XFlow
The Next Generation CFD

Unsteady and dynamic vehicle simulations using a Lattice-Boltzmann Method

Aerovehicles 2

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NEXT LIMIT TECHNOLOGIES

Outline

- Motivation
- Numerical methodology
- DrivAer Validation
  - Geometry
  - Setup
  - Refinement strategy
  - Numerical Results
- Overtaking simulation
  - Setup
  - Numerical Results
- Crosswind Adams Car-XFlow co-simulation
  - Adams-XFlow co-simulation
  - Setup simulation
  - Free steering
  - Driver control: Straight-line event

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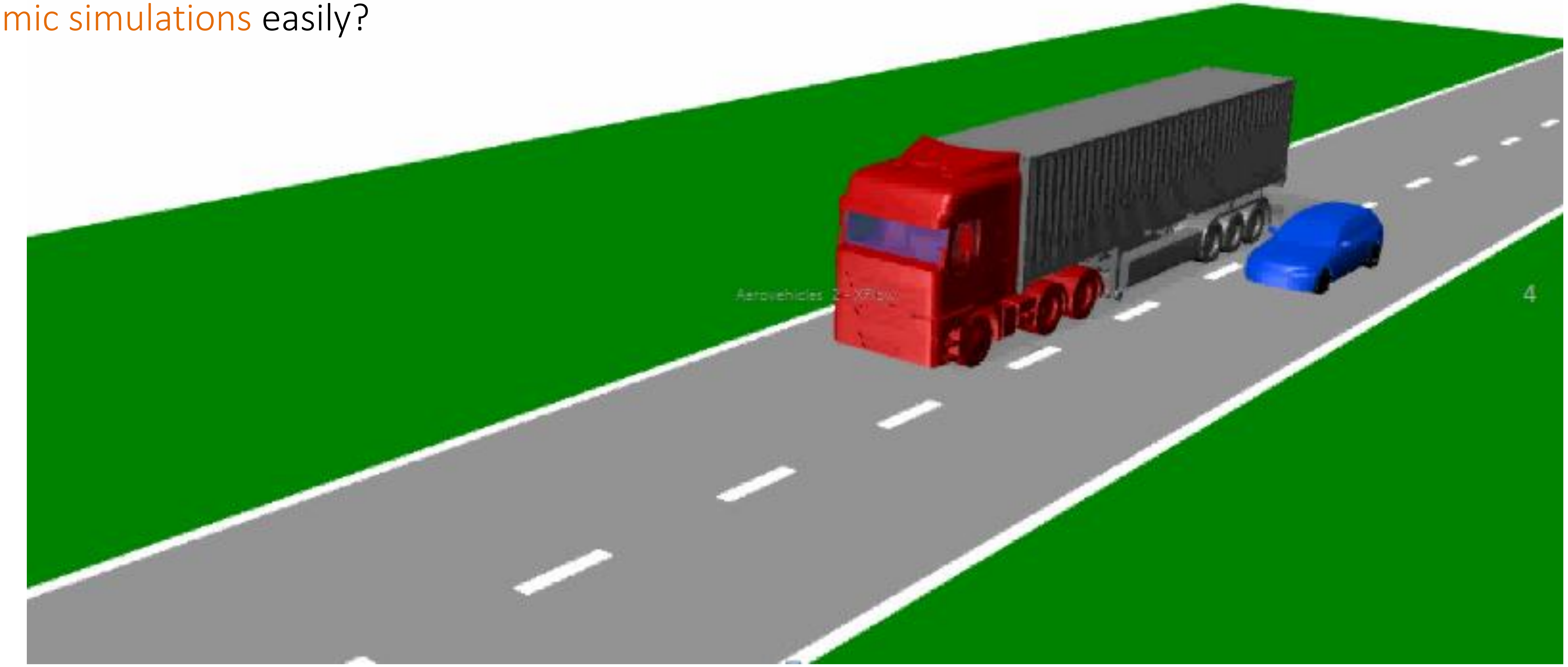
Motivation

Limitations of conventional NS methods in dynamic and unsteady simulations

→ Reliable unsteady aerodynamics for highly turbulent flow?

→ How can we handle geometries with all their details?

→ Is it possible to simulate flow at dynamic simulations easily?



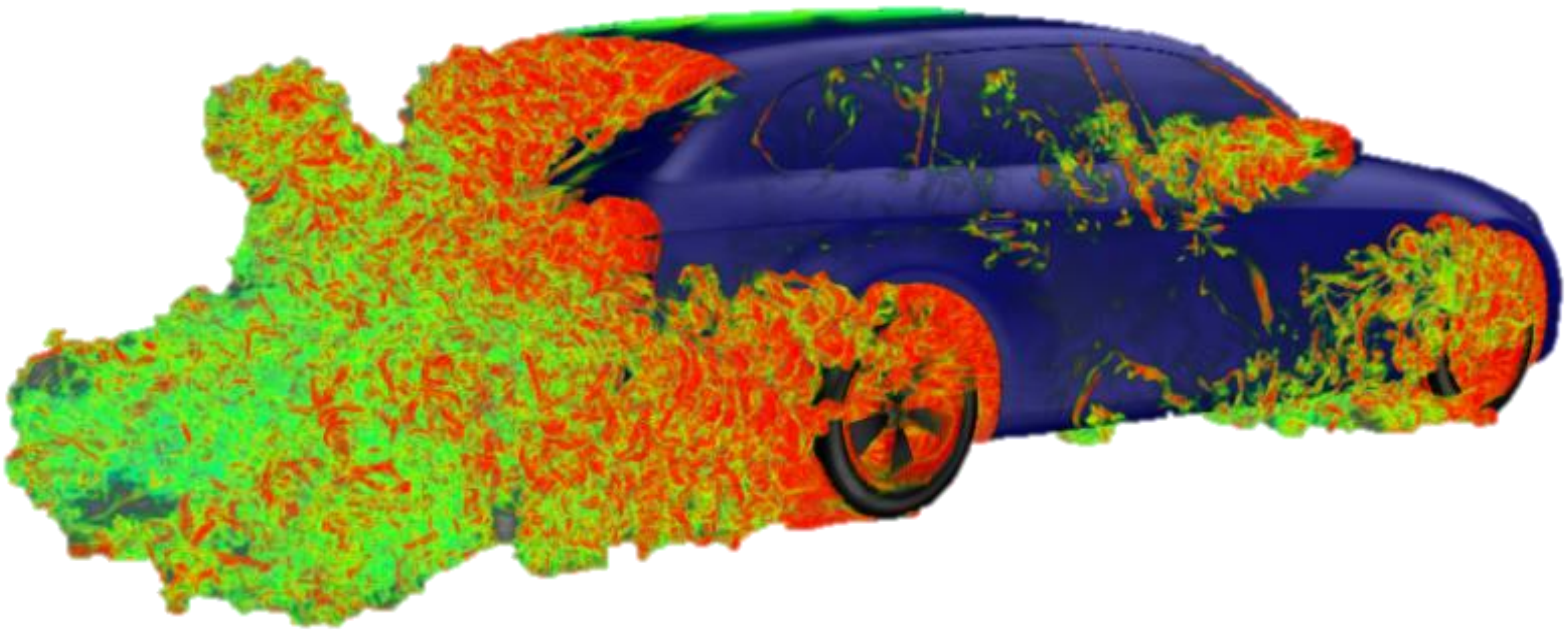
Motivation

XFlow a high fidelity approach for unsteady and dynamic simulations

→ Extremely efficient state-of-the-art WMLES (Wall model Large Eddy Simulation).

→ Particle-based approach that avoids the traditional meshing process.

→ Advanced wall treatment allows to address easily the dynamic geometries.



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Numerical Methodology

Lattice-Boltzmann Method

→ The Boltzmann equation is inspired by the kinetic theory of gases:

$$\frac{\partial f}{\partial t} + \mathbf{e} \cdot \nabla f = \Omega$$

- f : probability distribution function (PDF)
- e: microscopic velocity

Numerical Methodology

Lattice-Boltzmann Method

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$$\underbrace{\frac{\partial f}{\partial t} + \mathbf{e} \cdot \nabla f}_{\text{Streaming}} = \Omega$$

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Streaming

Lagrangian advection that exactly satisfies conservation laws.

Numerical Methodology

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- Ω: collision operator.

Streaming

Lagrangian advection that exactly satisfies conservation laws.

Collision

Redistributes the particles that arrive simultaneously at the same position.

Numerical Methodology

Lattice-Boltzmann Method

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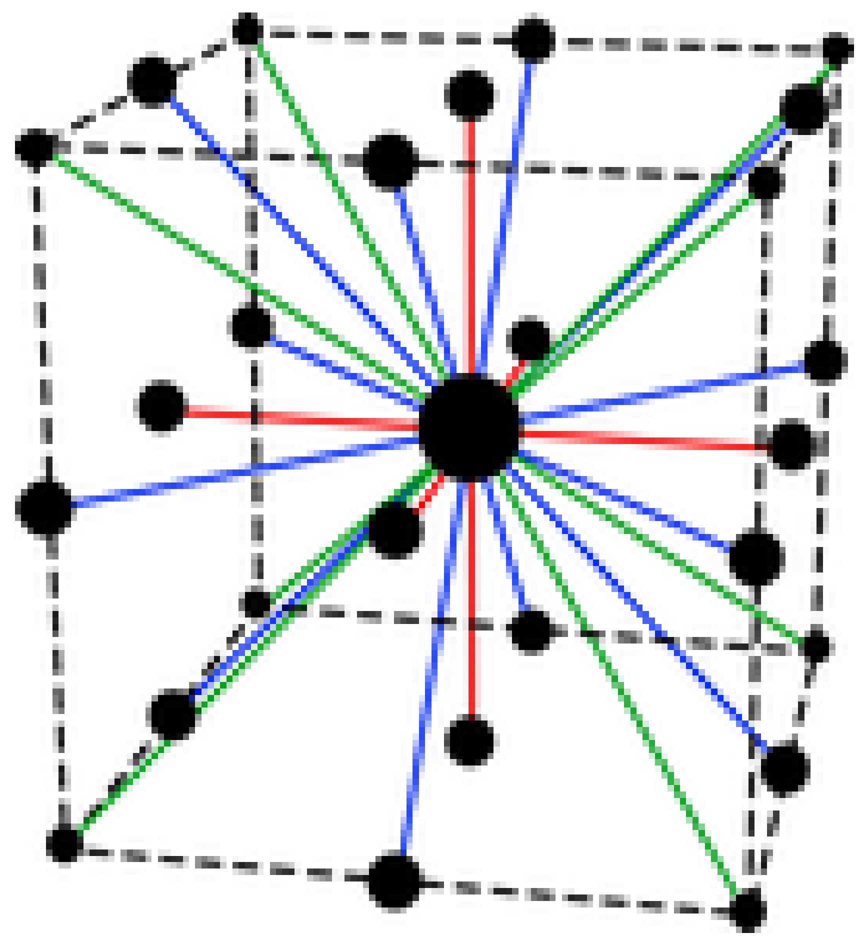
→ The function f is a particle distribution function (PDF) and depends on time, space, and velocity direction:

$$f = f(\mathbf{x}, t, \boldsymbol{e})$$



Structure D3Q27

Numerical Methodology

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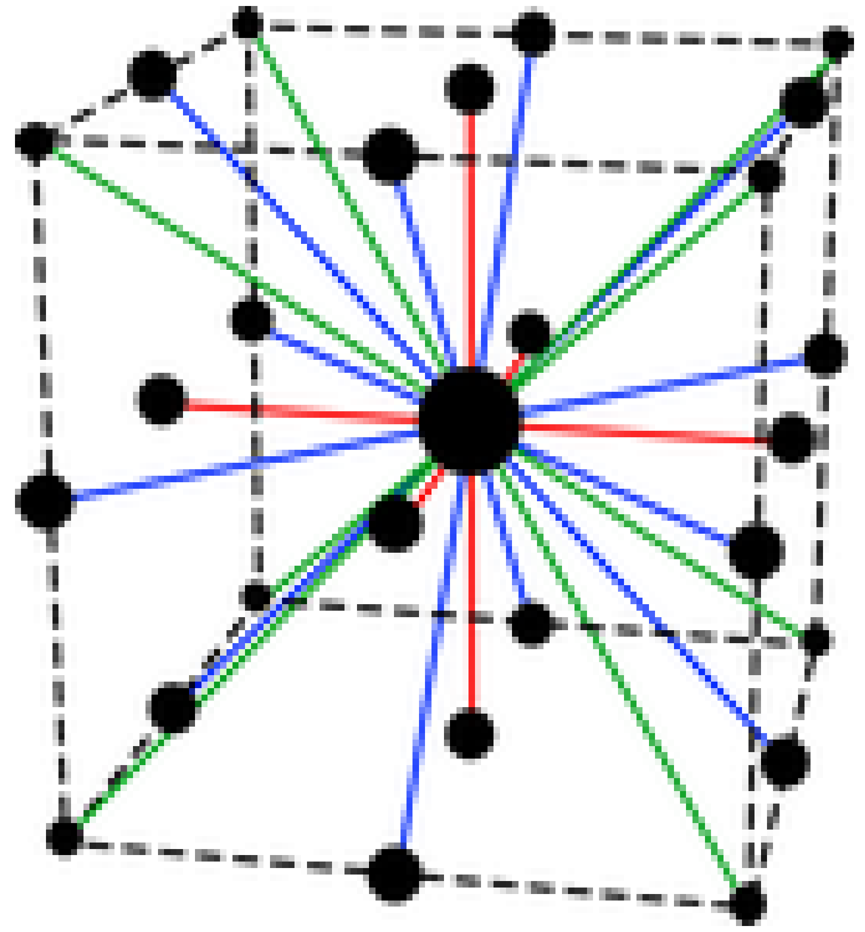
→ Macroscopic variables are statistical moments of the PDF:

27 velocity directions

$$\rho = \int f \, dv$$ Density

$$\rho u = \int f v \, dv$$ Linear momentum



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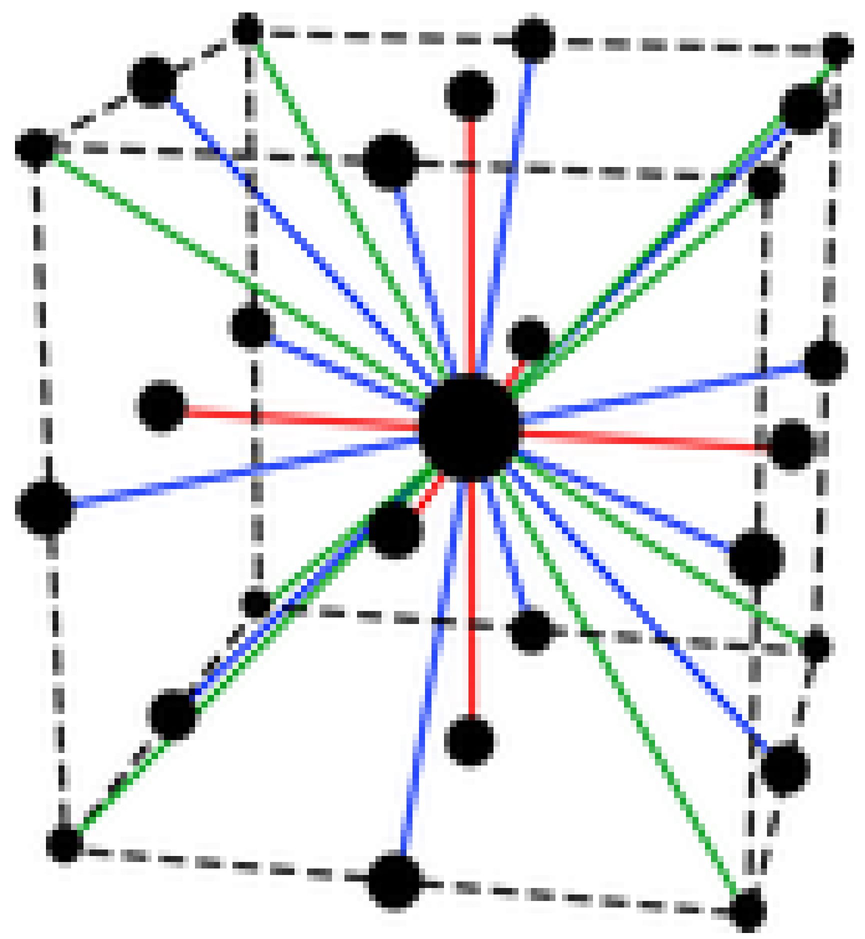
→ Macroscopic variables are statistical moments of the PDF.

→ The collision operator in XFlow is based on a multiple relaxation time scheme:

$$\Omega_i^{\mathrm{MRT}} = M_{ij}^{-1} \hat{S}_{ij} (m_i^{\mathrm{eq}} - m_i)$$

S : relaxation time matrix
m_i : moments matrix



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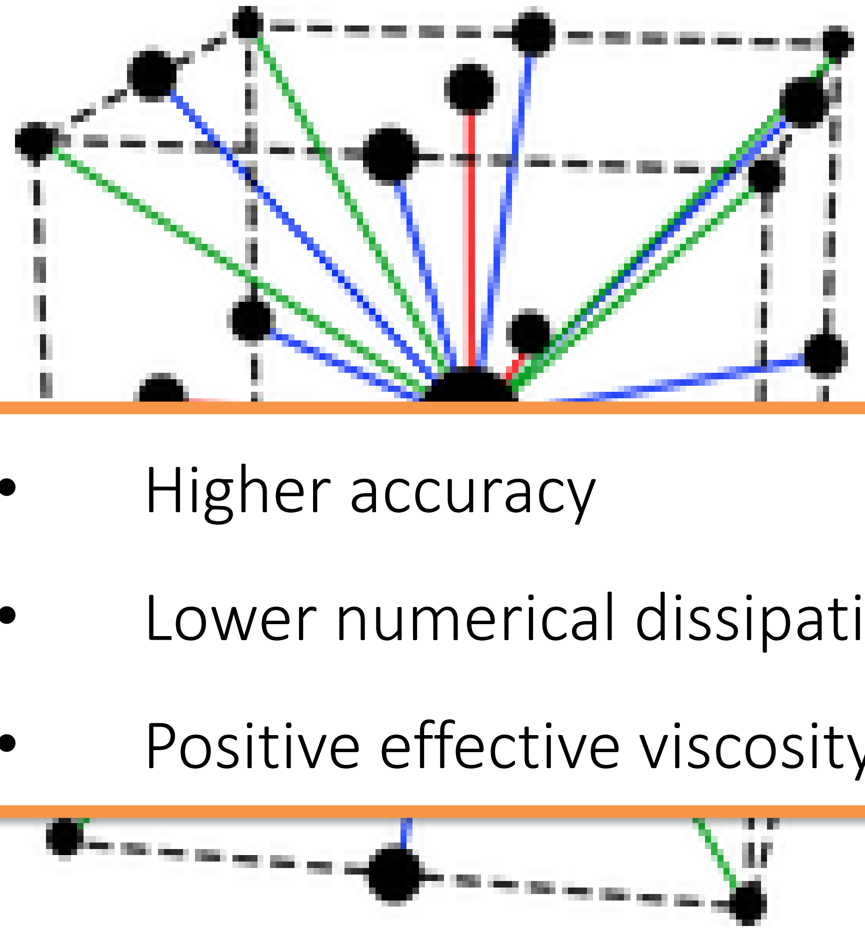
→ The collision operator in XFlow is based on a multiple relaxation time scheme:

$$\Omega_i^{\mathrm{MRT}} = M_{ij}^{-1} \hat{S}_{ij} (m_i^{\mathrm{eq}} - m_i) \longrightarrow$$

Central moments space →

- Higher accuracy
- Lower numerical dissipation
- Positive effective viscosity

S : relaxation time matrix
m_i : moments matrix



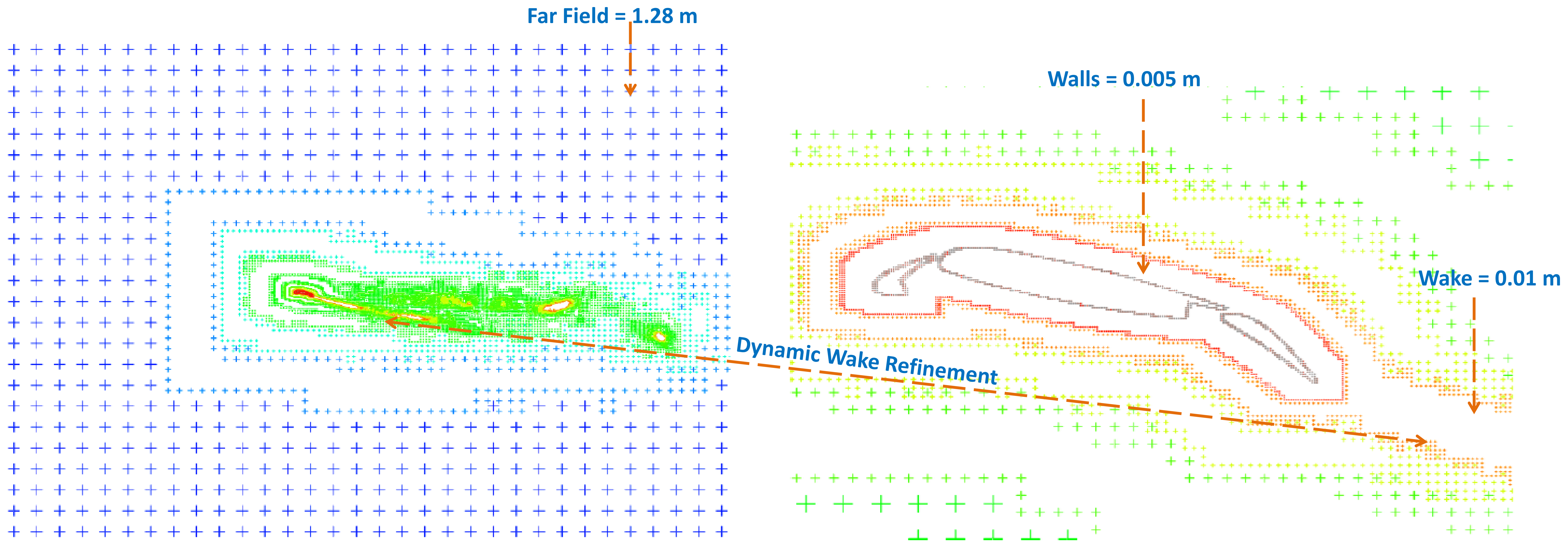
Structure D3Q27

Reference: Geier, M., Greiner, A., and Korvink, J., "A factorized central moment lattice Boltzmann method," *The European Physical Journal Special Topics*, Vol. 171, No. 1, 2009, pp. 55-61.

Numerical Methodology

Octree lattice structure

- → Automatic generation with octree structure which supports multi-resolution.
- → Refinement criterias: near geometries and curvature.
- → Adaptive & dynamic refinement: wake, moving parts, vorticity gradients and pressure gradients.

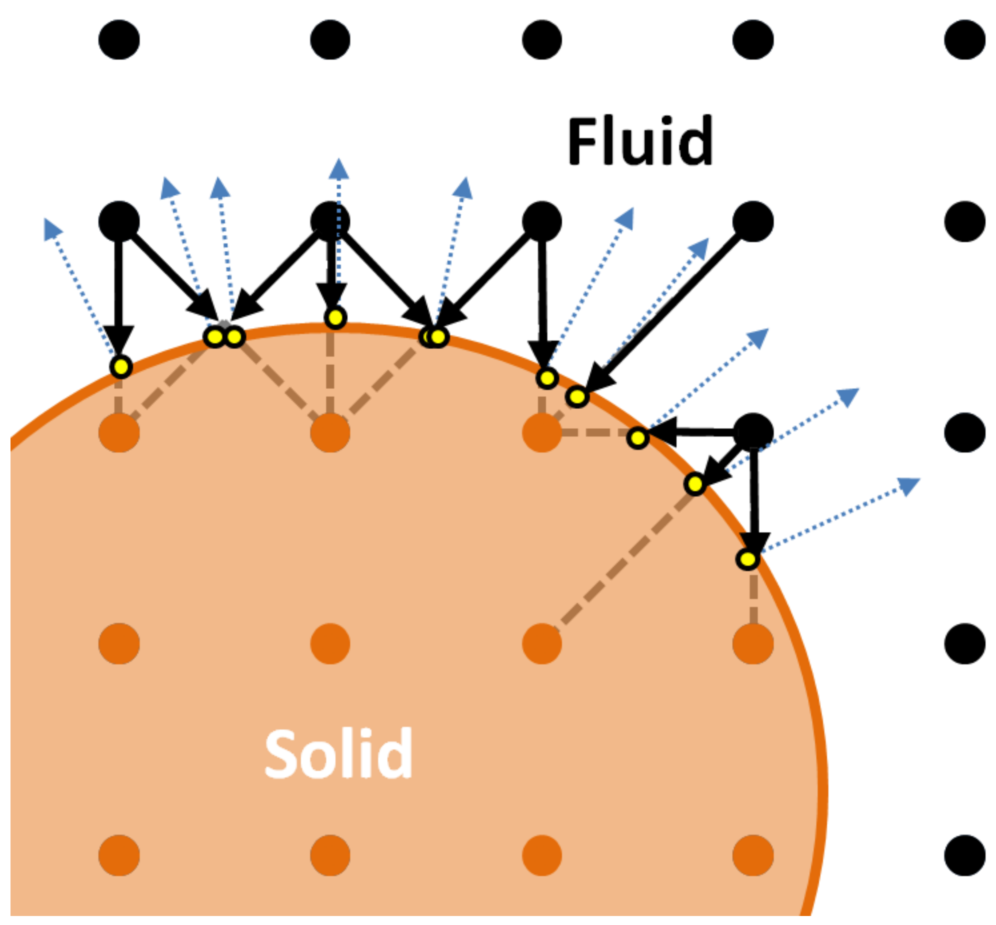


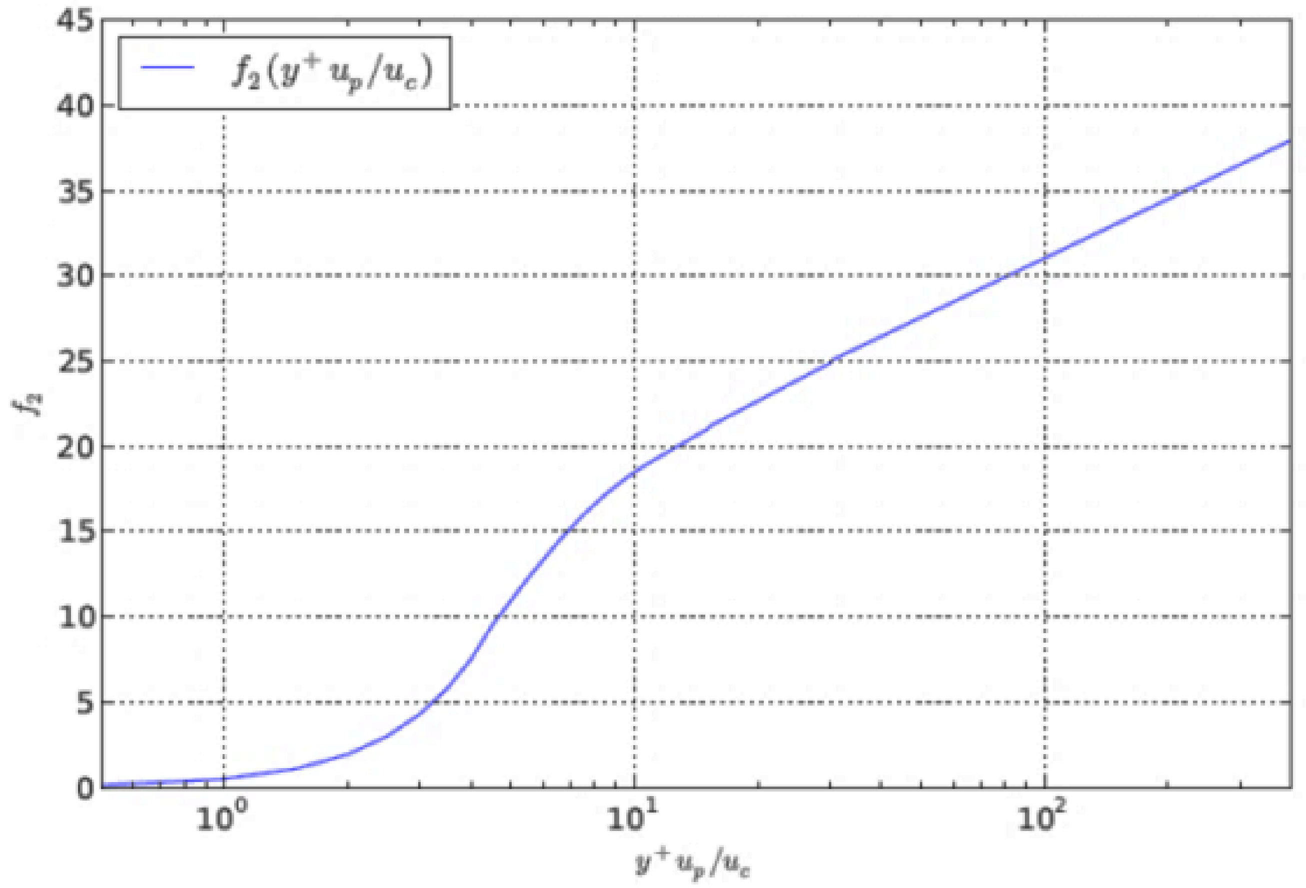
Numerical Methodology

Advanced dynamic geometries

→ The octree lattice flexibility coupled with the advanced wall treatment allows to address easily the dynamic geometries.

→ A generalized law of the wall is used to model the boundary layer.





$$
\begin{aligned}
\frac{U}{u_c} &= \frac{U_1+U_2}{u_c} = \frac{u_\tau}{u_c}\frac{U_1}{u_\tau} + \frac{u_p}{u_c}\frac{U_2}{u_p} \\
&= \frac{\tau_w}{\rho u_\tau^2}\frac{u_\tau}{u_c} f_1\left(y^+\frac{u_\tau}{u_c}\right) + \frac{\mathrm{d}p_w/\mathrm{d}x}{|\mathrm{d}p_w/\mathrm{d}x|}\frac{u_p}{u_c} f_2\left(y^+\frac{u_p}{u_c}\right) \\
y^+ &= \frac{u_c y}{\nu} \\
u_c &= u_\tau + u_p \\
u_\tau &= \sqrt{|\tau_w|/\rho} \\
u_p &= \left(\frac{\nu}{\rho}\left|\frac{\mathrm{d}p_w}{\mathrm{d}x}\right|\right)^{1/3}.
\end{aligned}
$$

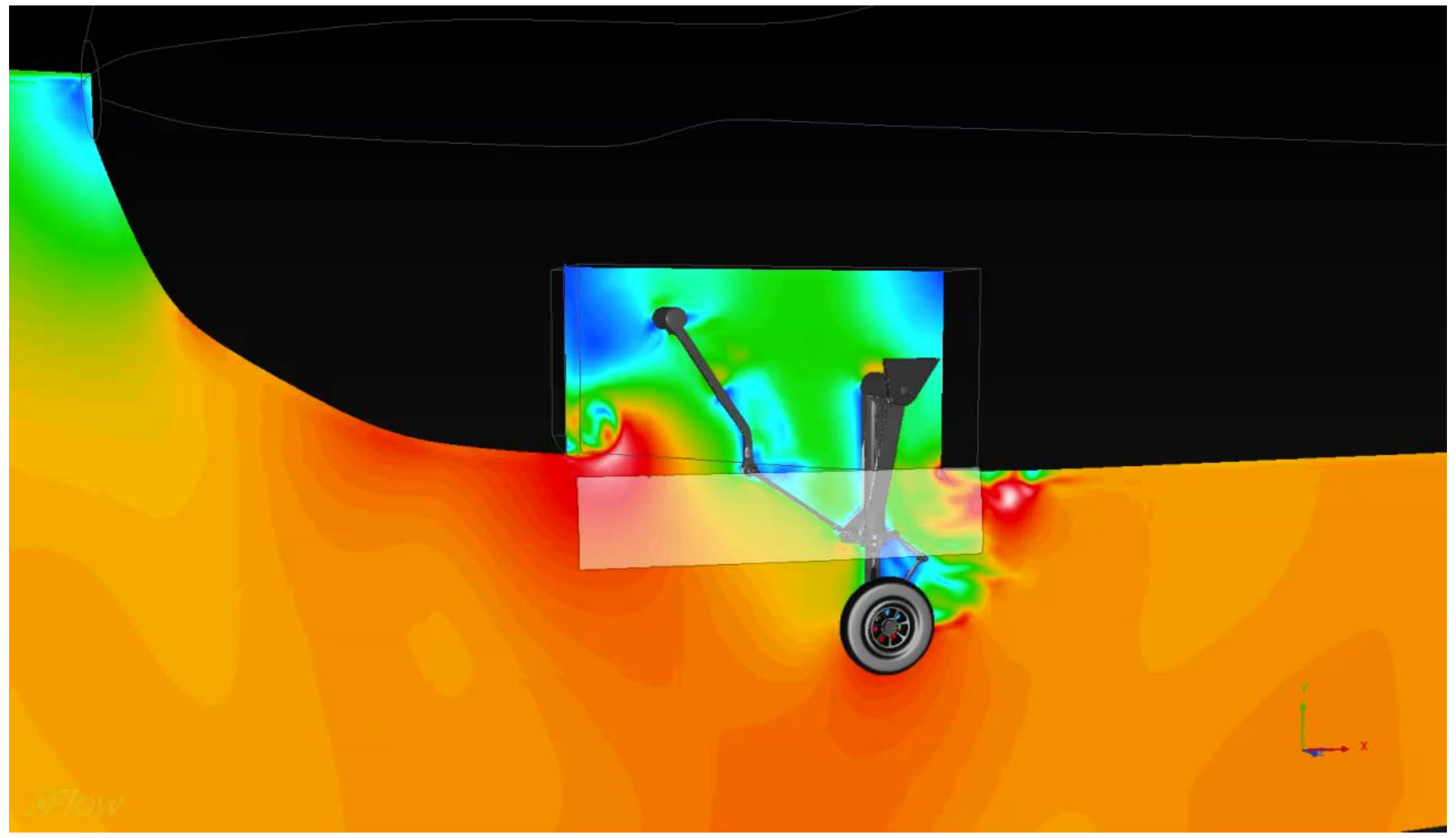
Numerical Methodology

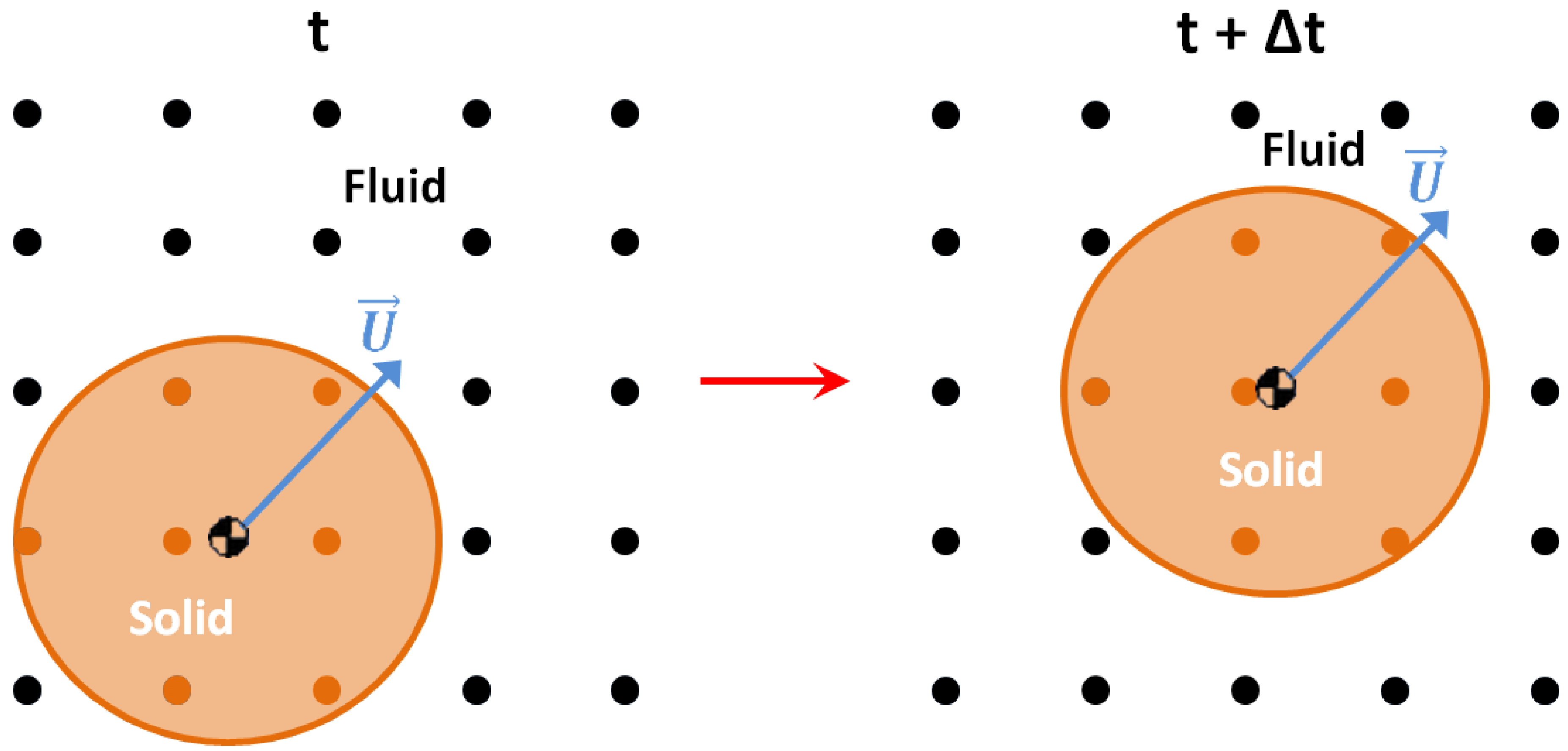
Advanced dynamic geometries

→ The octree lattice flexibility coupled with the advanced wall treatment allows to address easily the dynamic geometries.

→ XFlow proposes two options to handle dynamic geometries:

- Enforced behavior → Position and orientation input as user-defined laws.
- Rigid body dynamics behavior → FSI through multi-body solver allowing up to 6 DOF.





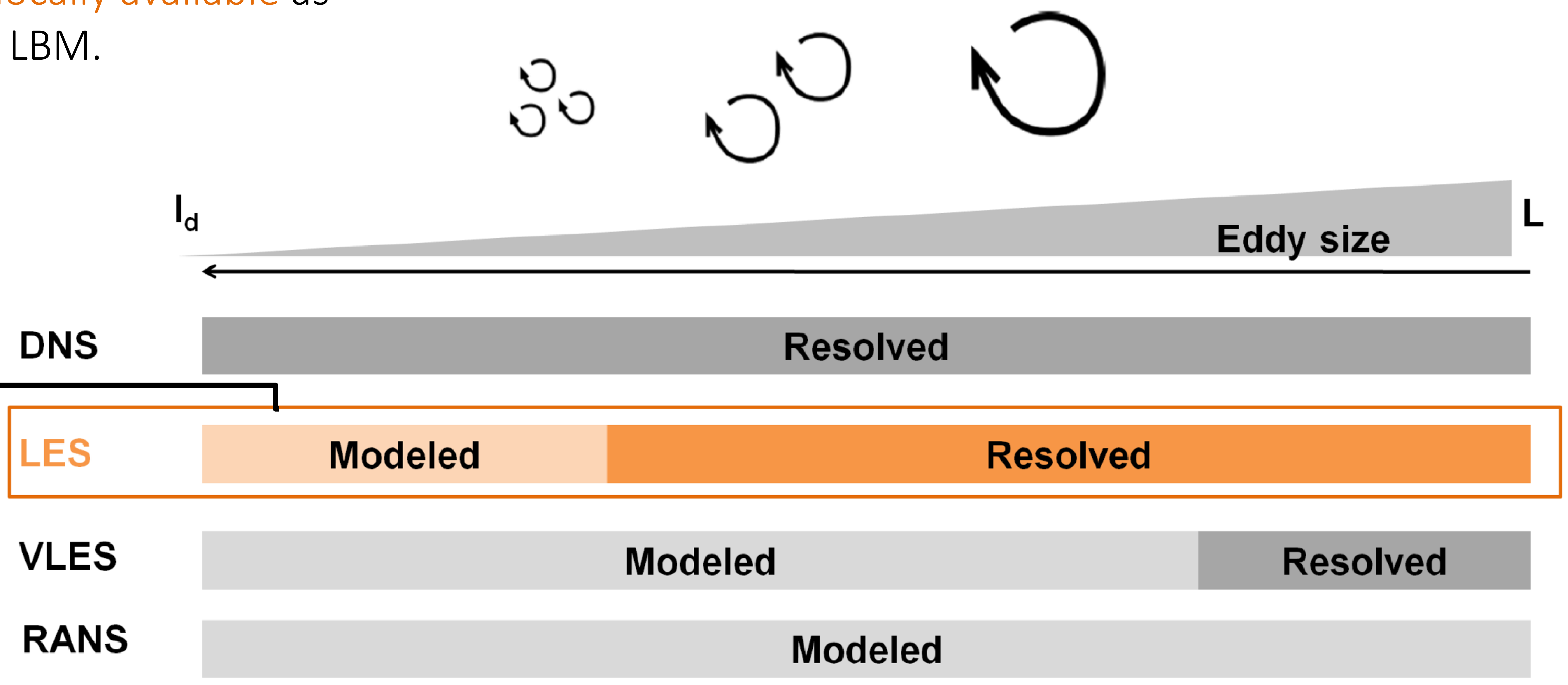
Numerical Methodology

Turbulence modeling - High fidelity WMLES

→ The LES turbulence models are the natural turbulence modelling approach for LBM for three main reasons:

- LBM is inherently unsteady.
- The turbulence is inherently three-dimensional and isotropic which fits perfectly the lattice structure.
- The strain rate tensor ($g_{\alpha\beta}$) is locally available as the second-order moment with LBM.

Wall-Adapting Local Eddy (WALE) ←



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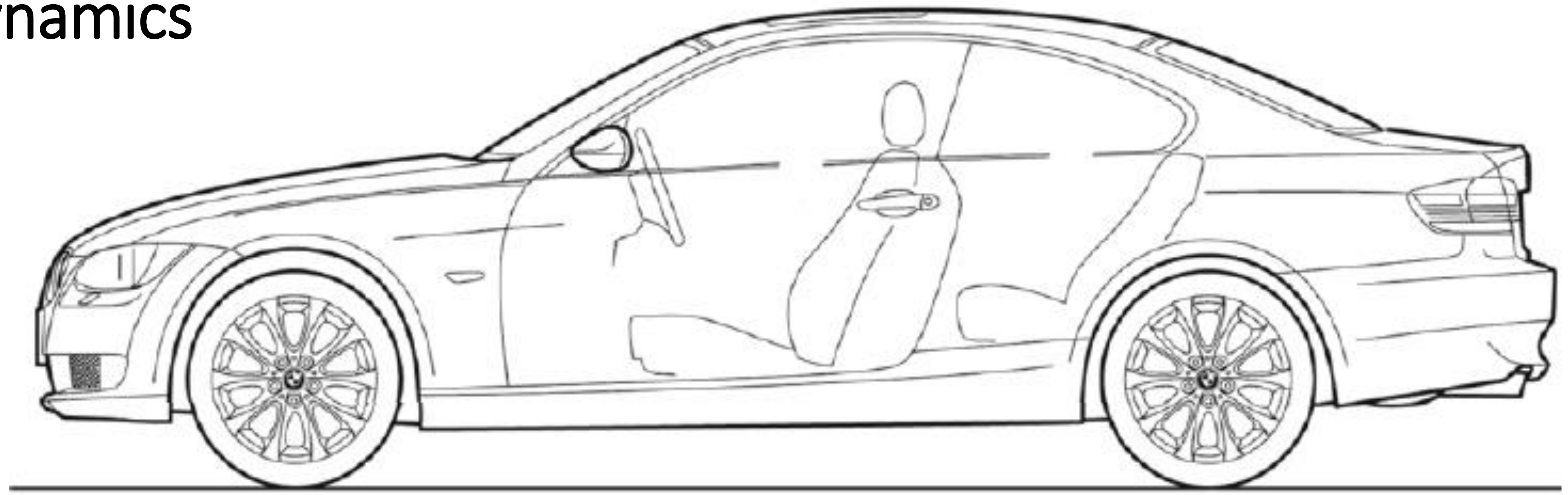
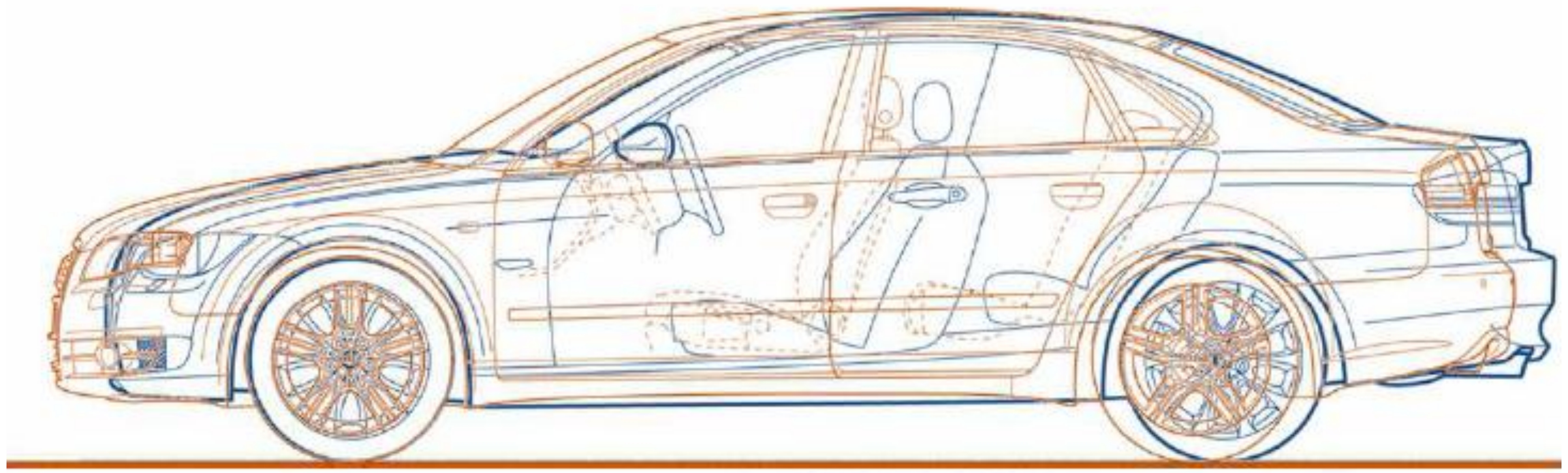
Geometry

Developed by TU Munich, Inst. Of Aerodynamics

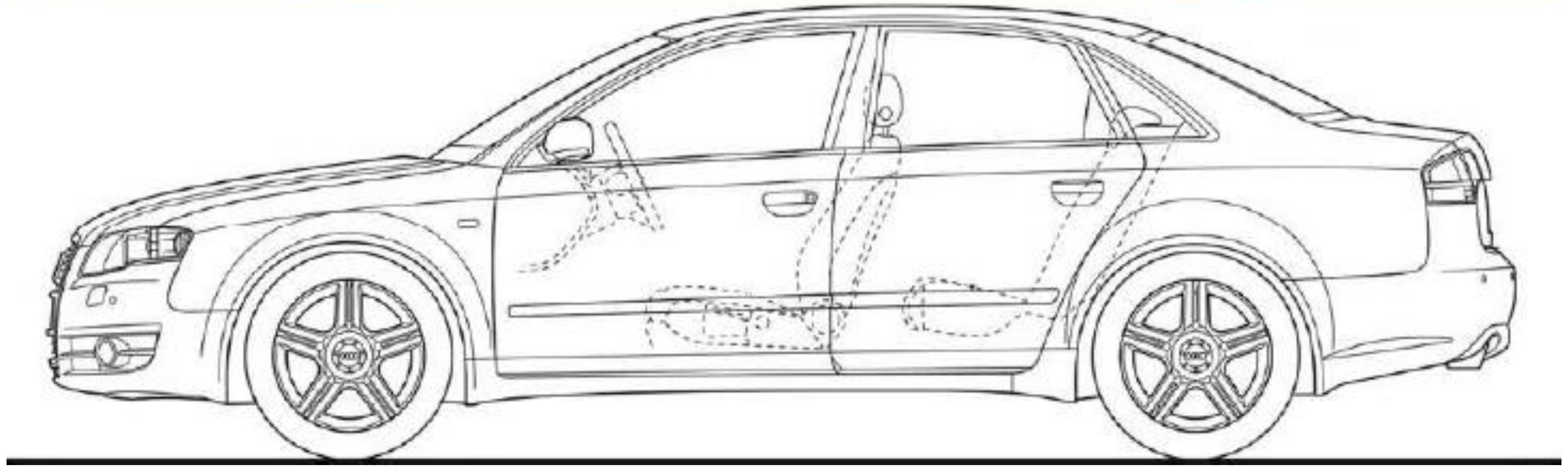
BMW 3 Series
Limousine



DrivAer Model

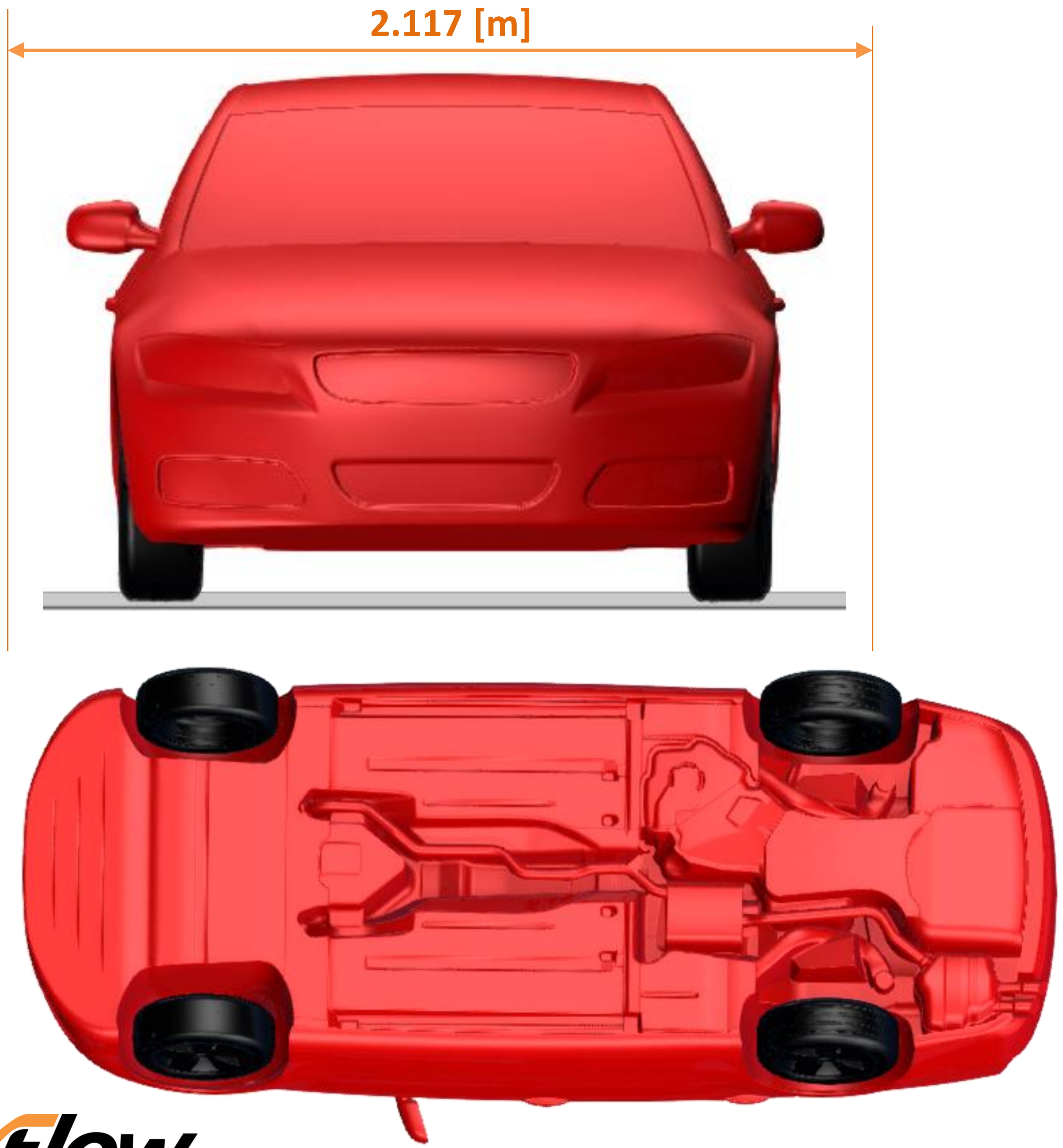


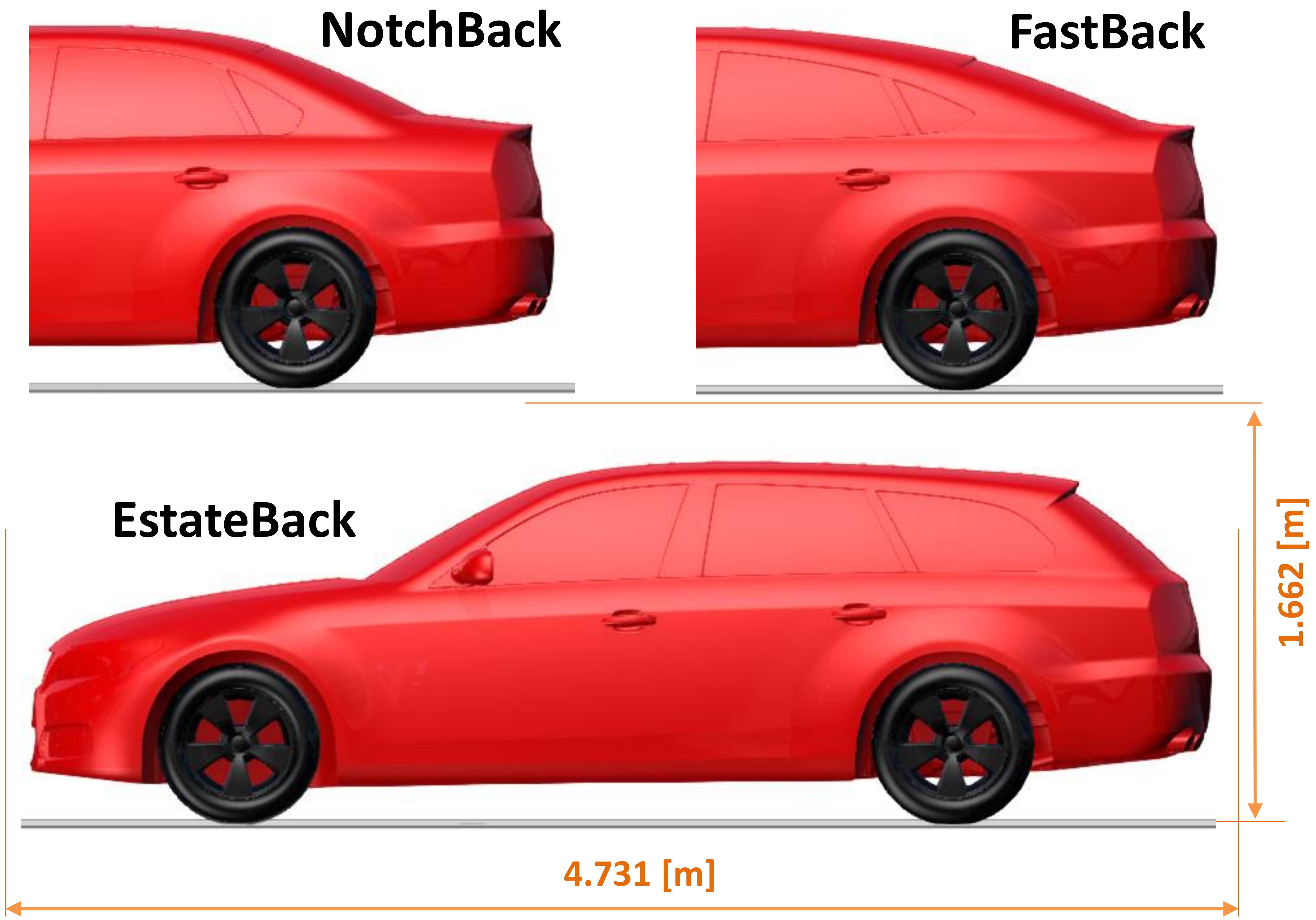
Audi A4
Limousine



Geometry

Detailed underbody with Mirrors with Wheels – D_wM_wW. Three different rear geometry has been simulated.

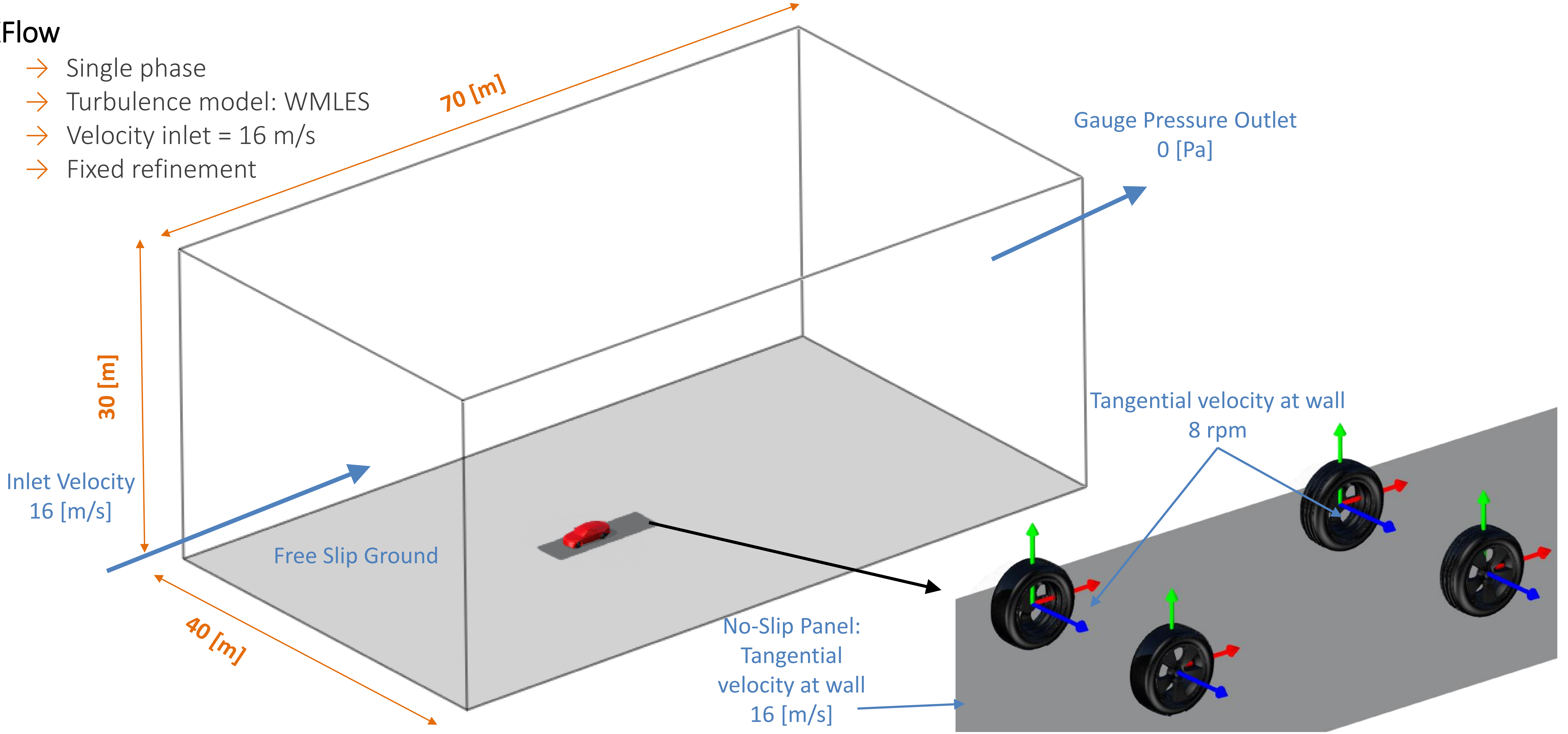




Setup simulation

XFlow

- Single phase
- Turbulence model: WMLES
- Velocity inlet = 16 m/s
- Fixed refinement



Refinement strategy

The fine grid refinement is based on the pressure coefficient field of the coarse simulation in order to refine in an efficient way.

EstateBack	Far Field [m]	Near Walls [m]	# Elements	Simulated Time [s]	Initial Conditions	# Nodes	# Cores	Run Time [h]
Coarse	1.28	0.04	**599.141**	1.0	V=16 [m/s]	1	12	**1.84**
Fine	1.28	0.005*	**39.394.140**	1.0	V=16 [m/s]	3	36	**57.2**

Coarse

Refinement strategy

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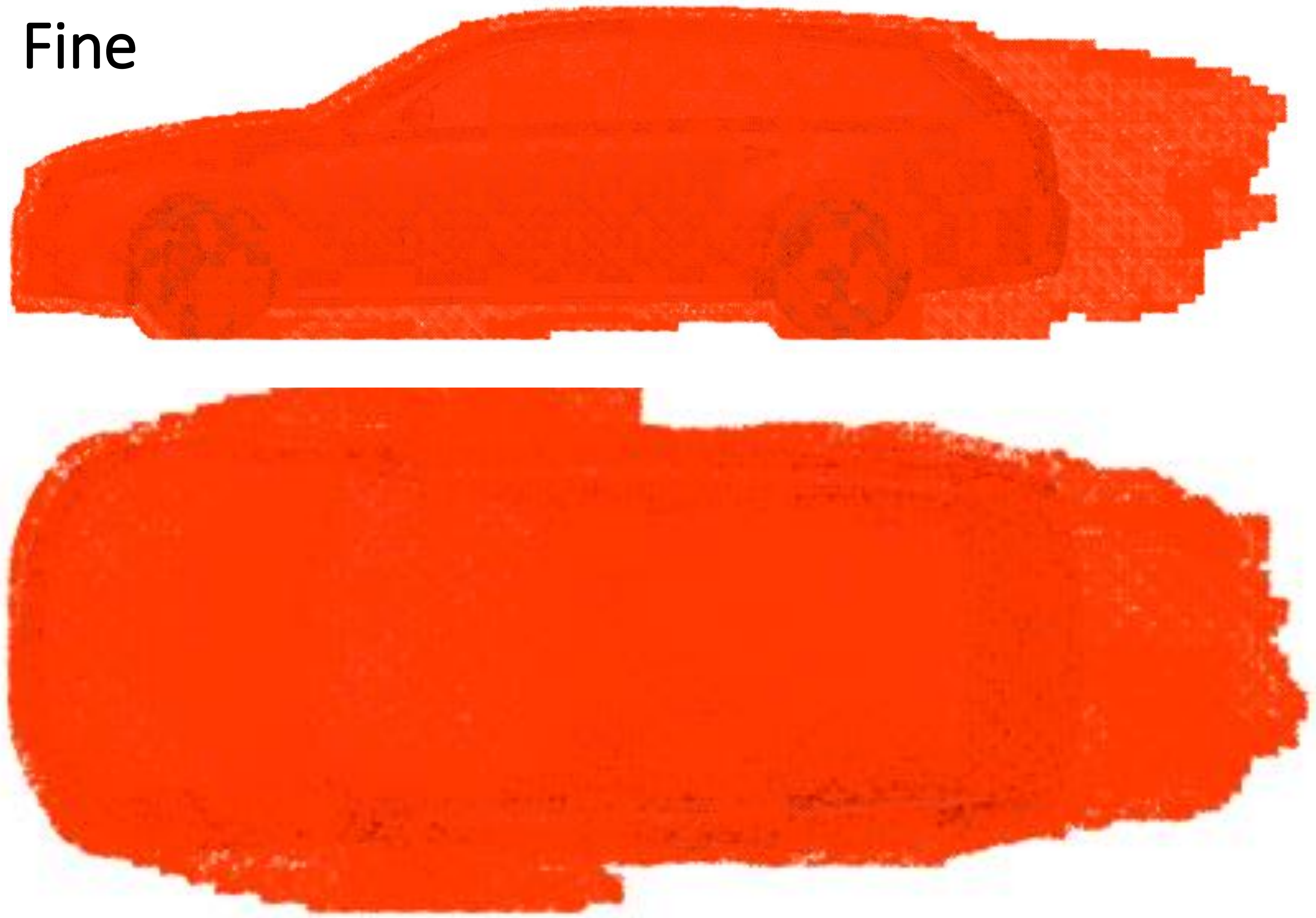
Coarse

Fine

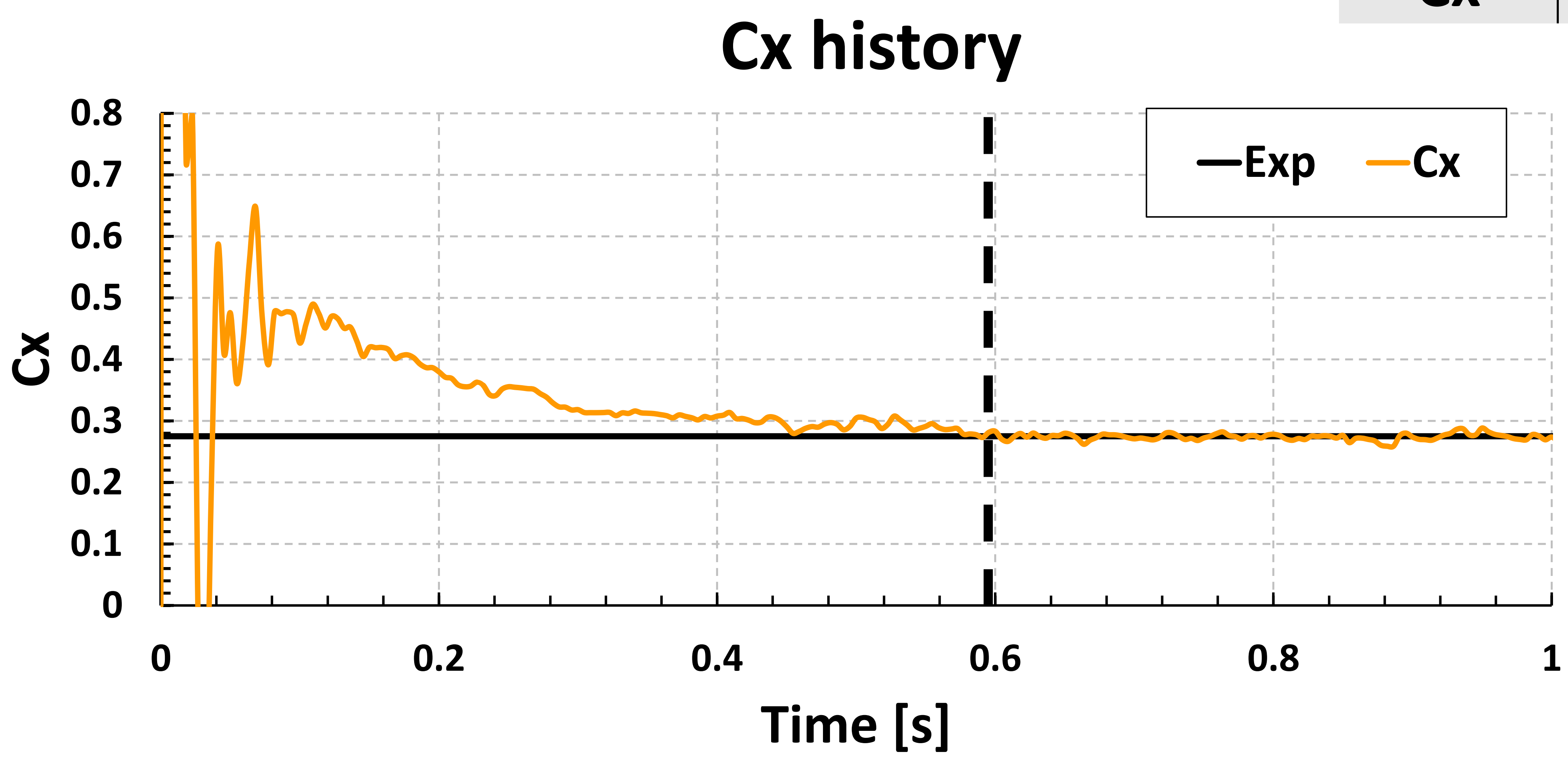


Numerical results

Drag coefficient : Fastback configuration

S_{ref} = **2.612 m²**

	XFlow	Exp.	Error %	Std. Dev.
Cx	0.2781	0.275	**+1.14**	**0.0061**



Numerical results

Drag coefficient and Cp distribution: Fastback configuration

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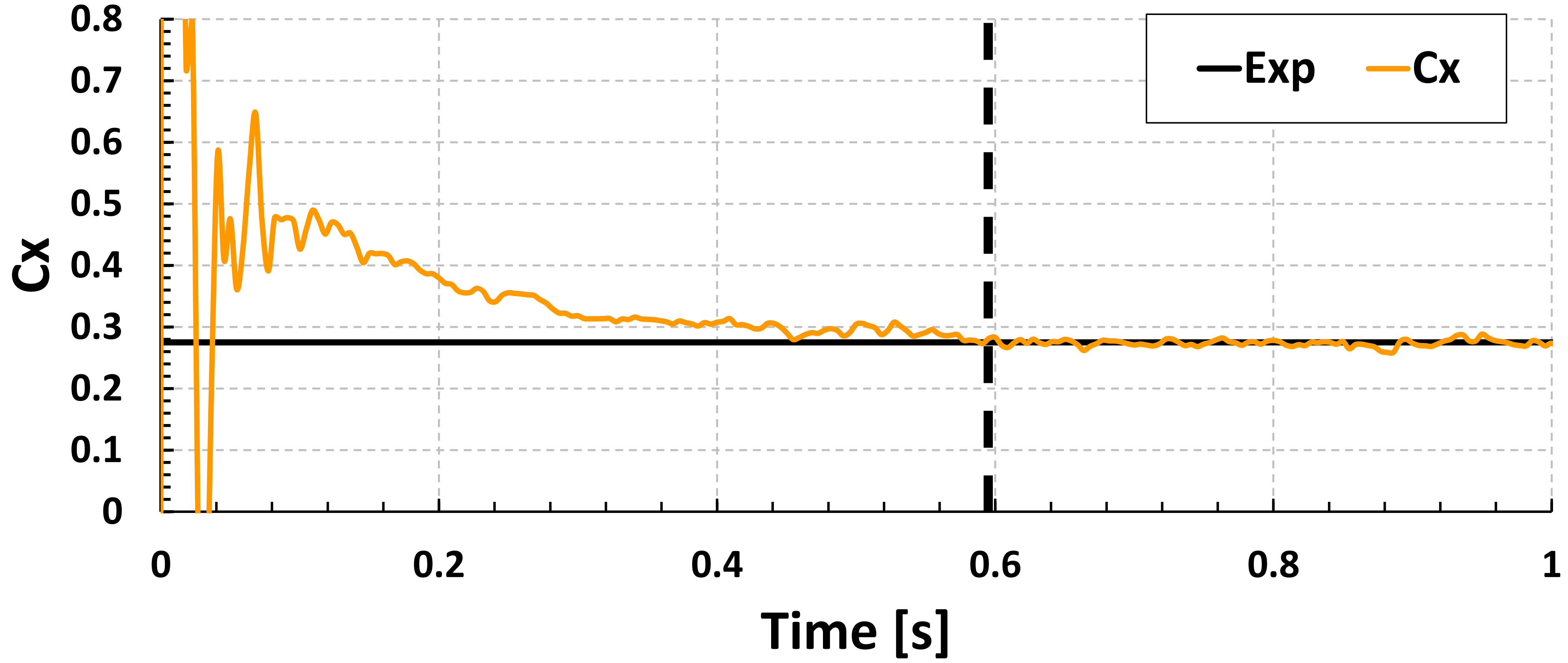
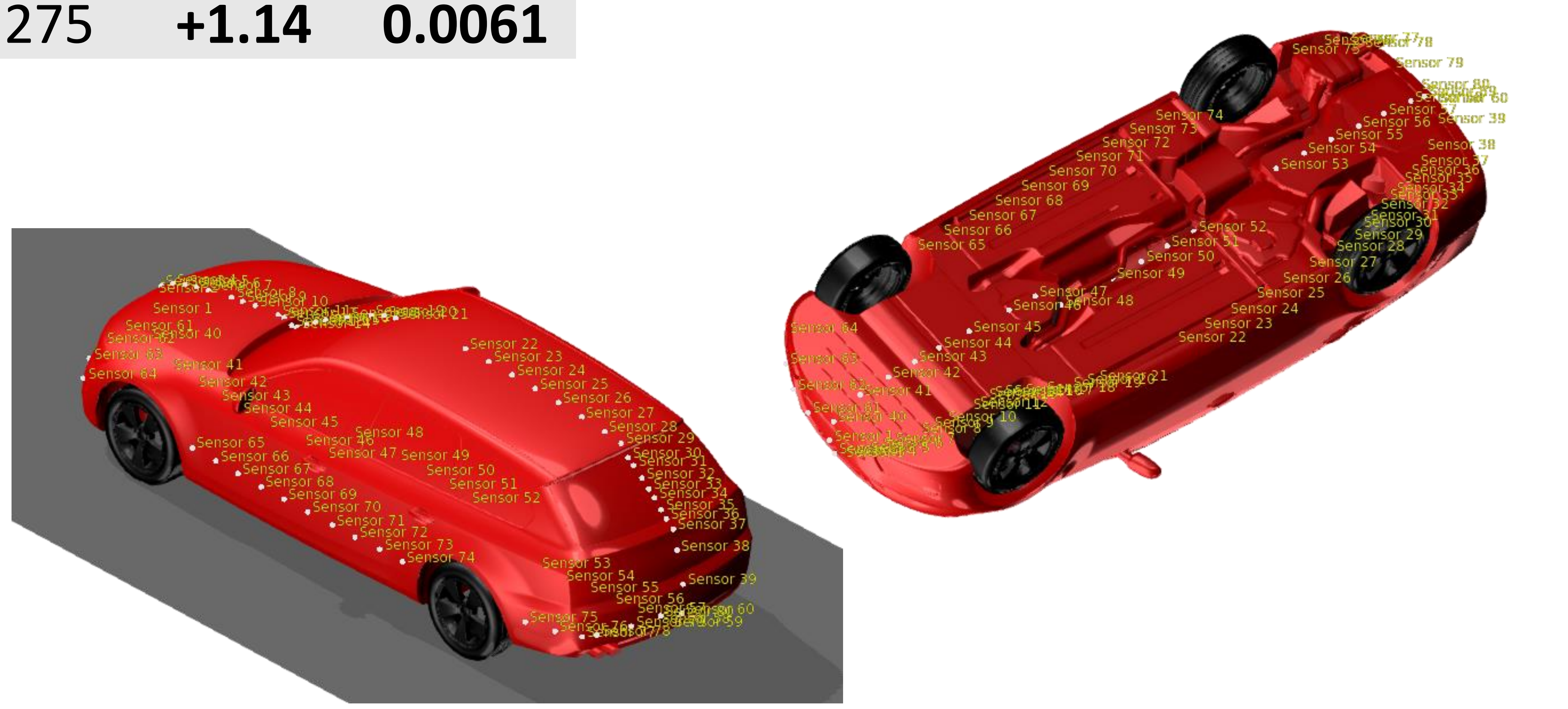
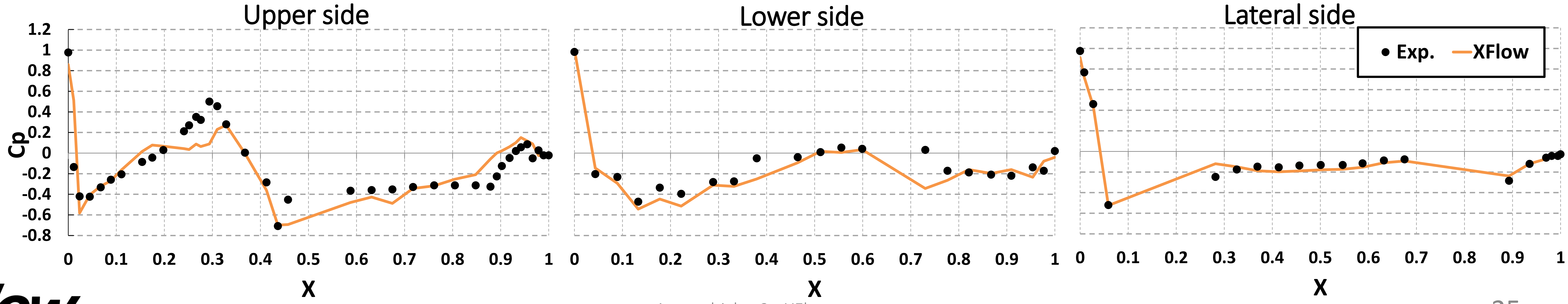
Cx history







Numerical results

Summary DrivAer averaged results

Cx	XFlow	Exp.	Error %	Std. dev	Δ XFlow	Δ Exp.
FastBack	0.2781	0.275	**+1.14**	**0.0061**	-	-
EstateBack	0.3219	0.319	**+0.92**	**0.0070**	+0.0438	+0.044
NotchBack	0.2808	0.277	**+1.38**	**0.0064**	+0.0027	+0.002

FastBack

EstateBack

NotchBack

Numerical results

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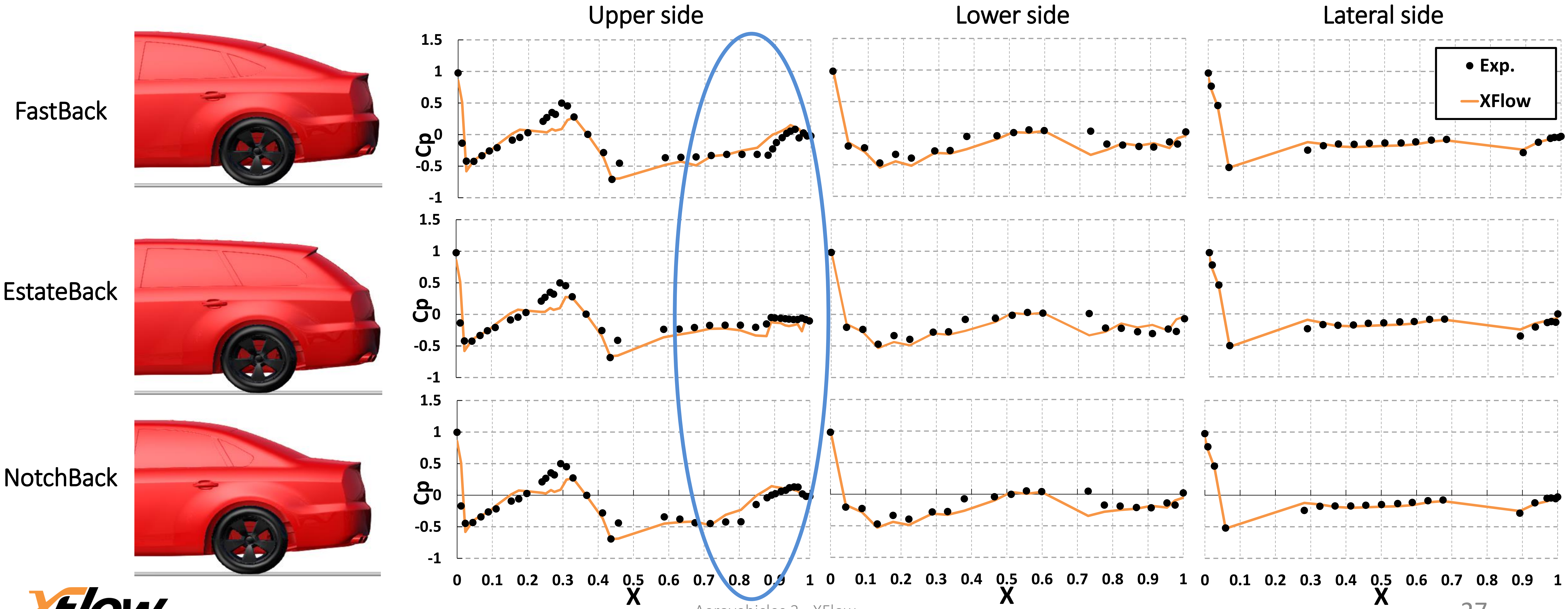
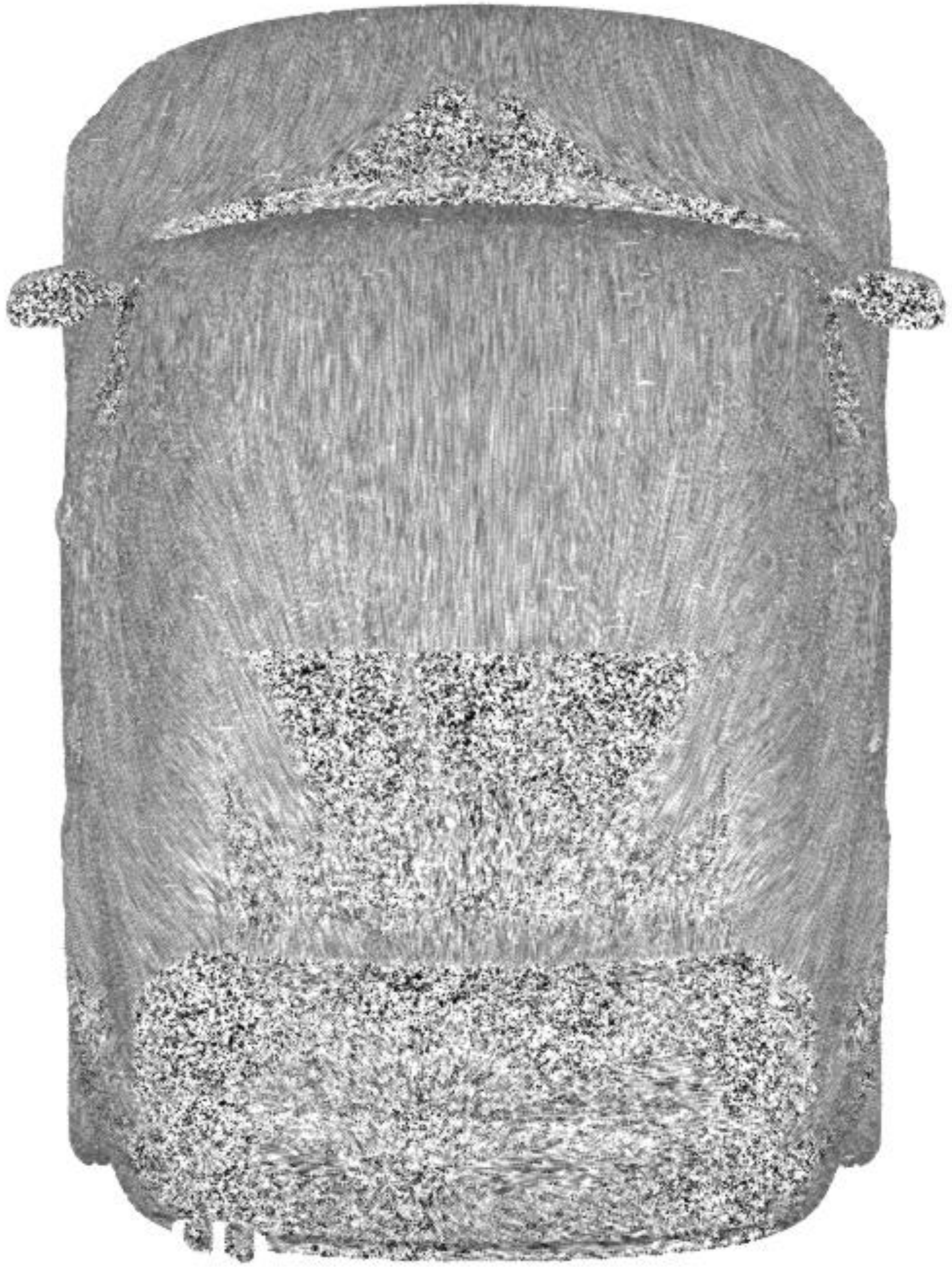


Numerical results

Detached flow

NotchBack
Cx=0.2808

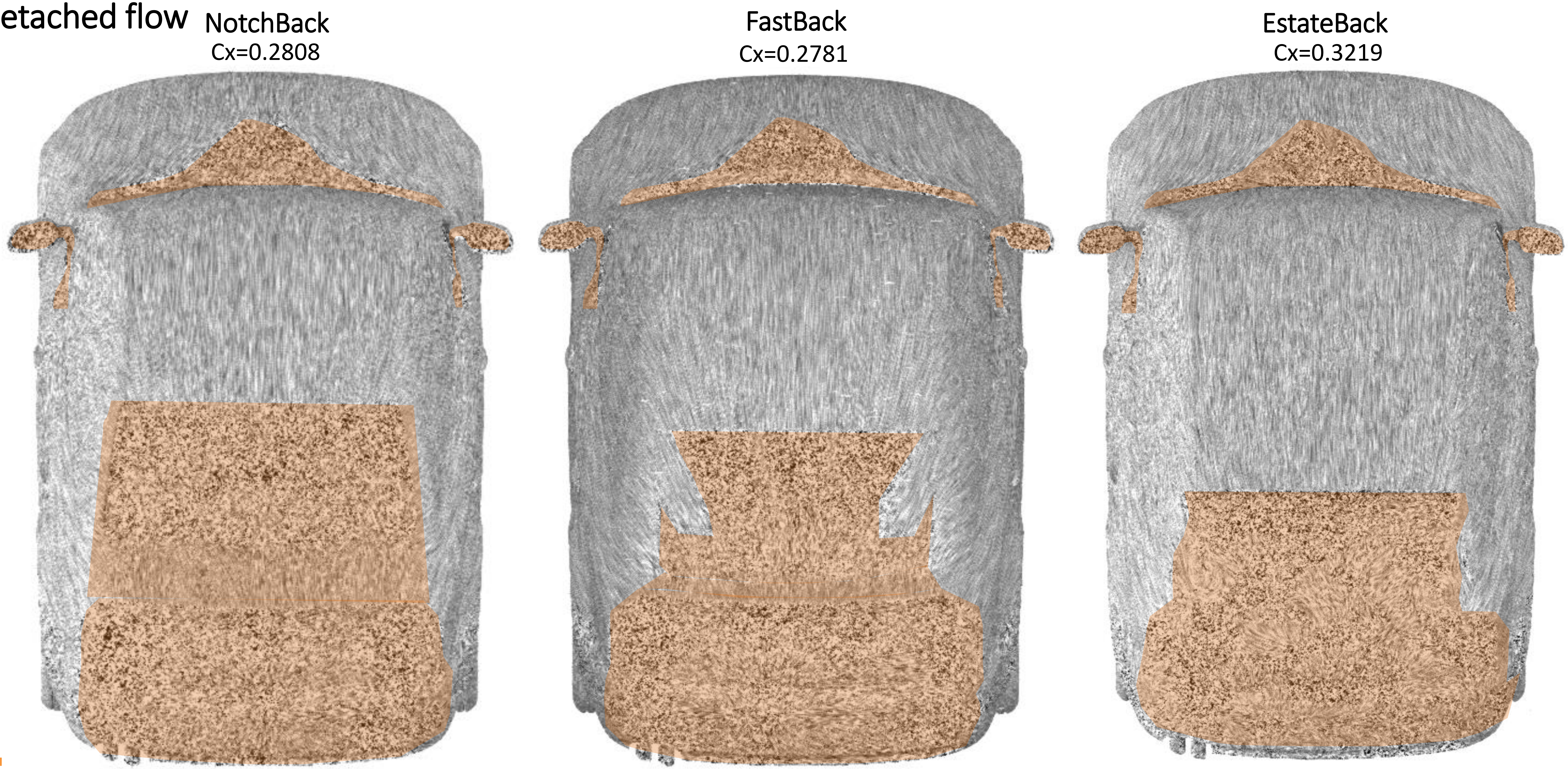
FastBack
Cx=0.2781



EstateBack
Cx=0.3219

Numerical results

Detached flow



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Overtaking simulation

Simulation setup

→ Single phase

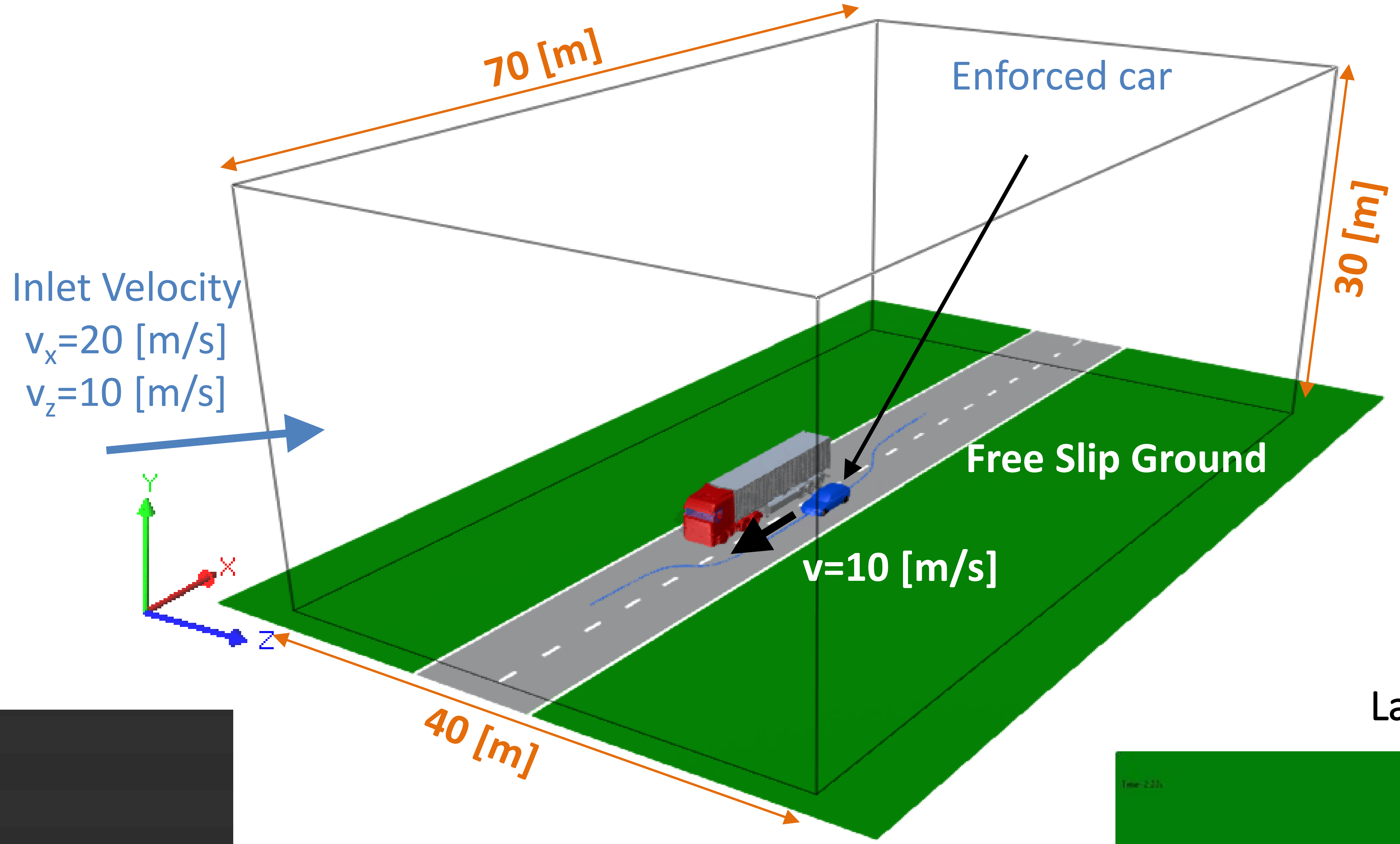
→ Crosswind

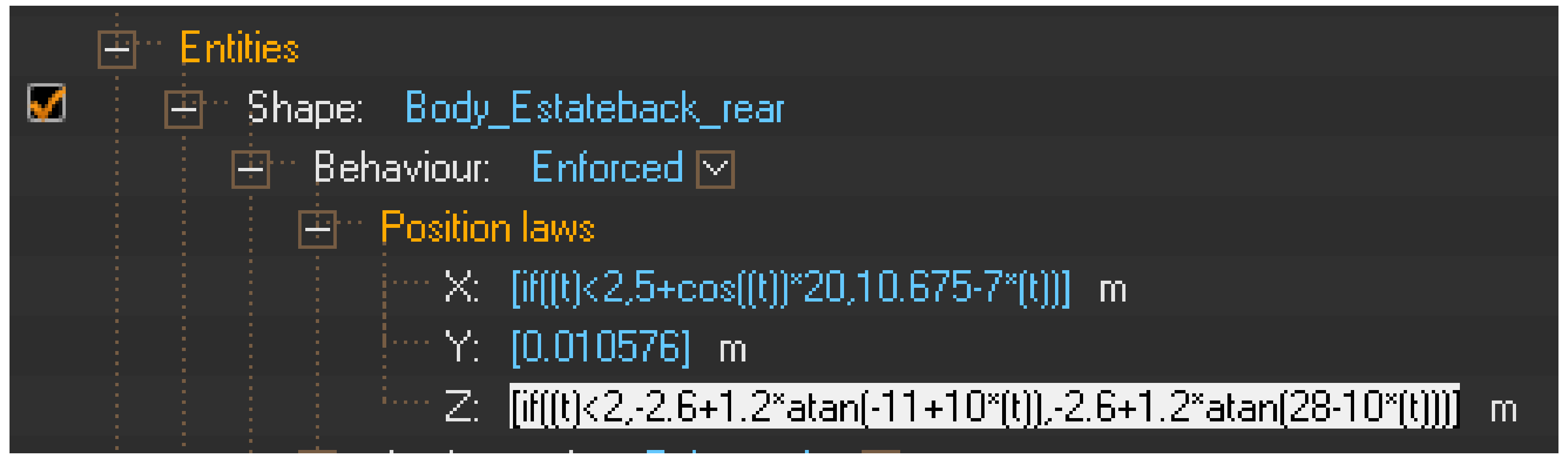
→ Enforced geometry car

→ Fixed truck

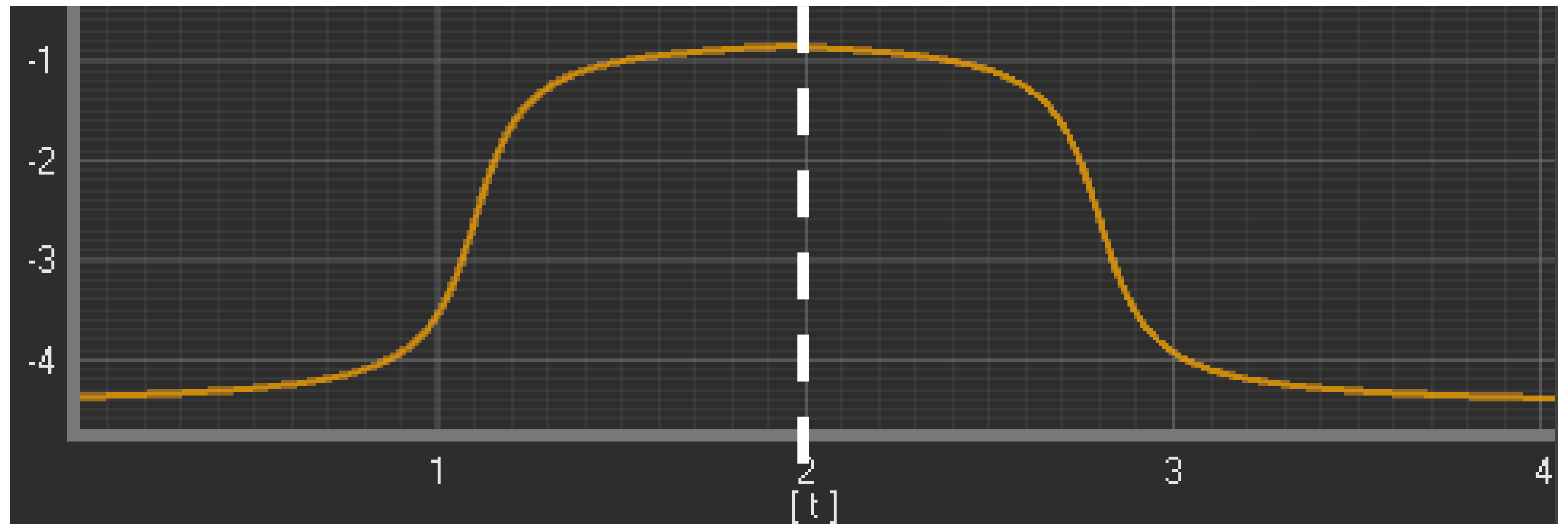
→ Simulation time = 4s

→ Adaptive refinement

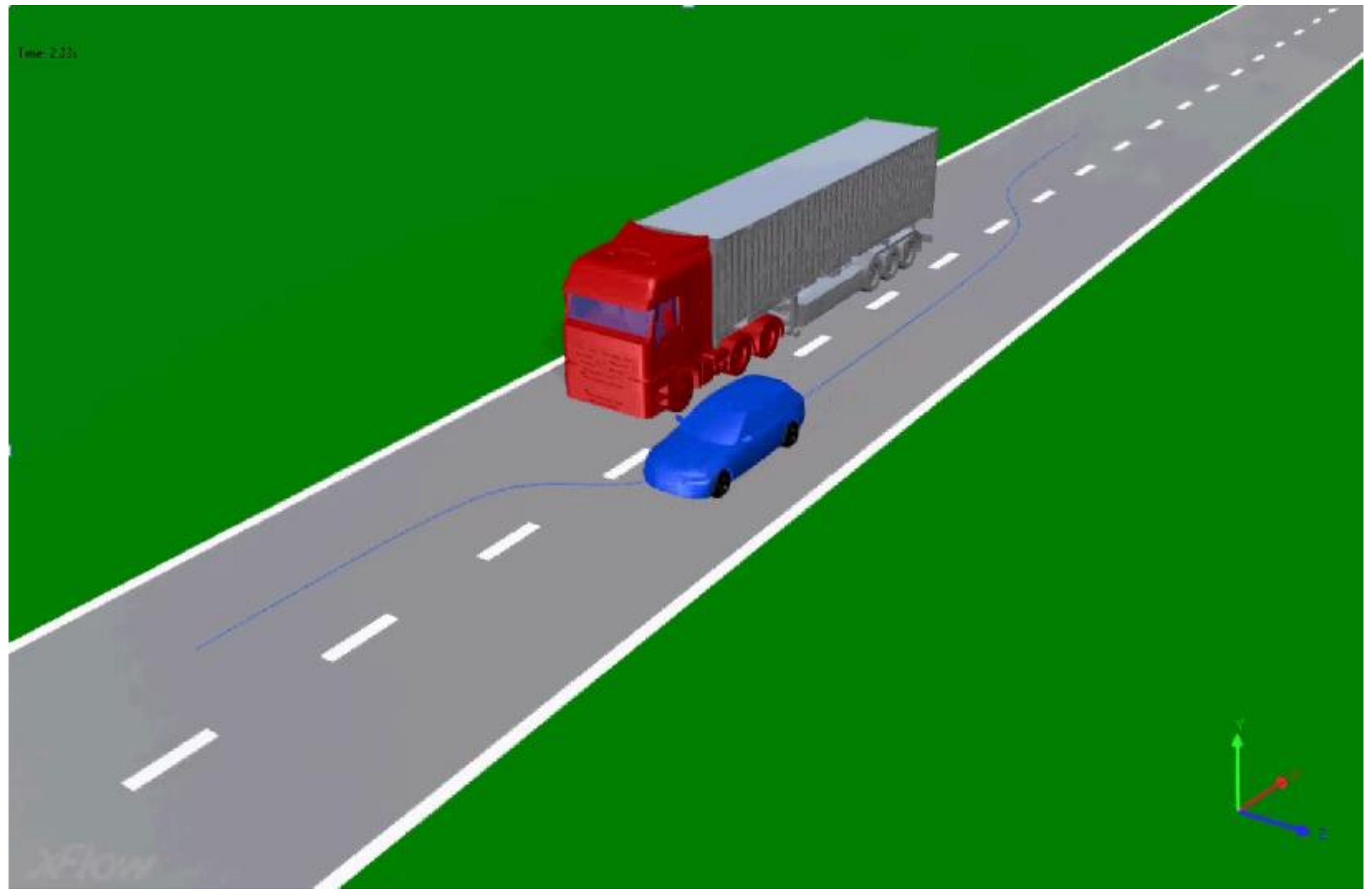




$$if(t > 2, -2.6 + 1.2 * \tan^{-1}(-11 + 10t), -2.6 + 1.2 * \tan^{-1}(28 - 10t))$$



Law motion overtaking



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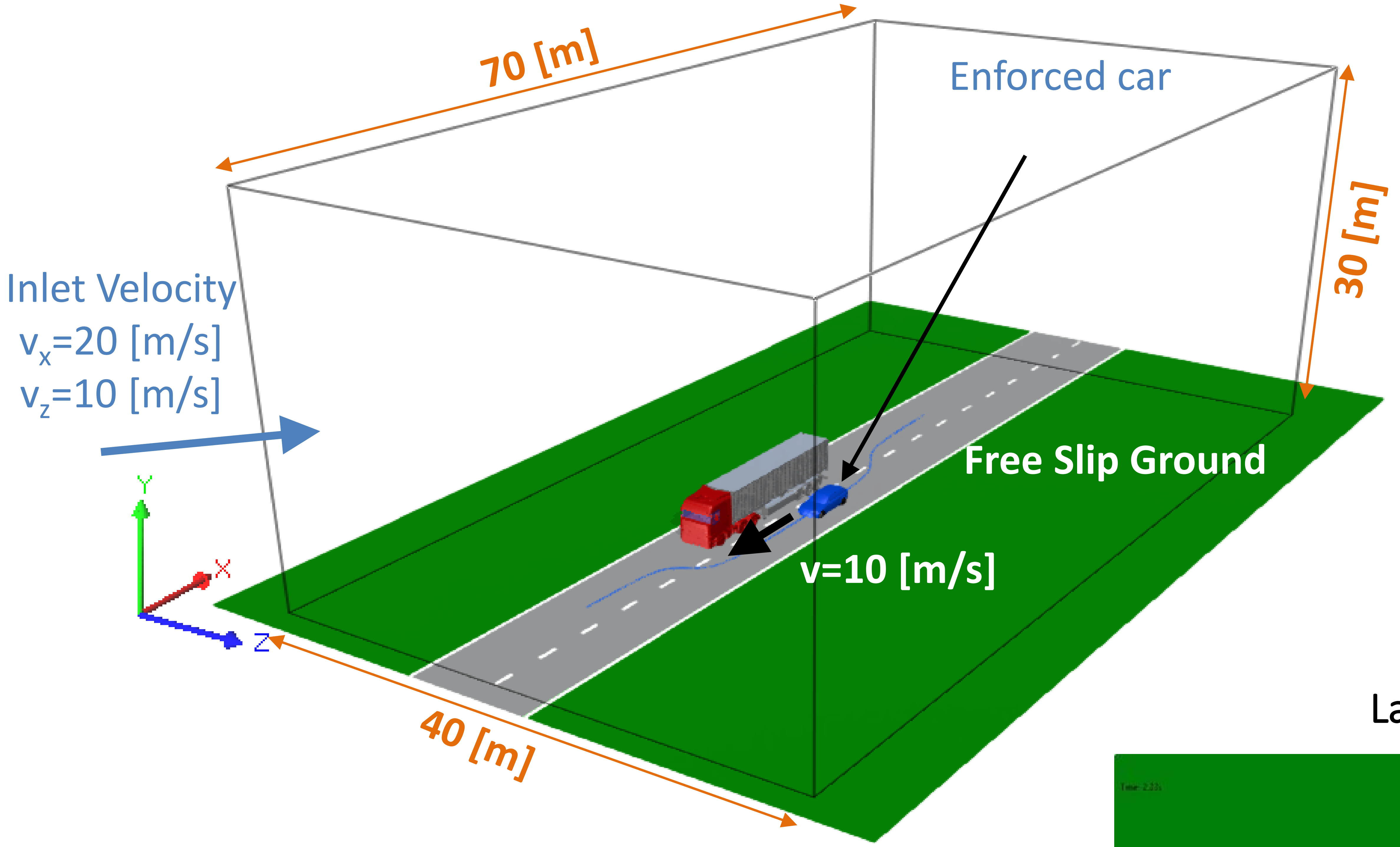

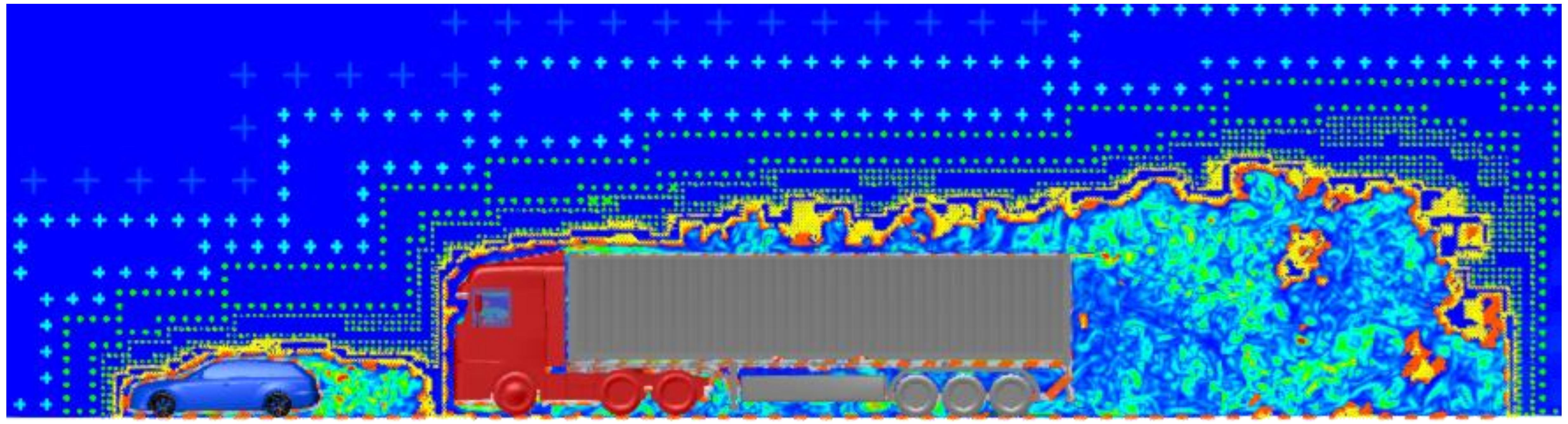

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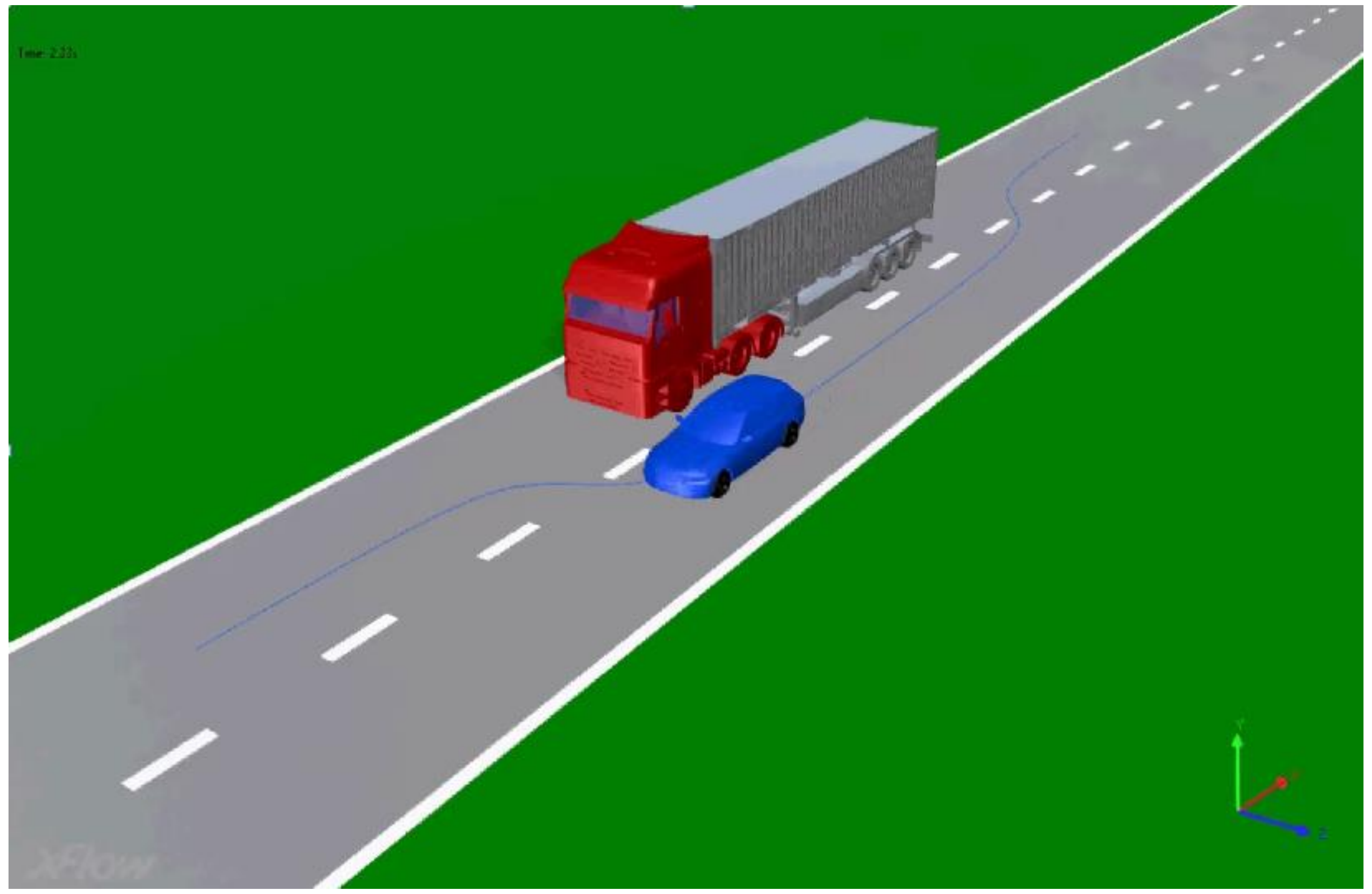
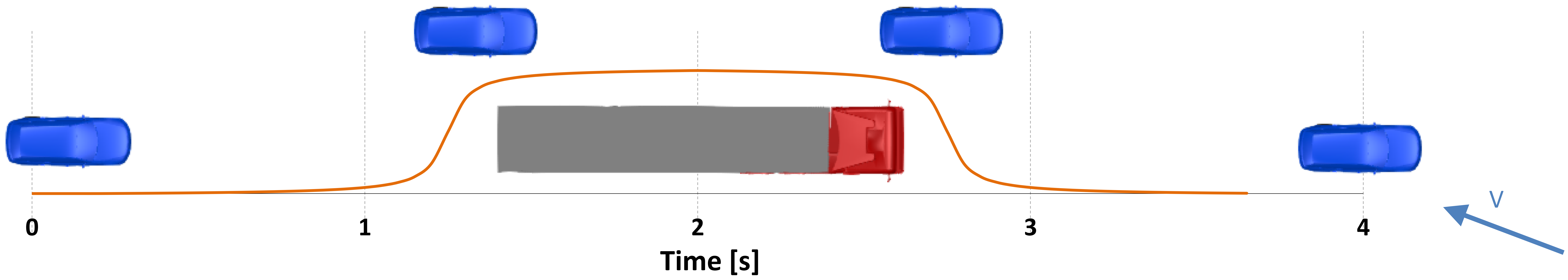
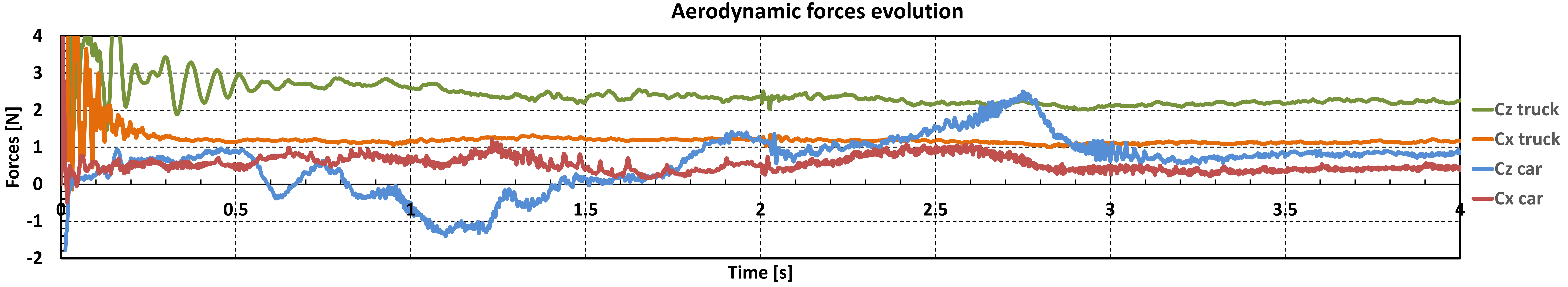


Overtaking simulation

Numerical results

	Far Field [m]	Near Walls [m]	Max. # Elements	Simulated Time [s]	# Nodes	# Cores	Run Time [days]
Overtaking	1.28	0.04	**12.000.000**	4.0	1	24	**6**





Overtaking simulation

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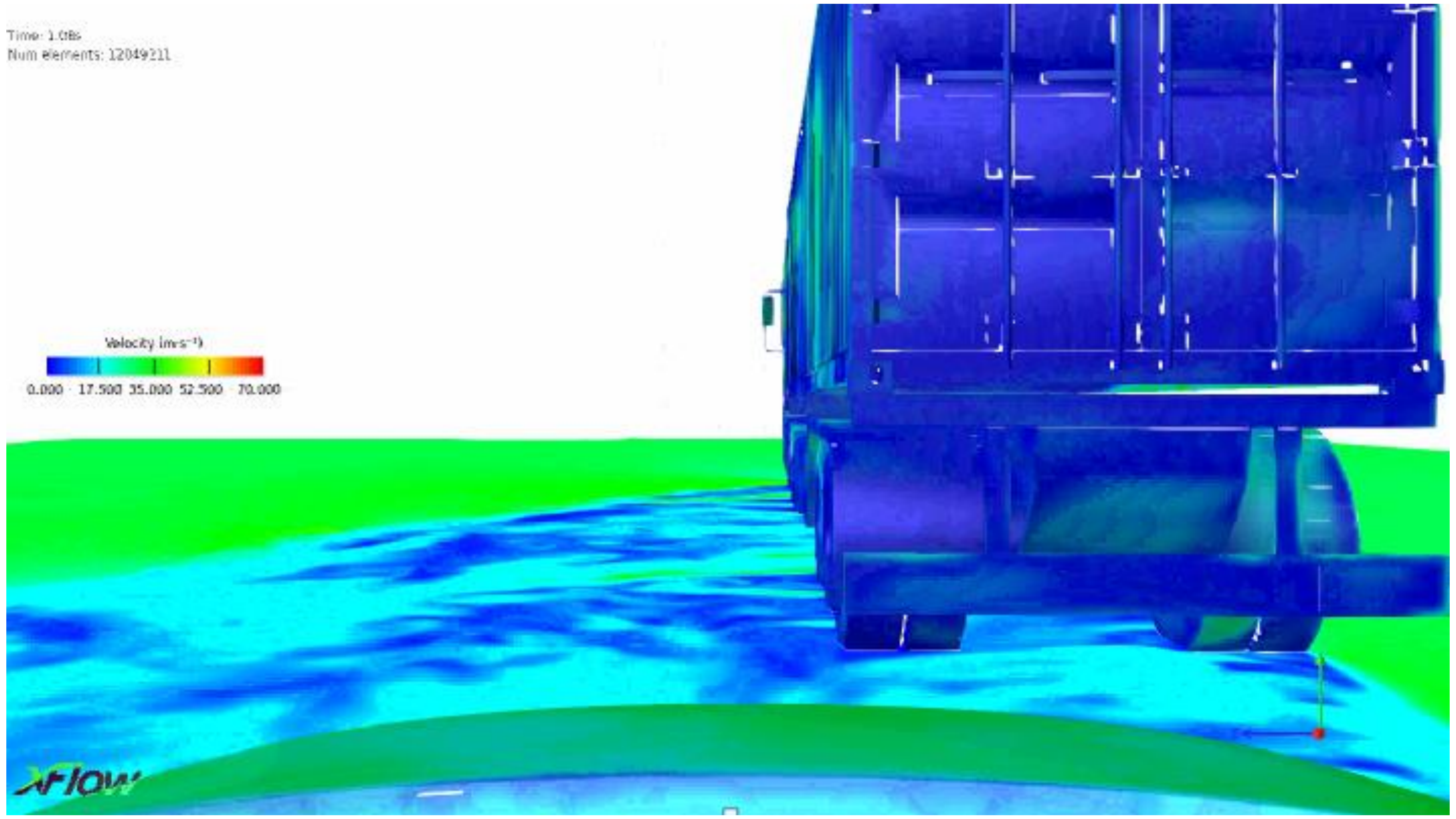

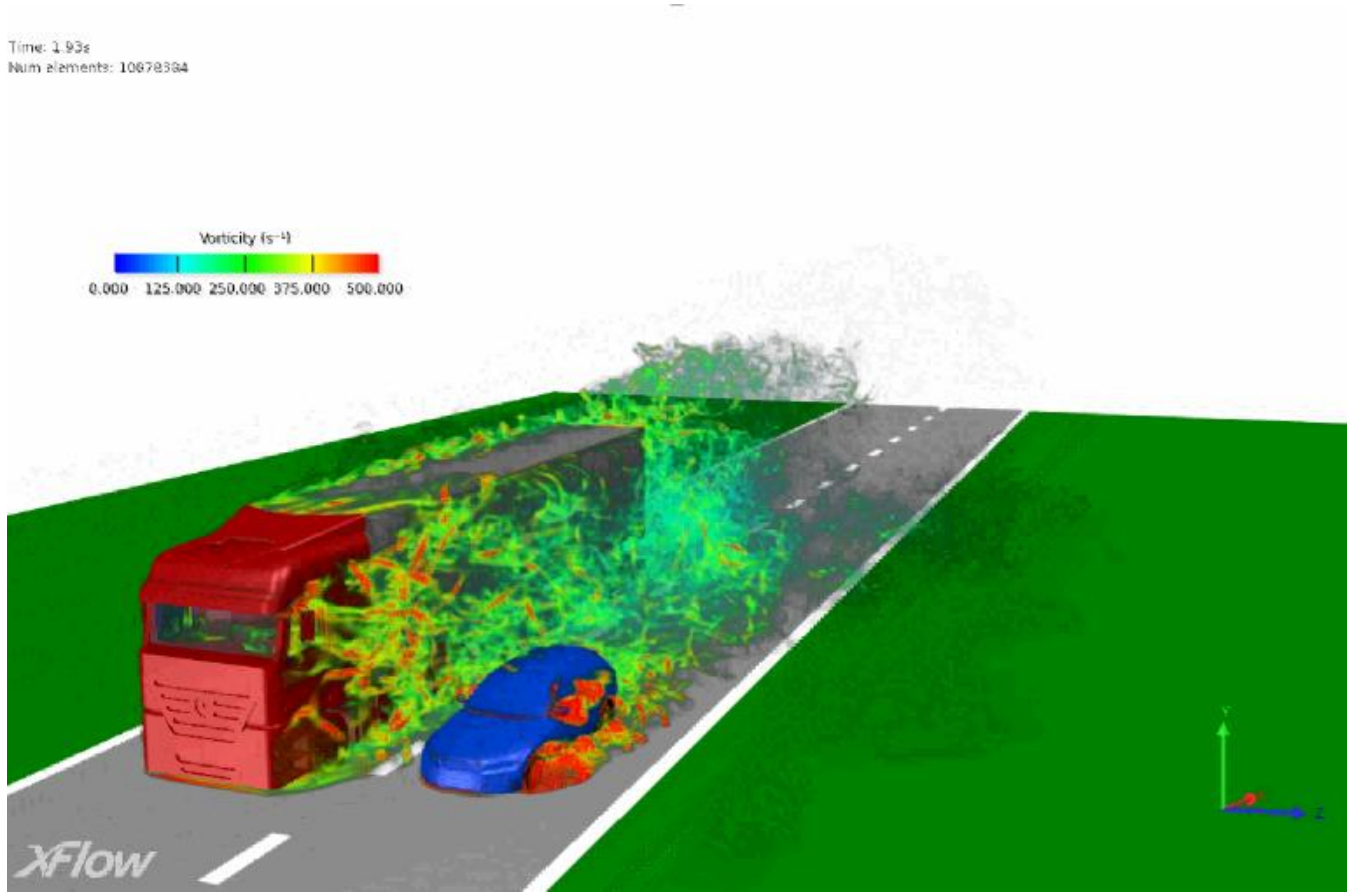

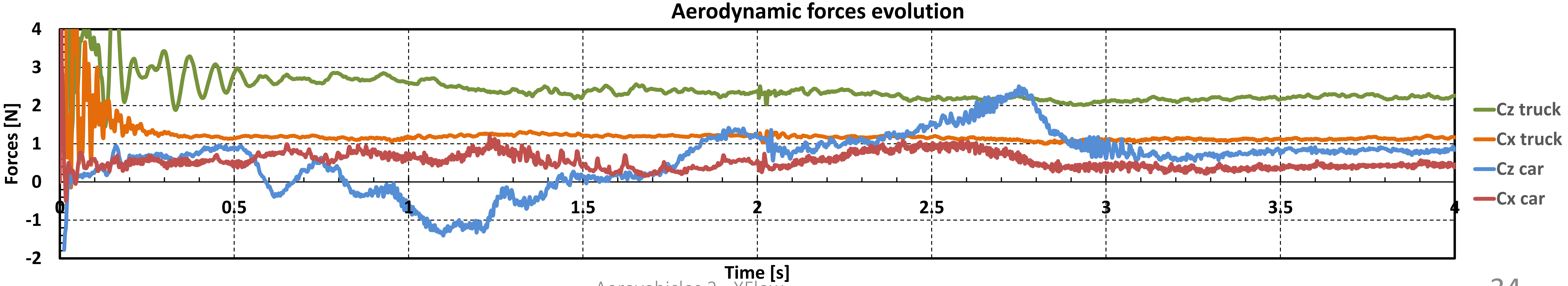

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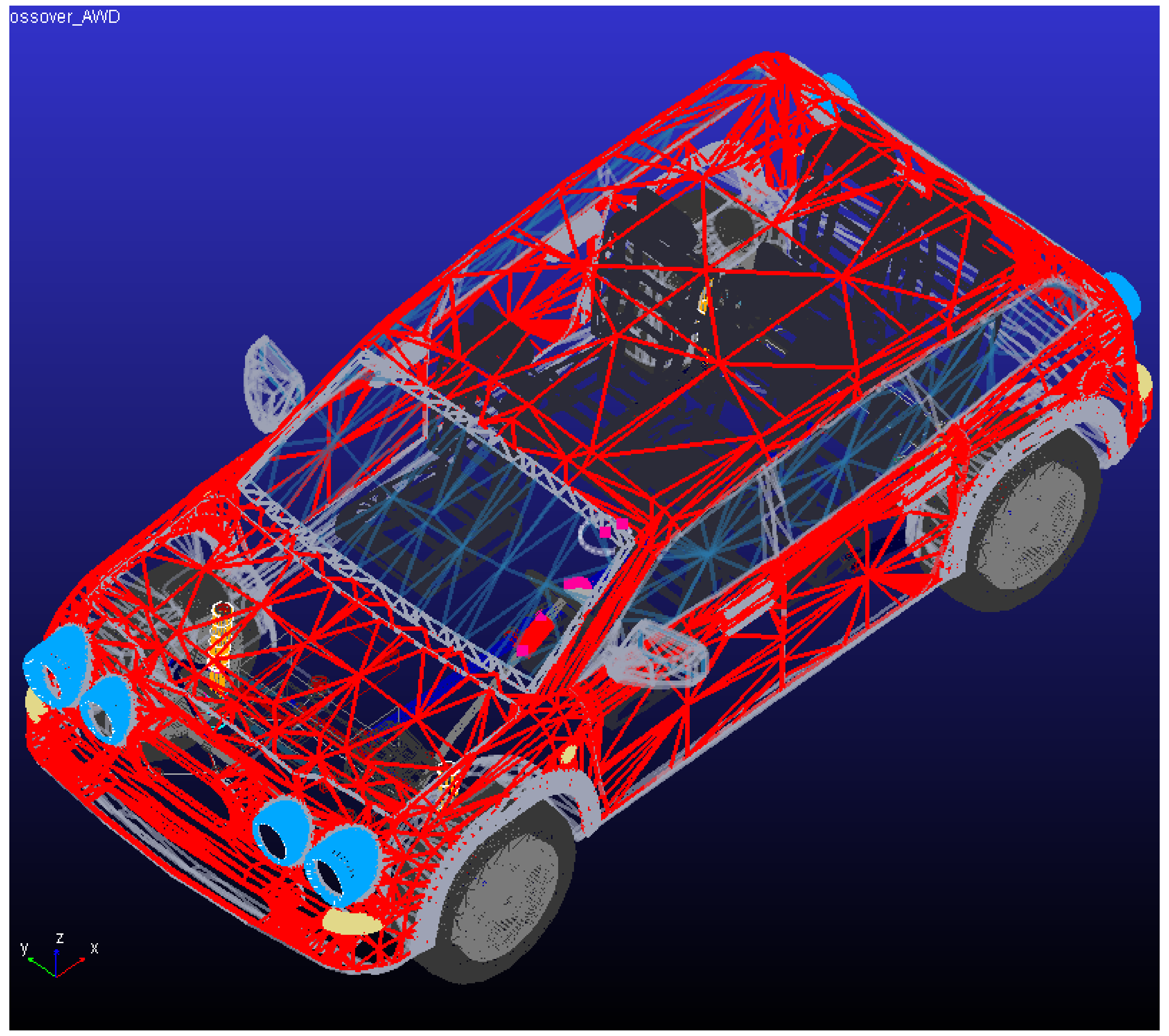
Crosswind Adams Car-XFlow co-simulation

Adams-XFlow co-simulation



Export each part's location and orientation

Apply as each shape's law (Enforced)

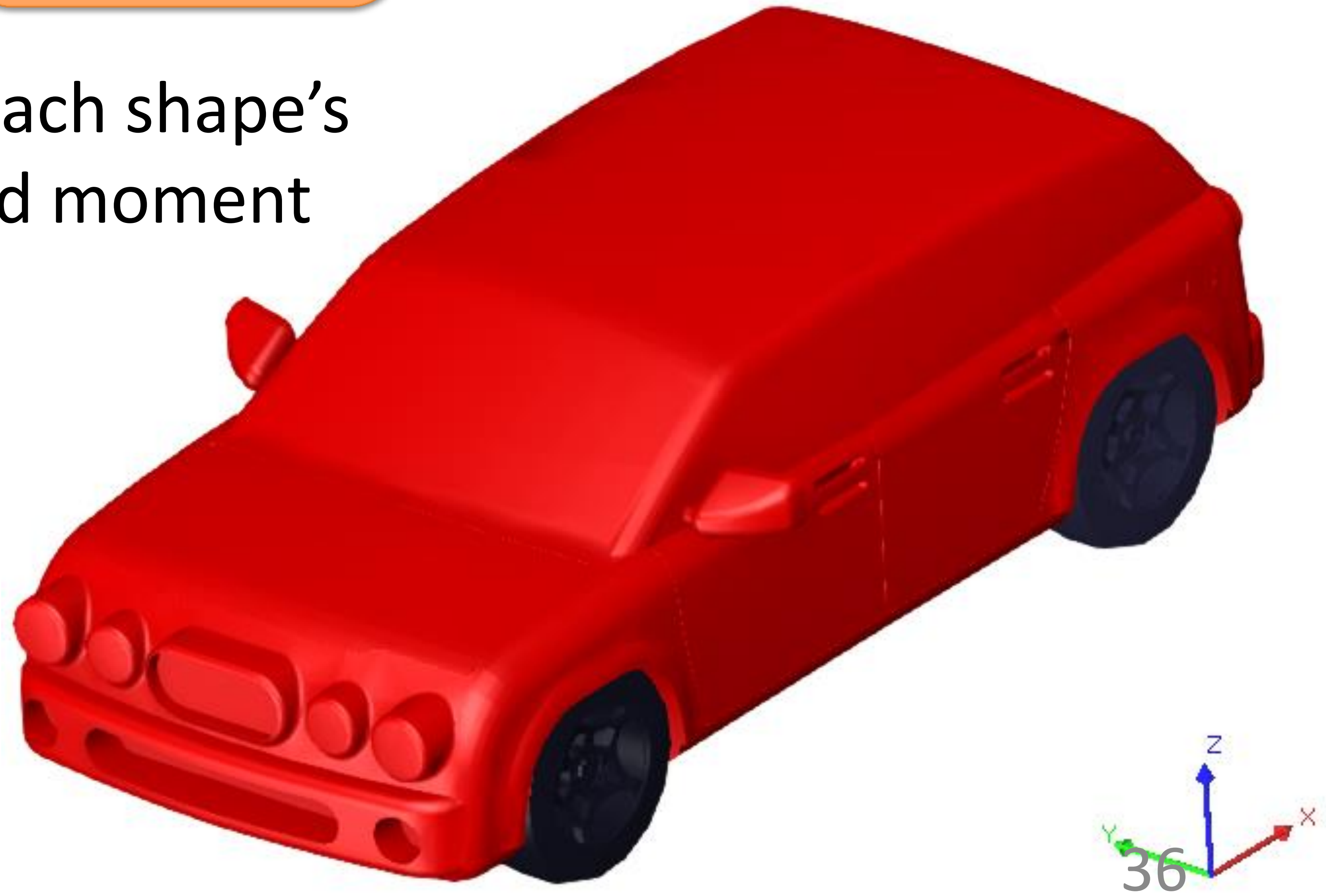
Adams

FMU Co-Simulation

XFlow

Apply as each GFORCE's force and torque value

Export each shape's force and moment

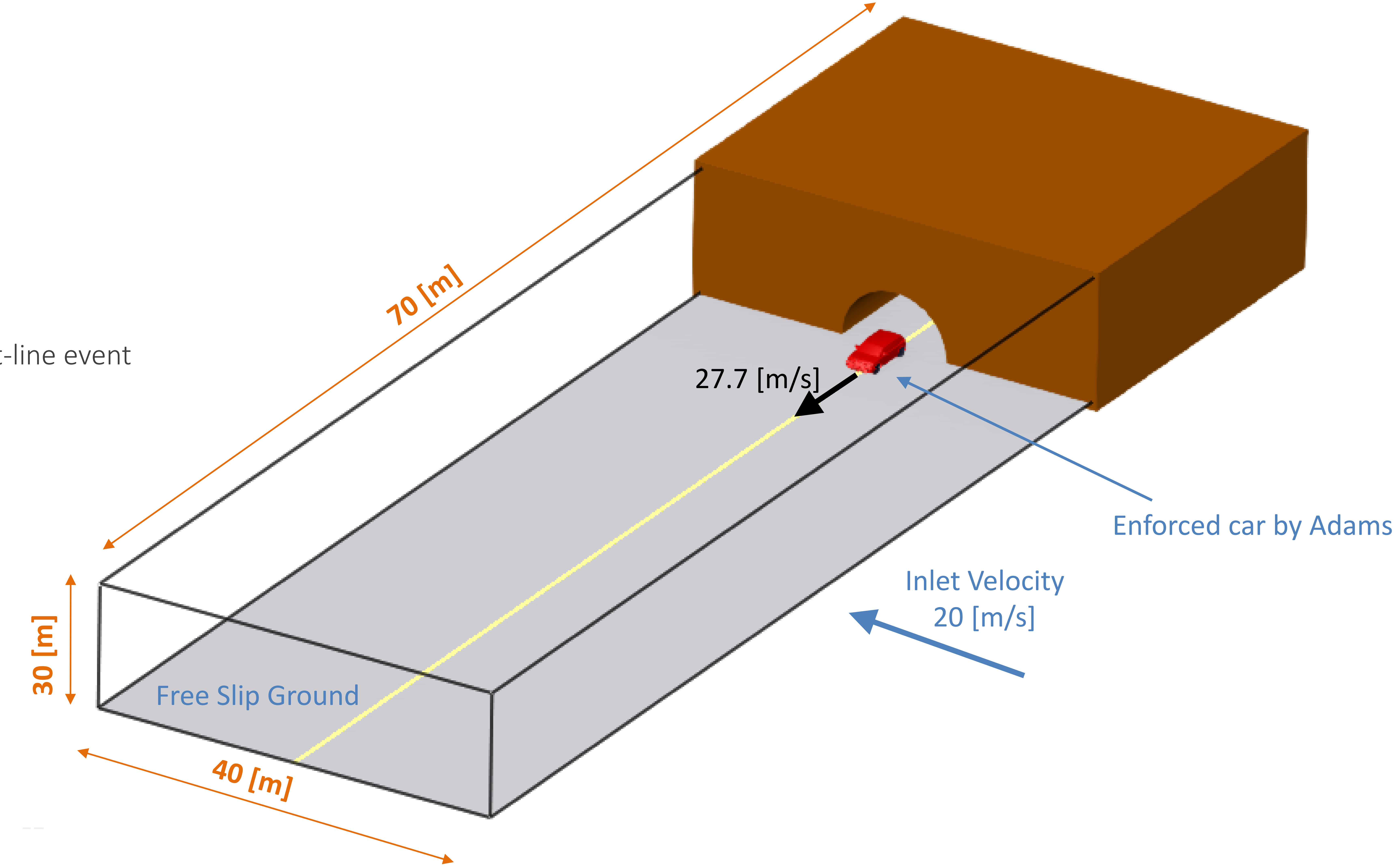


Crosswind Adams Car-XFlow co-simulation

Simulation setup

XFlow
- → Single phase
- → Lateral wind (20 m/s)
- → Adaptive refinement

Adams-Car
- → Crossover model:
  - - Free steering
  - - Driver control: Straight-line event

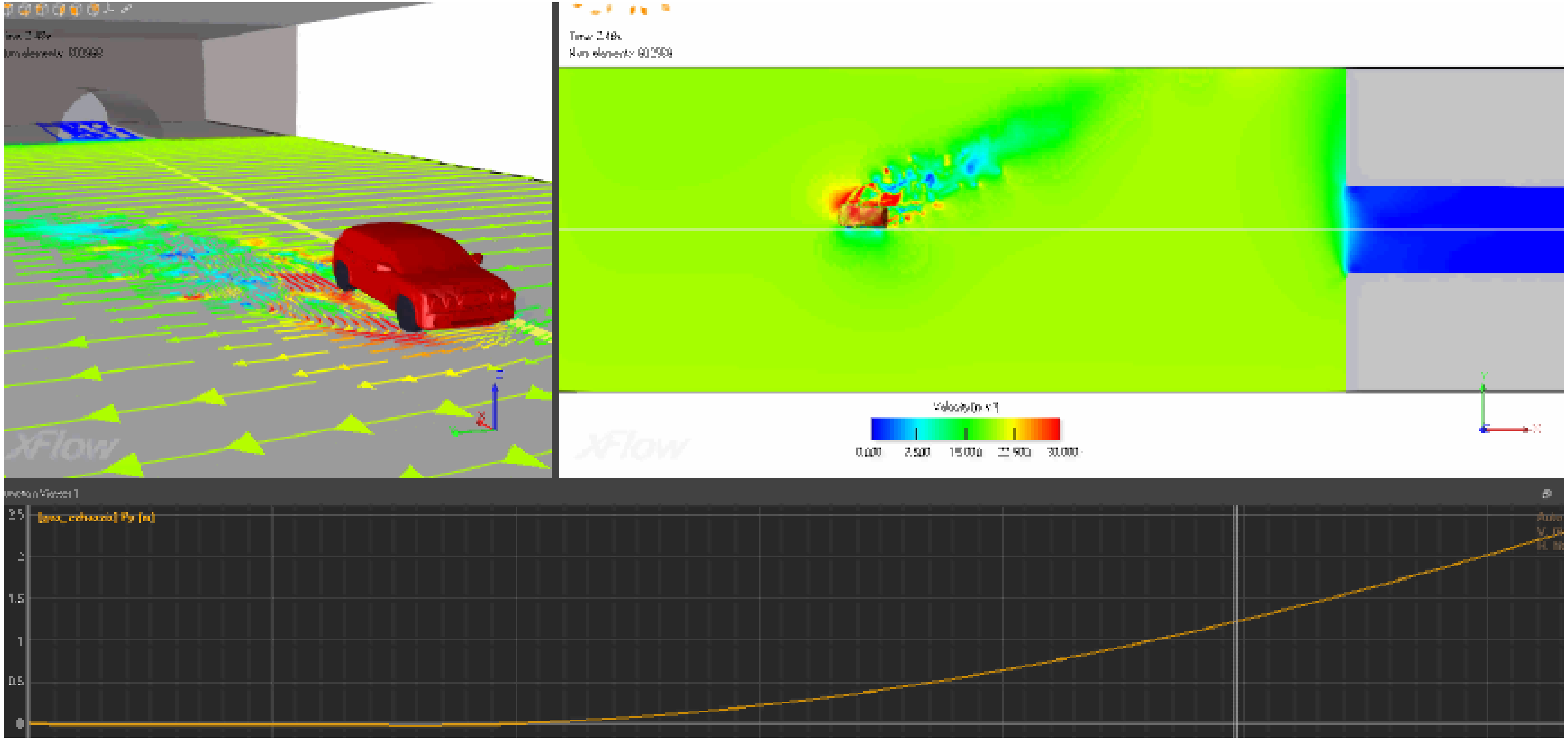


Crosswind Adams Car-XFlow co-simulation

	Far Field [m]	Near Walls [m]	# Elements	Simulated Time [s]	# Nodes	# Cores	Run Time [h]
Overtaking	0.512	0.064	**400.000**	3.2	1	16	**12**

Free steering

→ 2m of maximum lateral displacement.

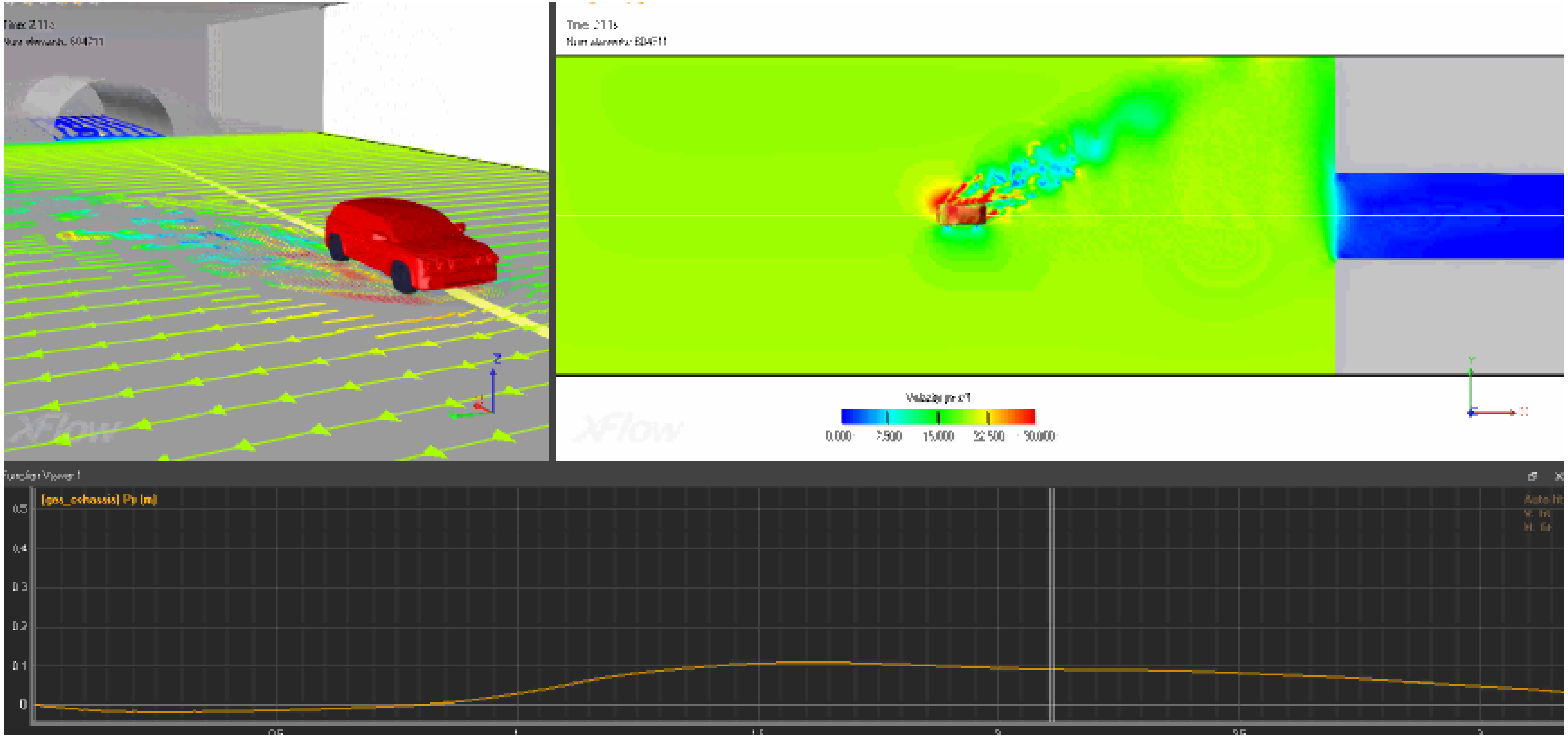


Crosswind Adams Car-XFlow co-simulation

	Far Field [m]	Near Walls [m]	# Elements	Simulated Time [s]	# Nodes	# Cores	Run Time [h]
Overtaking	0.512	0.064	**400.000**	3.2	1	16	**12**

Driver control: Straight-line event

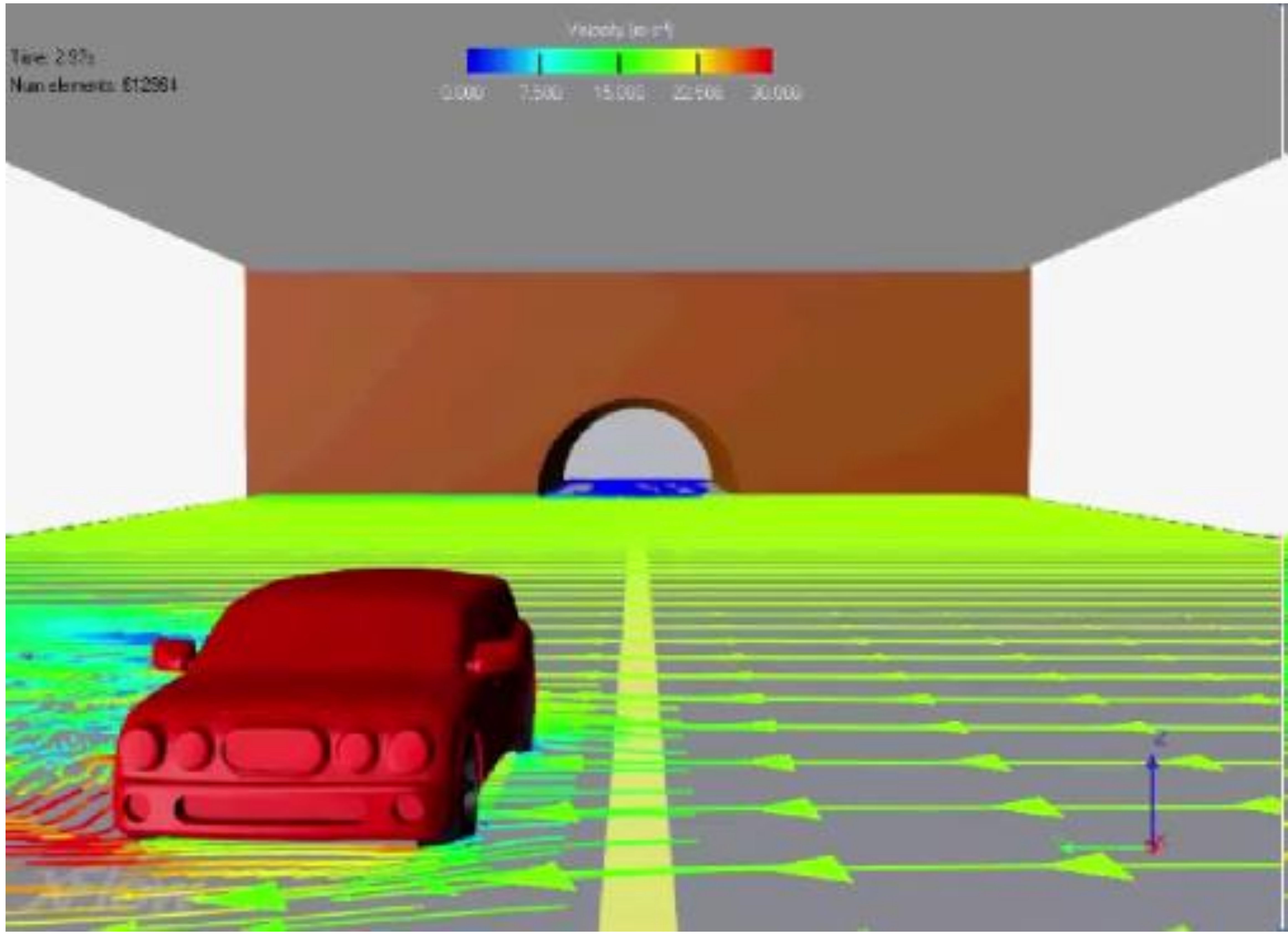
→ 0.1m of maximum lateral displacement.



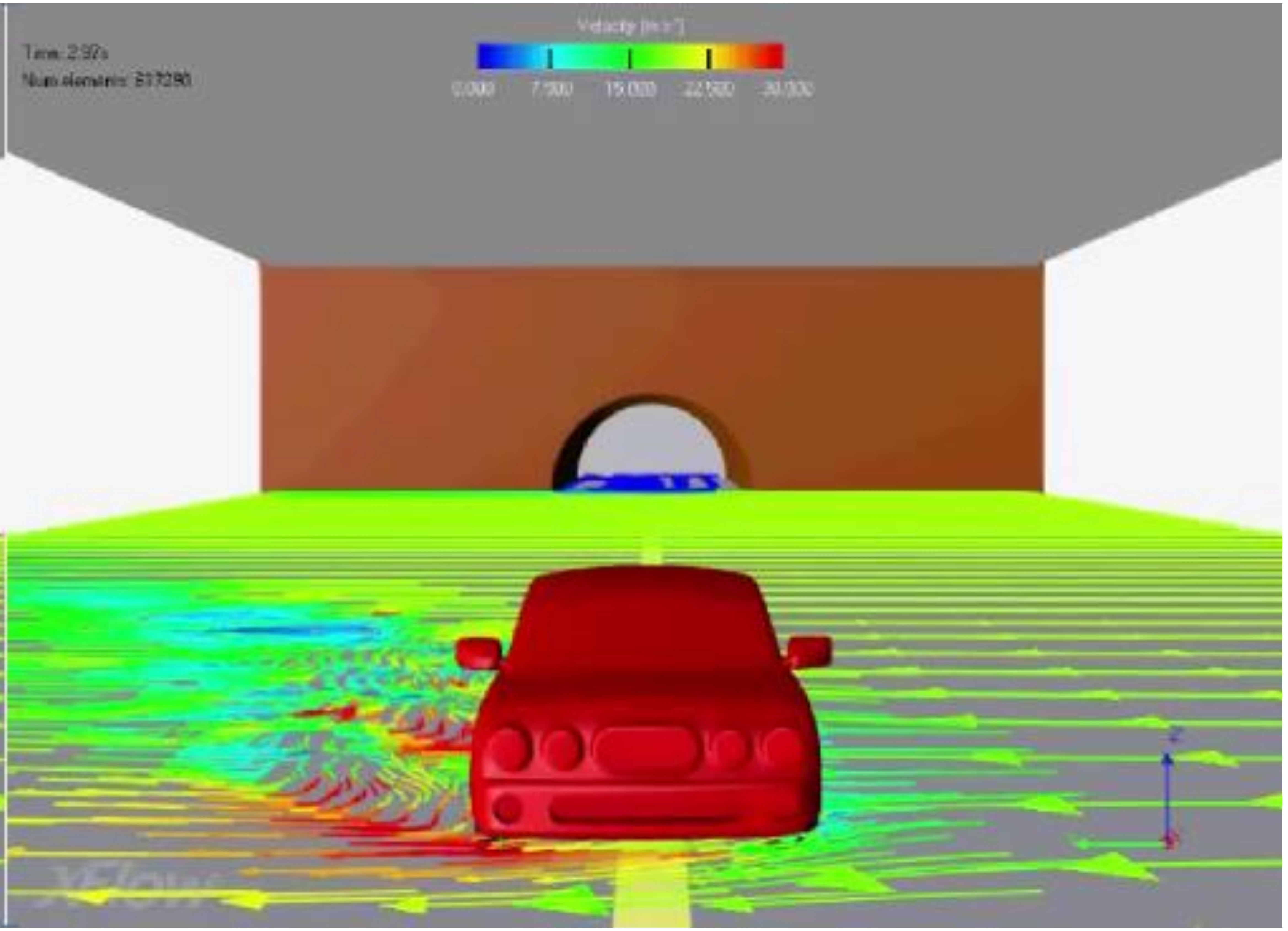
Crosswind Adams Car-XFlow co-simulation

Configuration comparison

	Far Field [m]	Near Walls [m]	# Elements	Simulated Time [s]	# Nodes	# Cores	Run Time [h]
Overtaking	0.512	0.064	**400,000**	3.2	1	16	**12**



Max. lateral displacement = 2m



Max. lateral displacement = 0.1m

Conclusions

→ Detailed geometry is easily handle by XFlow due to the particle-based approach.

→ Simulation tool for the analysis of unsteady flow and an accurate drag (≈1%) prediction of flow separation from the vehicles geometry.

→ The potential of the method to simulate dynamic geometries, without time consuming remeshing processes, has been shown.

→ FMU co-simulation allows to model the car dynamic and study fluid-structure interactions. It could be useful to design an stability control in order to increase the safety car.

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