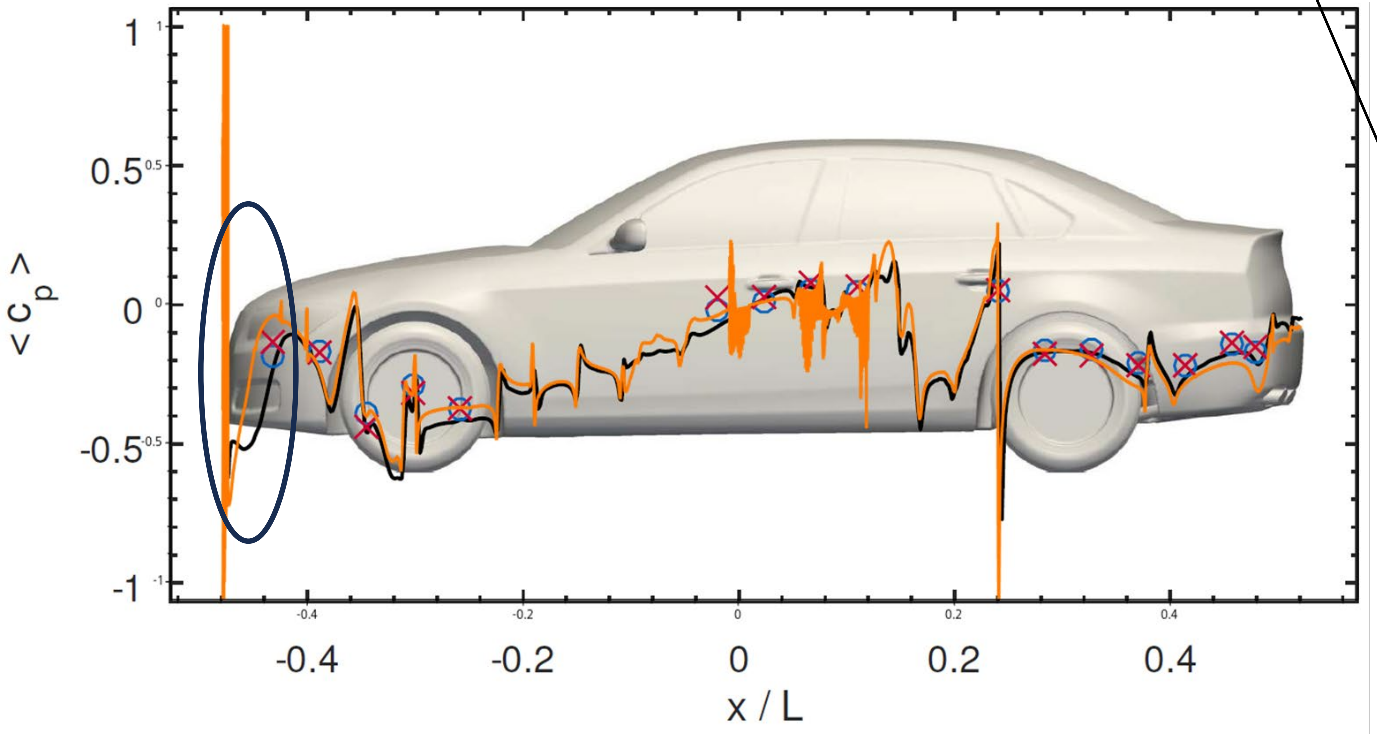


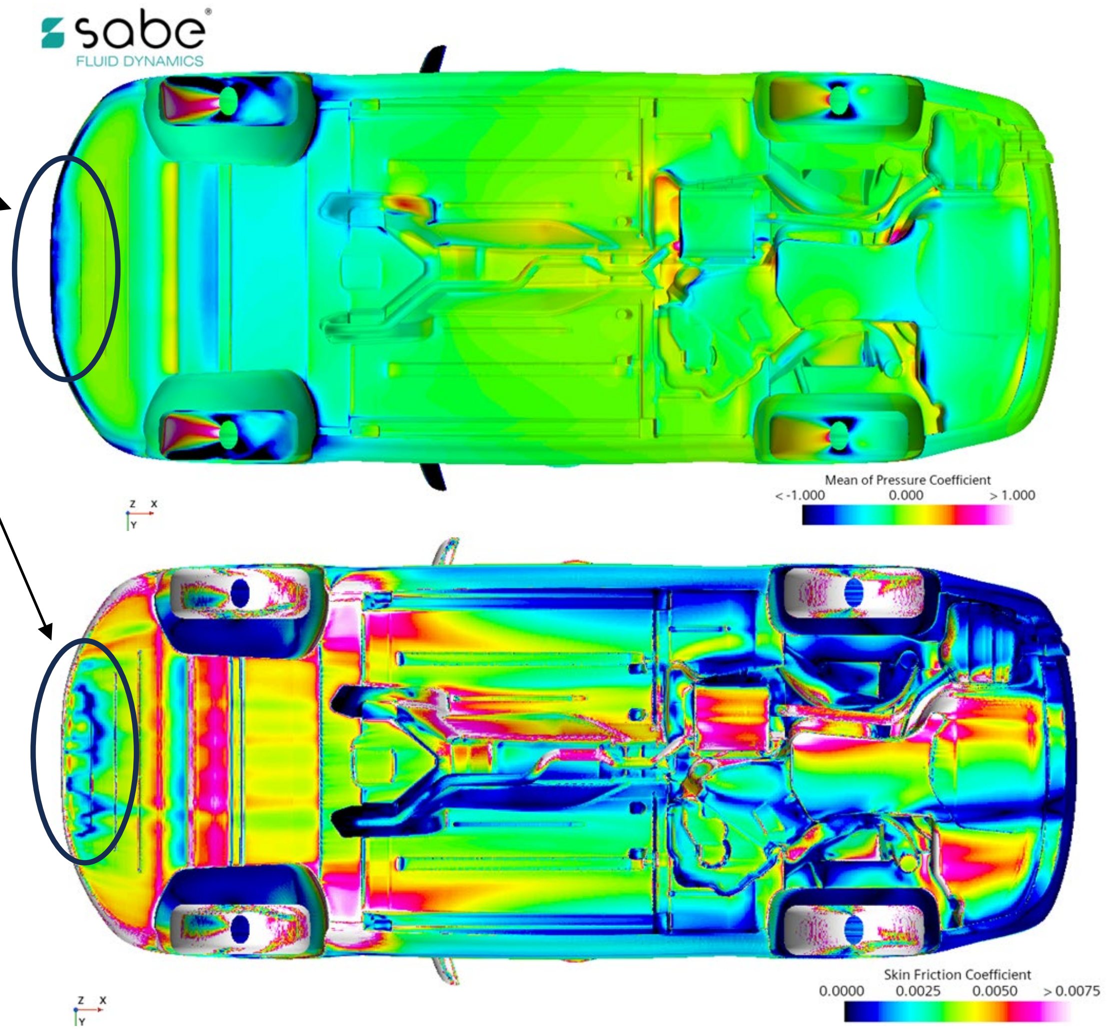


Set 1: Cp – Underbody Centreline

- Good agreement between CFD and WT data
- Some discrepancy in pressure prediction in the underbody leading edge, a well-known sensitive area of the car.

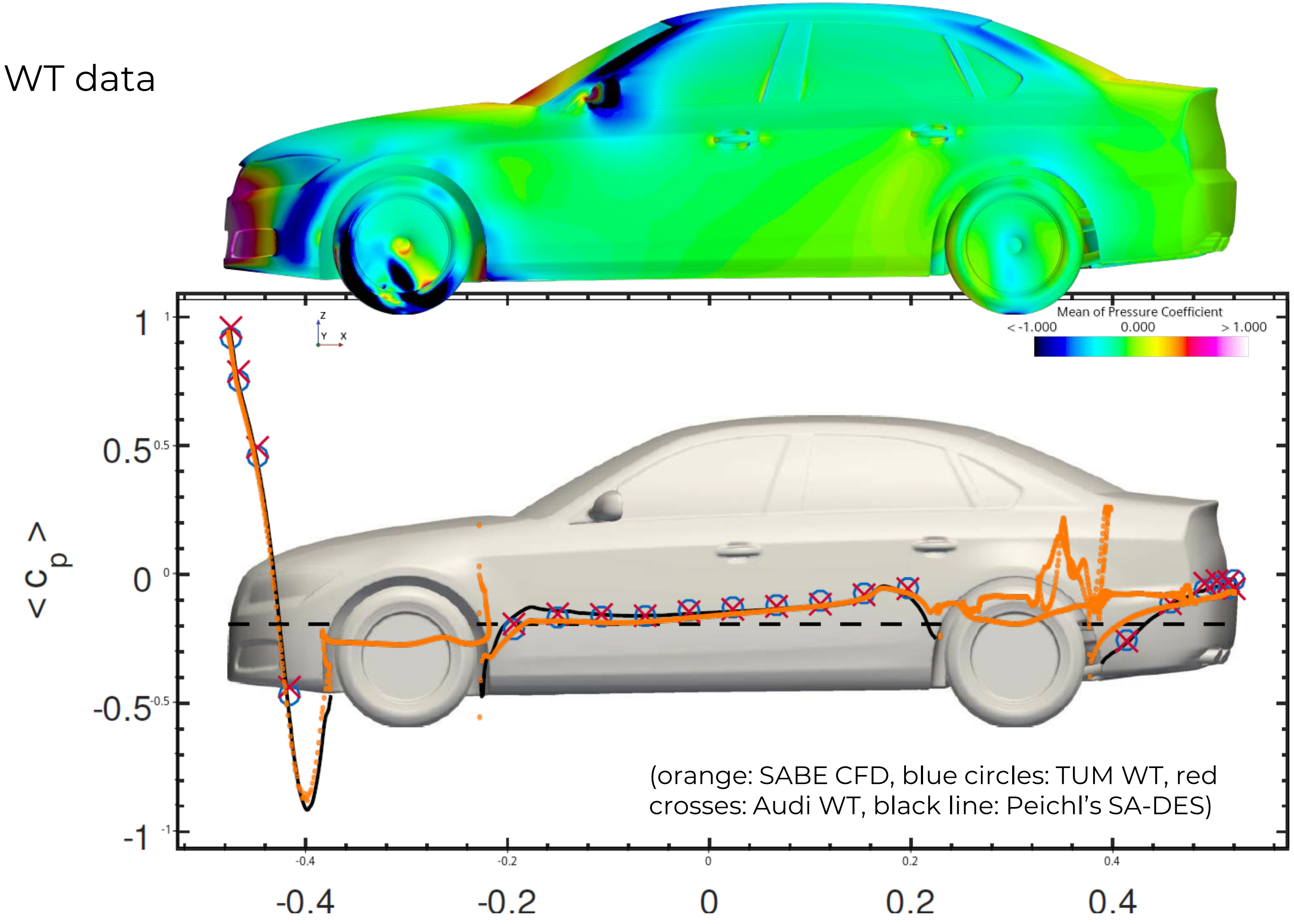
(orange: SABE CFD, blue circles: TUM WT, red crosses: Audi WT, black line: Peichl's SA-DES)





Set 1: Cp – Side z = 60mm

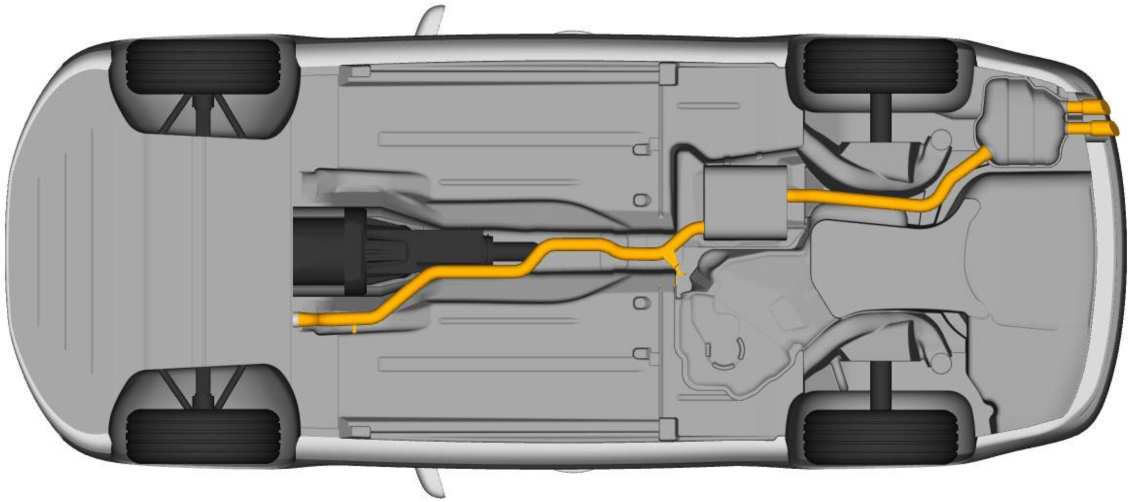
- Good agreement between CFD and WT data

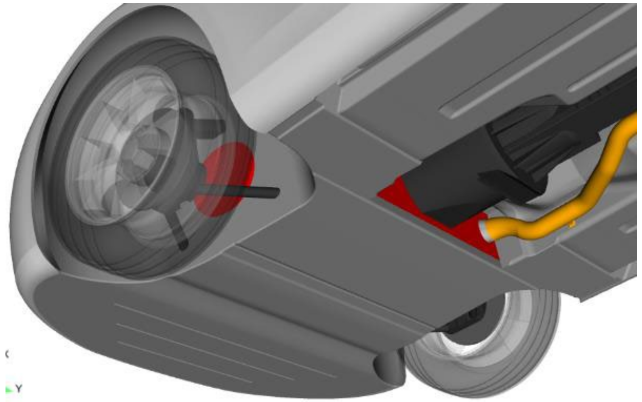


Correlation Set 2

AutoCFD 2/3/4 DrivAer Model

- ➢ **Ford modified DrivAer model**





AutoCFD 2/3 public reports; https://autocfd.eng.ox.ac.uk/#presentations

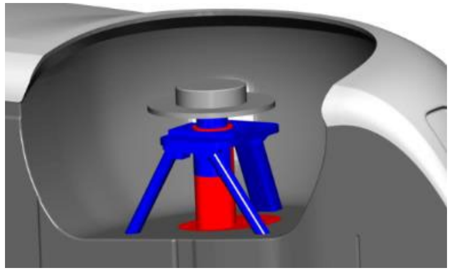
Hupertz, B. et al., *On the Aerodynamics of the Notchback Open Cooling DrivAer: A Detailed Investigation of Wind Tunnel Data for Improved Correlation and Reference*. SAE Int. J. Advances & Curr. Prac. in Mobility, 2021-01-0958, 2021.

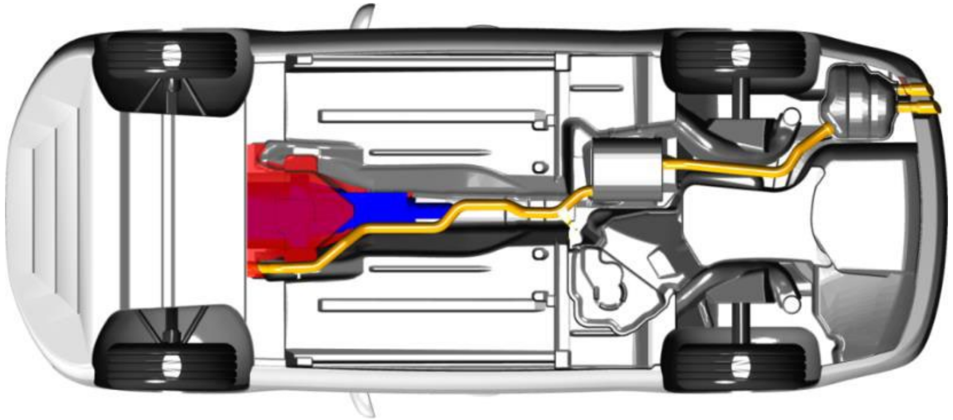
Correlation Set 2

FLUID DYNAMICS

Set2

- Ford Motor Company (see ref. below)
- Test facility: Pininfarina full-scale WT: https://pininfarina.it/en/wind-tunnel
  - Full scale model
  - Notchback + detailed underbody (slightly modified from the original DrivAer)
  - Simplified front suspension assembly and rear drive shaft
  - Closed cooling
  - Detailed rims
  - Grooved rigid tyres
  - Fixed wheels + static ground
  - V_∞ = 140kph => Re_L = 11.9 million.





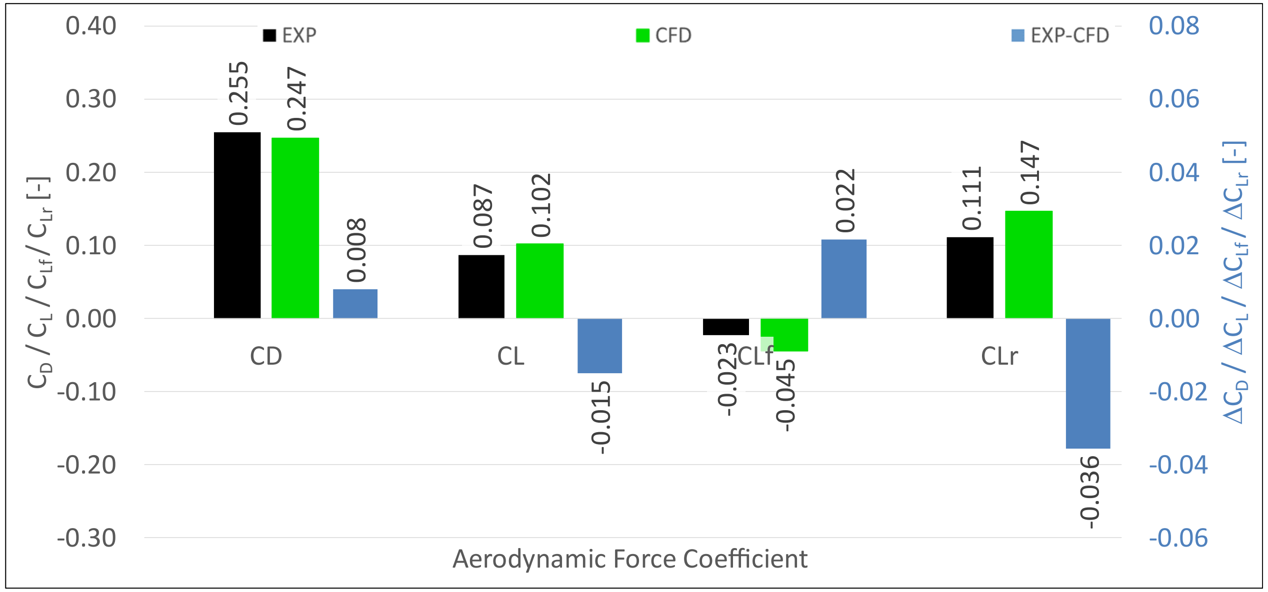
- Data: Forces, surface pressure, velocity profiles, and flowfield contour plots.

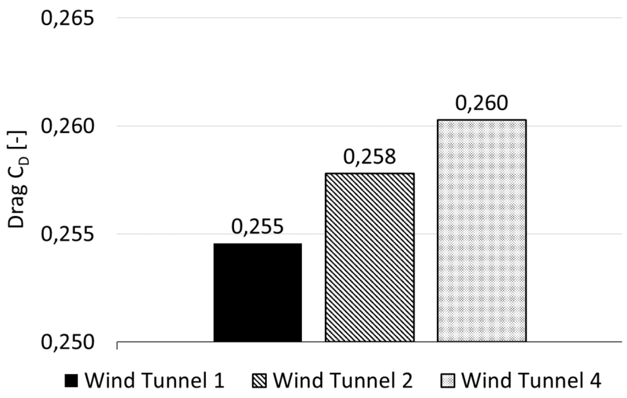
AutoCFD 2/3 public reports; https://autocfd.eng.ox.ac.uk/#presentations

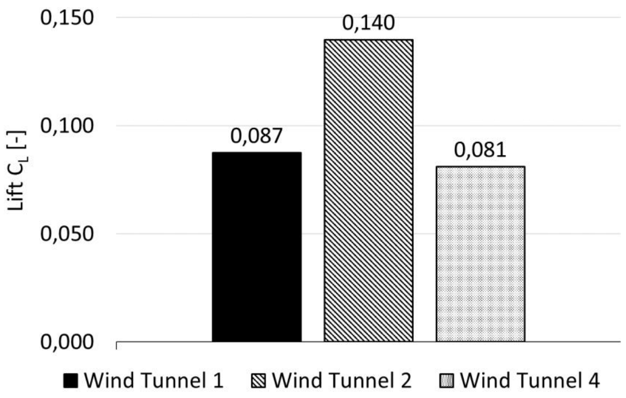
Hupertz, B. et al., *On the Aerodynamics of the Notchback Open Cooling DrivAer: A Detailed Investigation of Wind Tunnel Data for Improved Correlation and Reference*. SAE Int. J. Advances & Curr. Prac. in Mobility, 2021-01-0958, 2021.

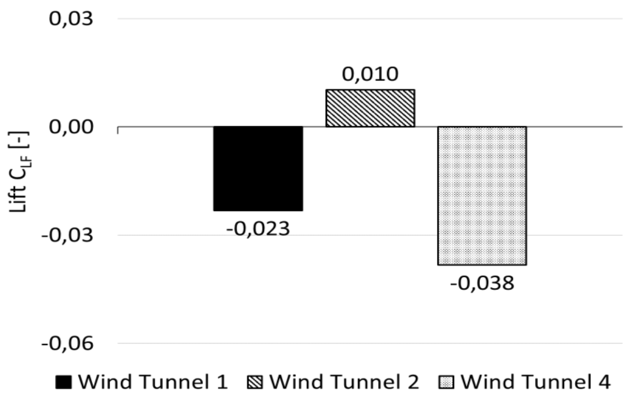
Set 2: Force Coefficients

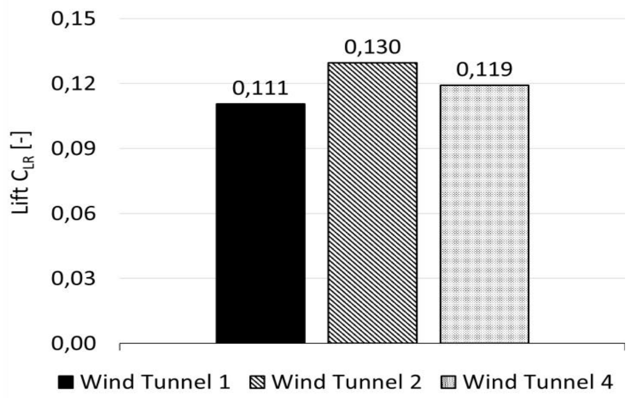
- Good agreement between CFD and WT force data
- Some front balance shift in CFD
- AutoCFD2 'Case2-Result Overview' report showed quite a significant variation in forces from different wind tunnels (see below).









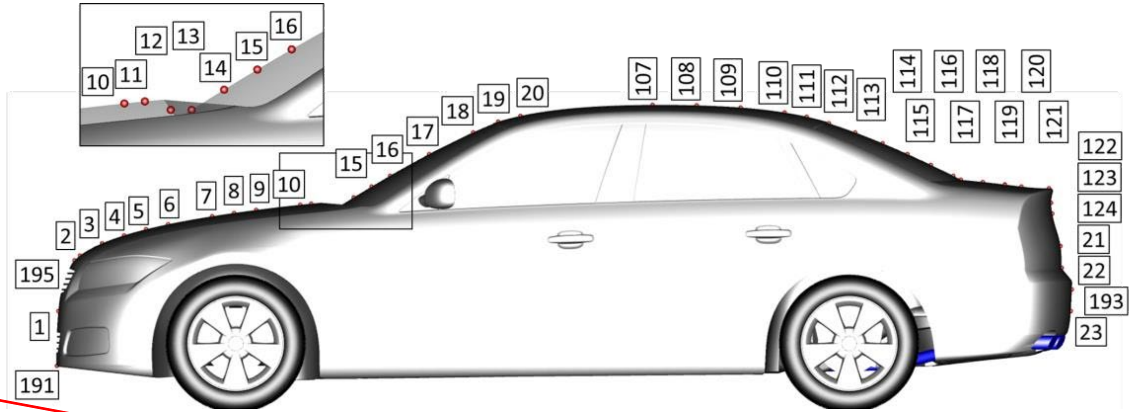


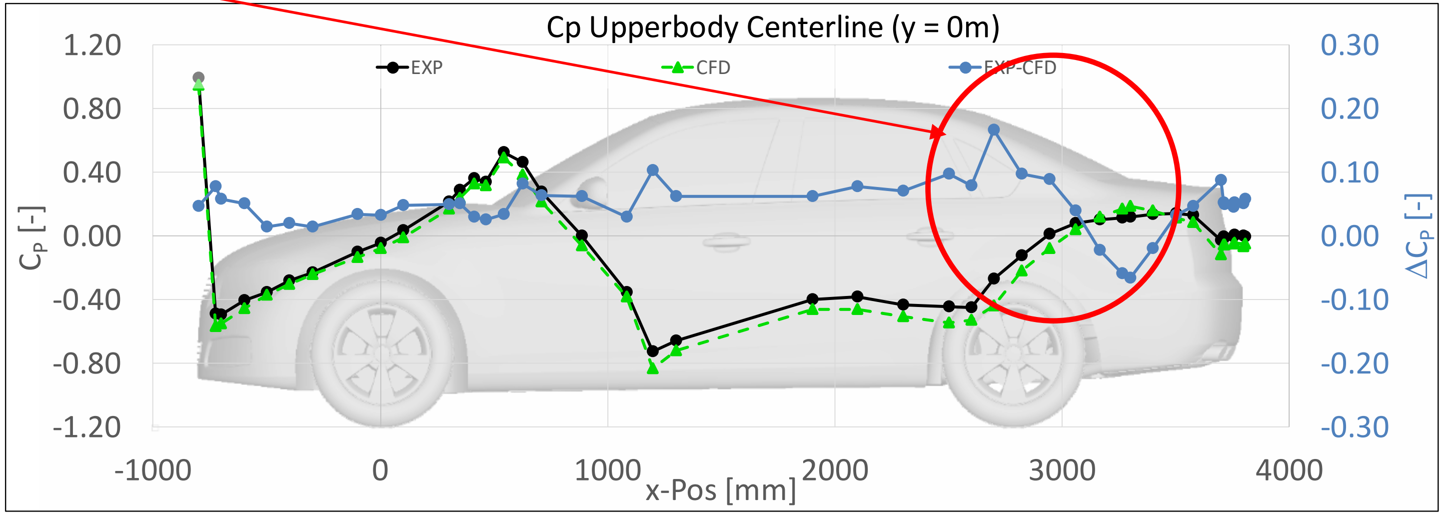
Set 2: Surface Cp

- Generally, very good prediction of surface pressure distributions over the whole car with varying deltas between CFD and WT data in different locations
- Spatial trends and distributions are predicted well with CFD
- There is a slight under-prediction of surface pressure with CFD globally.

Set 2: Surface Cp – Upperbody y=0

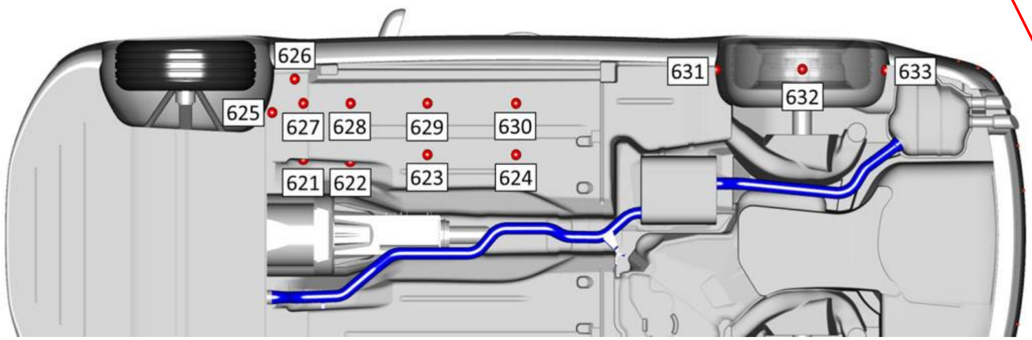
Well known sensitivity to separation of the rear window region; junctions with the roof and trunk

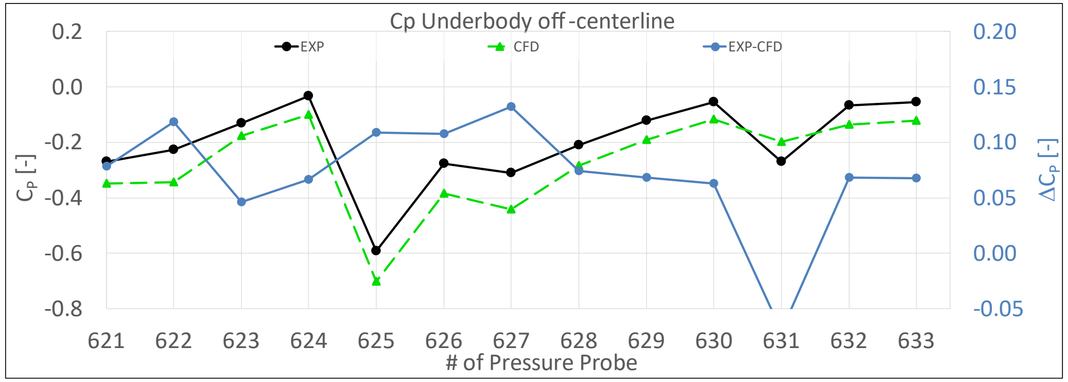


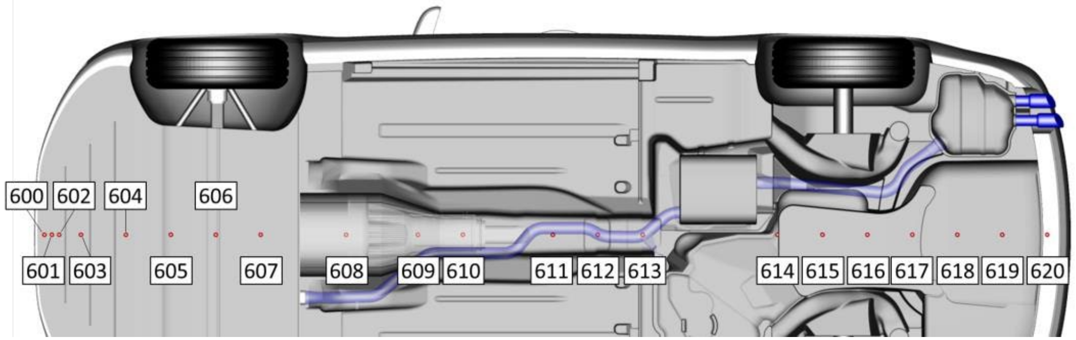


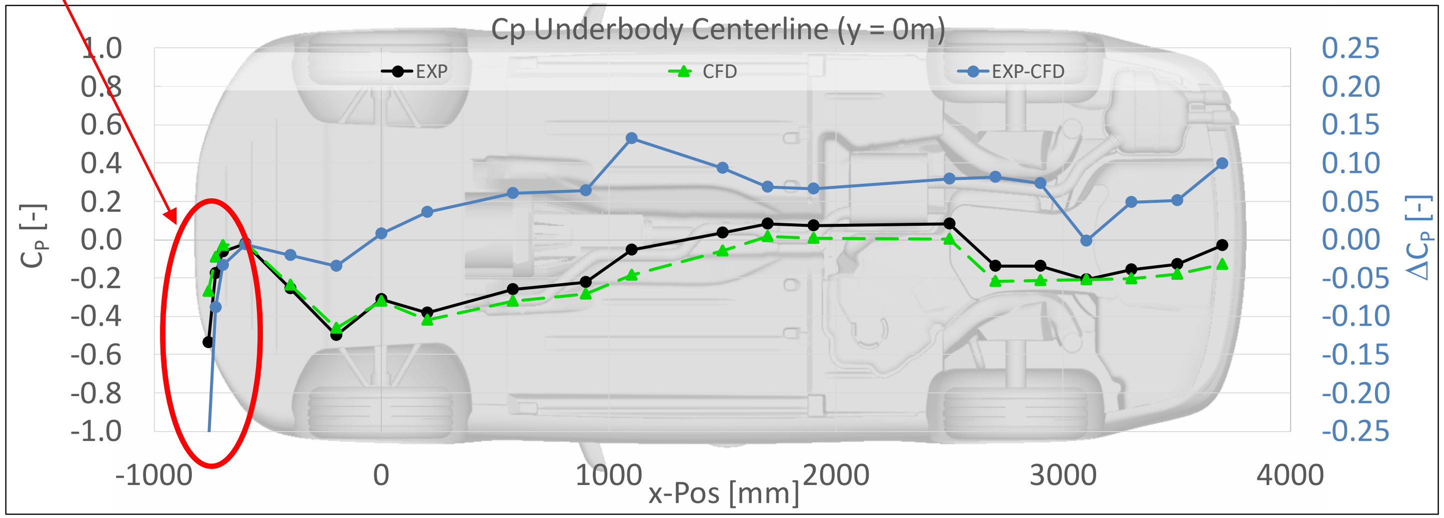
Set 2: Surface Cp – Underbody y=0

- Under-prediction of the suction peak in the front underbody, a well-known sensitive area



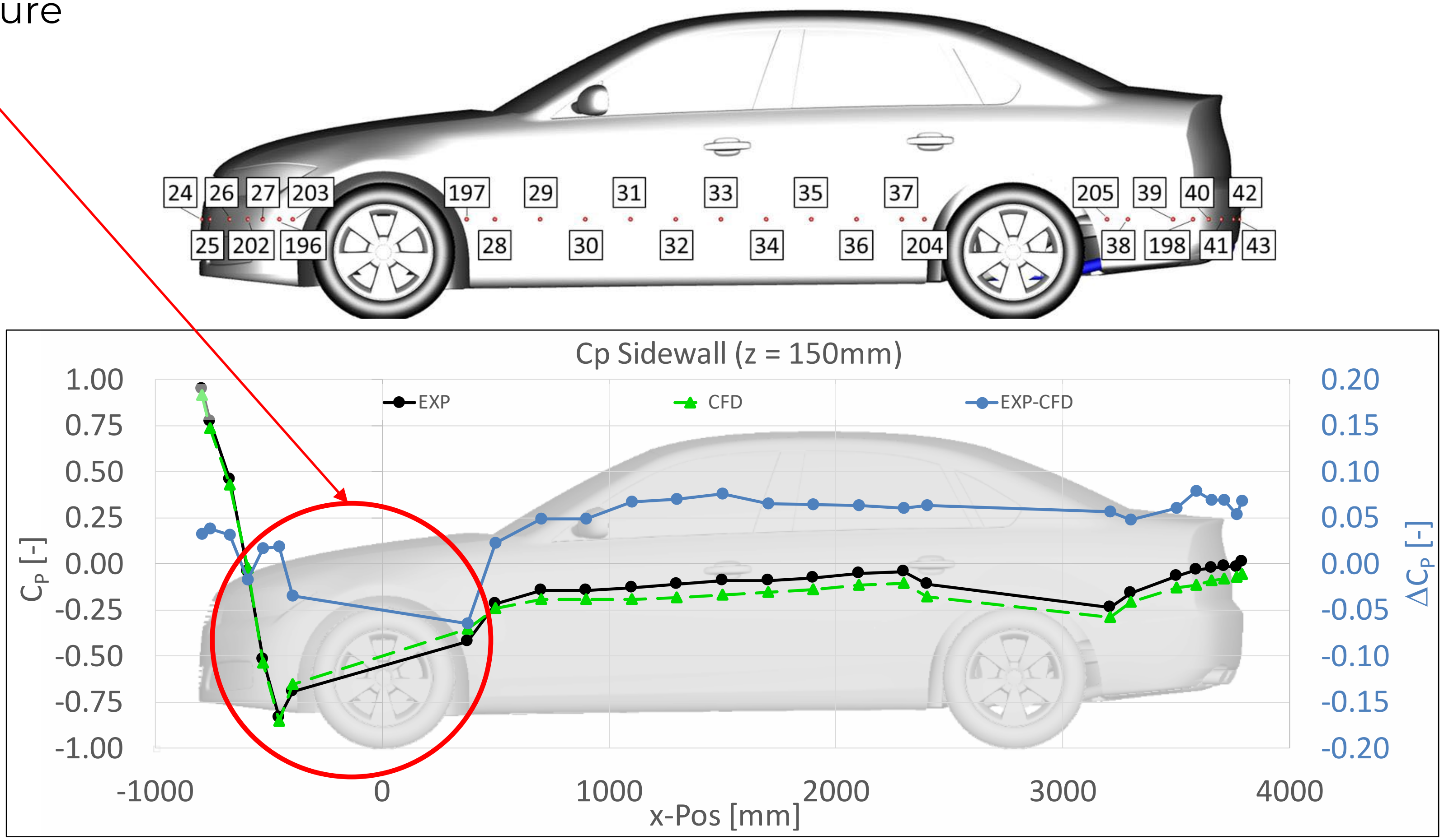






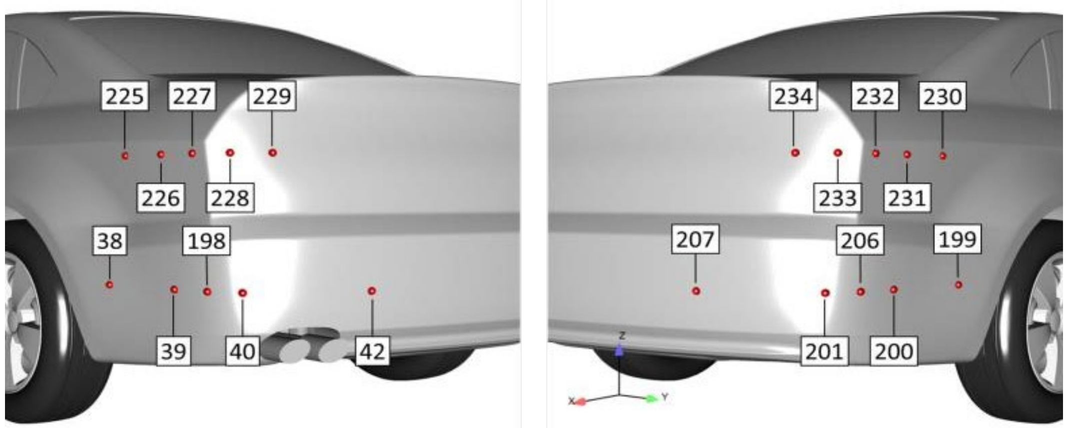
Set 2: Surface Cp – Side

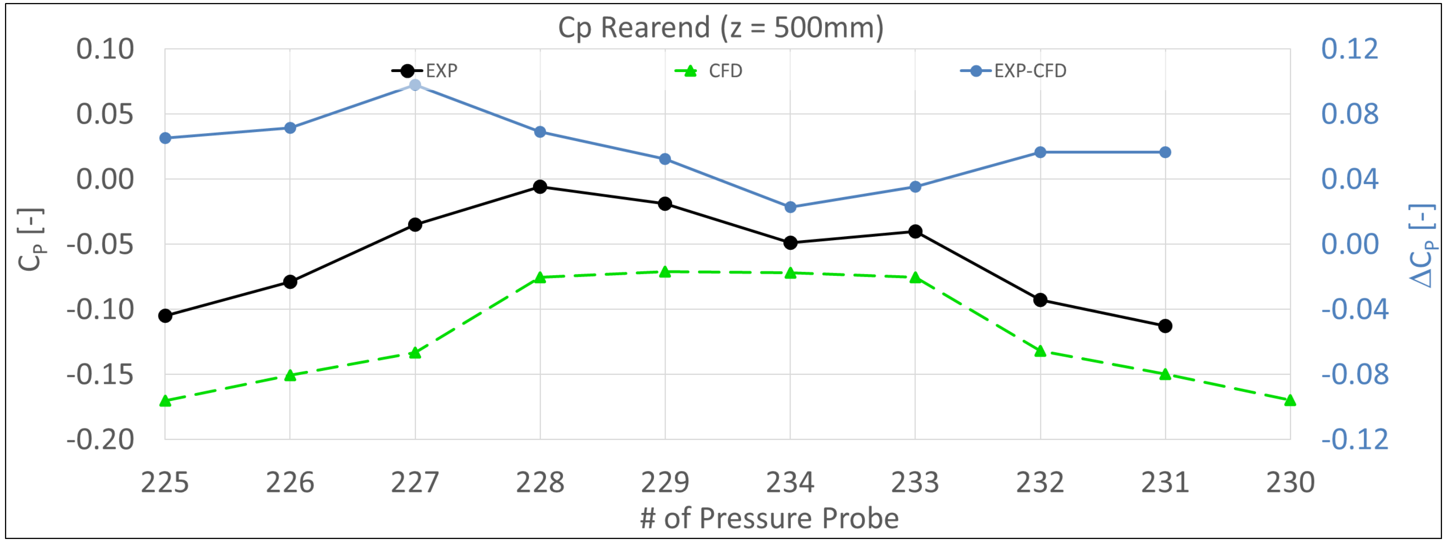
- Slight over-prediction of the pressure across the front tyre wake.

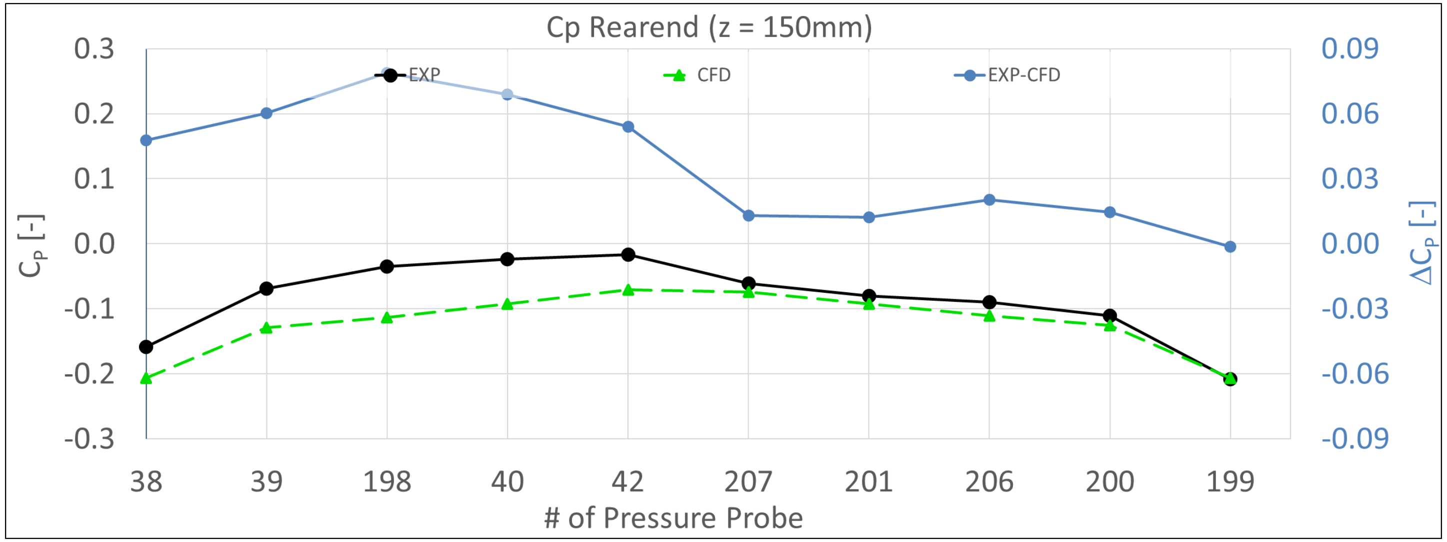


Set 2: Surface Cp – Rear-Sides

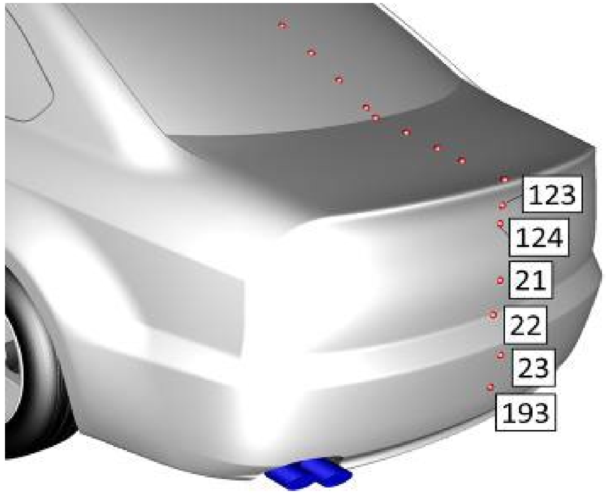
- Asymmetry in pressure distribution in relation to the asymmetric underbody geometry.

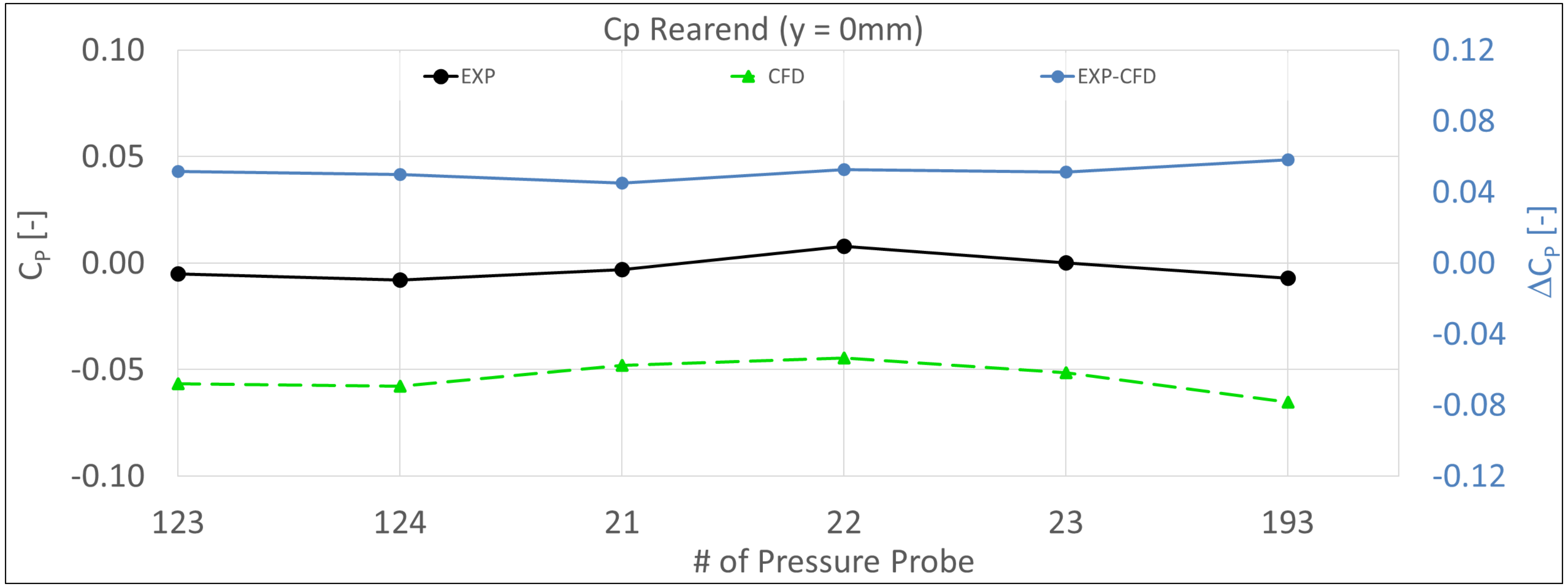






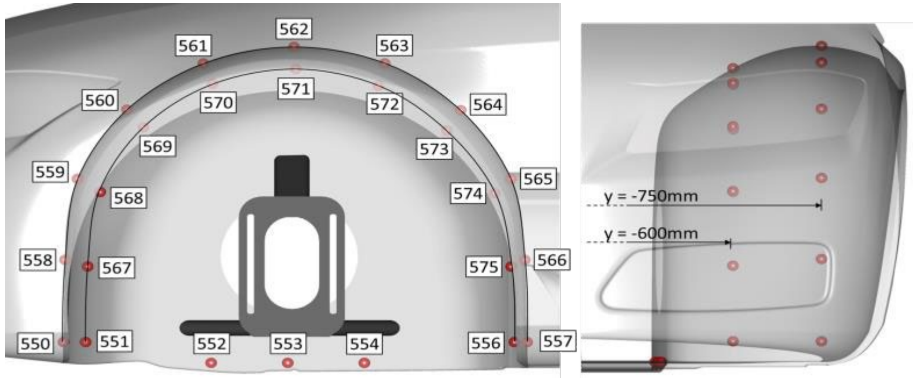
Set 2: Surface Cp – Rear

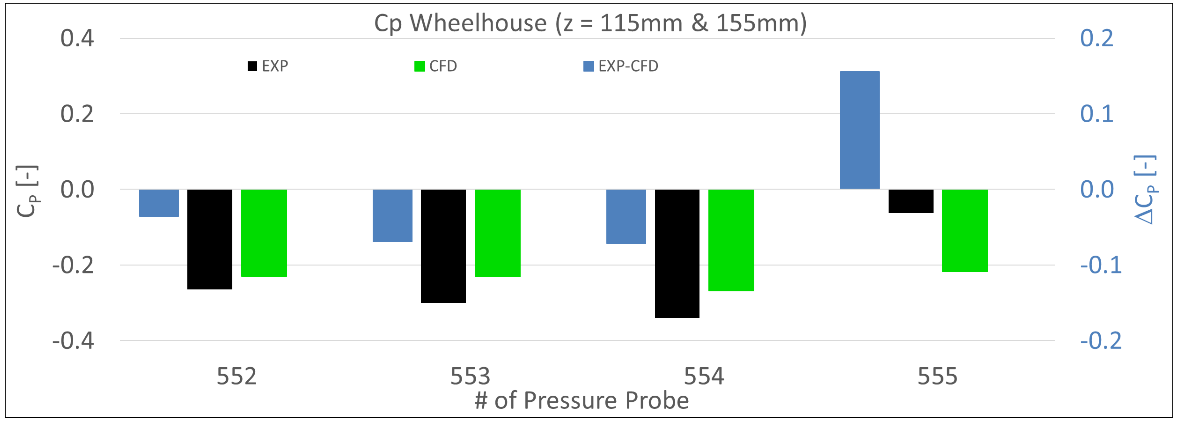


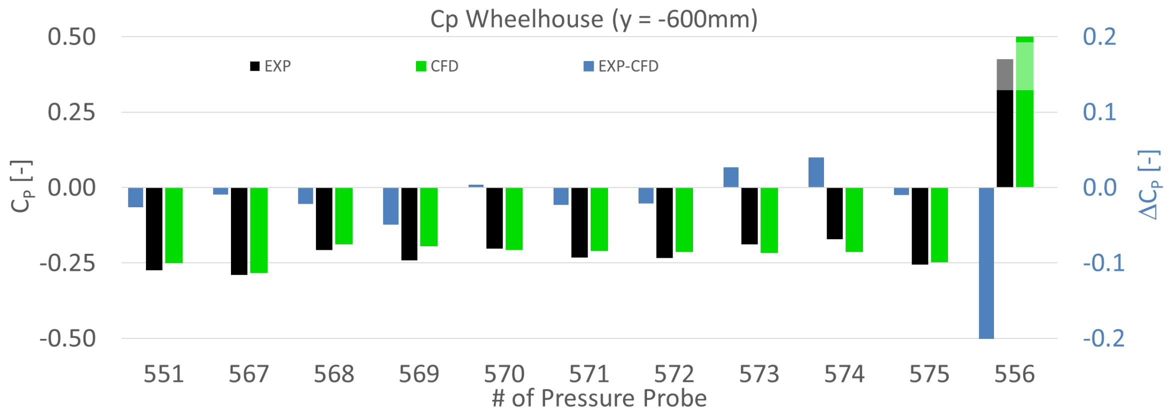


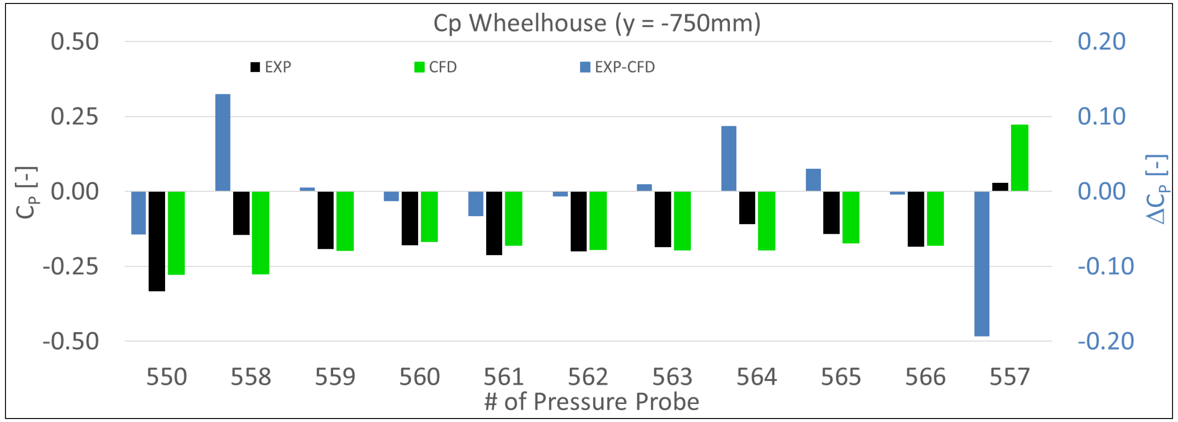
Set 2: Surface Cp – Wheelhouse

- Some variation in delta signs due to the predominantly lossy flow within this region and difference in wheel flow field and wake.

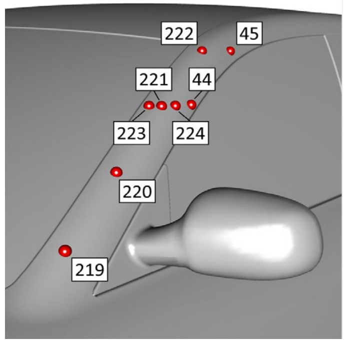


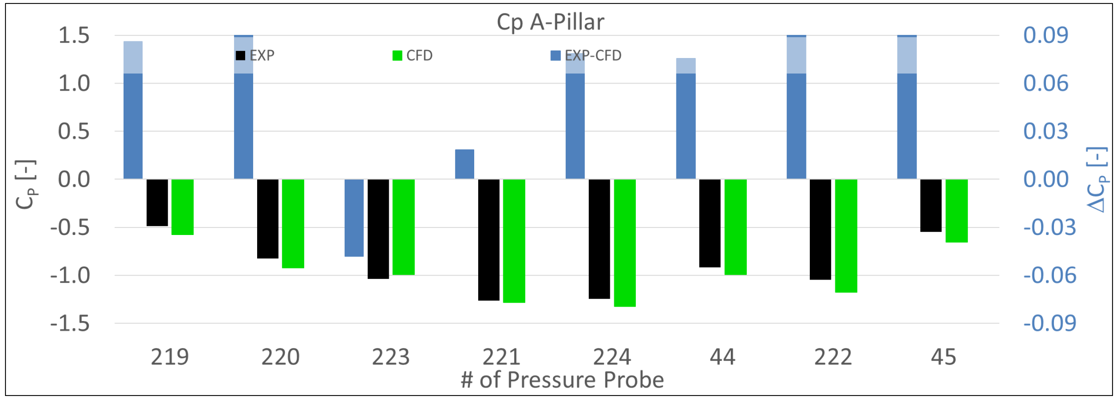


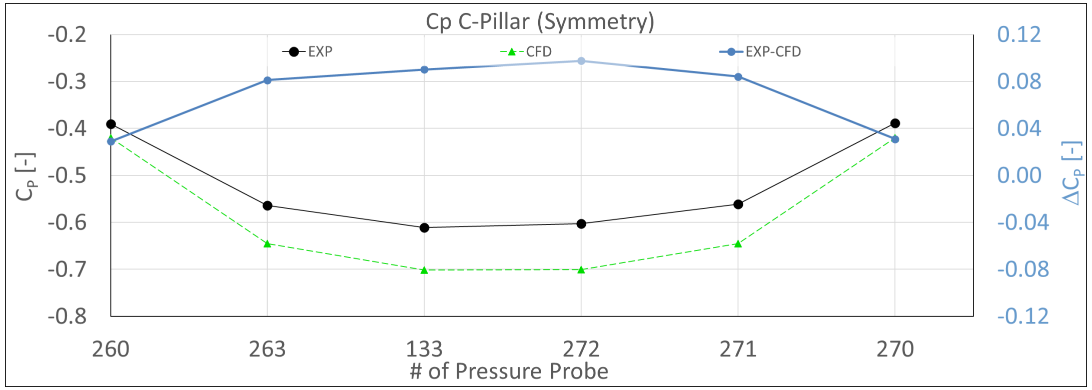


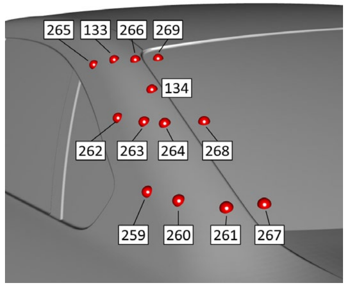


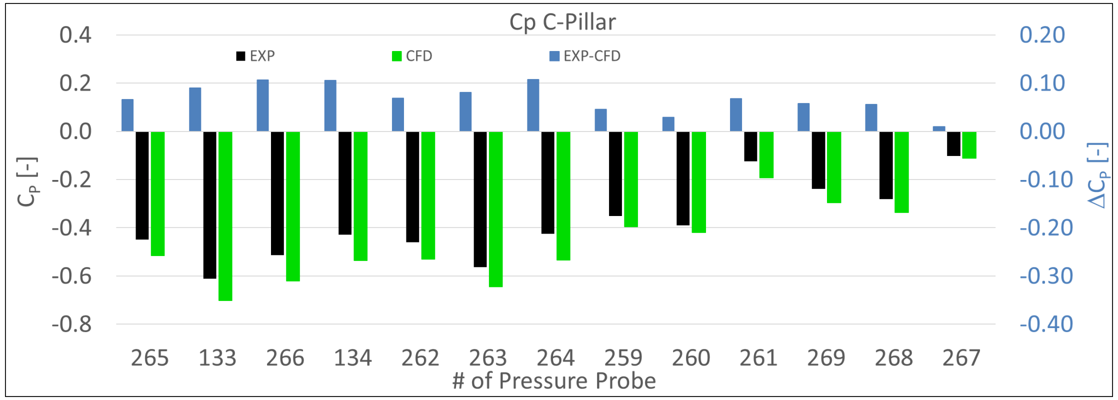
Set 2: Surface Cp – A-Pillar & C-Pillar



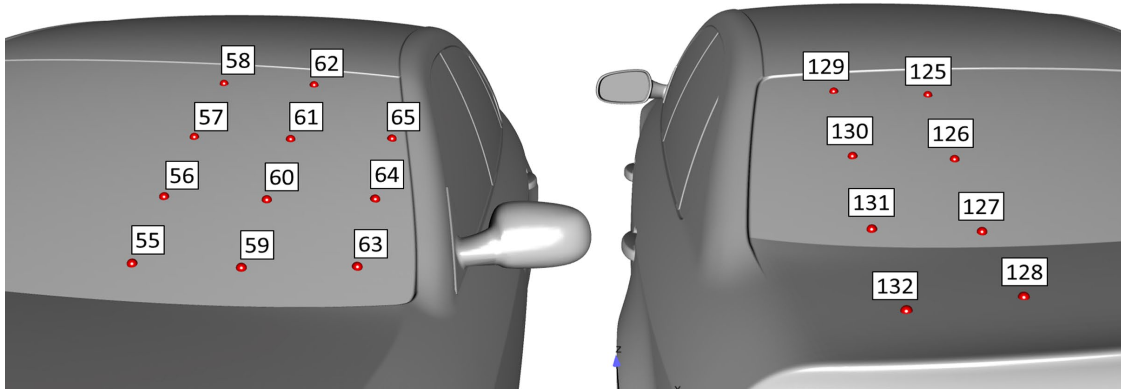


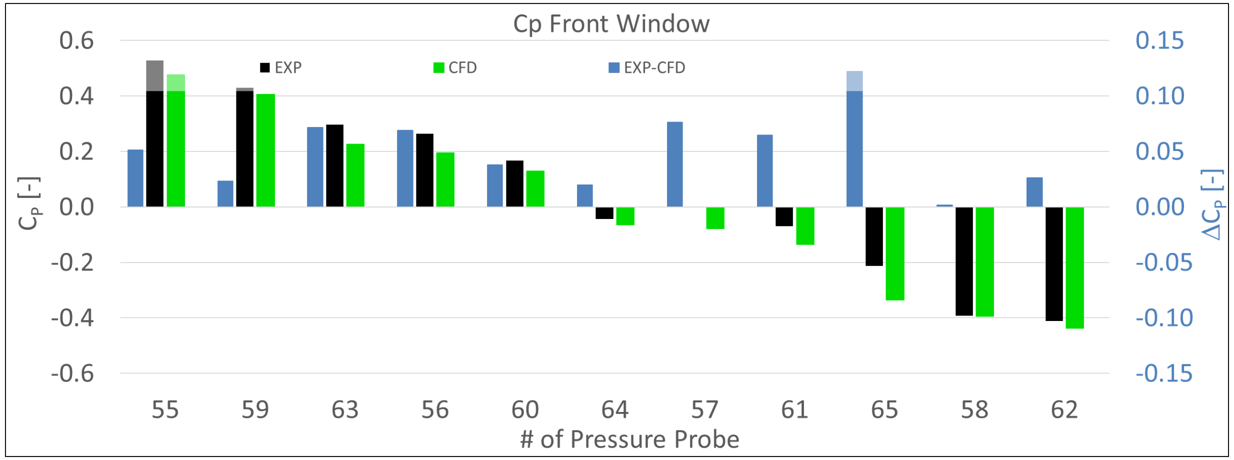


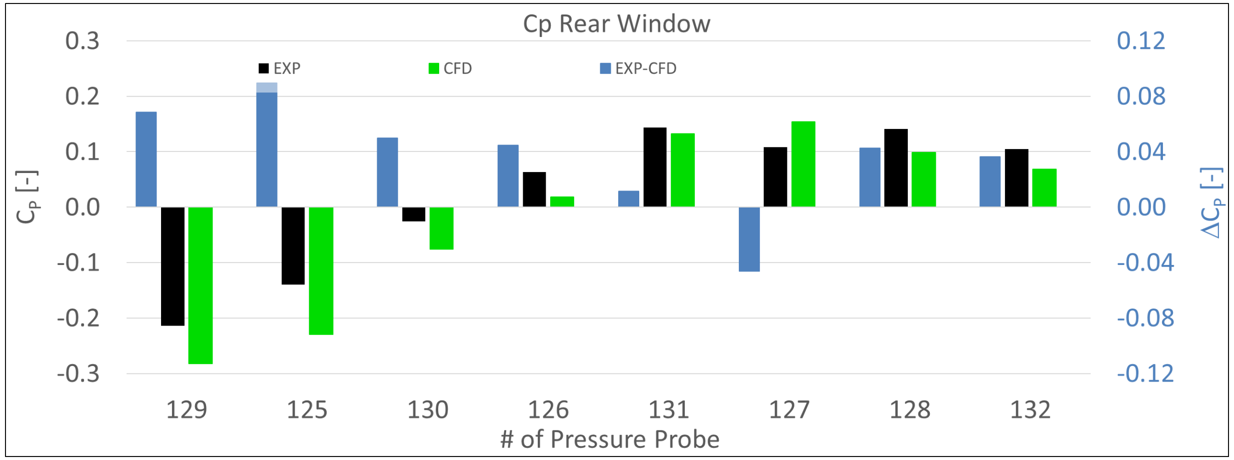




Set 2: Surface Cp – Front & Rear Windows

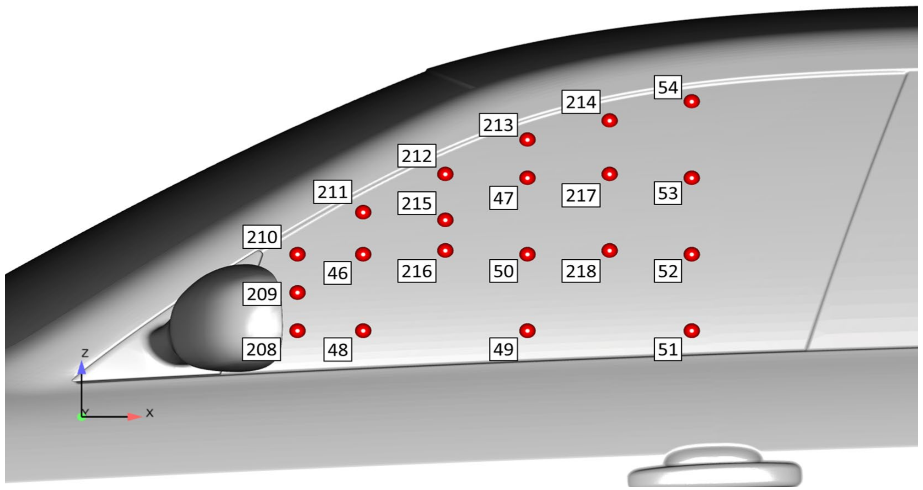


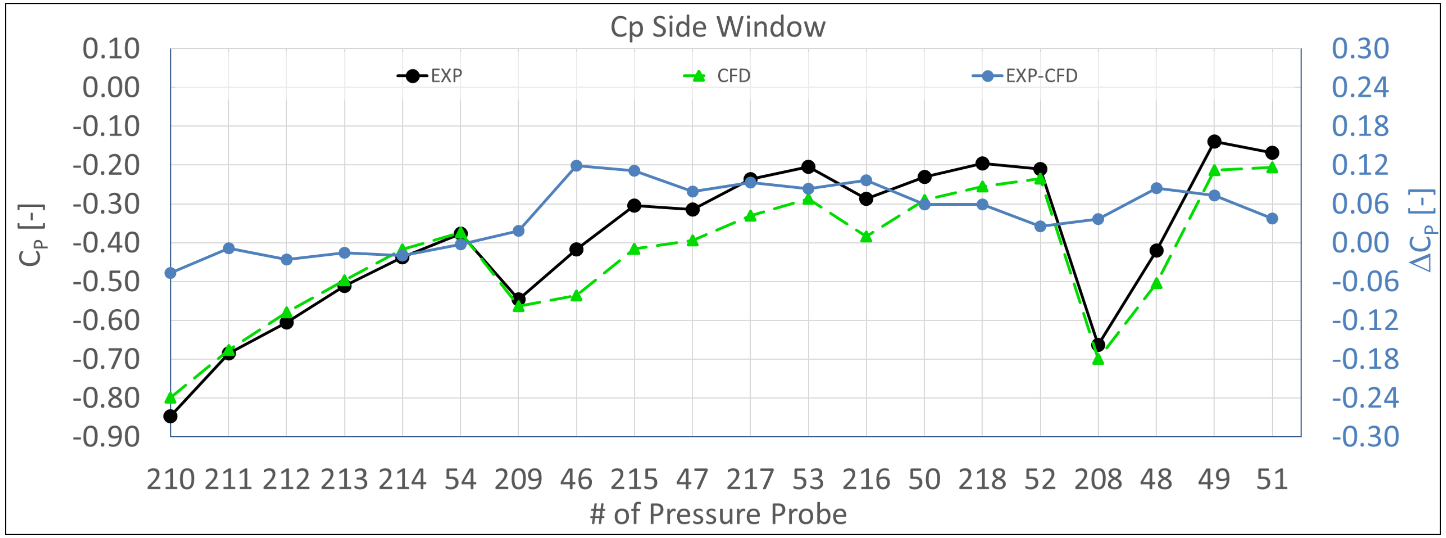




Set 2: Surface Cp – Front-Side Window

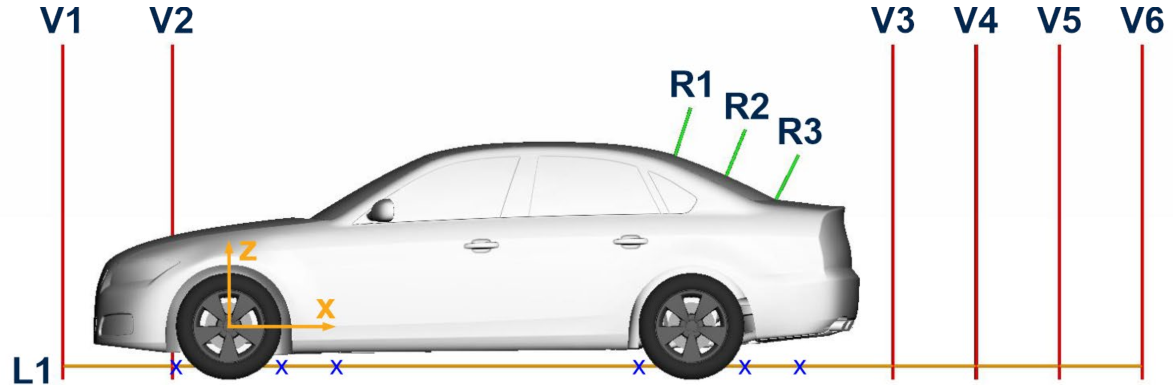
- Very good prediction downstream of the A-pilar and away from the mirror
- Under-prediction of the pressure field downstream of the mirror.

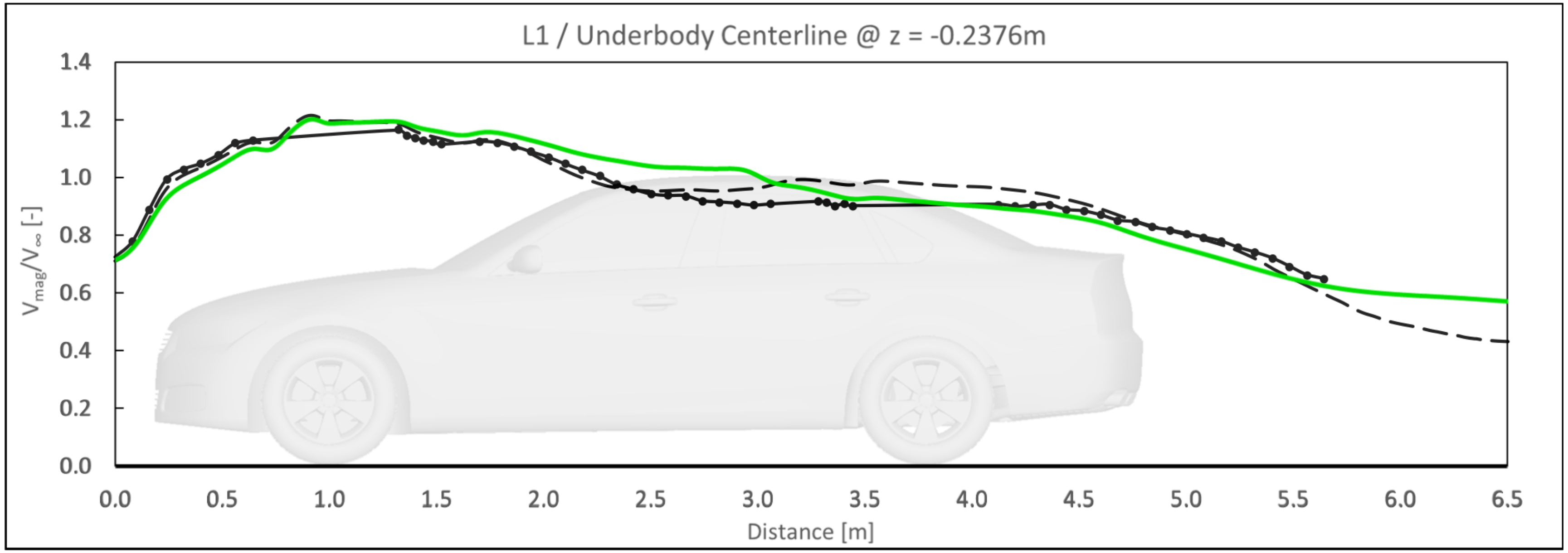




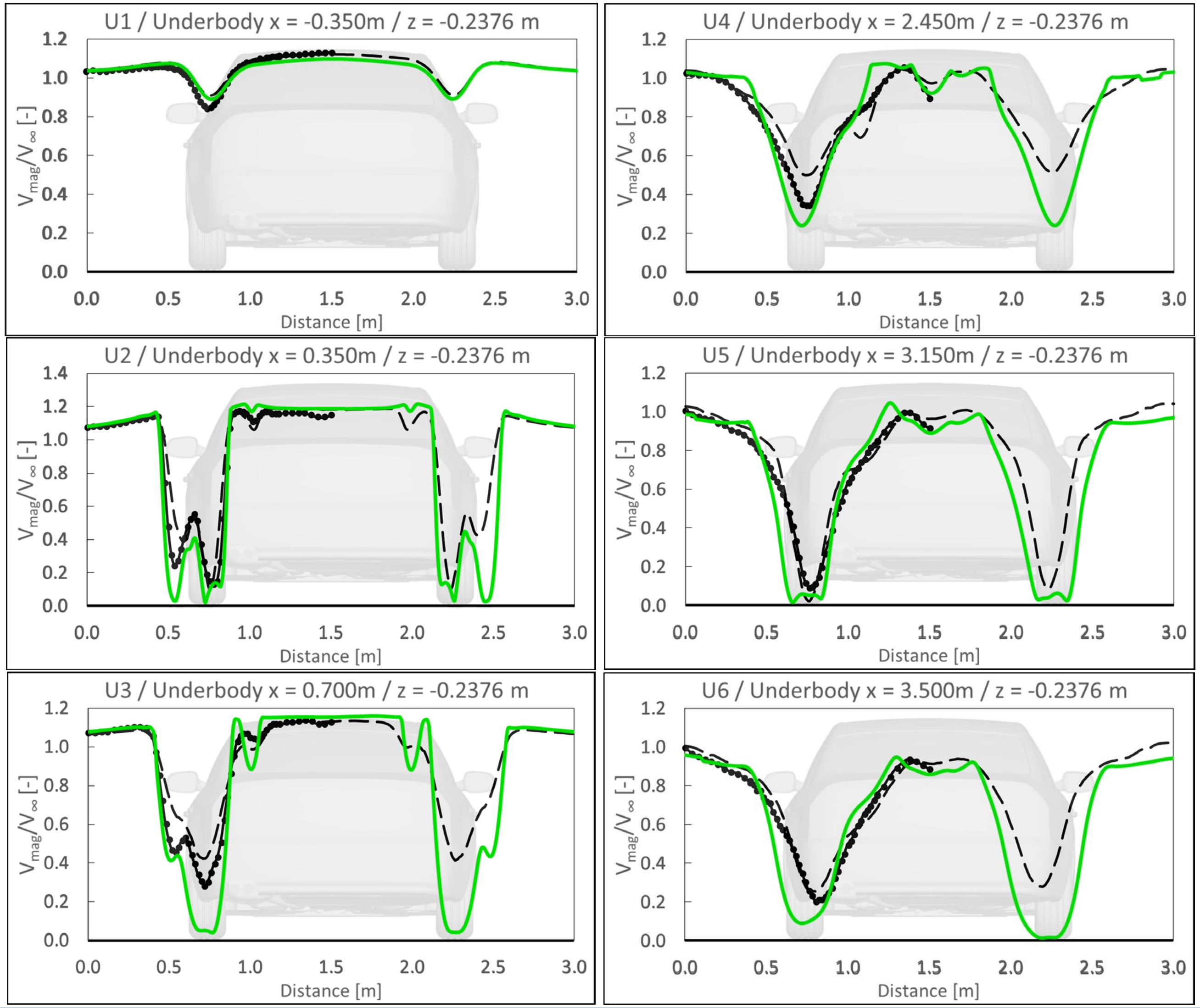
Set 2: Velocity Profiles – Streamwise
z = -237.6mm ; 80mm from ground

- Overall, good prediction of the velocity field beneath the car
- Some under-prediction ahead of the front axle as a result of underpredicting the suction peak at the front edge of the underbody
- Mid floor over-prediction probably associated with the ground boundary layer build-up and separation from gearbox.

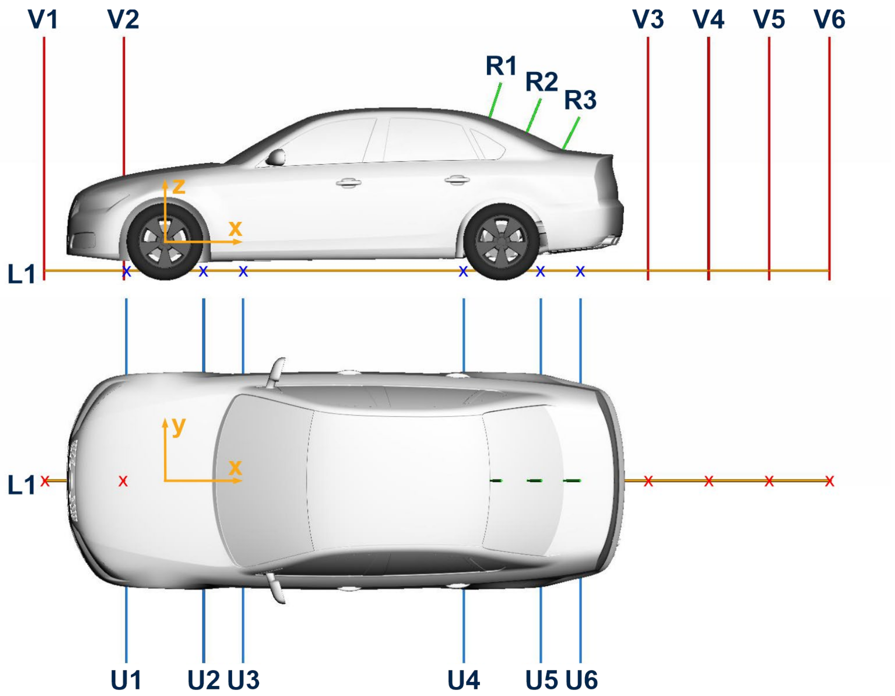




Set 2: Velocity Profiles – Spanwise z = -237.6mm ; 80mm from ground

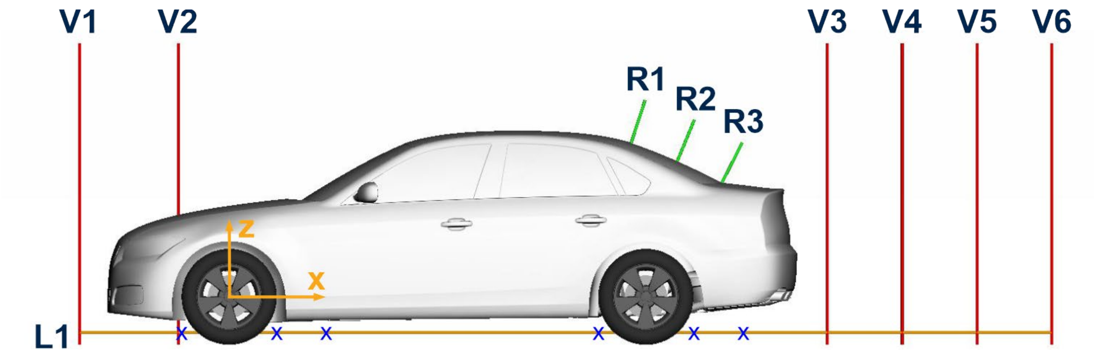


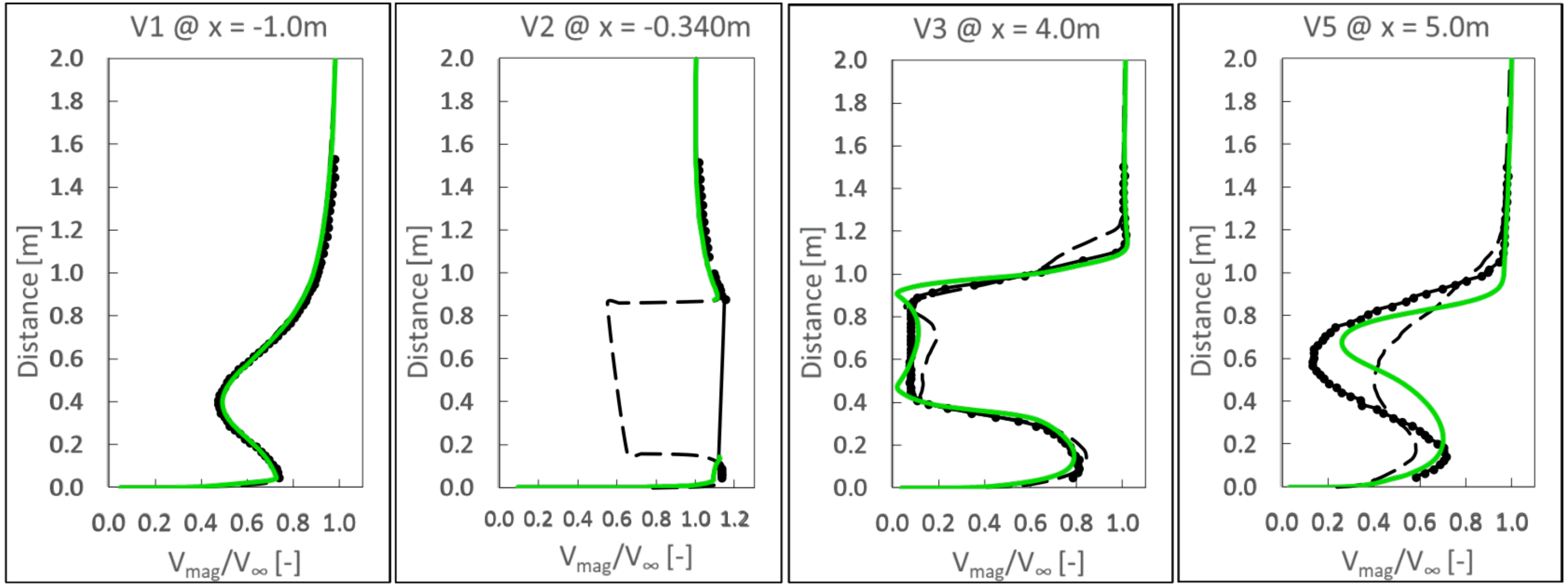
- Overall, good prediction of the velocity field
- some over-prediction of tyre wake loss and core width due to high tyre surface roughness setting.



Set 2: Velocity Profiles – Ground-Normal

- Very good prediction of velocity distribution in the front part of the model; V1, V2
- The front part of the rear wake is well predicted with slight over prediction of the ground boundary layer; V3
- Further downstream => slight underprediction of wake loss & height; V5.

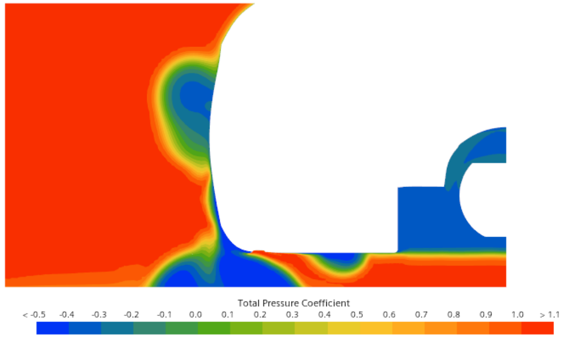


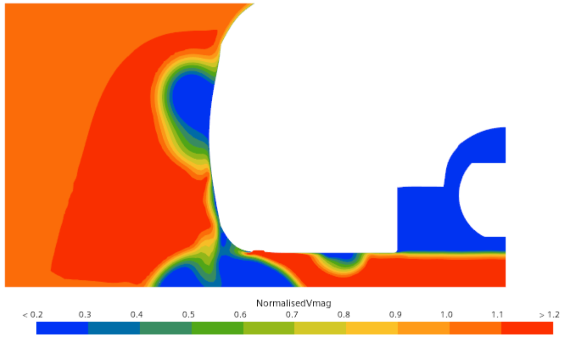


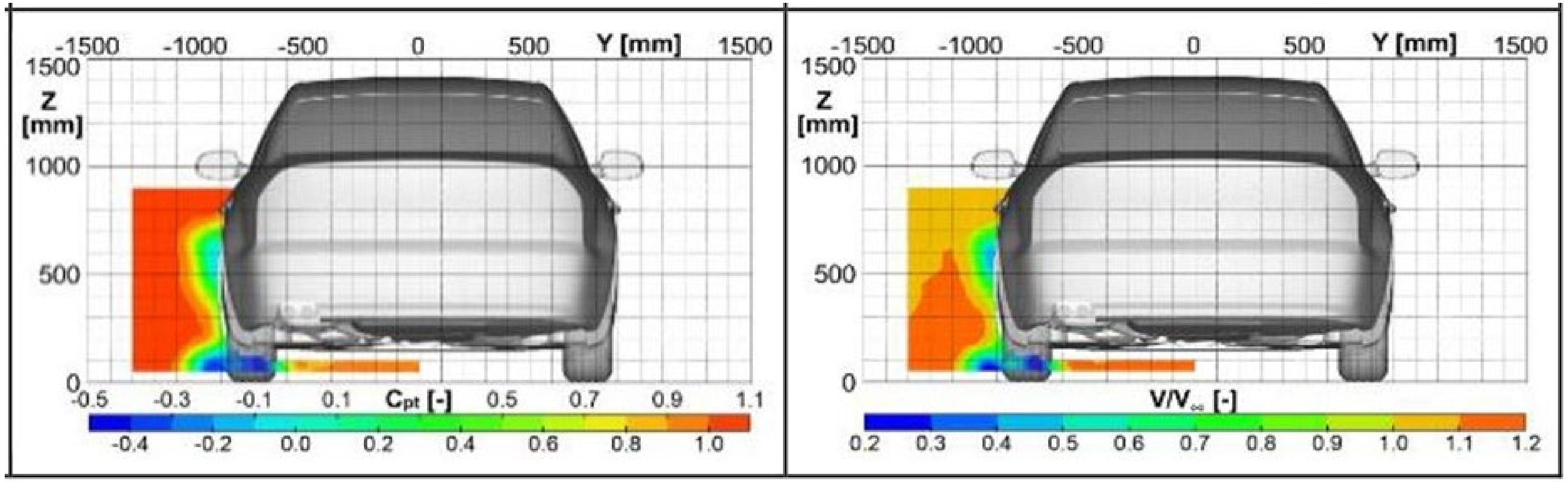
Set 2: Contour Plots x = 400mm

- Lower front tyre wake extent predicted reasonably well
- Lossier and less diffused wake edges in CFD, but WT data spatial resolution is unknown (diffused wake edges).

- Over-prediction of the upper wake resulted from the mid-tyre outer side wall, due to high surface roughness setting in CFD.

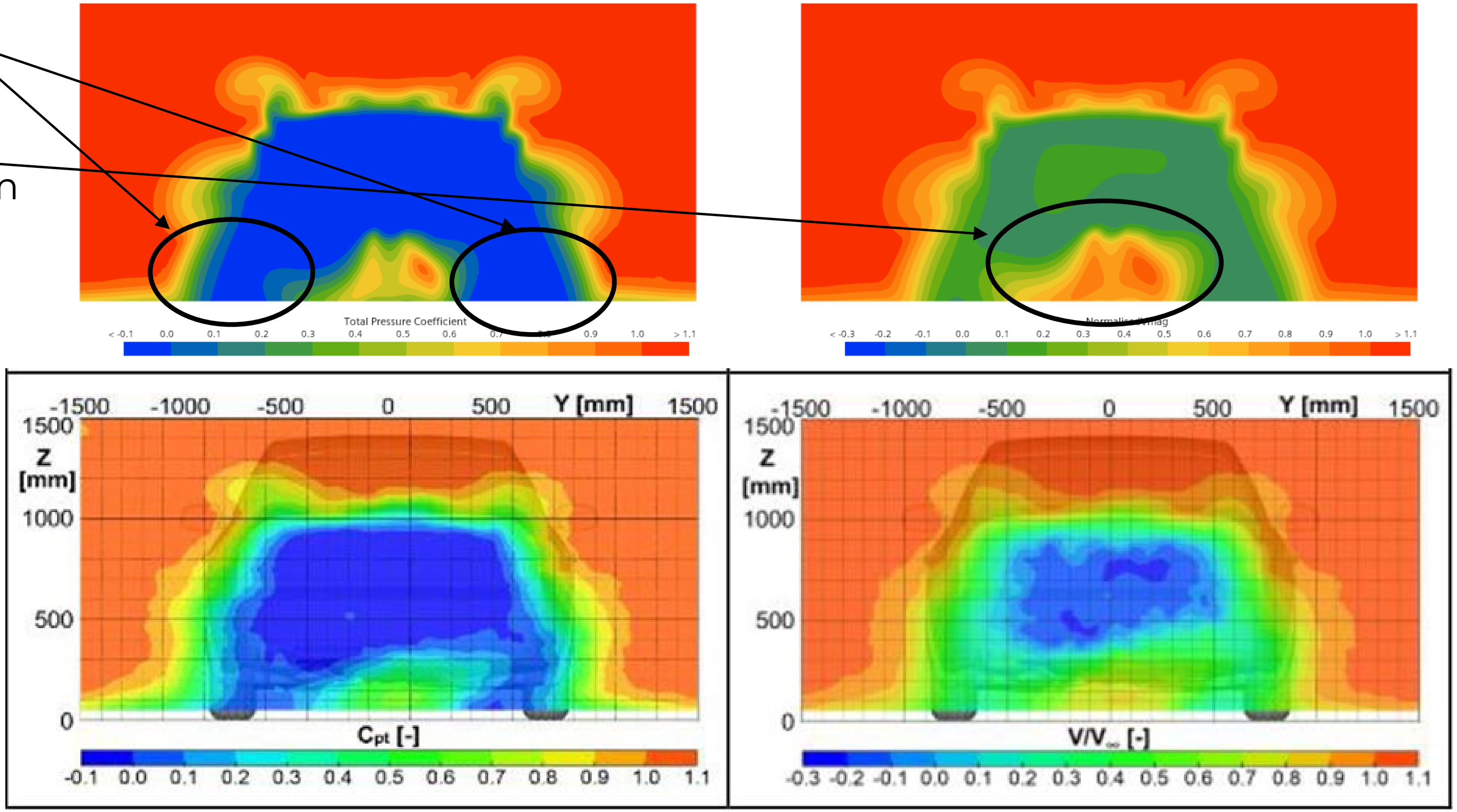






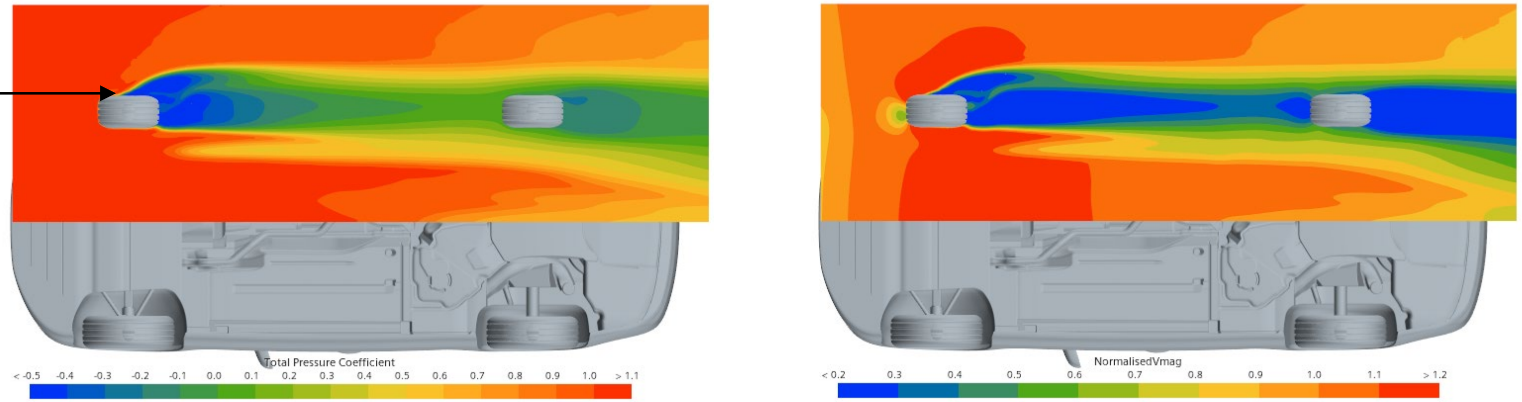
Set 2: Contour Plots x = 4000mm

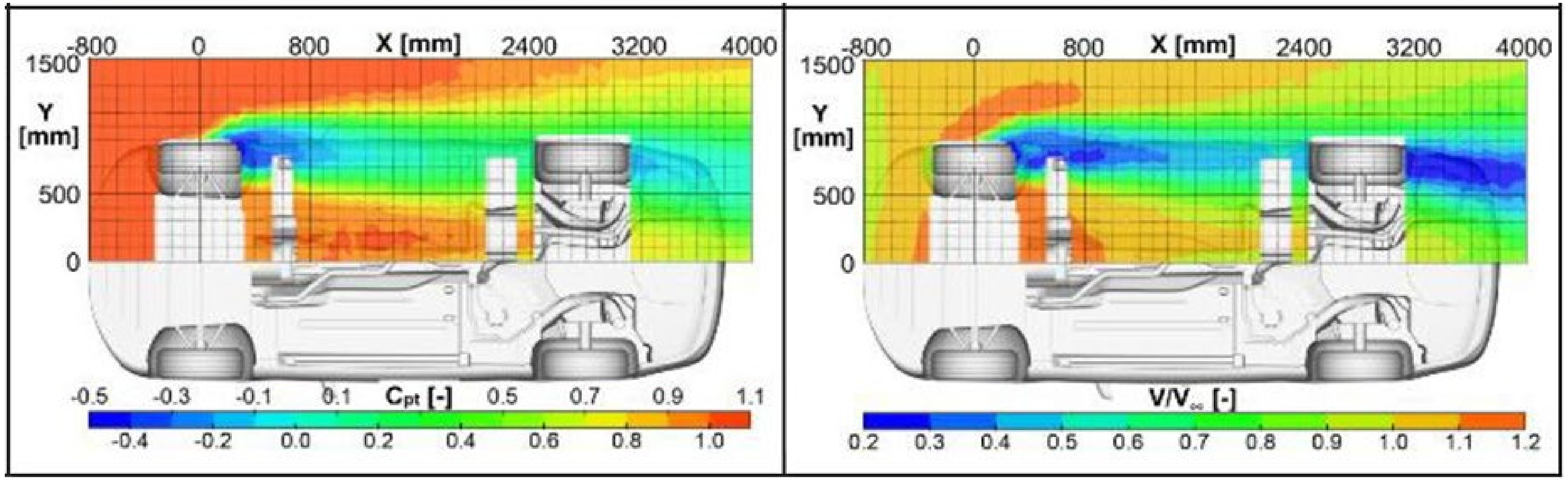
- Again, more diffused wake region edges in the WT data
- More defined wake features in CFD with lossier and wider rear tyre wakes
- This caused a higher momentum flow in the central region of the underbody



Set 2: Contour Plots z = -237.6mm
80mm from ground

- Confirmation of more defined tyre wake regions in CFD with less diffusion and greater momentum loss
- A greater extent of the separation off the front tyre side wall mid-section
- Higher momentum flow beneath the underbody as a result of the narrow tyre wakes.





Conclusion

- SABE's CFD methodology has been demonstrated to well predict aerodynamic characteristics of a representative road vehicle, namely DrivAer car model
- The CFD data correlated well with WT data in terms of forces, surface pressure distributions, cross-flow velocity profiles and 2D contour plots
- A CFD-WT correlation exercise should account for both WT experimental detailed setup and execution as well as CFD methodology settings
- CFD methodology should replicate as much as possible the WT test section geometry, test conditions, model fidelity and setup within the specific test the data in concern are provided for
- CFD-WT correlation requires both better reporting and evaluation of experimental data as well as improvement in CFD methodology.