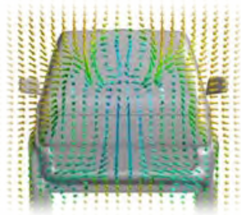
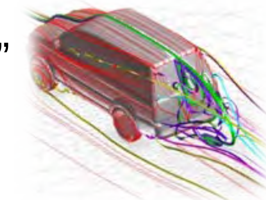
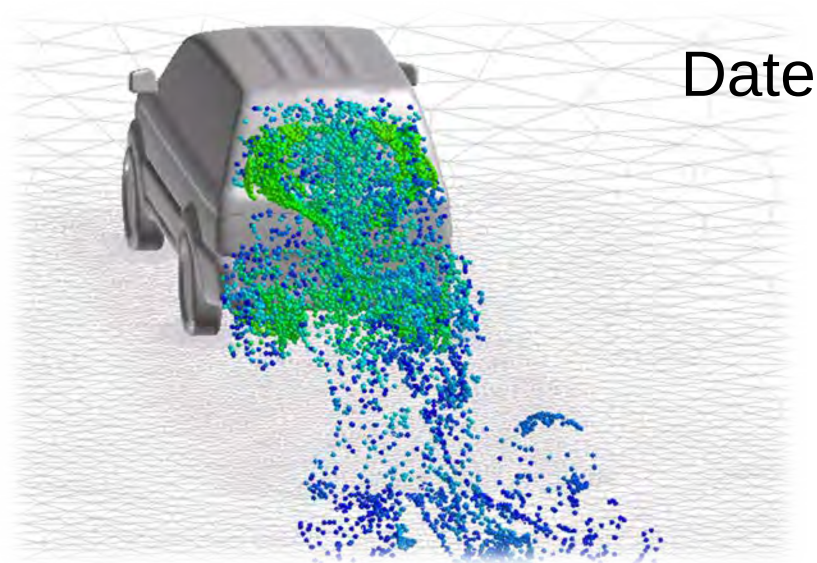


“International Conferenceon Progress in Fluid Dynamics and Simulation”
Celebrating the 60th birthday anniversary of Tony Wen-Hann Sheu

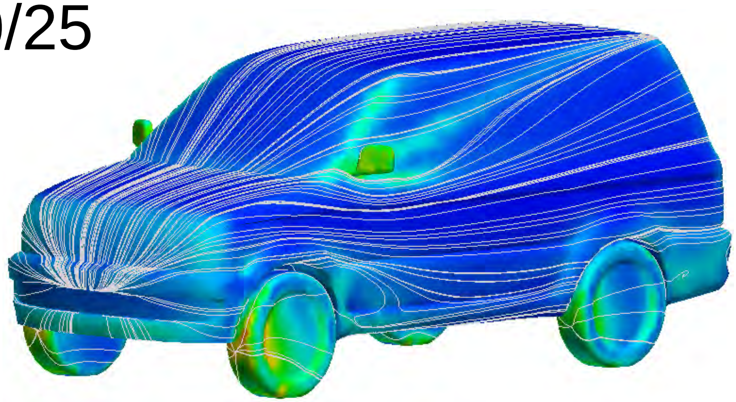


Vortical flow structure in the wake of an estate car

Phillip Gwo-Yan Huang & Tony Wen-Hann Sheu



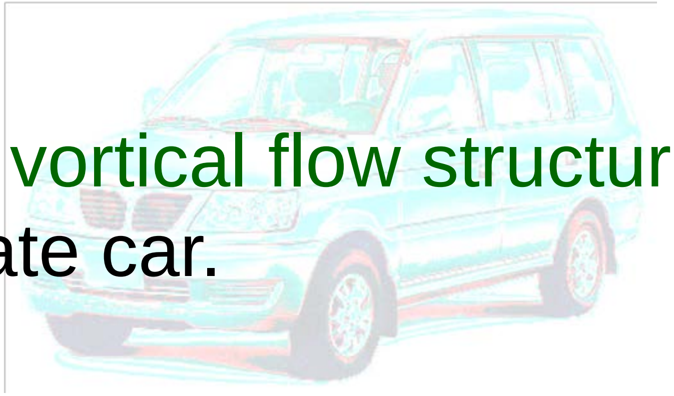
Date：2014/10/25



N.T.U.

Objectives

- Construct a numerical wind tunnel for an estate car, Freeca



- Investigate the vortical flow structure behind the square-back estate car.

- Calculate the aerodynamic forces (drag force, side force and lift force) exerting on the car.

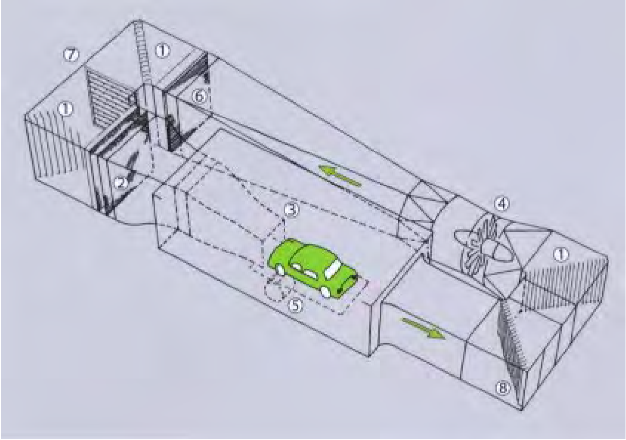
Conventional wind tunnels

The first wind tunnel.
Wright brothers.

Wind tunnel of NASA
Ames research center.

Wind tunnel testing.Volvo C.C.

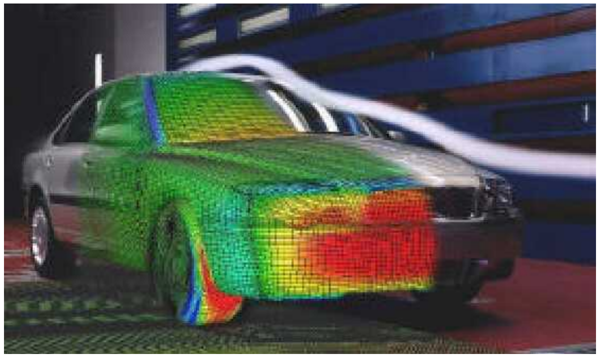
Wind tunnel testing. Audi.



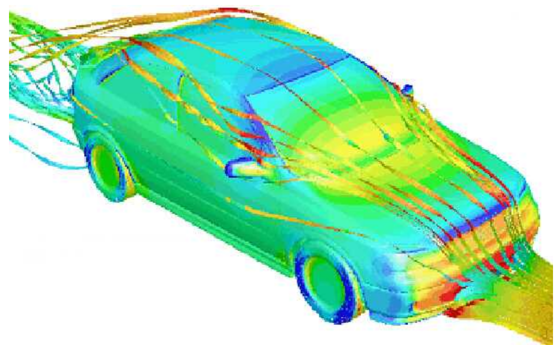
Big fan for
wind tunnel.

SCIENTIFIC COMPUTING & CARDIOVASCULAR SIMULATION LABORATORY
N.T.U.

Numerical wind tunnels



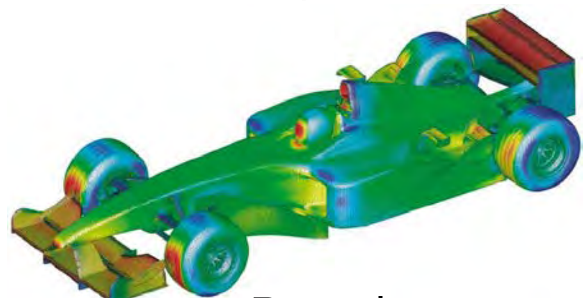
Volvo S800



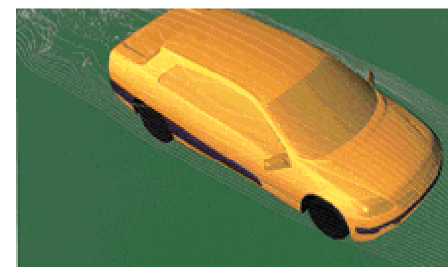
Opel

Alpha Romeo

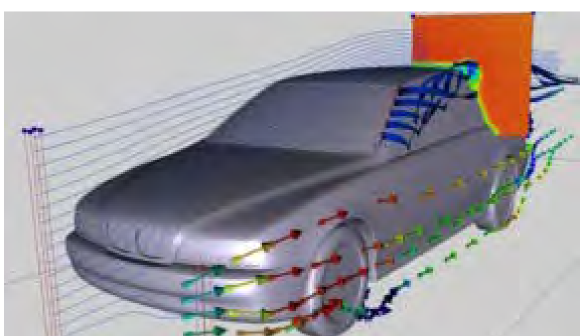
Mercedes-Benz.



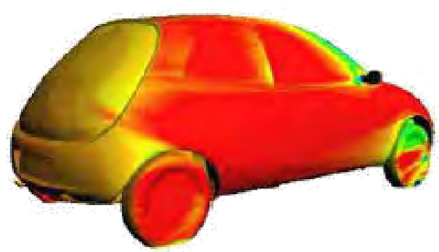
Renault



Nissan



BMW



Ford Ka.

Numerical wind tunnel simulation steps

CAD ~Pro/E~	→	Meshing ~ICEM-CFD~	→	Problem definition	→	Solving ~CFX~	→	Post-procession ~ FIELDVIEW~

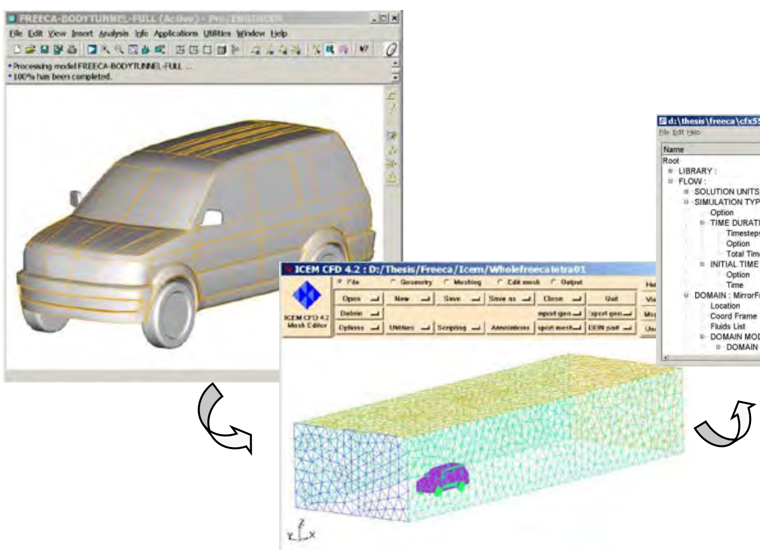
CAD
- -Create
- -Import

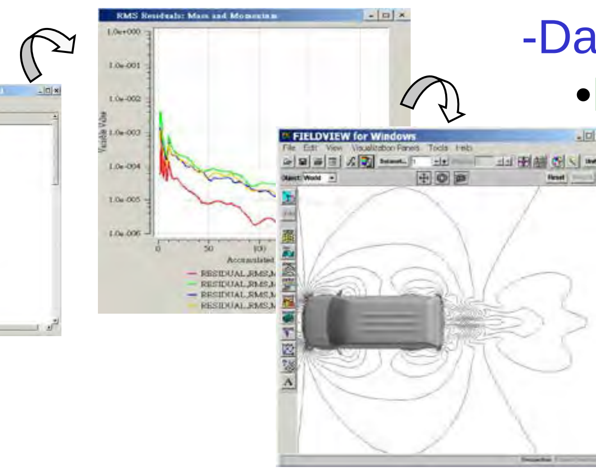
Meshing
- -Unstructured grid
- -Mesh quality !

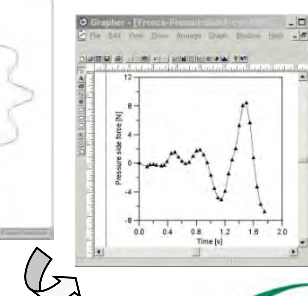
Problem definition
- -Transient state
- -Physical model
- -Governing equation
- -Boundary condition

Solving
- -Scheme
- -Calculation time
- -Convergence !

Post-procession
- -Visualization
  - •Pressure
  - •Velocity
  - •Streamline
  - •Streaklines
- -Data analysis
  - •External flow:
    - - Drag, lift, side forces





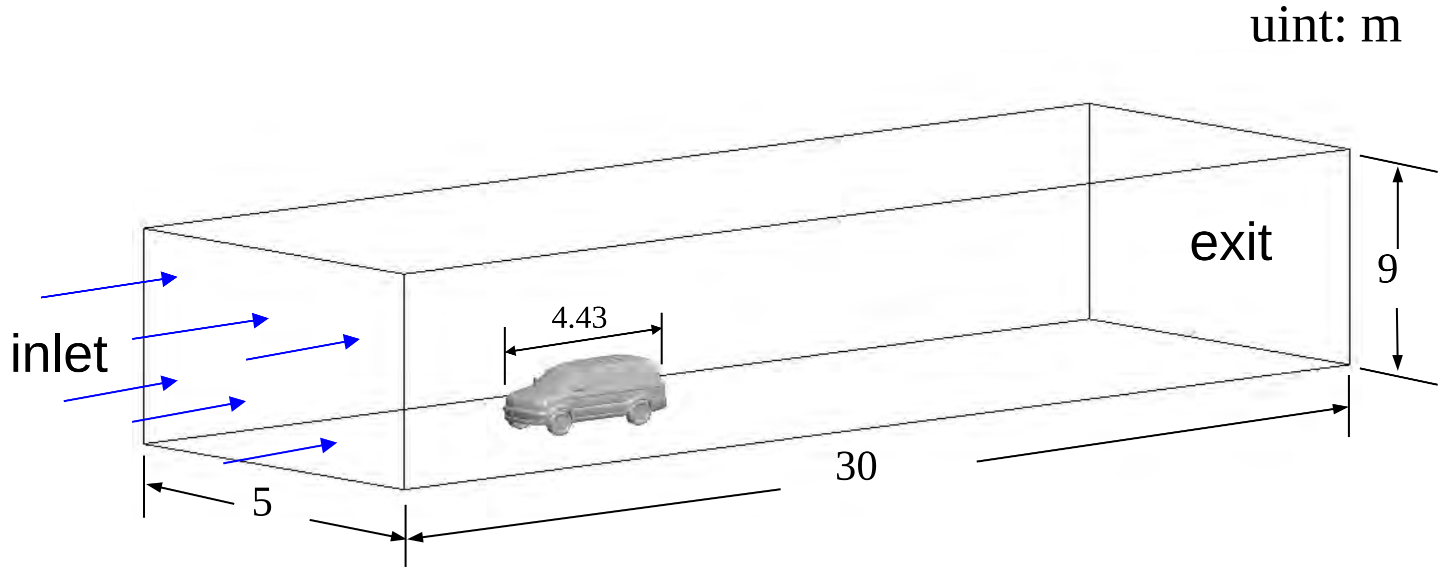


An estate car model _Freeca

Mitsubishi Freeca.
Photograph courtesy of China Motor Car.

CAD model for Freeca.

A numerical wind tunnel for Freeca



Boundary conditions:

- inlet: U =110 km/hr air flow
- exit: 0.0 pa static pressure initially
- ceiling, side walls: free slip
- car surface & ground: no-slip

Re = 8.05 x 10^6

Governing equations

- Continuity equation :

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \underline{U}) = 0$$

- Reynolds-averaged momentum equation:

$$\frac{\partial \rho \underline{U}}{\partial t} + \nabla \cdot (\rho \underline{U} \otimes \underline{U}) - \nabla \cdot (\mu (\nabla \underline{U} + (\nabla \underline{U})^{T})) = -\nabla p^{'} - \nabla \cdot (\rho \overline{\underline{u} \otimes \underline{u}})$$

- Reynolds stress turbulence model :

$$\frac{\partial \rho \overline{\underline{u} \otimes \underline{u}}}{\partial t} + \nabla \cdot (\rho \underline{U} \otimes \overline{\underline{u} \otimes \underline{u}}) - \nabla \cdot ((\mu + \frac{2}{3} C_{s} \rho \frac{k^{2}}{\varepsilon}) \nabla \overline{\underline{u} \otimes \underline{u}}) = P + G + \varphi - \frac{2}{3} \rho \varepsilon \delta$$

A finite volume simulation method

Governing equations: $$\frac{\partial \rho \Phi}{\partial t} + \nabla \cdot (\rho \underline{U} \Phi) - \nabla \cdot (\Gamma \nabla \Phi) = S$$

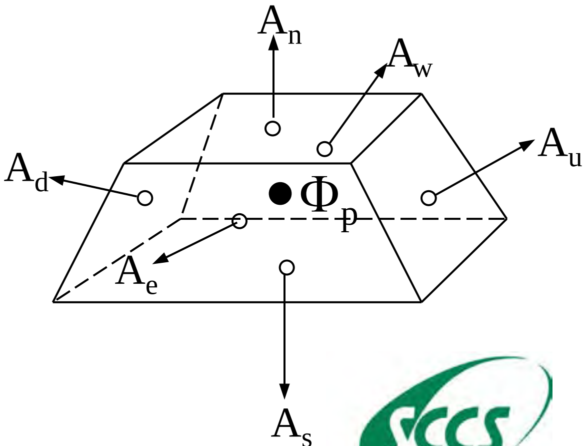
Integrating over a control volume Ω: $\longrightarrow$ $$\int_{\Omega} \frac{\partial \rho \Phi}{\partial t} dV + \int_{\partial \Omega} \rho \Phi \underline{U} \cdot \hat{n} dA - \int_{\partial \Omega} \Gamma \nabla \Phi \cdot \hat{n} dA = \int_{\Omega} S dV$$

Spacial discretisation : $$\frac{\partial (\rho \Phi_p)}{\partial t} V_{\Omega} + \sum_f \rho U A_f \Phi_f - \sum_f \frac{\Gamma A_f}{h_f} (\Phi_p - \Phi_f) = S_p V_{\Omega}$$

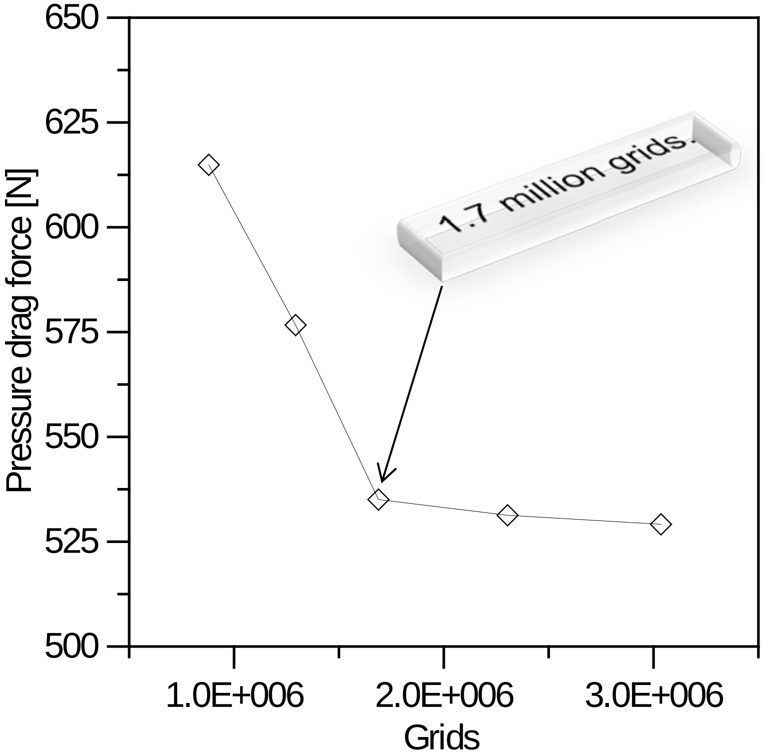
Temporal discretisation: $$\frac{\Phi^n - \Phi^{n-1}}{\Delta t} = F(\Phi^n)$$

A matrix equation to be solved: $\longrightarrow$ $$C_p \underset{\sim}{\Phi}_p - \sum_{nb} C_{nb} \underset{\sim}{\Phi}_{nb} = \underset{\sim}{S}_{\Phi} - S_o \underset{\sim}{\Phi}_p$$

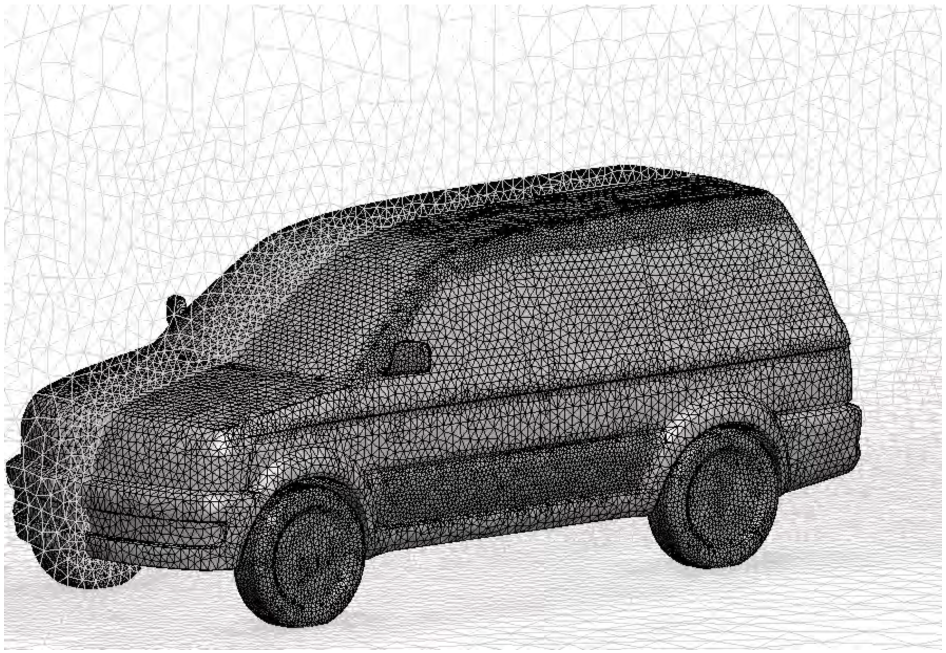
$\longrightarrow$ $$[A] \underset{\sim}{\Phi}_p = \underset{\sim}{B}$$



Mesh & Grid-independent test



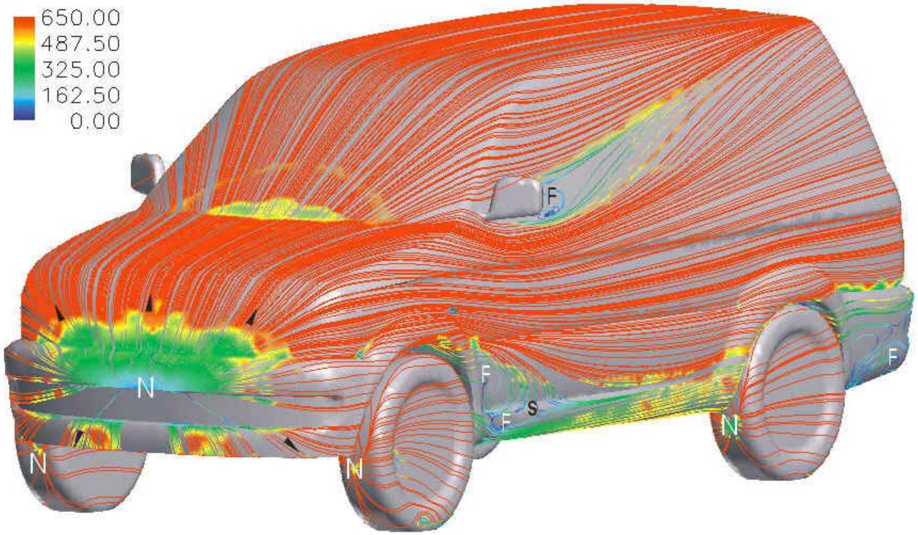
Effect of grids on the simulated pressure drag force at t=1.0 s.



Tetrahedral grids with local refinement.

Topological analysis of surface streamlines

Wall shear stress [N/m^2]



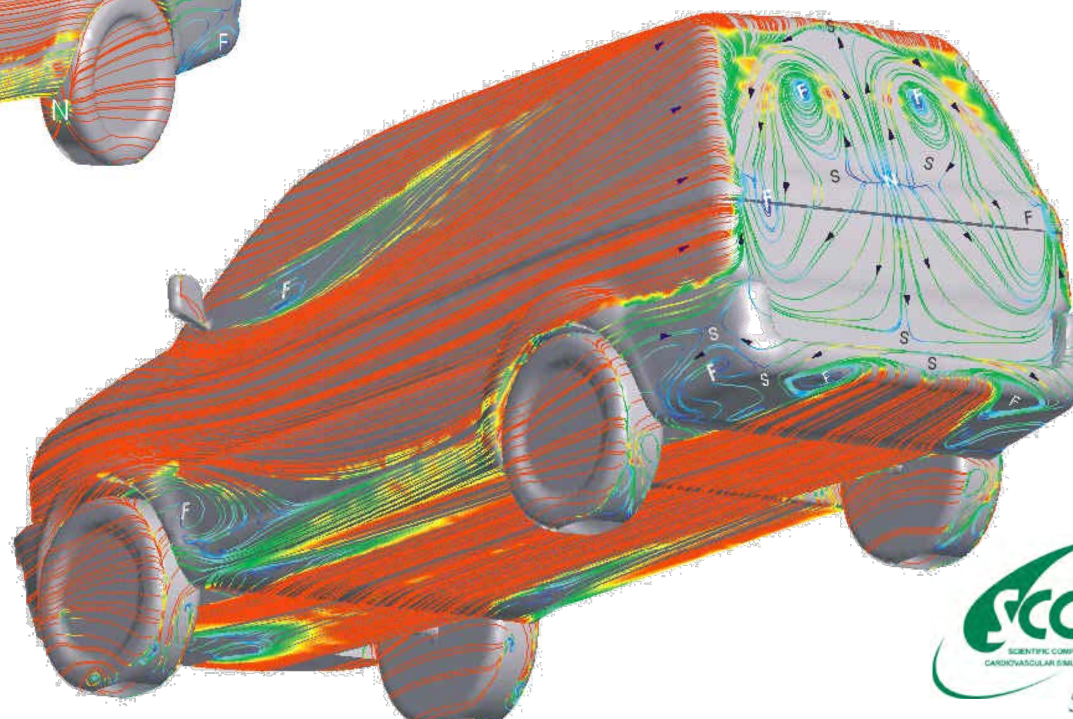
* Critical points of separation:

F: Spiraling focus.

N: Nodal attachment node.

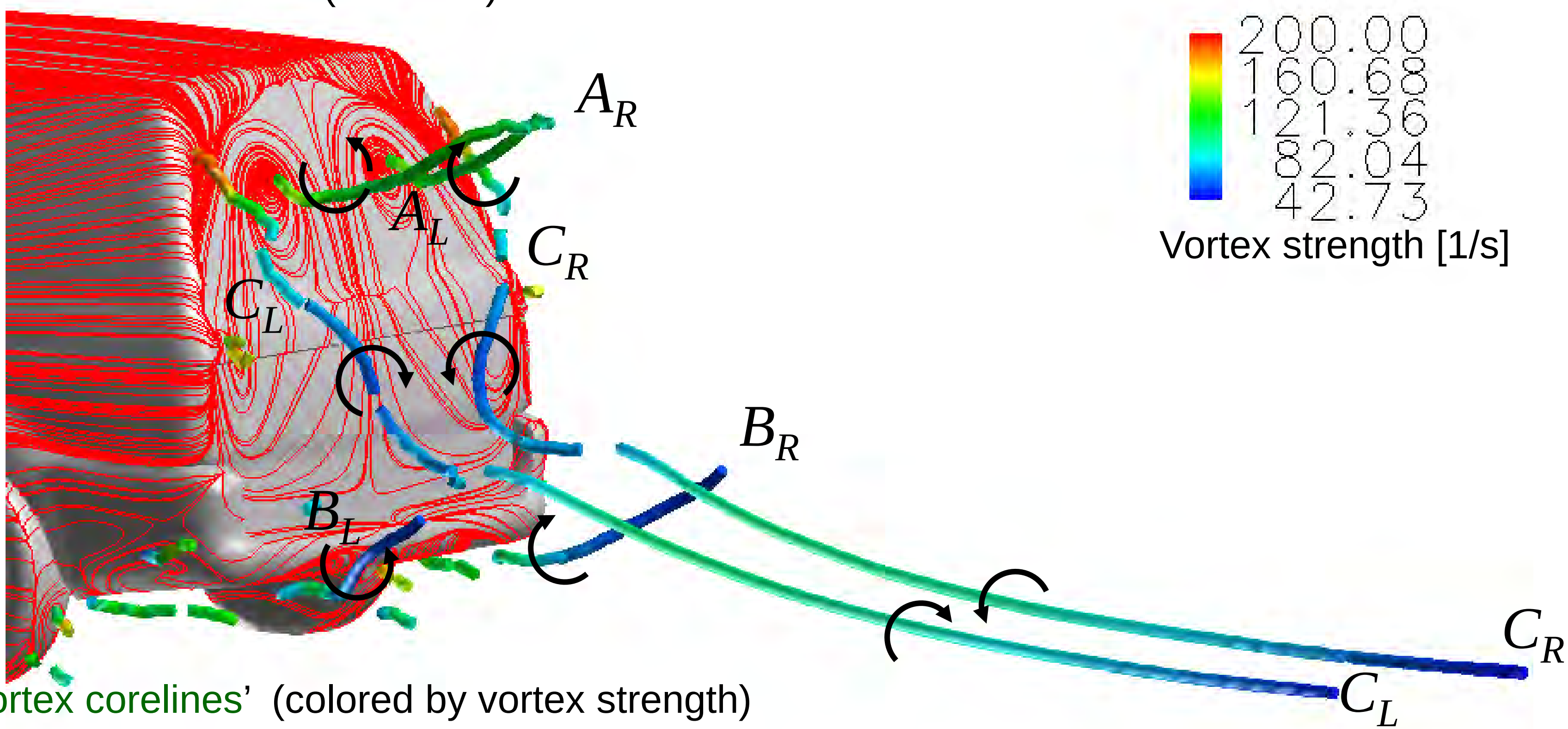
S: Saddle attachment point.

ps: The wall shear stress is zero at these critical points.



Three main wake vortex systems

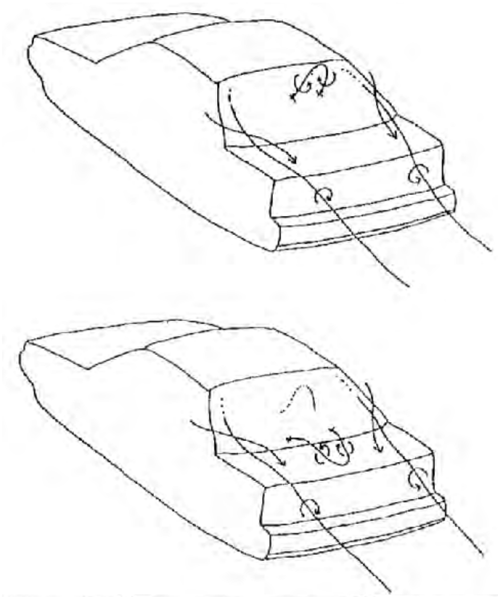
- ‘Surface streamlines’ (red lines)



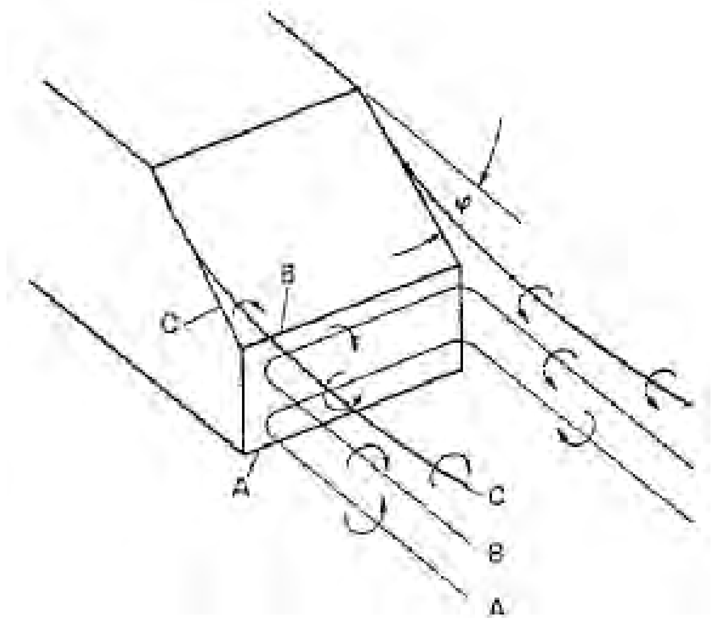
- ‘Vortex corelines’ (colored by vortex strength)
- Three typical ‘counter-rotating vortex pairs’ (denoted by *A*, *B*, and *C*) in the wake of the square-back car.

  $A(A_L, A_R)$: arch-type vortex pair, generated near the rear window.
  $B(B_L, B_R)$: uptilting vortex pair, generated near the rear fender.
  $C(C_L, C_R)$: trailing vortex pair, generated near the rear-side pillars.
- These vortex corelines are started from the spiraling foci.

*Reference
Vortex systems behind the car

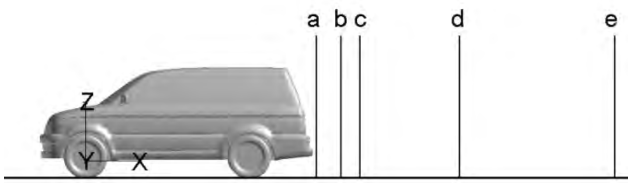


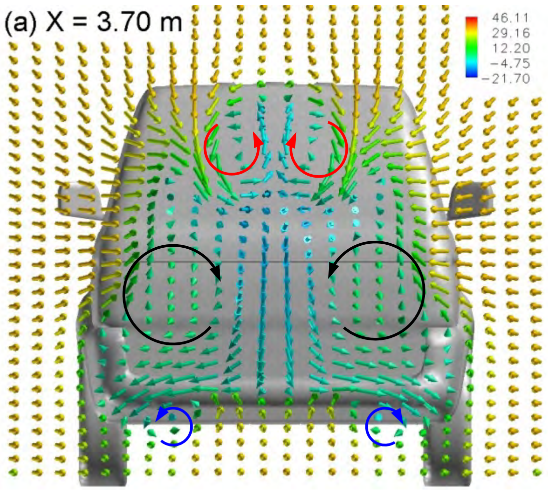
Ref.1: Periodic vortex motion in the wake of a **notch-back** sedan. Himeno et.al. (1990).



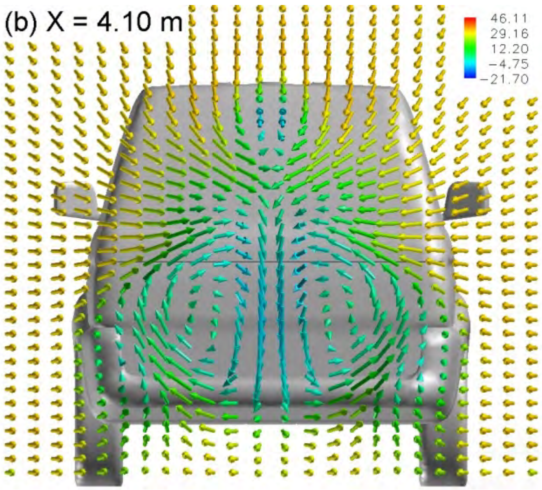
Ref.2: The vortex systems generated around the pillars and edges in the rear of a **fast-back** car. Hucho .

3D velocity vectors

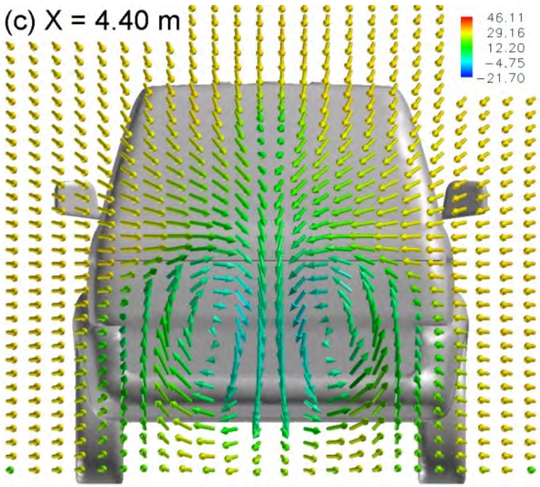




Arch-type, uptilting, & trailing vortex systems, formed by their corresponding counter-rotating vortex pairs.

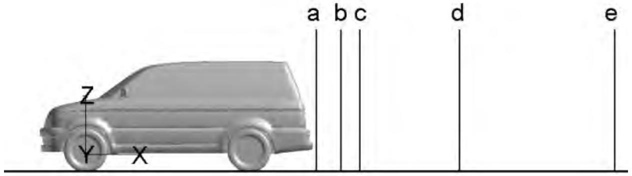


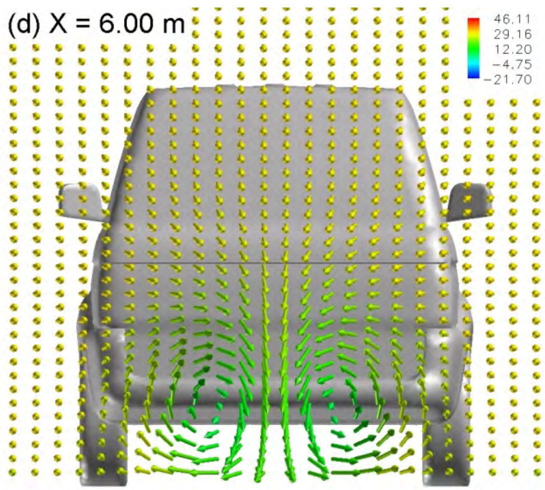
Uptilting vortex is merged by the trailing vortex.



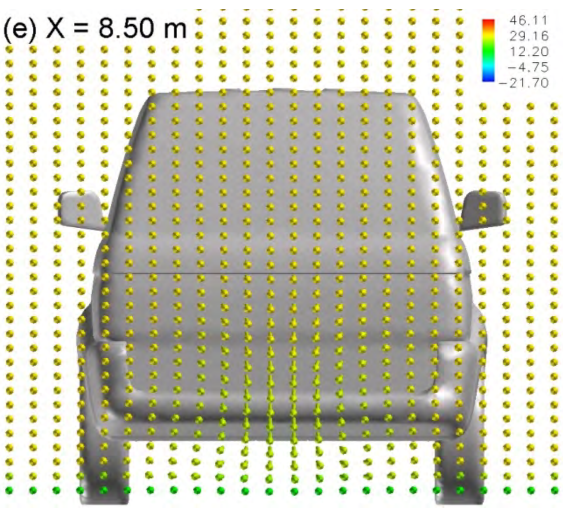
Arch-type votrtex is also merged by the trailing vortex.

3D velocity vectors





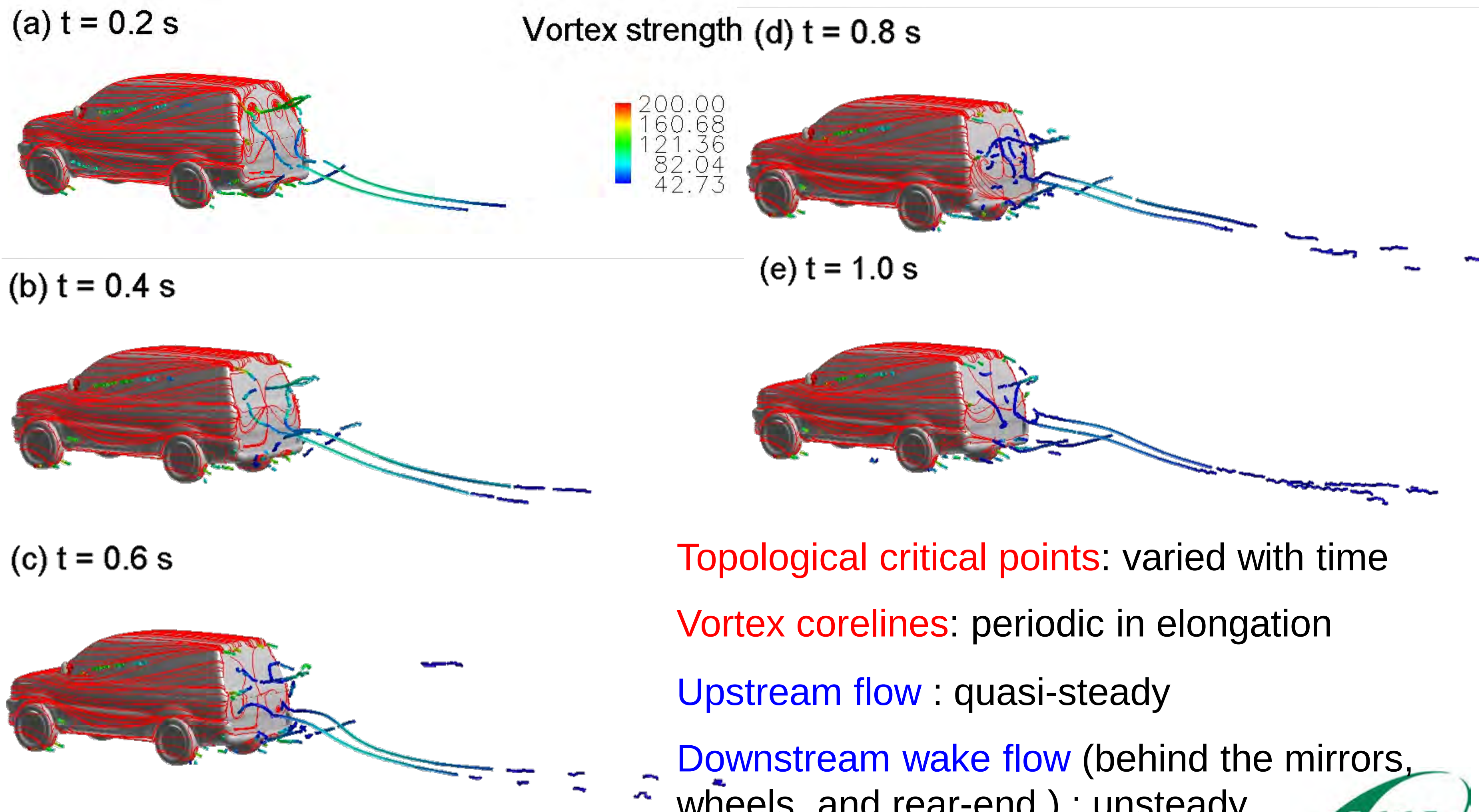
The strength of trailing vortex is diminished due to the dissipation effect.



No vortex exists, and the fluids move downstream.

Animation — 3D velocity field propagation

Time-evolving vortex corelines



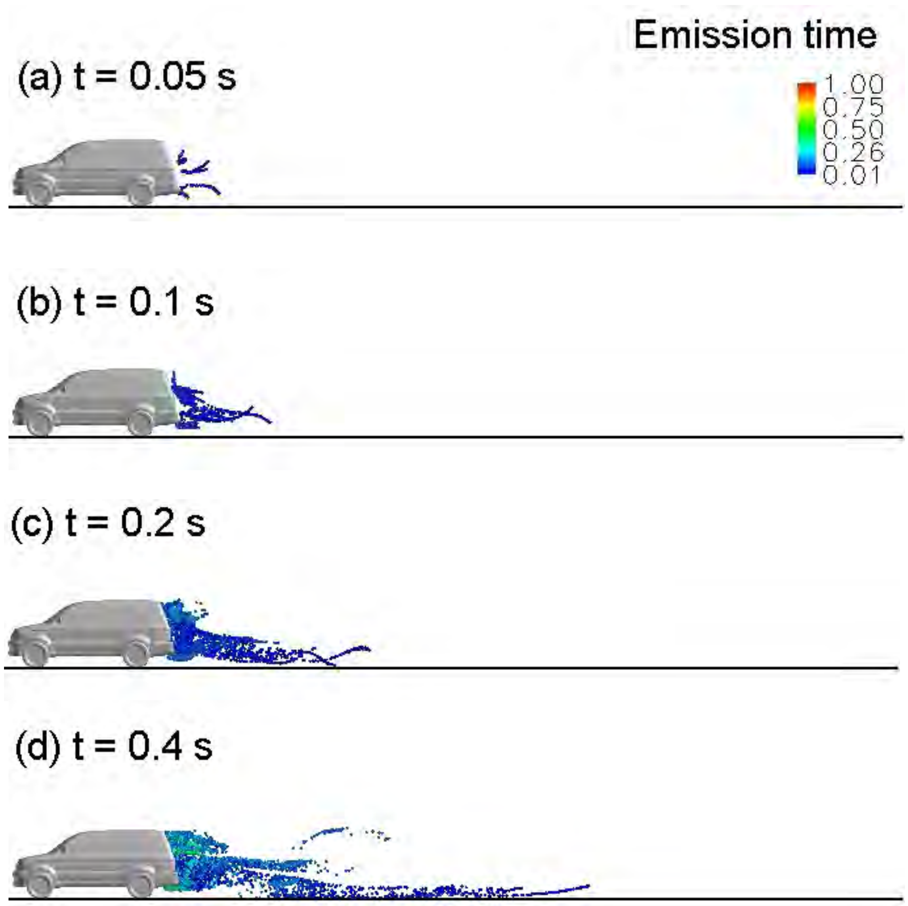
Topological critical points: varied with time

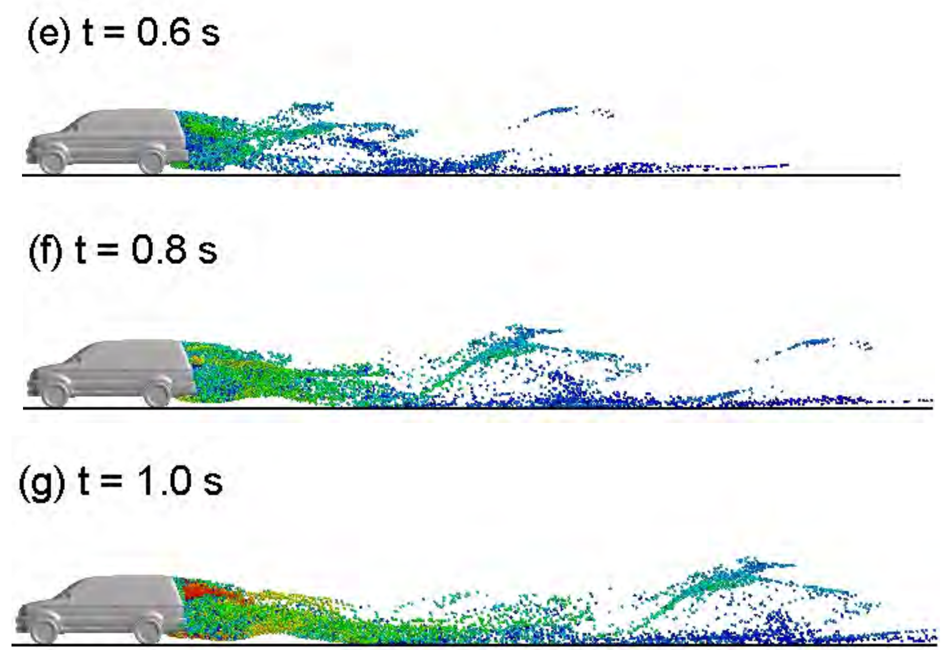
Vortex corelines: periodic in elongation

Upstream flow : quasi-steady

Downstream wake flow (behind the mirrors, wheels, and rear-end) : unsteady

Formation of a vortex street behind the car





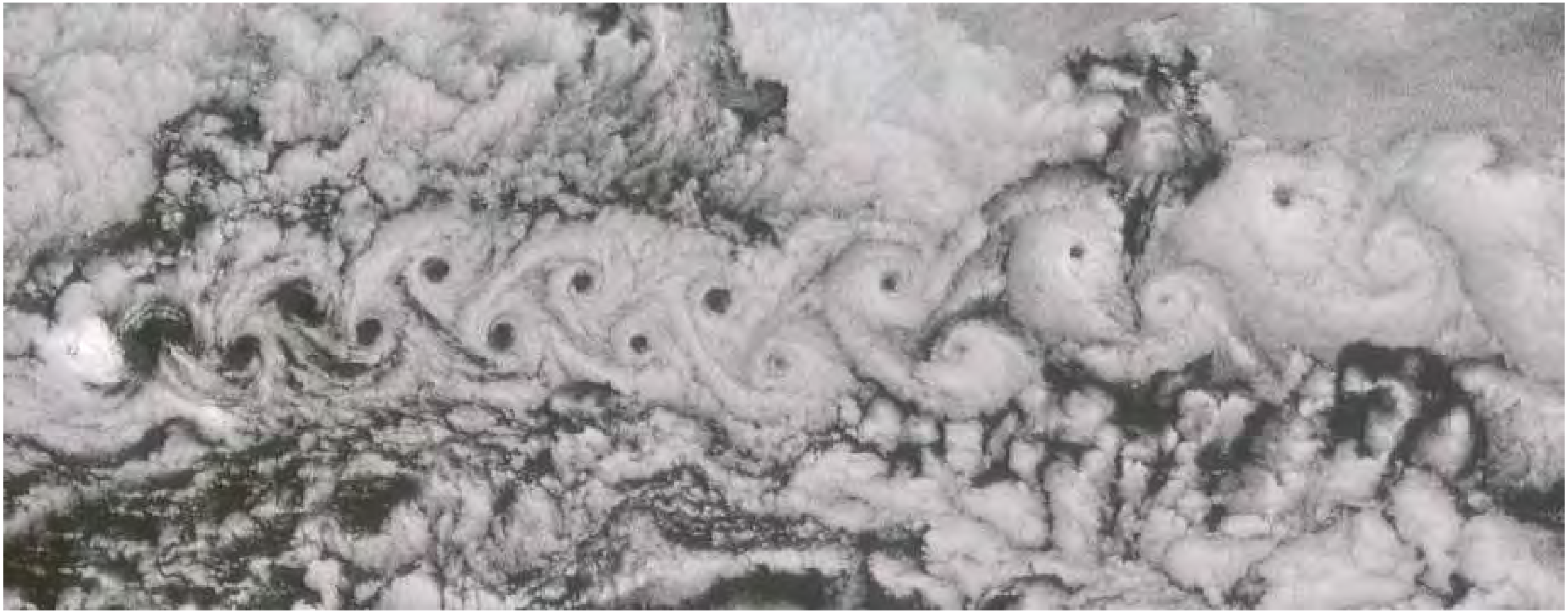
Particle streaklines from t=0.05 s to t=1.0 s.

The vortex are generated periodically and shedded away from the car.

The alternate vortex shedding leads to the formation of a vortex street behind the car.

Animation—Vortex street formation

*Reference
A vortex street behind an island



A series of organized eddies appear within the cloud layer downwind of Jan Mayen island (Norway), and a cloud-clearing effect is apparent at the vortex centers until finally closing on the sixteenth “hole”. This impressive vortex pattern continues for over 300 km southward of the island. Image courtesy of NASA/GSFC/LaRC/JPL, MISR Team, (2001).

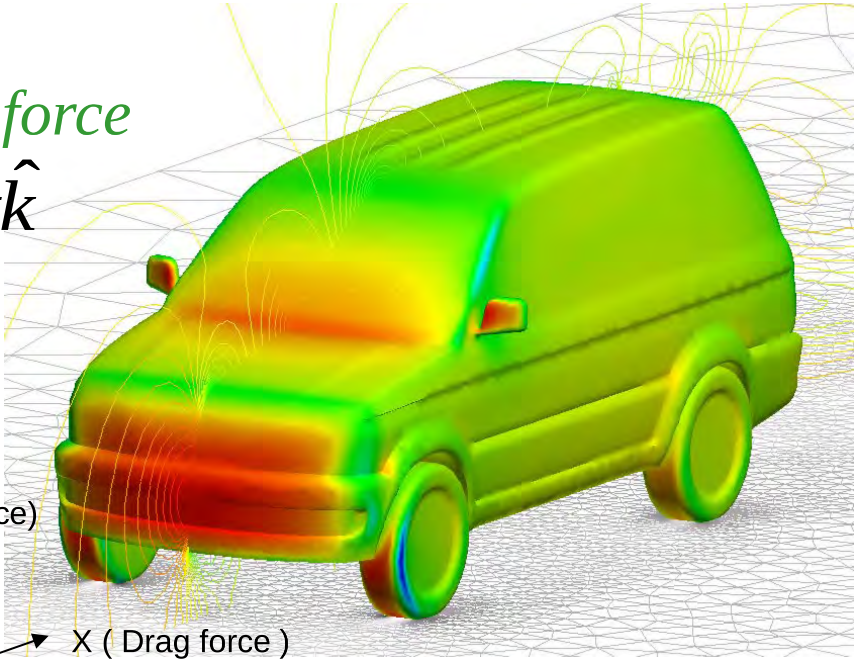
Aerodynamic forces acting on the car

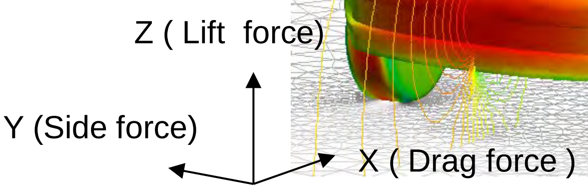
- The net aerodynamic force on the car:

$$\vec{F} = -\oint p\hat{n}dA + \oint \tau_w \hat{t}dA$$

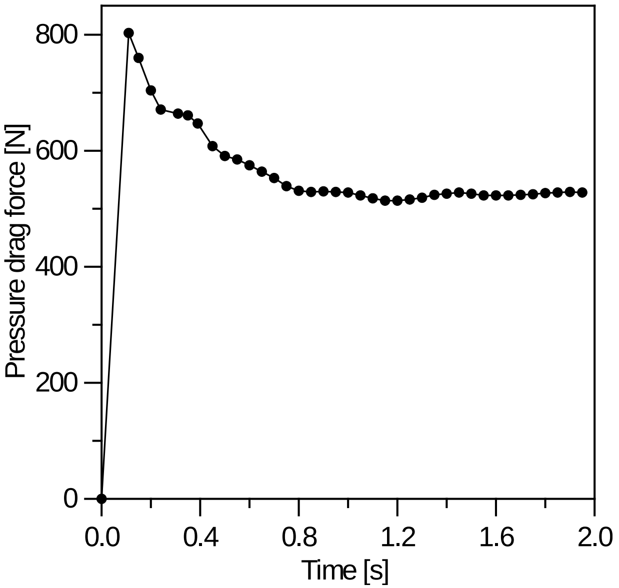
$$= \color{blue}{\textit{Pressure force}} + \color{green}{\textit{Viscous force}}$$

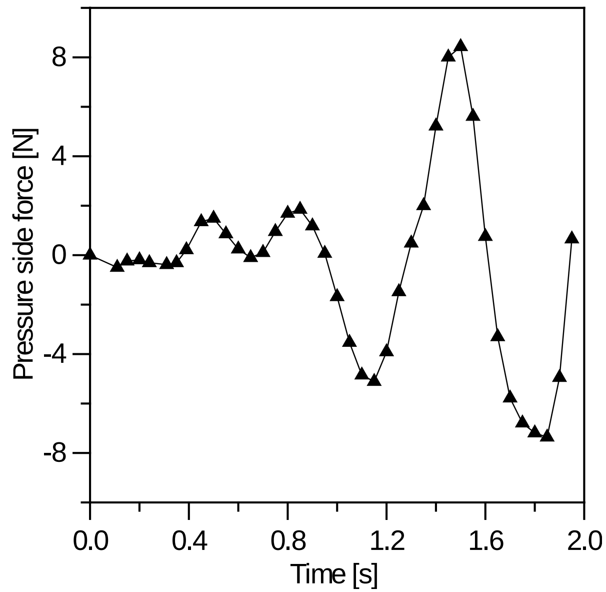
$$= Drag\hat{i} + Side\hat{j} + Lift\hat{k}$$

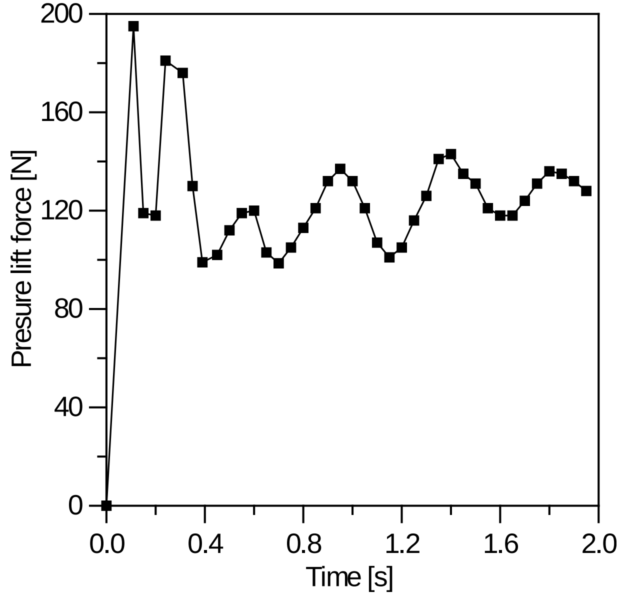




Time-varying pressure forces acting on the car







Pressure drag force:
vibrates between 515N~530N.
(downward)
Period: 0.55s

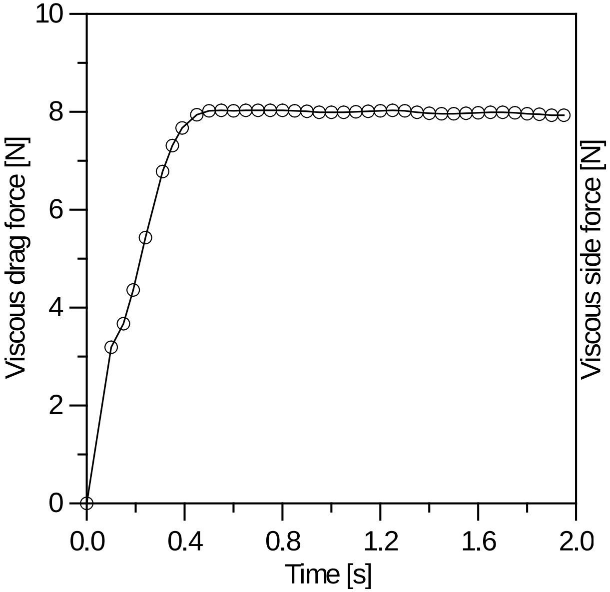
Pressure side force:
vibrates between -8N~8N.
(left and right)
Period: 0.65s

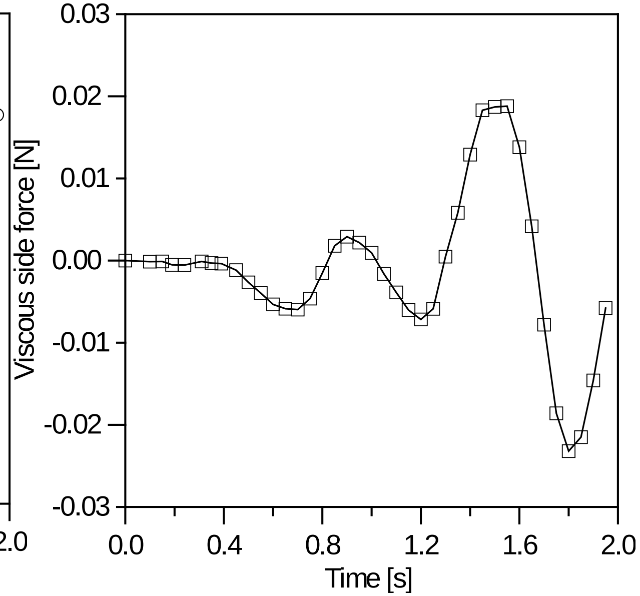
Pressure lift force:
vibrates between 90N~140N
(upward)
Period: 0.50s

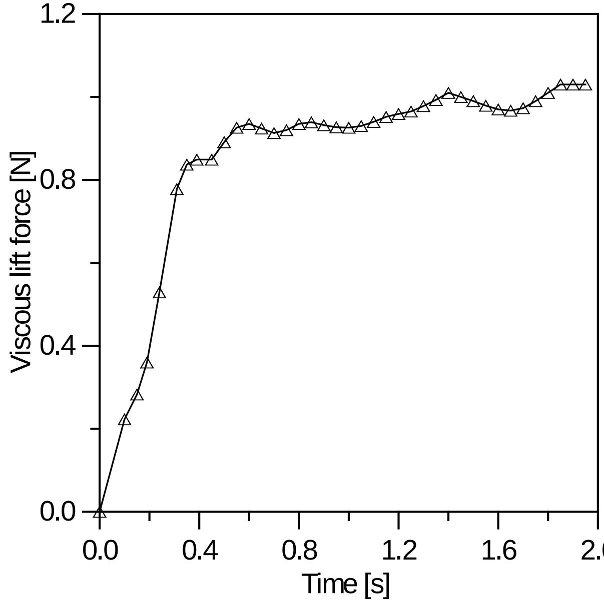
These time varying loads are caused by the alternate vortex shedding.

This oscillating phenomenon can be taken as a type of pitchfork bifurcation !

Time-varying viscous forces acting on the car







Viscous drag force:
vibrates between 7.9N~8.03N.
(downward)
Period: 0.60s

Viscous side force:
vibrates between-0.02N~0.02N.
(left and right)
Period: 0.65s

Viscous lift force:
vibrates between 0.9N~1.1N.
(upward)
Period: 0.60s

$$* \ \frac{\textit{pressure force}}{\textit{viscous force}} \cong 70 \sim 100$$

pressure drag » the other forces

Pressure drag (form drag) dominated

N.T.U.

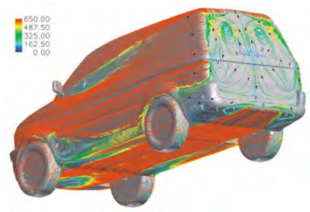
Conclusion

✧Accomplishment:

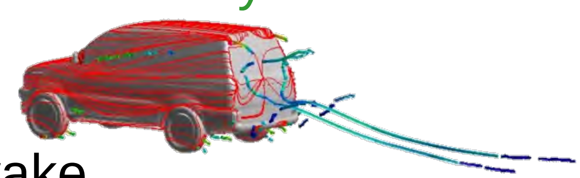
- A numerical wind tunnel for the square-back estate car, namely, the Freeca, has been constructed.
- The vortical flow around the estate car has been numerically studied.

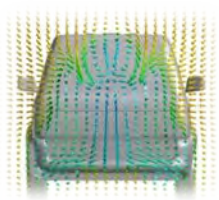
✧Discovery & contribution:

✓Surface streamline topology on the car surface.

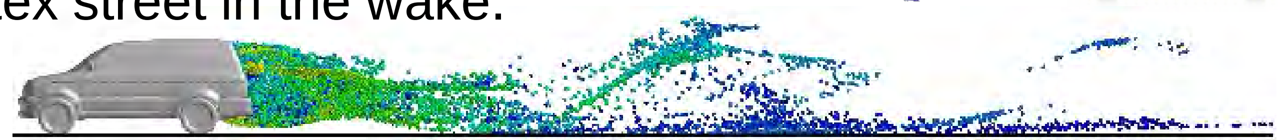


✓Interaction of three main vortex systems behind the estate car.

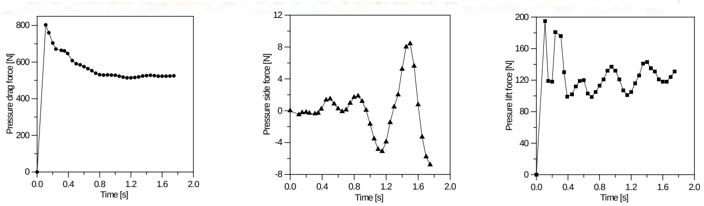




✓A vortex street in the wake.

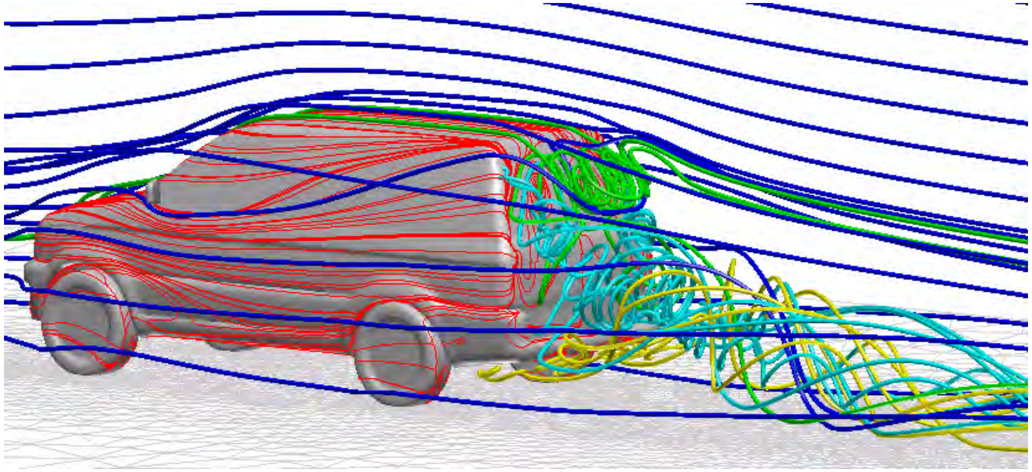


✓Vibration forces on the car.



The End!

Thank you for your attention!



Acknowledgments:
Support of this research provided by Ching-Lin Industrial Center is gratefully acknowledged.

SCCS
SCIENTIFIC COMPUTING & CARDIOVASCULAR SIMULATION LABORATORY
N.T.U.