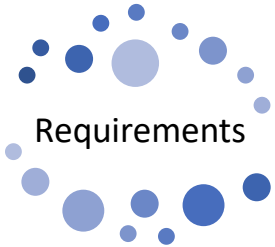
Targeting Enhanced Numerical Stability, Solver Performance & Accuracy on Industrial Applications

ICON Technology & Process Consulting

ICON

Introduction



- High-fidelity results
- Enhanced solver performance
- Efficient data management solutions

Methodology

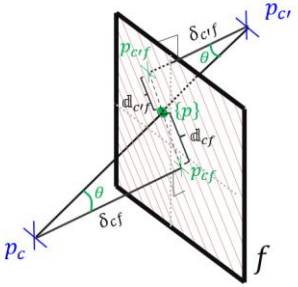
- **iconSeamlessSolve**: New pressure-based solver for both steady and transient flows
- **PBMAS**: Performance optimized by selective application of single precision
- **iconPlatform**: Cloud-based simulation environment

Outcome

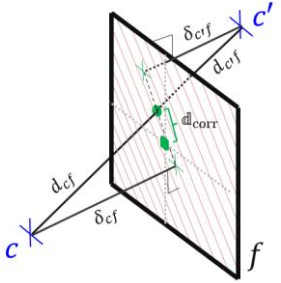
- Superior Stability and robustness
- Runtime performance
- Not compromised accuracy
- Efficient and improved data analysis on iconPlatform

Background

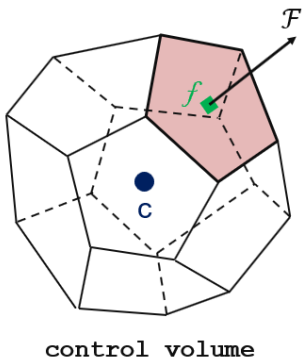
- Conventional numerical schemes: formulated for structured grids based on certain conditions
  - Orthogonal alignment of cells
  - Conjunctionality (no skewness)
- Contemporary CFD: polyhedral meshes for complex geometries
- Shortcomings: the baseline theory was not natively designed to handle such general configurations
- Legacy FV solvers (e.g. SIMPLE, PISO) are sensitive to mesh
  - Physics-fidelity (due to e.g. non-orthogonal limiters)
  - Robustness (Rhie-Chow pressure stabilization)
  - Performance (PISO convergence rate)



Orthogonality



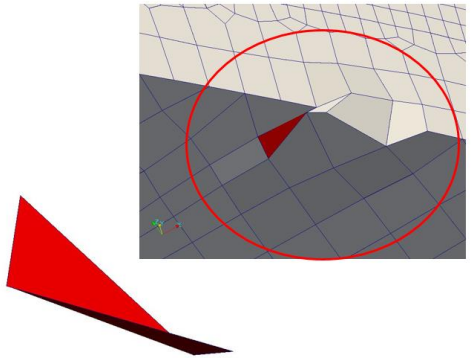
Conjunctionality



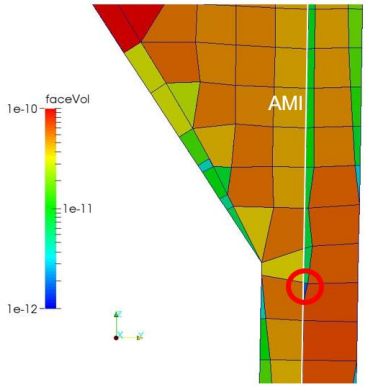
control volume

Background

- Conventional solution
  - Improve the overall mesh quality and meshing best practice to mitigate the effect of spurious “bad cells”
  - Need to resort to velocity damping for numerical stability (but at the risk of accuracy)

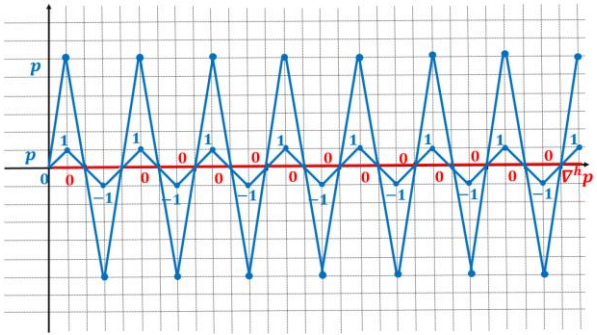


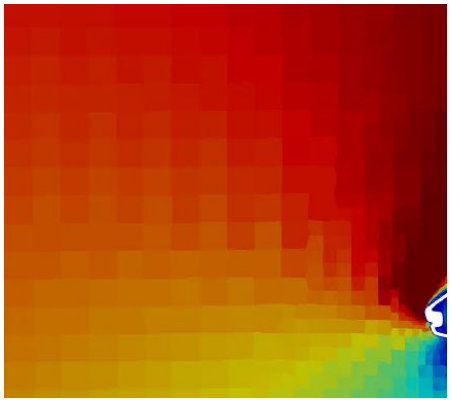
- Challenges with the most advanced meshing tools to get high fidelity CFD models
  - Balancing many conflicting constraints (e.g. perfect layer coverage, various quality metrics etc.)
  - Despite significant improvements, a few isolated tiny and/or twisted cells could still be produced



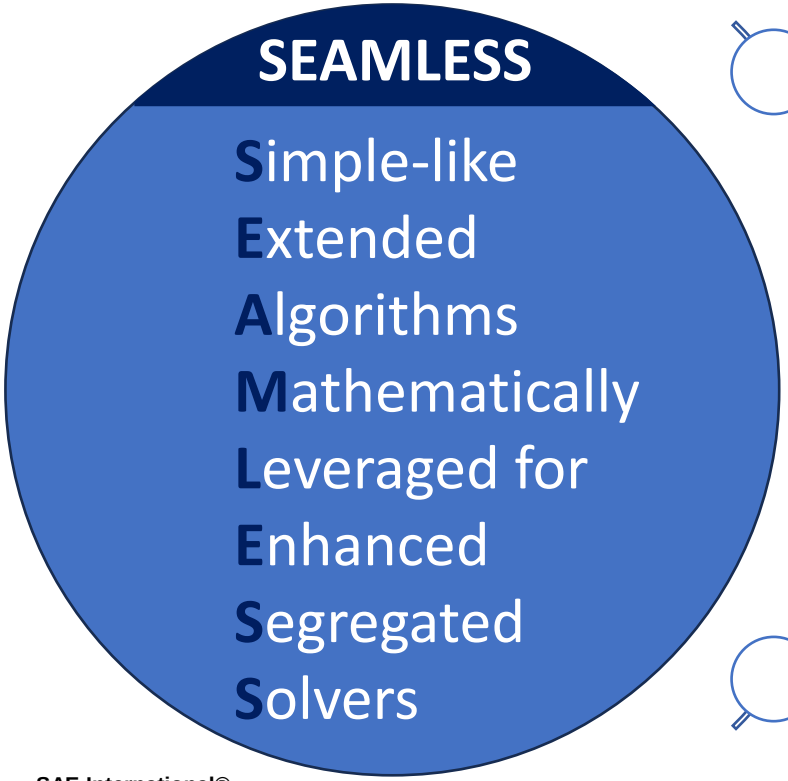
Methodology: SEAMLESS

- Motivation:
  - Increase robustness wrt mesh quality and prevent divergence despite a few bad cells without having to resort to very small time steps or URFs
- Approach:
  - Revise pressure stabilization method to fulfill a general inf-sup condition on ANY mesh guaranteeing the absence of checkerboard modes and FREE from non-orthogonal limiters
  - Devise a new preconditioner for pressure increment equation that guarantees convergence
- Further improvements to the p-U coupling solution algorithm:
  - Derivation of an optimal SIMPLE-like preconditioner (SIMPLEST - Semi Implicit Method for Pressure Linked Equation with Spectral Thinking)
  - Modification of the corrector step to solve for exact continuity equation as opposed to a simplified one in legacy solvers
  - Implementation of dynamic tolerance control to adapt the threshold in case of divergence





Methodology: SEAMLESS



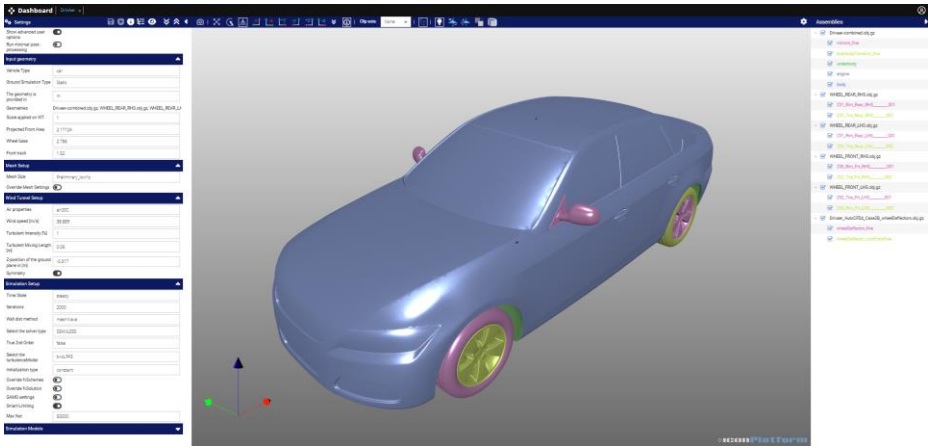
- Major revision of pressure stabilization method
- Higher order pU-coupling operators available
- Enhanced SIMPLEST preconditioner
- Dynamic algorithm controls
- Non-orthogonal limiters-free pressure equation solver
- Enhanced corrector step (solving for exact continuity equation)
- Unified solver for steady, transient and dynamic mesh

Methodology: PBMAS

- Performance Based Memory Aligned Streamlining
- Mixed precision approach in iconCFD
  - Precision-sensitive algorithms/methods evaluated at double precision and stored at single precision
- Combined with SEAMLESS, PBMAS significantly reduces runtime performance
- Entire workflow is accessible through an integrated double-precision/mixed-precision build
  - Geometry and mesh generation performed in double precision
  - Solver run in mixed precision
- iconCFD Process sets up cases compatible with SEAMLESS and PBMAS

Methodology: iconPlatform®

- All simulation data was managed on the single web-browser interface called iconPlatform®
  - Software agnostic graphical interface to all data / all simulations / all HPC
  - “App” created for analysing performance statistics
- Simulations submitted directly through iconPlatform® and results compared within same interface
- iconPlatform® helped to streamline CFD workflow and improved efficiency in analysing data
  - Allows easy sharing of data within teams
  - DoE filter allows filtering large subsets of data



Results: DrivAer (Steady)

- Legacy solvers struggle with bad quality mesh resulting in very high max pressure eventually leading to solver divergence
- SEAMLESS runs through seamlessly and robustly on same mesh


```
"ABORT WITH MIN/MAX VALUE (timeValue=0.024): stop+write data"
[1]
[1]
[1] --> FOAM FATAL ERROR:
[1] "ABORT WITH MIN/MAX VALUE (timeValue=0.024): stop+write data"
[1]
[1]     From function virtual Foam::Time &Foam::Time::operator++()
[1]     in file db/Time/Time.C at line 1032.
[1]
FOAM parallel run aborting
[1]
[1] #0  Foam::error::printStack(Foam::Ostream&) at ??:?
[1] #1  Foam::error::abort() at ??:?
[1] #2  Foam::Time::operator++() at ??:?
[1] #3
[1]  at ??:?
[1] #4  __libc_start_main in "/lib/x86_64-linux-gnu/libc.so.6"
[1] #5
[1]  at ??:?
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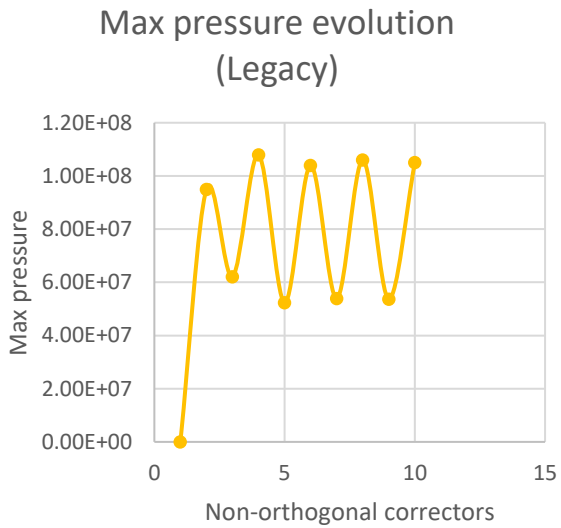
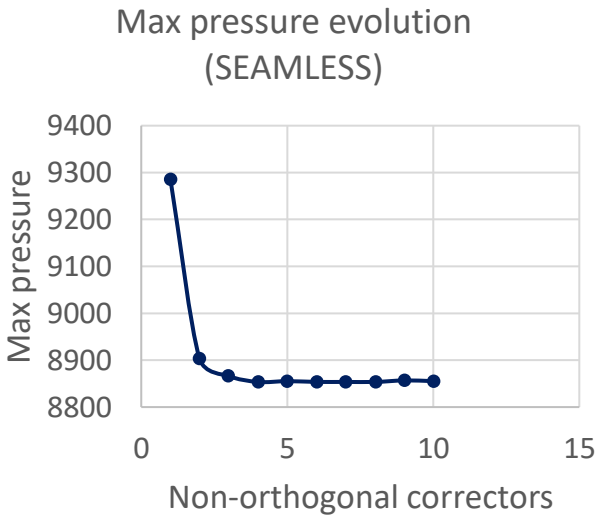


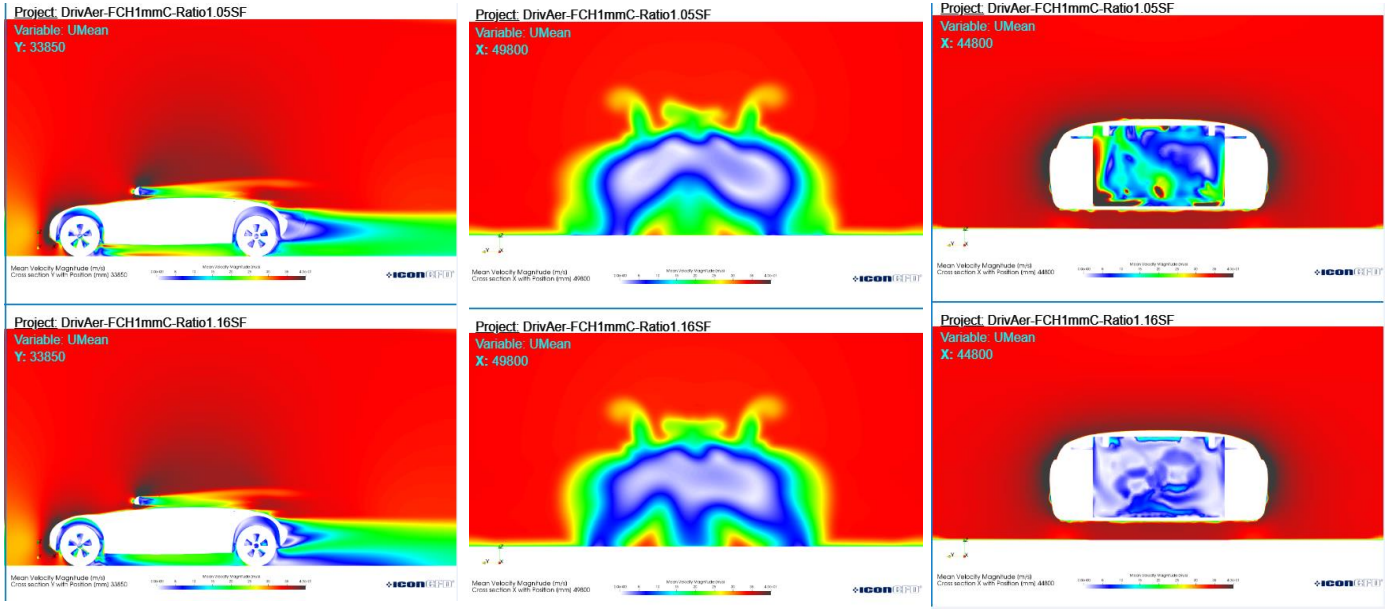


Results: DrivAer (SIMPLEC Steady)

- Different wake flow physics on different meshes
- Velocity damping triggered on fine mesh on some bad cells in underhood compartment
- Although not diverged, physics is not captured correctly

Mesh 1
(fine)

Mesh 2
(coarse)

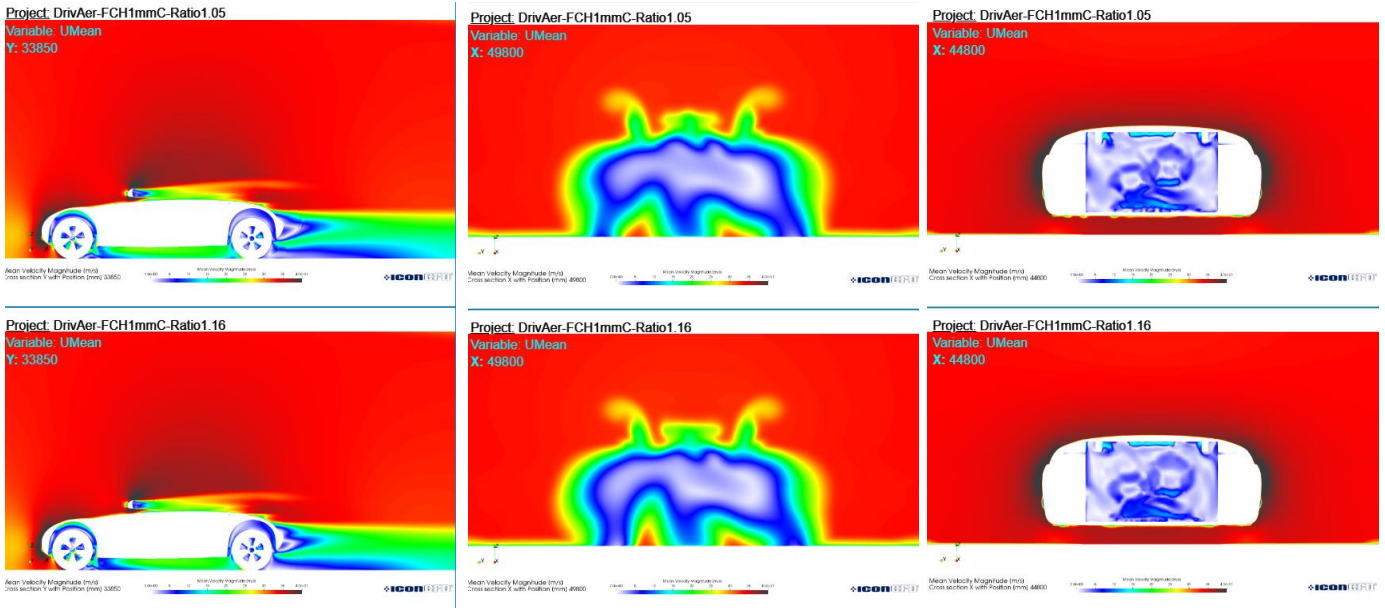


Results: DrivAer (SEAMLESS Steady)

- Results on 2 meshes using SEAMLESS solver with velocity contours
- Consistent wake flow physics on different meshes
- No velocity damping needed nor any pressure checkerboarding occurring with SEAMLESS

Mesh 1
(fine)

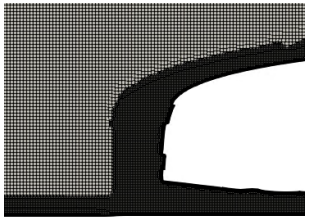
Mesh 2
(coarse)



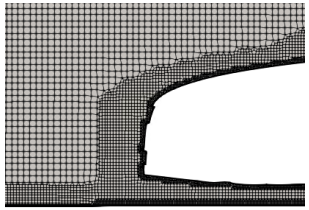
Results: DrivAer (Steady)

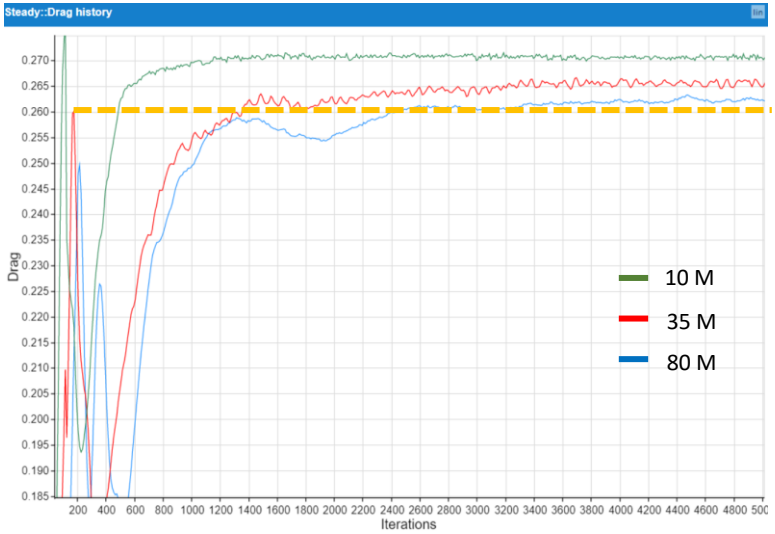
- Mesh refinement study on 3 grids with 10M, 35M and 80M cells
- Legacy solver converges to different Cd on different mesh densities
  - Requires a fine grid density to obtain Cd value close to experiment
- SEAMLESS solver converges to similar Cd on different mesh densities
  - Even on coarse grid, SEAMLESS correlates well with experiment

80 M cells

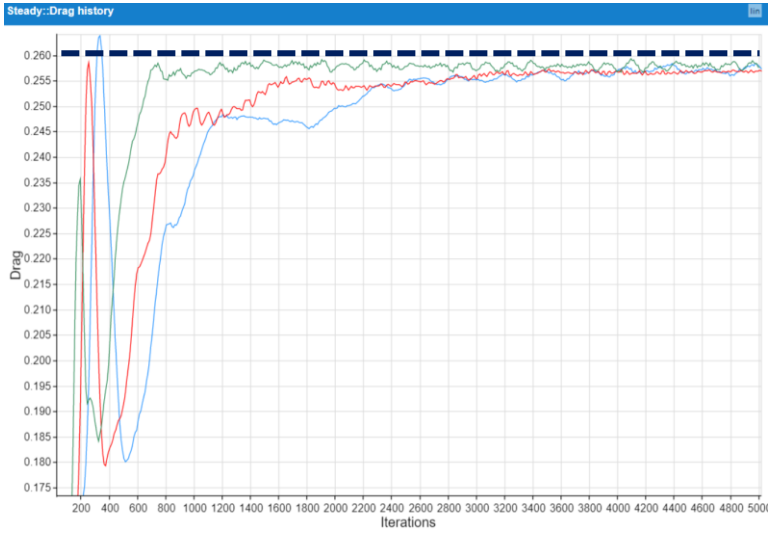


10 M cells





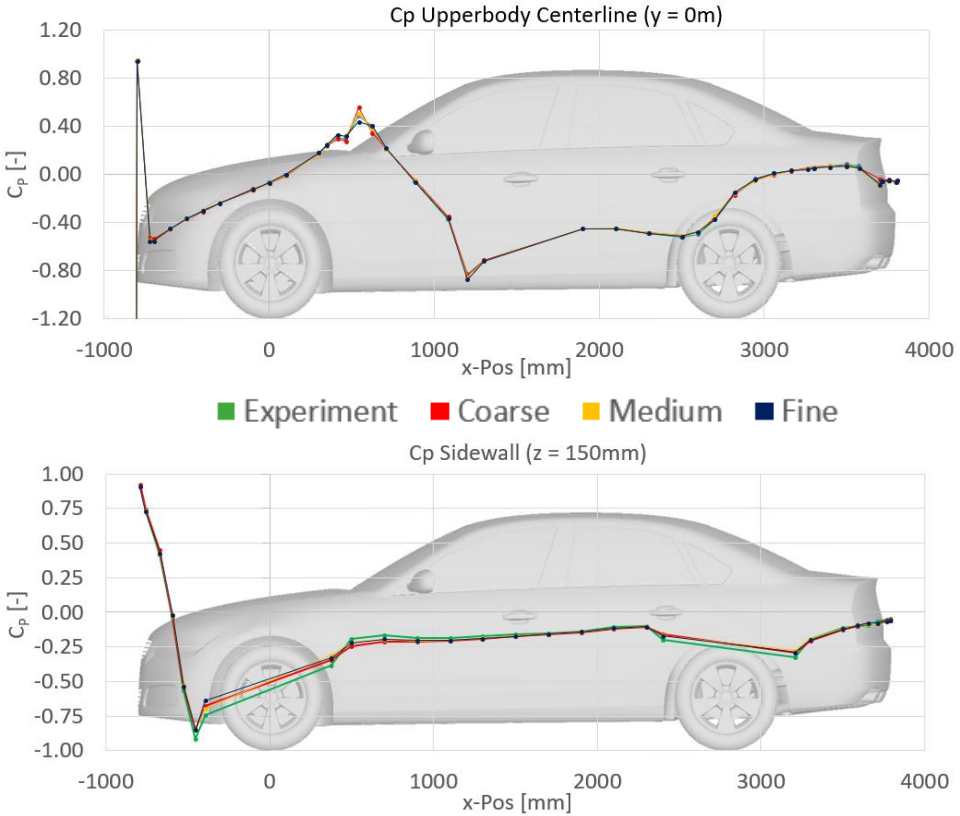
Legacy



SEAMLESS

Results: DrivAer (Steady)

- Steady solution results on DrivAer show good agreement to experimental data
- Case setup:
  - Realizable k-ε turbulence model
  - Resolved boundary layer (y+ ~ 1)
- Studied on three mesh resolution
  - Accurate results even on coarse mesh

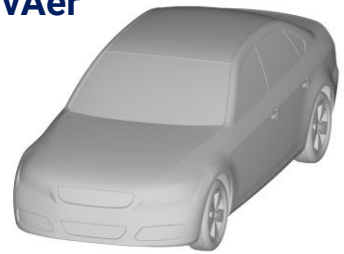


Hupertz, Burkhard, et al. "On the aerodynamics of the notchback open cooling DrivAer: A detailed investigation of wind tunnel data for improved correlation and reference." SAE International Journal of Advances and Current Practices in Mobility 3.2021-01-0958 (2021): 1726-1747.

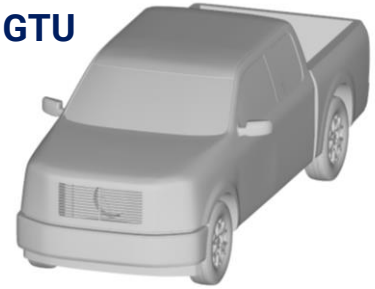
Results: Industrial Cases (Transient)

- In addition to DrivAer, three extra industrial geometries were tested in transient simulation
  - DrivAer (~ 60 mil cells)
  - GTU (~ 90 mil cells)
  - SUV (~ 110 mil cells)
  - Truck (~ 160 mil cells)
- Setup details
  - Run for 5s, averaging start at 1s
  - Steady state initialization
  - Run on 500+ cores
- Parametric studies
  - Time-step: 2e-4, 5e-4, 1e-3 s
  - Mesh resolution: Fine, 40 and 70 % less cell count

DrivAer

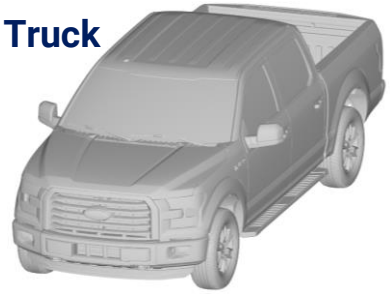


GTU



SUV

Truck

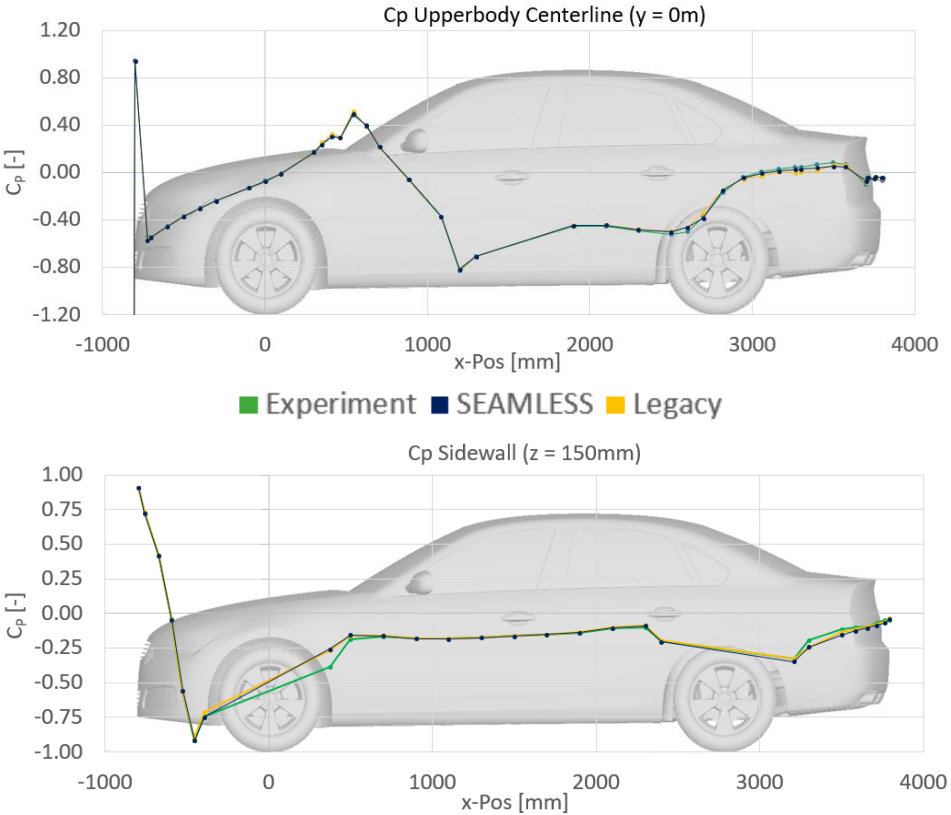


Howard, Kevin, et al. *A Detailed Aerodynamics Investigation of Three Variants of the Generic Truck Utility*. No. 2021-01-0950. SAE Technical Paper, 2021.

Lietz, Robert, et al. An extensive validation of an open source-based solution for automobile external aerodynamics. No. 2017-01-1524. SAE Technical Paper, 2017.

Results: Industrial Cases (Accuracy)

- Comparing SEAMLESS to Legacy solver on DrivAer test case on good quality mesh
  - Results on the upper body centerline and side wall show similar trend between the solvers
    - Rear window separation is crucial in this model
  - Cp values on the side of the car at a height of 467 mm above the ground shows similar values between two solvers



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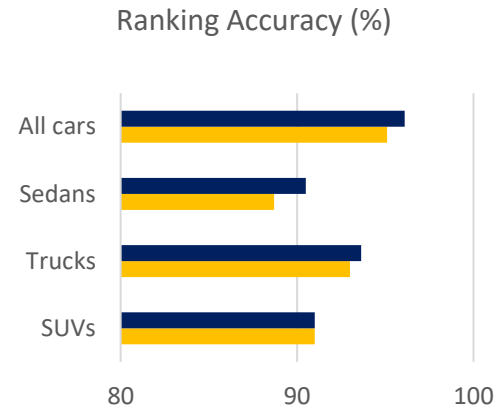
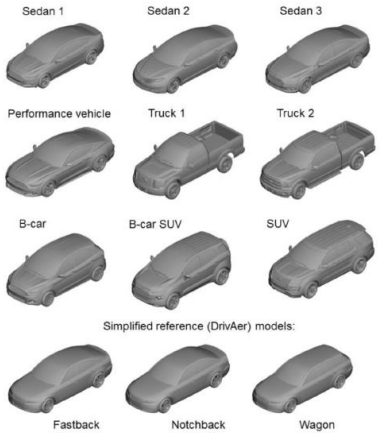
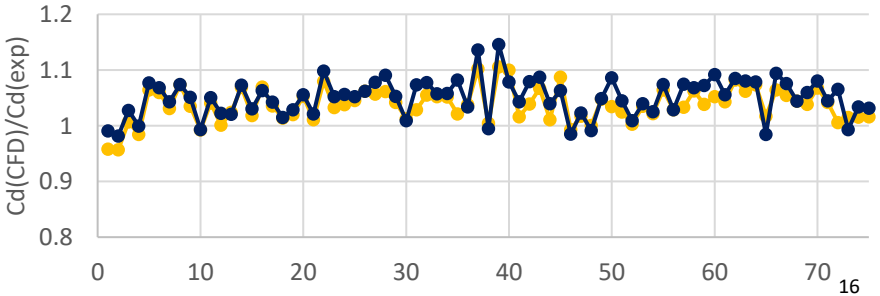
Results: Industrial Cases (Accuracy)

- Testing on a set of cases (over 70) from FMC that were published at SAE (Lietz et al. 2017)
  - Categories: sedan, truck, SUV, others
  - The overall Cd values are in similar range between the two solvers
  - Ranking accuracy: the percentage of correct prediction of Cd deltas between different configurations on the same vehicle
  - All the modification in newer version of iconCFD (including SEAMLESS solver and PBMAS) shows improvement in the ranking accuracy from 95% to 96%



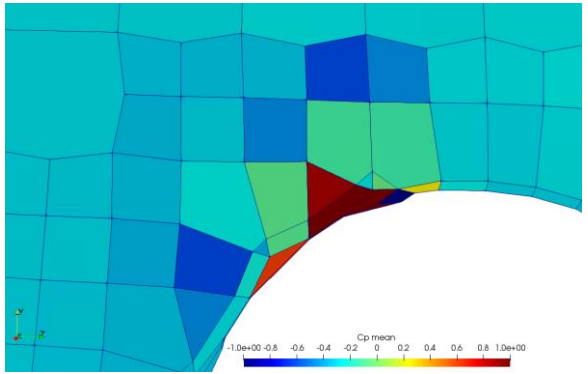




Lietz, Robert, et al. An extensive validation of an open source-based solution for automobile external aerodynamics. No. 2017-01-1524. SAE Technical Paper, 2017.

Results: Industrial Cases (Stability)

- On legacy solvers, high velocity values were observed in regions of low-quality mesh
- In Legacy solver, velocity damping is activated at those locations to prevent divergence
- With SEAMLESS, stable values for velocity were observed on the same mesh
- A significant change in the Cd development plot over the vehicle is observed at those points




```
Time = 5

velocityDamping_1 applied to 138 cells (9.48926310508e-05%)
DILUBiCGStab:  Solving for Ux, Initial residual = 4.04059571072e-06, F
DILUBiCGStab:  Solving for Uy, Initial residual = 0.00245805714082, Fi
DILUBiCGStab:  Solving for Uz, Initial residual = 0.000429669611552, F
PISO corrector = 1
GAMG:  Solving for p, Initial residual = 0.0363625494114, Final residu
GAMG:  Solving for p, Initial residual = 0.00226860939031, Final resid
time step continuity errors : sum local = 4.09472029956e-10, global =
```

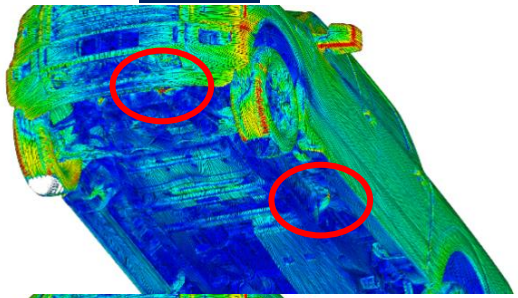
Results: Industrial Cases (Stability)

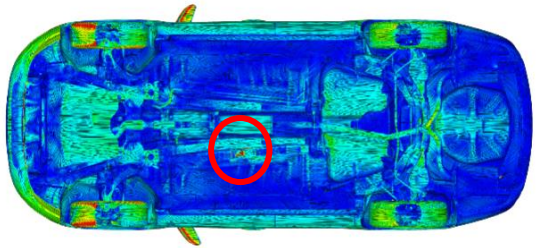
Truck

Mean near wall velocity contours

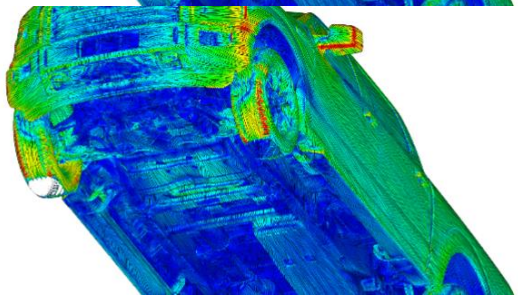
SUV

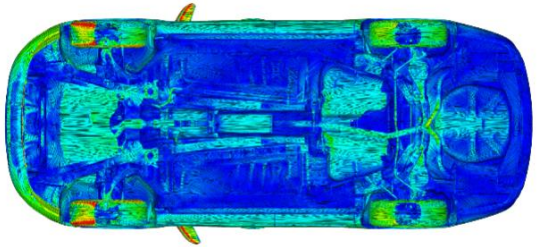
Legacy



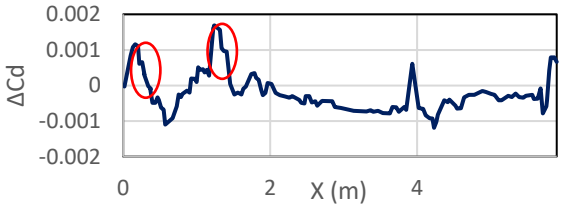


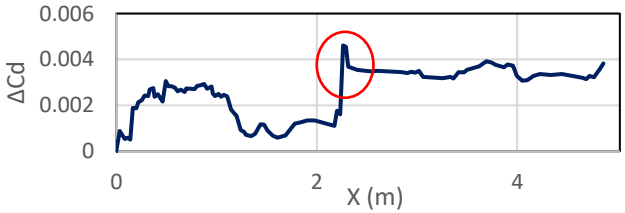
SEAMLESS





Cd dev. Delta between solvers



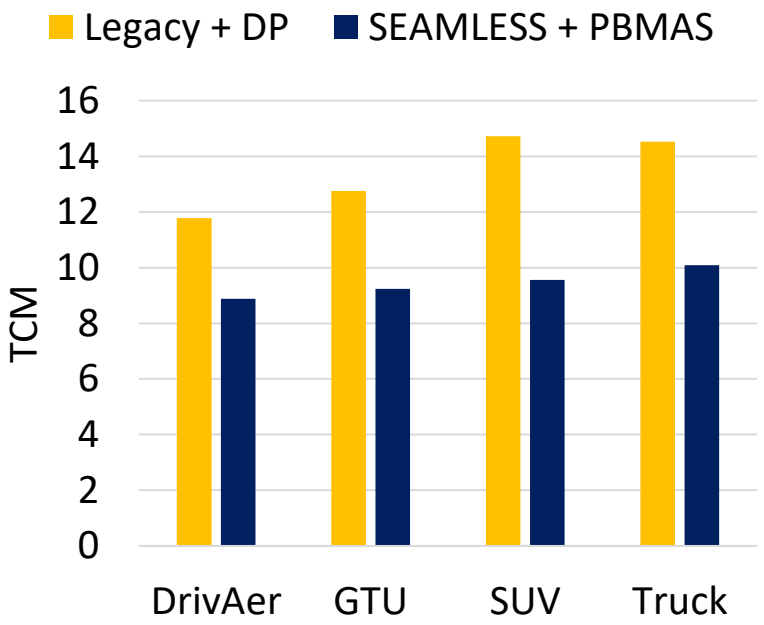


Results: Industrial Cases (Performance)

- Timing Comparison Metric (TCM) is defined as:

$$TCM = \frac{total\ solver\ run\ time\ (h) \times n\ CPU}{total\ cell\ count \times total\ sim\ time\ (s)} \times 1e6$$

- SEAMLESS + PBMAS shows 25 - 35% runtime improvement



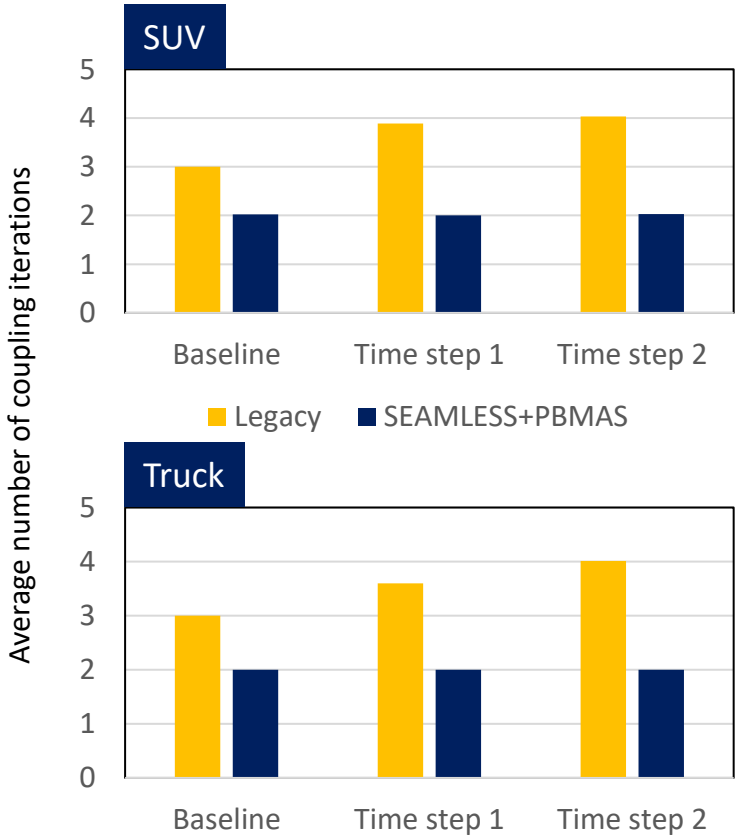
runtime reduction (%)	25	28	35	31

Results: Industrial Cases (Performance)

- Each solver behave differently in few initial time steps (Stabilization steps)
- After initial stabilization
  - Legacy solver takes 3 PISO corrector loops
  - SEAMLESS takes 2 p-U coupling iterations

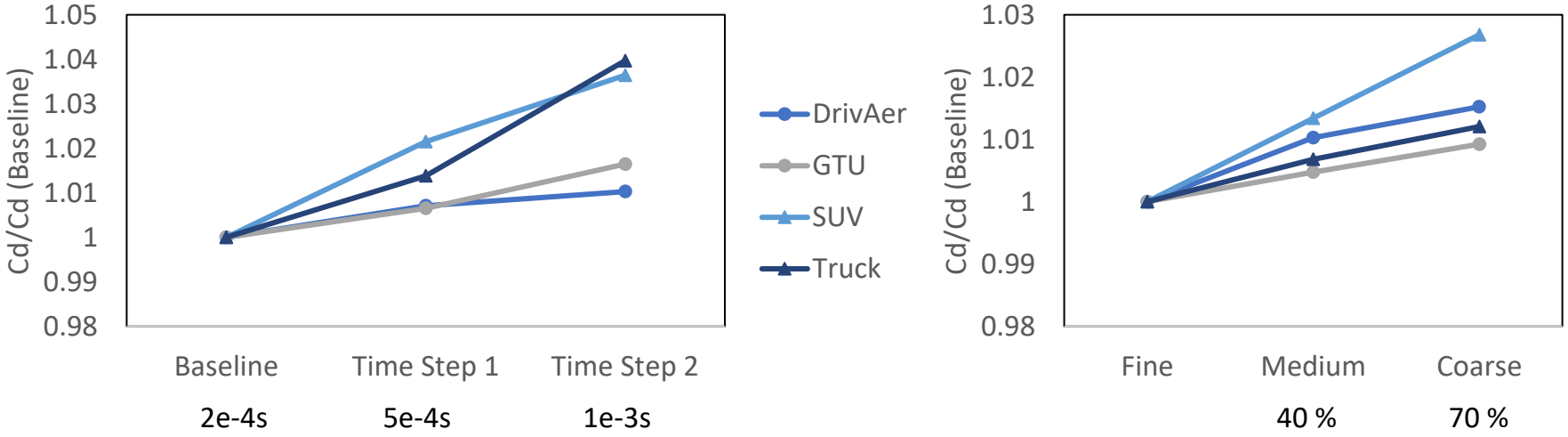
Results: Industrial Cases (Robustness)

- Mesh and time step effect on the solver performance in transient setups
  - Three mesh base sizes (2.5, 3, 3.75 m)
  - Three time-step values (2e-4, 5e-4, 1e-3 s)
- The Legacy solver struggles to reach solver convergence as the time step increases
  - The required number of coupling iterations increases
- SEAMLESS shows more robustness at larger time steps
  - Increasing time step, the number of coupling iterations in SEAMLESS is almost constant
- Mesh base size increase has no effect in the convergence rate in both solvers



Results: Industrial Cases (Robustness)

- SEAMLESS+PBMAS results show reasonable results (drag coefficients) on coarse mesh
  - Less than 4% on time step variation
  - Less than 3% on mesh size variation



Summary

- Results using the new SEAMLESS solver in iconCFD with PBMAS has been demonstrated on DrivAer and 3 industrial cases

- SEAMLESS was observed to be superior to legacy solvers in 3 aspects
  - Stability:
    - SEAMLESS shows more stability on local problematic cells
    - SEAMLESS requires no velocity damping
  - Runtime performance:
    - SEAMLESS with PBMAS shows a significant 25-35% reduction in runtime
  - Robustness:
    - SEAMLESS shows significant robustness and small variation of results at coarser mesh and time steps on transient cases

Future work

- More physics to be supported
- SEAMLESS-like OPTIMIZE (bring SEAMLESS improvement into Adjoint solver)
- Revised viscous operator and wall functions

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