CFD Based Air Flow and Contamination Modeling of Subway Stations

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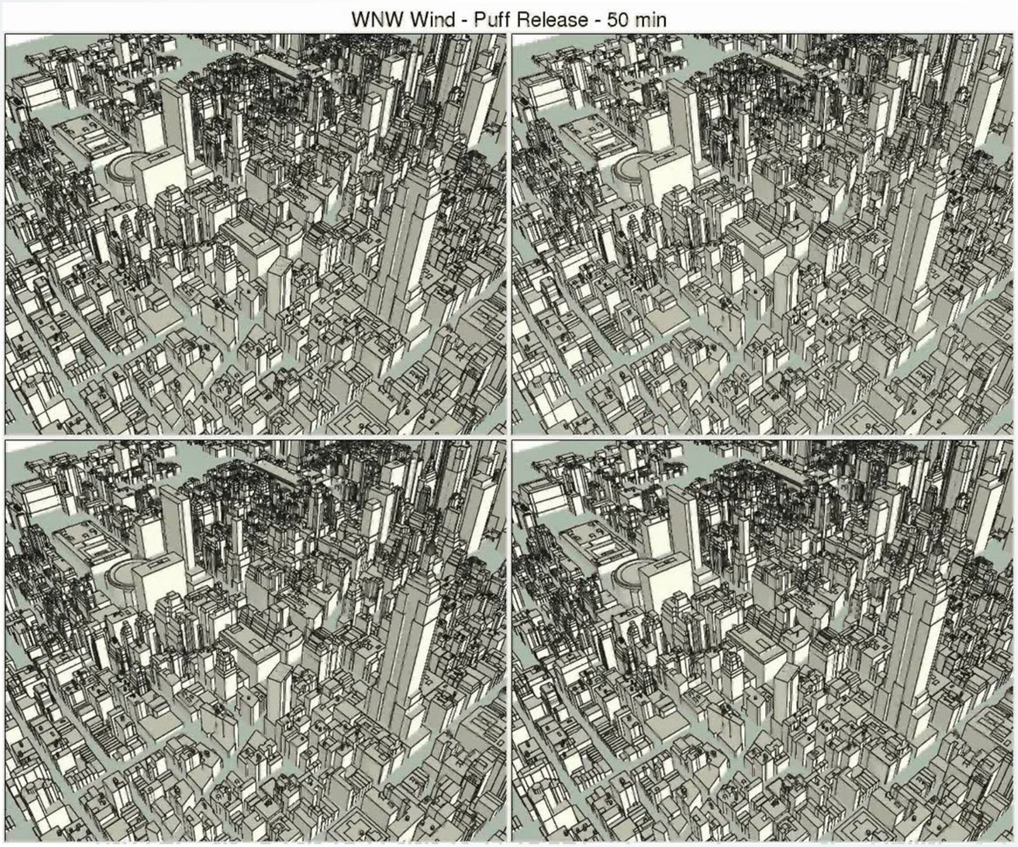
Urban Flows

- Computational fluid dynamic simulations play an important role in predicting atmospheric mixing, transport and dispersion in urban environments.

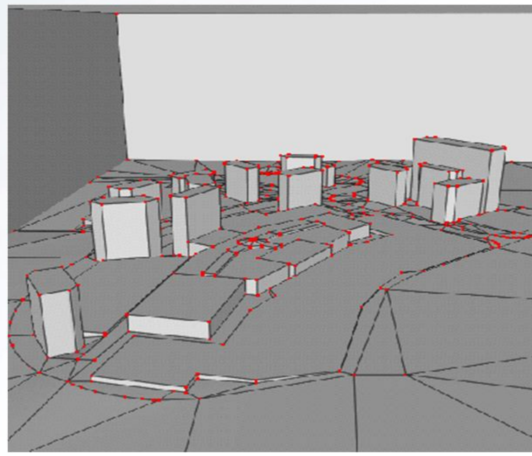
4 iso-surfaces of contaminant concentration during a release in Manhattan



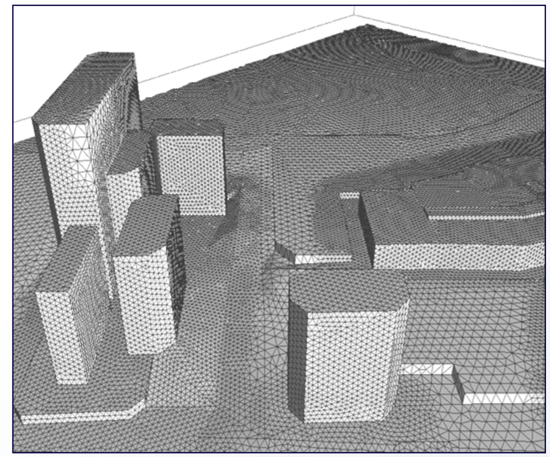
Computational Pipeline

Site Survey

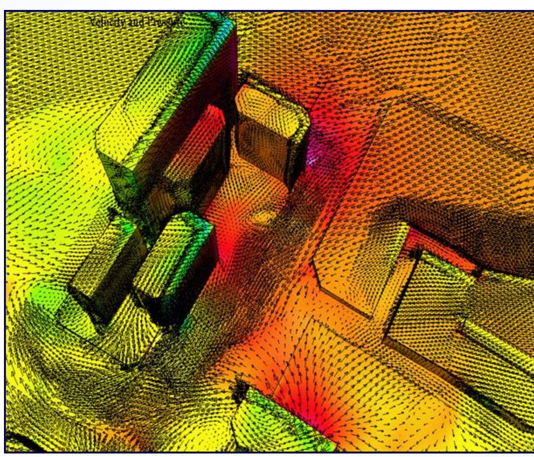
Geometric Modeling



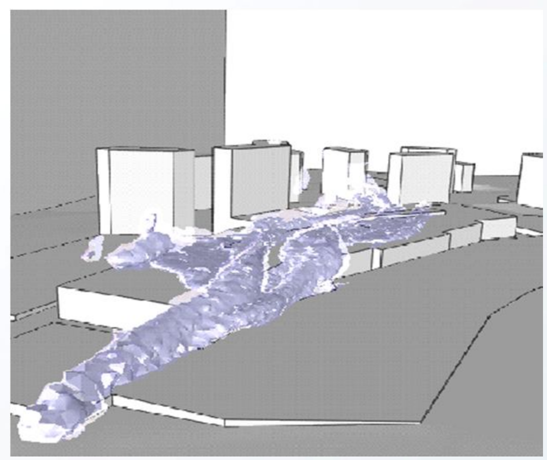
Unstructured Meshing



Flow/Dispersion Solver



Post-processing



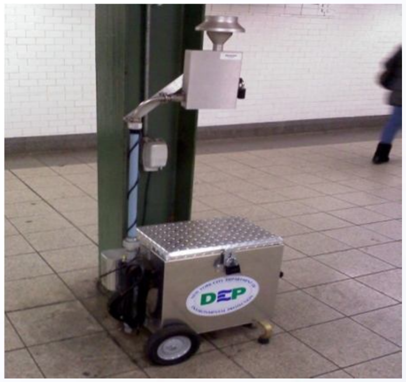
CFD Based Air Flow Modelling

- Subway stations are important urban infrastructures with complex spatiotemporal air flow patterns.
  - Use computational fluid dynamics to predict temperature, mixing, transport and dispersion.
  - Enable future improvements in safety and health.

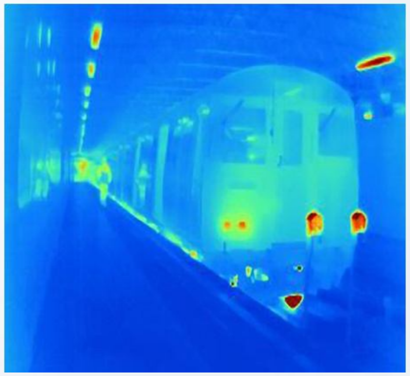
Sarin Attack
Tokyo, Japan, 1995

Subway Fire
Daegu, Korea, 2003

Air Quality Studies
Buenos Aires, AR, 2009



Temperature Regulation
(future design tool)

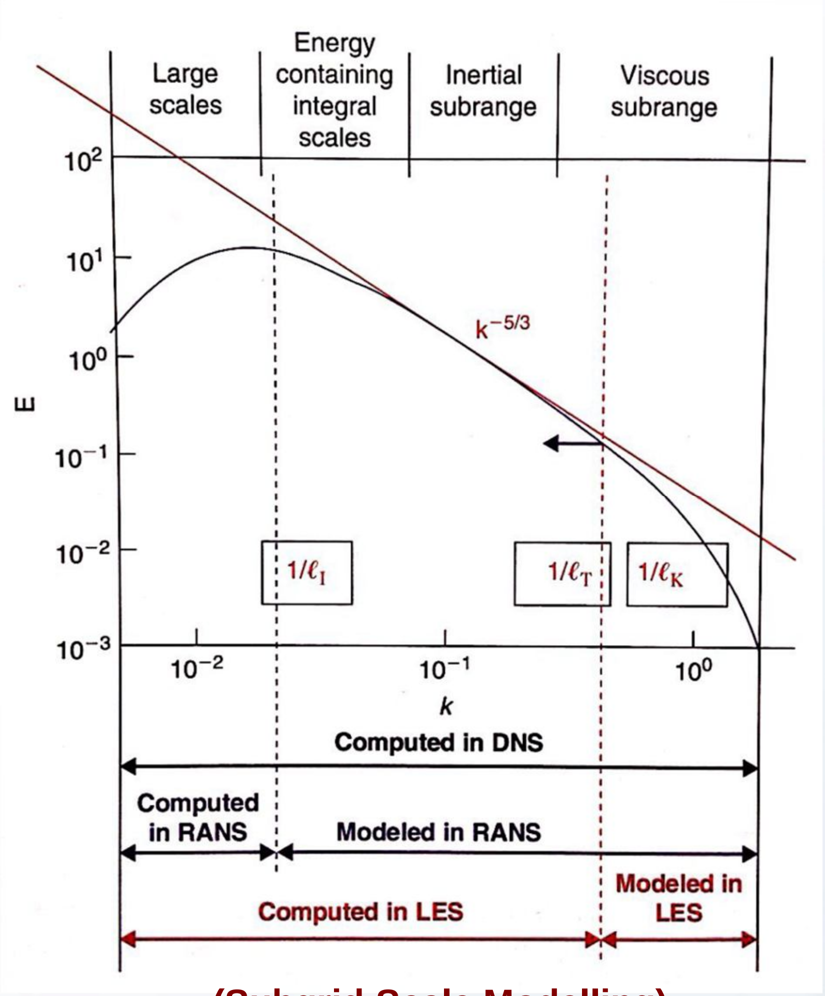


Urban Flow Simulations

Subway Environment Simulator (American Public Transit Association)	Fire Dynamics Simulator (NIST)	Air Quality Simulation (Private & commercial codes)
~1975	~2003	~2005
Continuity Equation	Navier-Stokes	Navier-Stokes
Solves sets of linear equations for bulk mean air flow (analogous to current in a Kirchhoff circuit)	Large-eddy simulation (LES) code for low-speed flows, with an emphasis on smoke and heat.	Dynamic inflow and outflow coupling to the street level. Realistic platform temperature distributions
Train motion modeled as a piston. Ignores nonlinear effects	Ignores effects of moving trains.	Piston driven flows. Experimental data available.

FEFLO Urban

- Explicit 2nd order time integrator
- 2nd order in space
- Large Eddy Simulation (LES) for turbulence
- Smagorinsky (WALE) turbulence model
  - Wall Adapting Local Eddy Viscosity



(Subgrid Scale Modelling)

Time Discretization: Δ Scheme

- Advective / Diffusive Prediction: $\vec{u}^n \rightarrow \vec{u}^*$

$$\left[\frac{1}{\Delta t} - \theta \nabla \mu \nabla\right](\vec{u}^* - \vec{u}^n) + \vec{u}^n \cdot \nabla \vec{u}^n + \nabla p = \nabla \mu \nabla \vec{u}^n$$

- Pressure Correction: $p^n \rightarrow p^{n+1}$

$$\nabla \cdot \vec{u}^{n+1} = 0, \qquad \frac{\vec{u}^{n+1} - \vec{u}^*}{\Delta t} + \nabla(p^{n+1} - p^n) = 0$$

$$\Rightarrow \nabla^2(p^{n+1} - p^n) = \frac{\nabla \cdot \vec{u}^*}{\Delta t}$$

- Velocity Correction: $\vec{u}^* \rightarrow \vec{u}^{n+1}$

$$\vec{u}^{n+1} = \vec{u}^* - \Delta t \nabla(p^{n+1} - p^n)$$

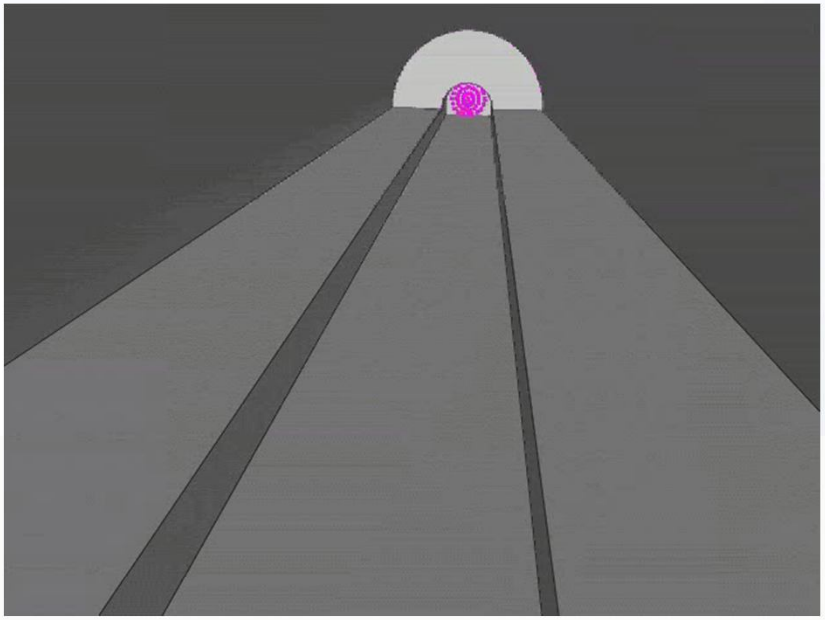
Previous Work: Piston Driven Flows

Conservation of mass

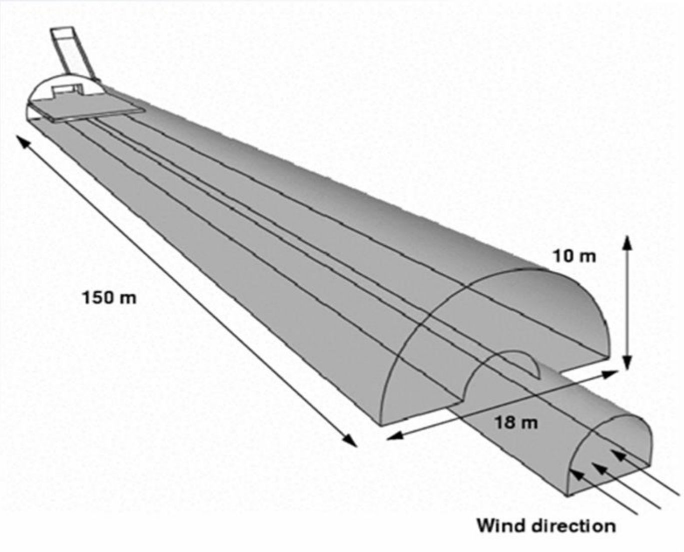
$$\nabla \cdot \vec{u} = 0$$

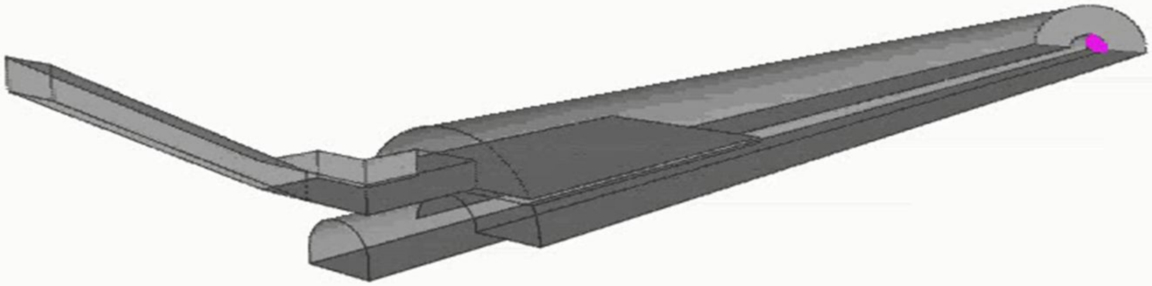
Conservation of momentum

$$\rho \left[\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} \right] = \rho \vec{f_e} - \nabla p + \mu \nabla^2 \vec{u}$$



- Passive tracer release from tunnel





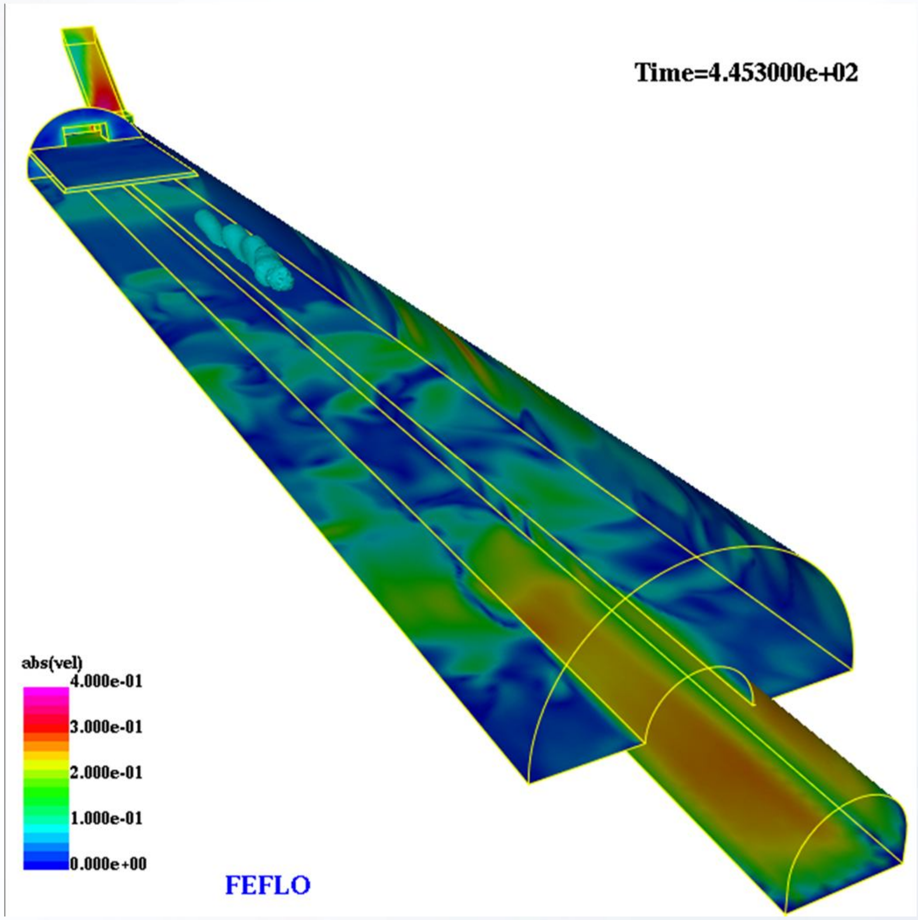
Previous Work: Contaminant Release

- Dispersion:

$$\frac{\partial c}{\partial t} + \vec{u} \cdot \nabla c = \nabla \cdot (D \nabla c) + S$$

- Dynamic Deactivation:
  Change in *c* only possible if

$$|\nabla c| > 0, \qquad |S| > 0$$



- Algorithm: Every 5-10 Steps:
  - Identify Elements/Edges/Points Where Update Required
  - Surround Active Elements/Edges/Points With `Safety Zone'
  - Only Compute/Update in Active Zone

Objectives

Extend code to include dynamic components

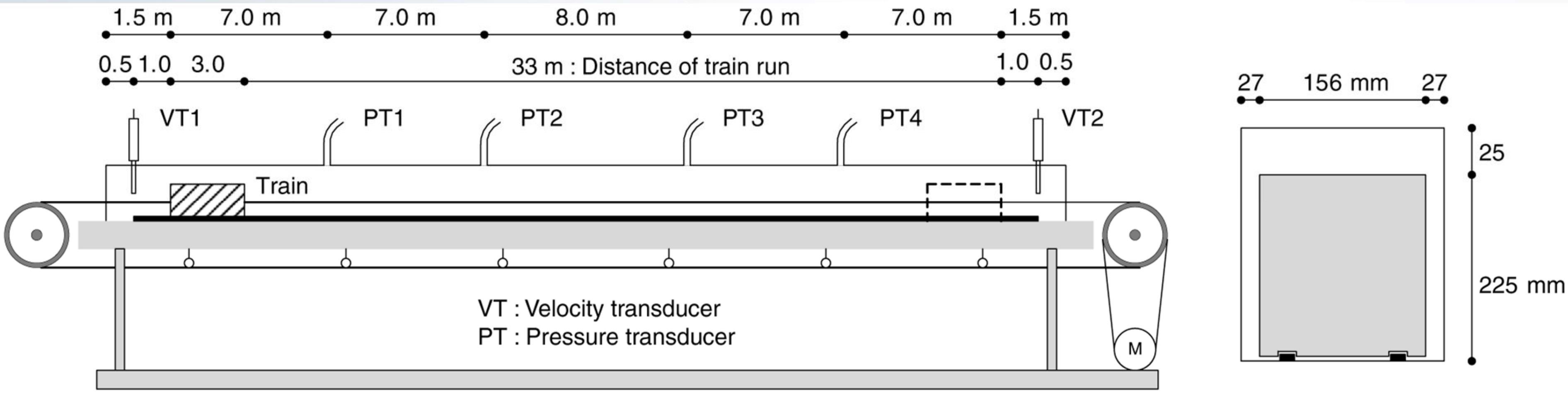
- Include train motion in CFD simulations
- Validate methodology against experimental data

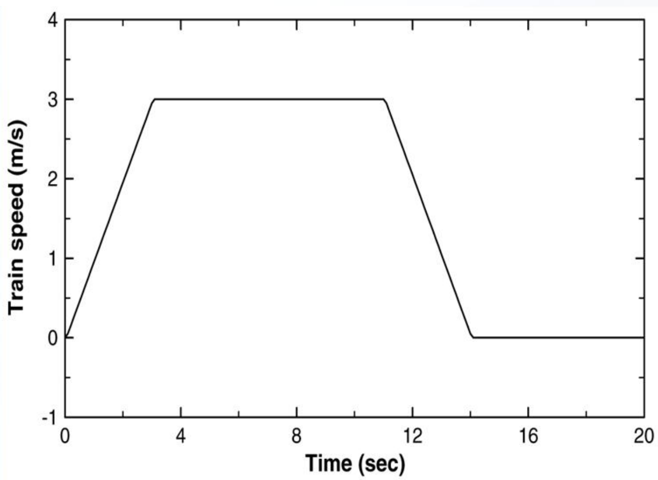
Include detailed components

- Multi-car trains with variable speeds and schedules
- Thermal effects
- Air flow coupling to the street level
- Realistic subway station geometries and networks
- Include sources of contamination
- Quantify the air flow dynamics in stations

Kim and Kim's Experiment

Kim, J.Y., et. al. Experimental and numerical analyses of train-induced unsteady tunnel flow in subway. Tunneling and Underground Space Technology 22, 166-172. (2007)



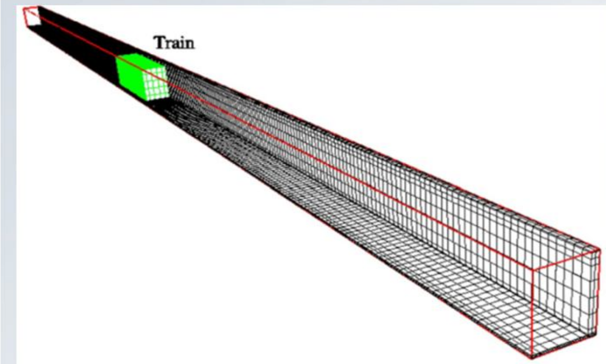


$R_{e_{max}} = 4.9\text{x}10^4$

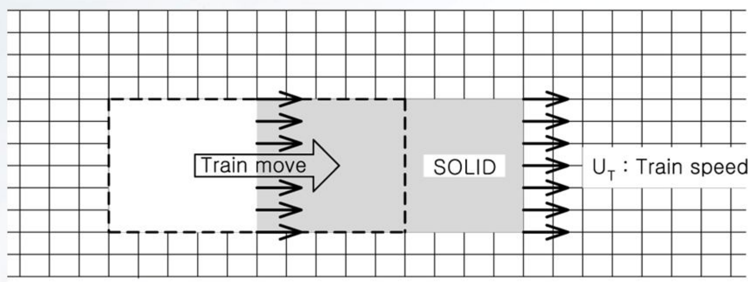
$\Delta t_{sensor} = 0.1s$

$U_{max} = 3.0\ m/s$

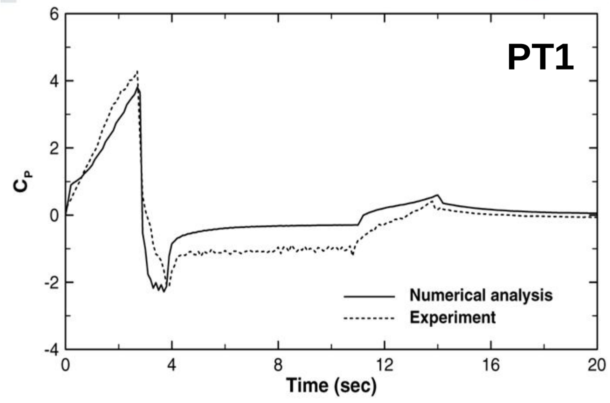
Kim and Kim's Simulation

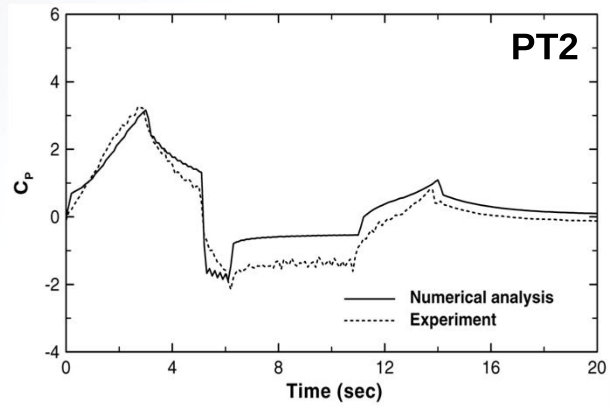


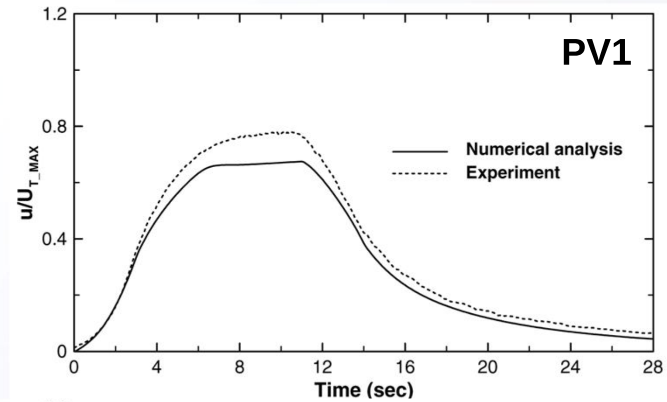
300k mesh cells

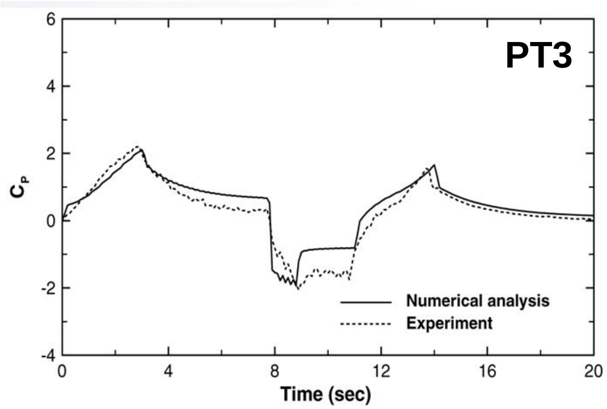


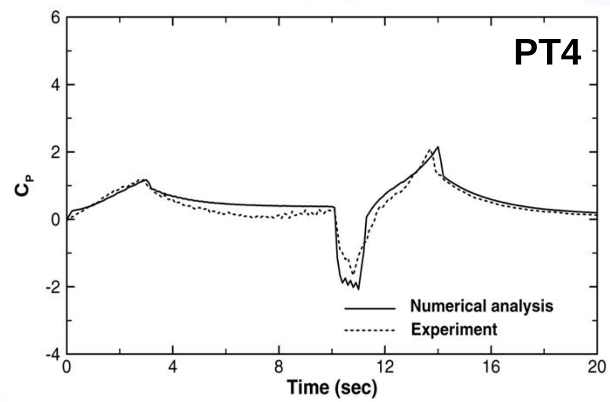
Spectral Solver
Sharp front method

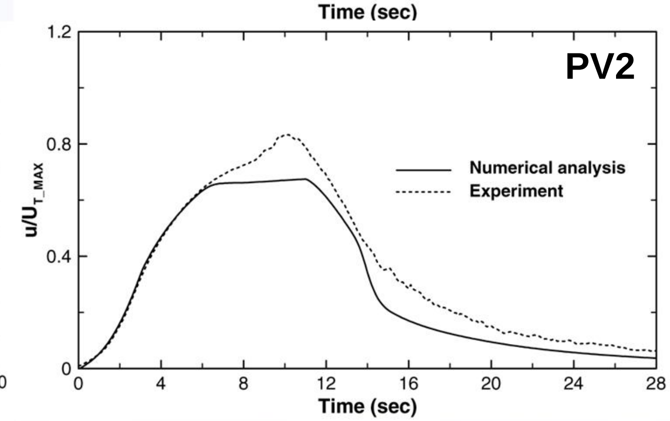








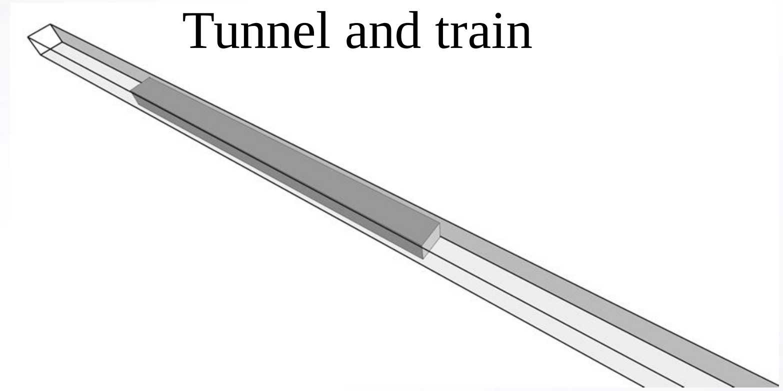




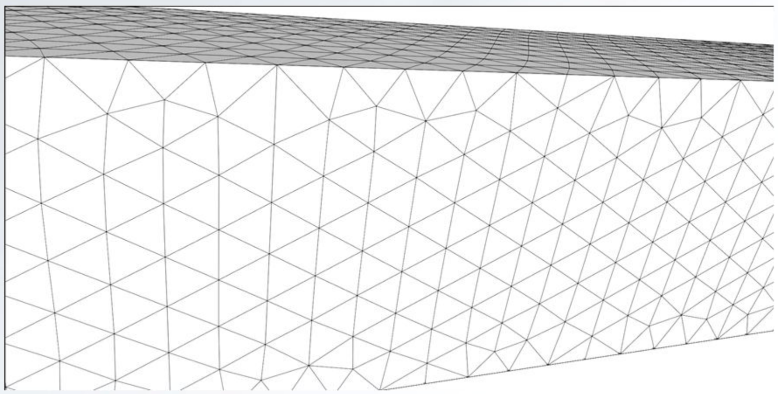
How to Handle Dynamic Components?

Volume mesh: 4 M elements

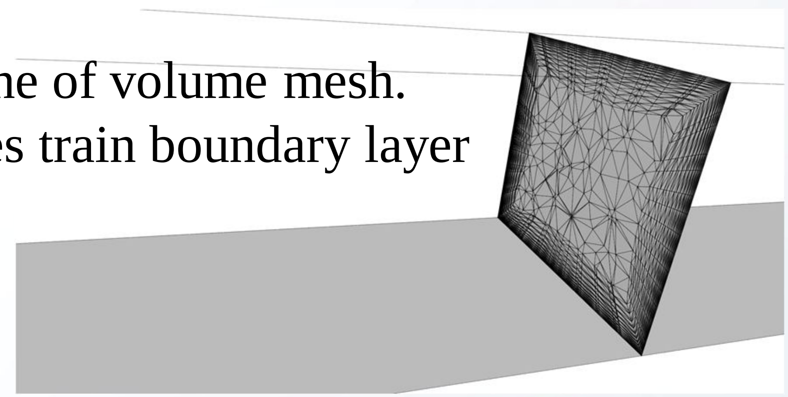
Tunnel and train



Surface mesh

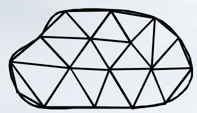


Cut plane of volume mesh.
Resolves train boundary layer

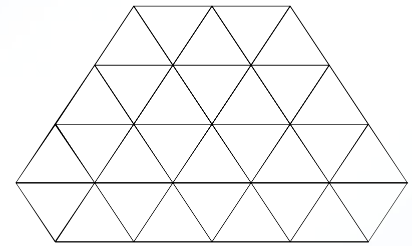


- Body fitted meshing
  - Requires local/global remeshing at each time step
- Immersed meshing
  - Represent the train as a volume tessellation and immerse it into a background mesh

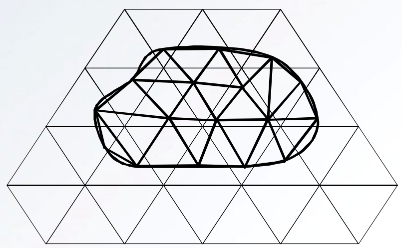
Dynamic Meshing: Immersed Method



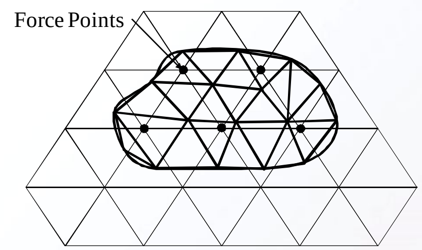
(a) Tessellated immersed body.



(b) Background or CFD mesh.



(c) CFD mesh and the immersed body.



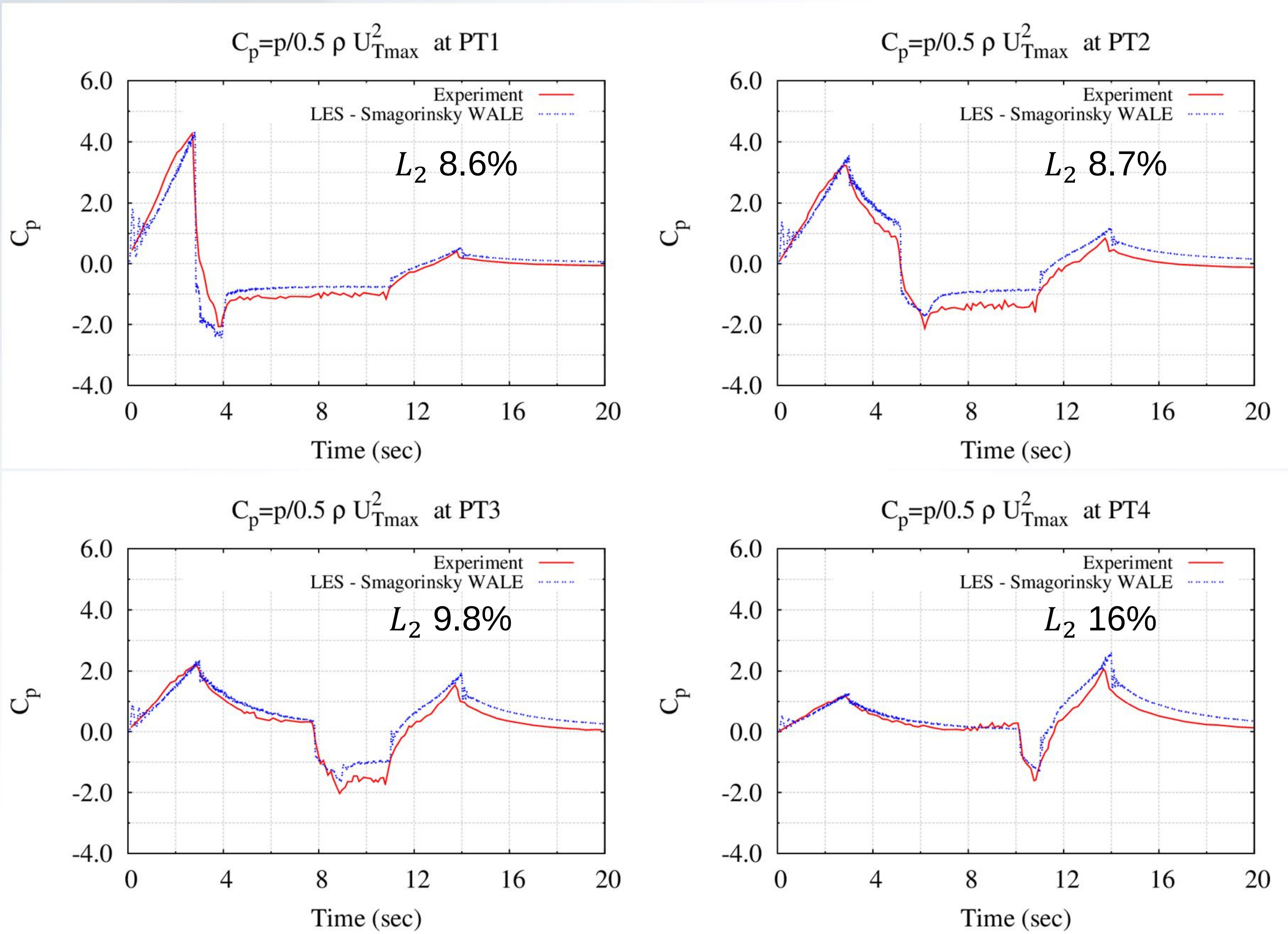
(d) Points in CFD mesh where forces are applied from immersed body.

$$\vec{f} = -c_0(\vec{w}_b - \vec{u}) \longrightarrow$$ Direct force scheme $$\mathbf{M}\frac{\Delta \vec{u}_i}{\Delta t} = \vec{r}_i + \vec{f}_i$$

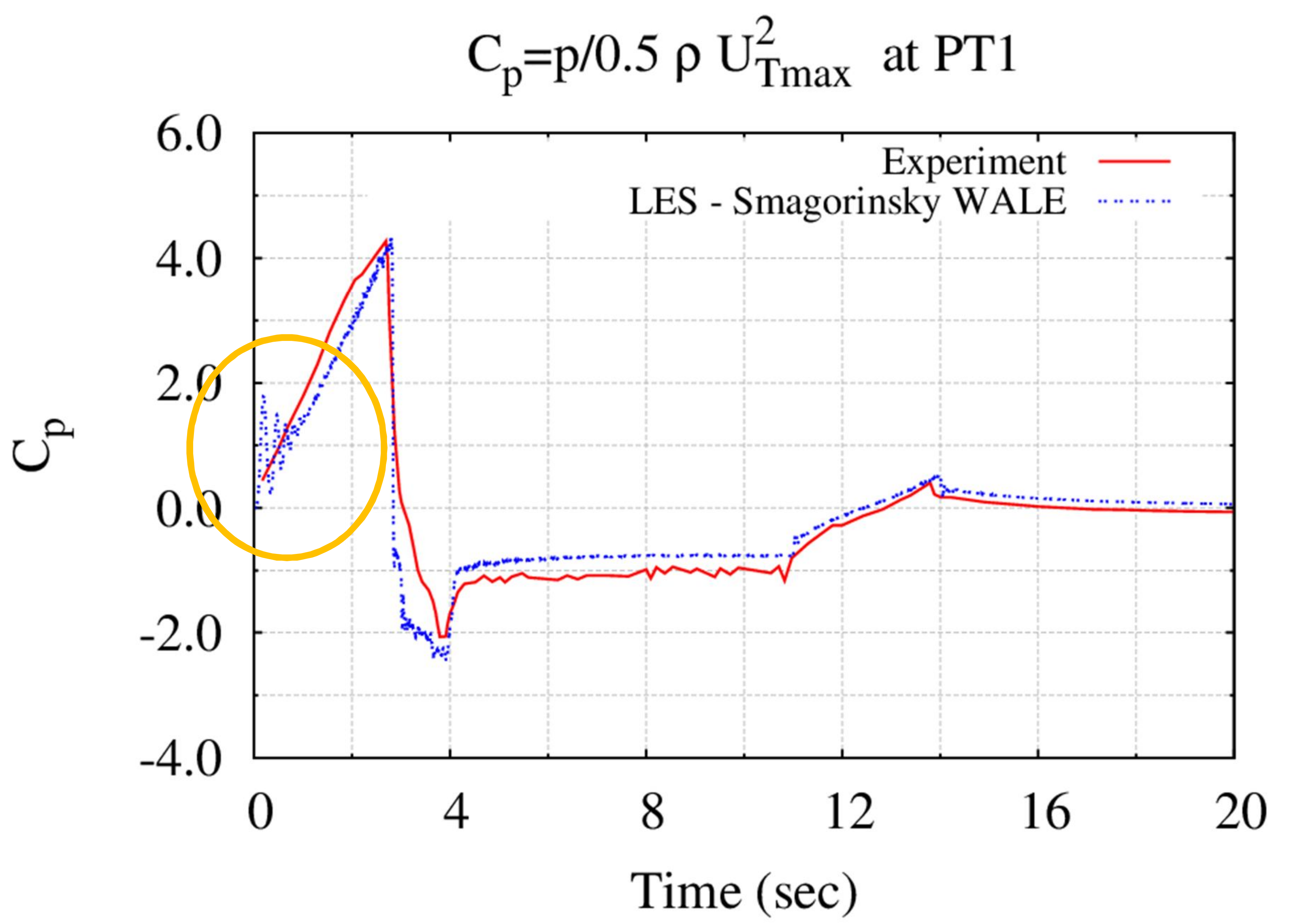
- c_0 small flow can't adjust rapidly enough to the motion of the body
- c_0 large produces artificial stiffness

$$\vec{f}_i = \mathbf{M}\frac{\vec{w}_i^{\,n+1} - \vec{u}_i^{\,n}}{\Delta t} - \vec{r}_i$$

Pressure Comparison

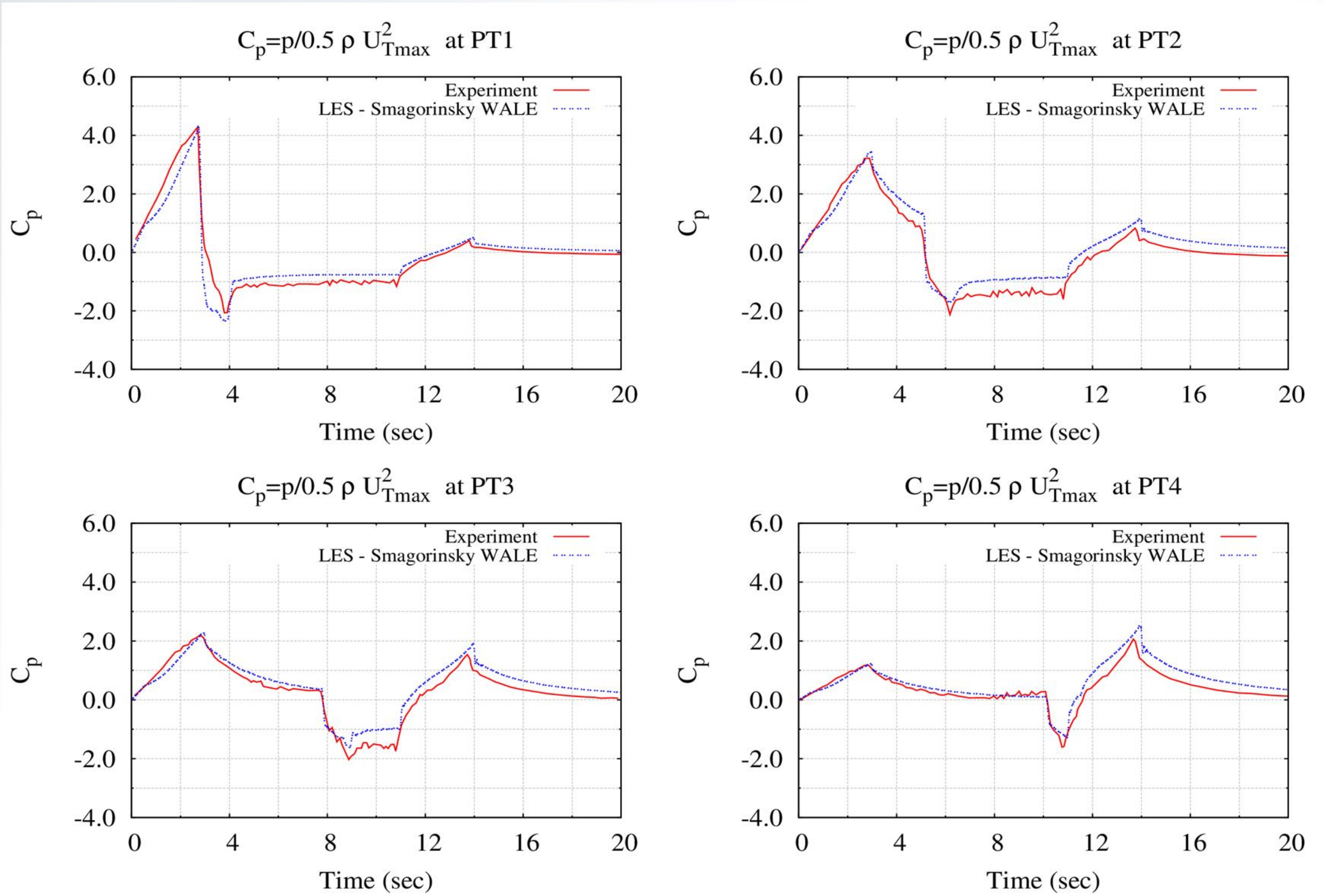


Pressure Comparison

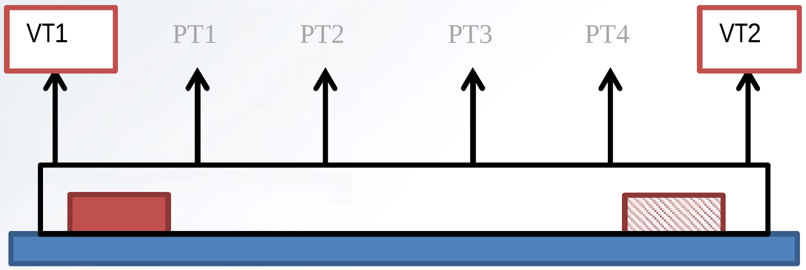


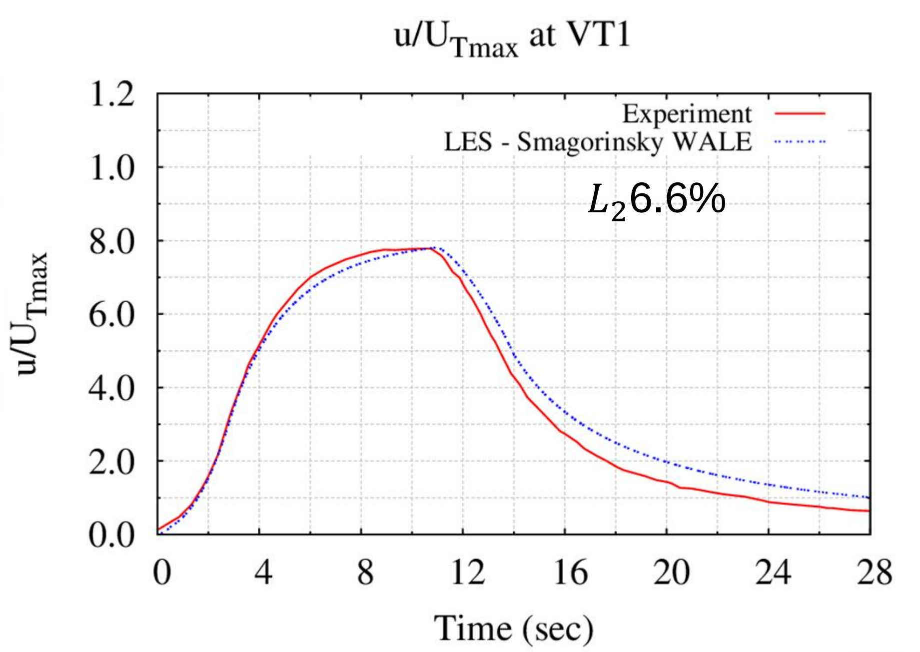
Pressure Comparison

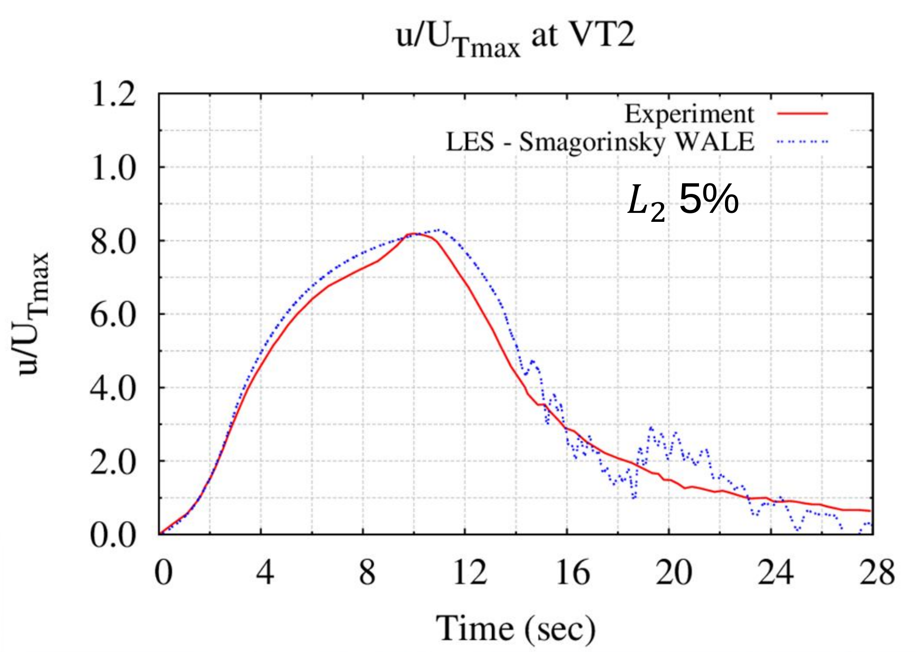
Refine the time step during the initial acceleration of moving body



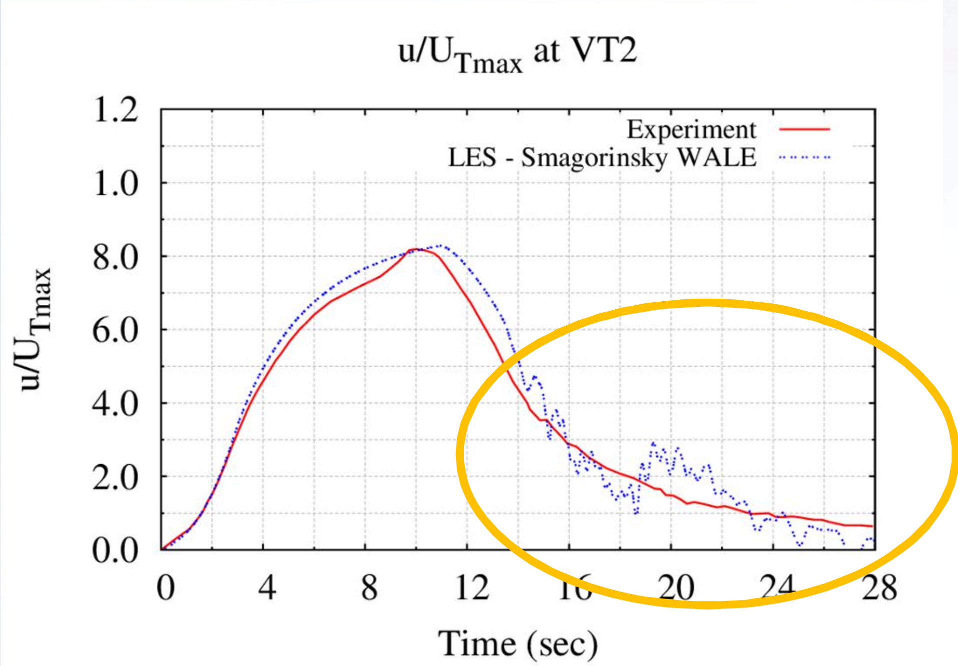
Velocity Comparison

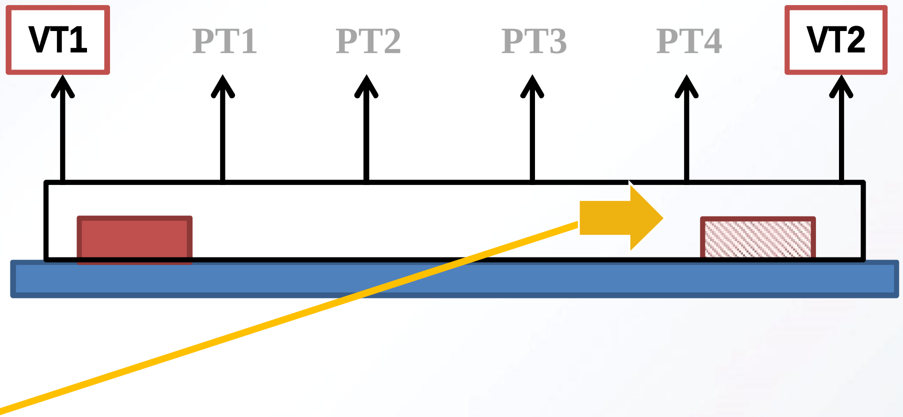




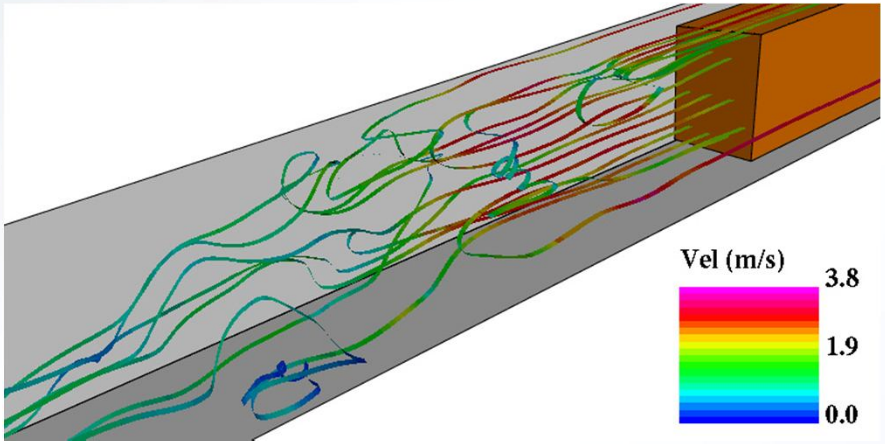


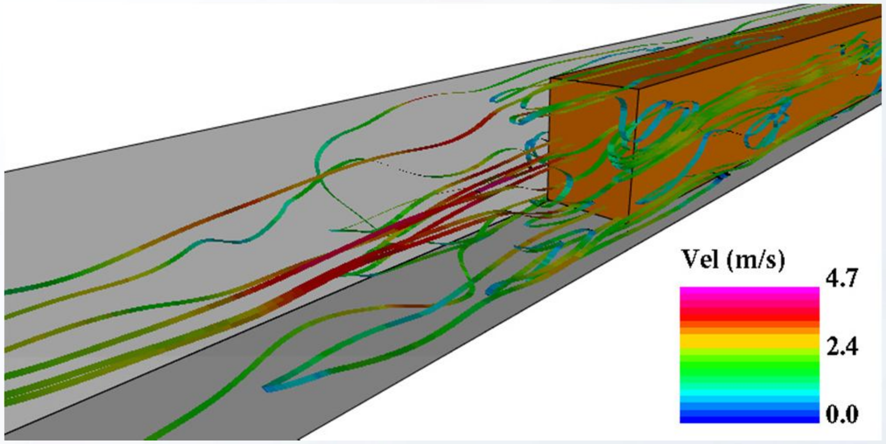
Velocity Comparison



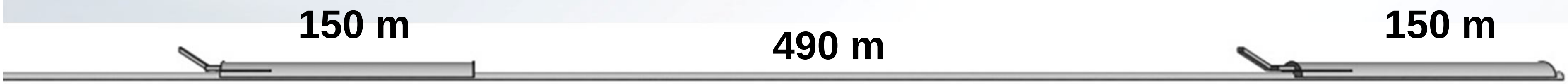


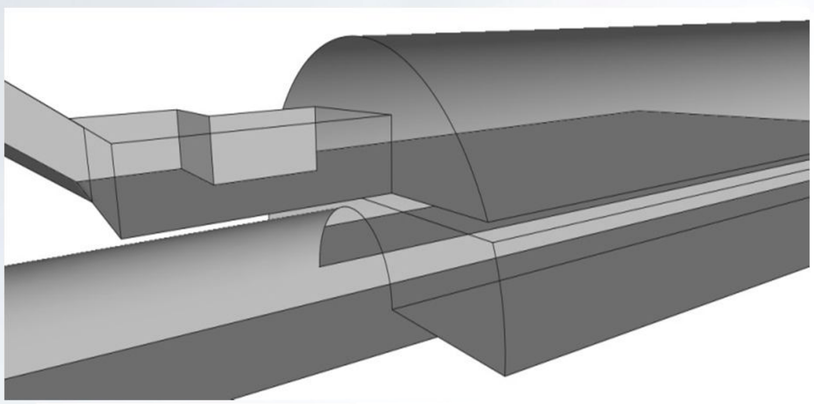
High frequency velocity fluctuations due to wake blowback after the train comes to a stop.

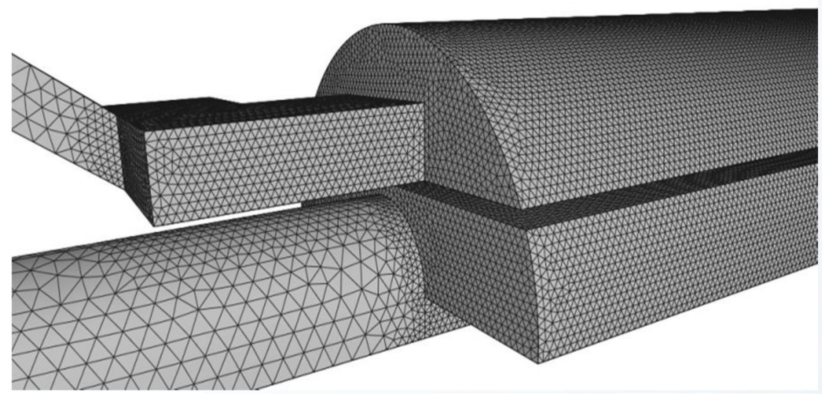


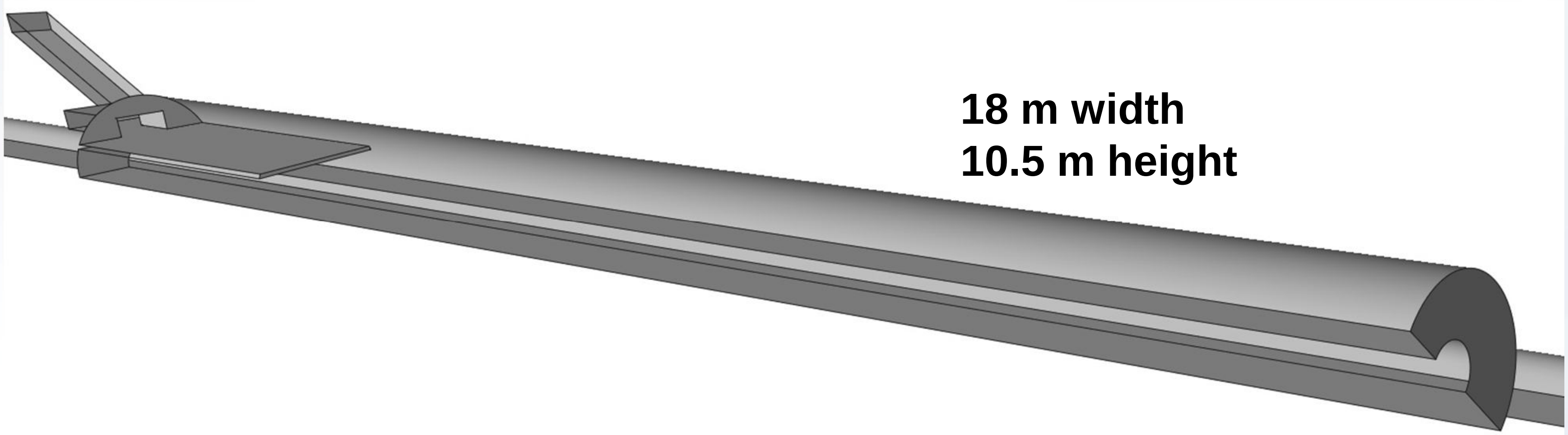


Two Subway Stations









Conditions

- Single subway car
- Speed 50 km/h
- Ambient temperature 20°C
- Temperature of subway base 50°C

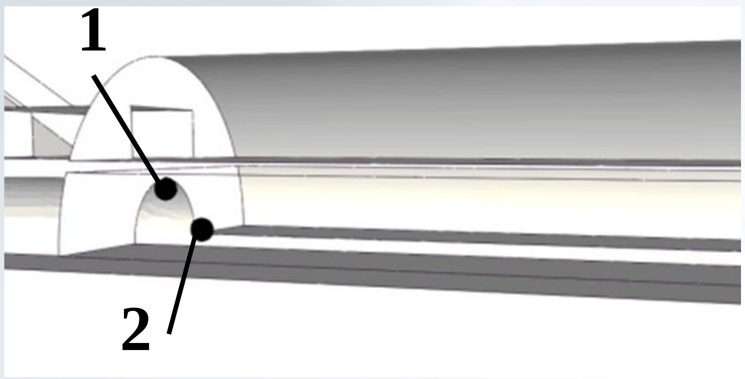
Governing Equations

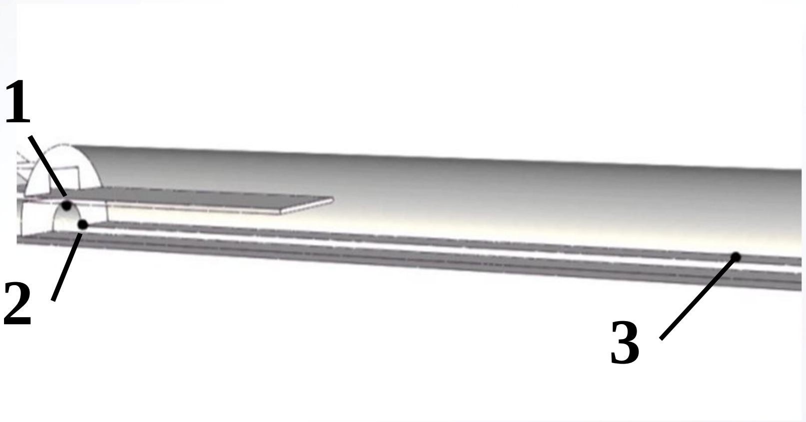
Continuity $\nabla \cdot \vec{u} = 0$

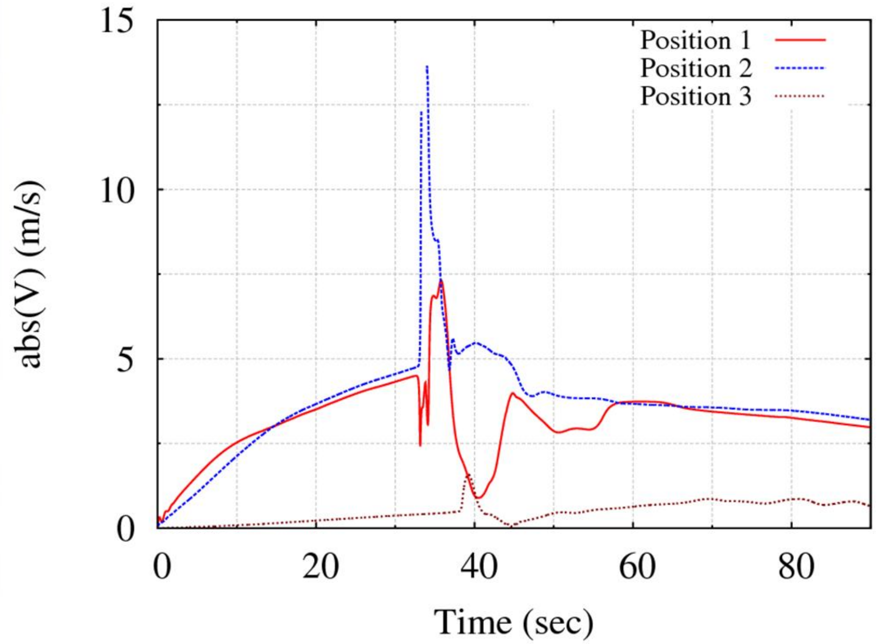
Navier-Stokes $\rho \frac{D\vec{u}}{Dt} = \rho \vec{f}_e + \rho \vec{g}[1 - \beta(T - T_0)] - \nabla p + \mu \nabla^2 \vec{u}$

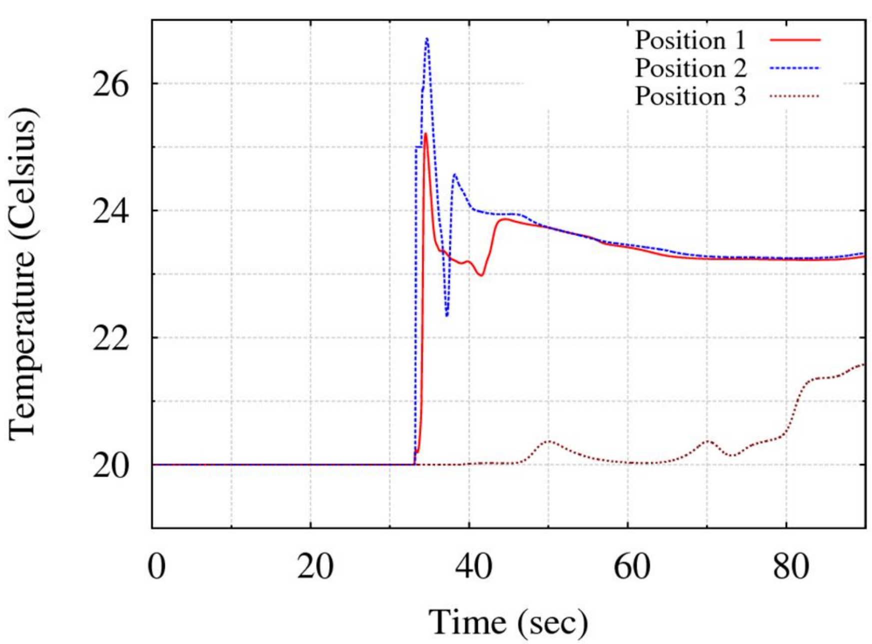
Temperature $\rho c_p \left[\frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T \right] = \nabla \cdot (\kappa \nabla T)$

Velocity and Temperature in Station 2

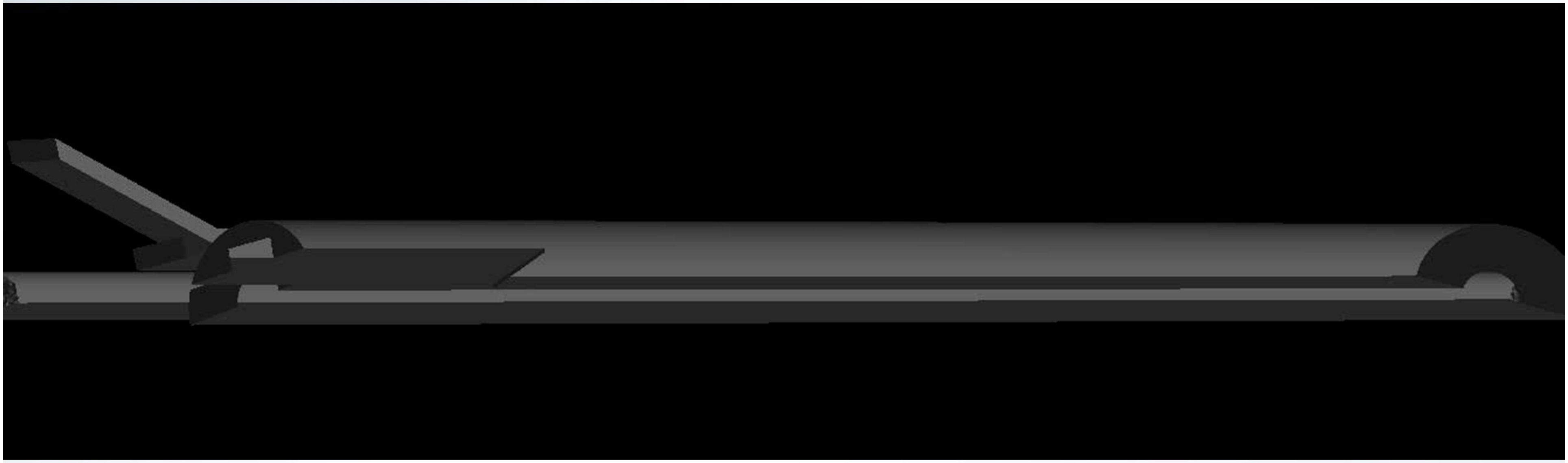




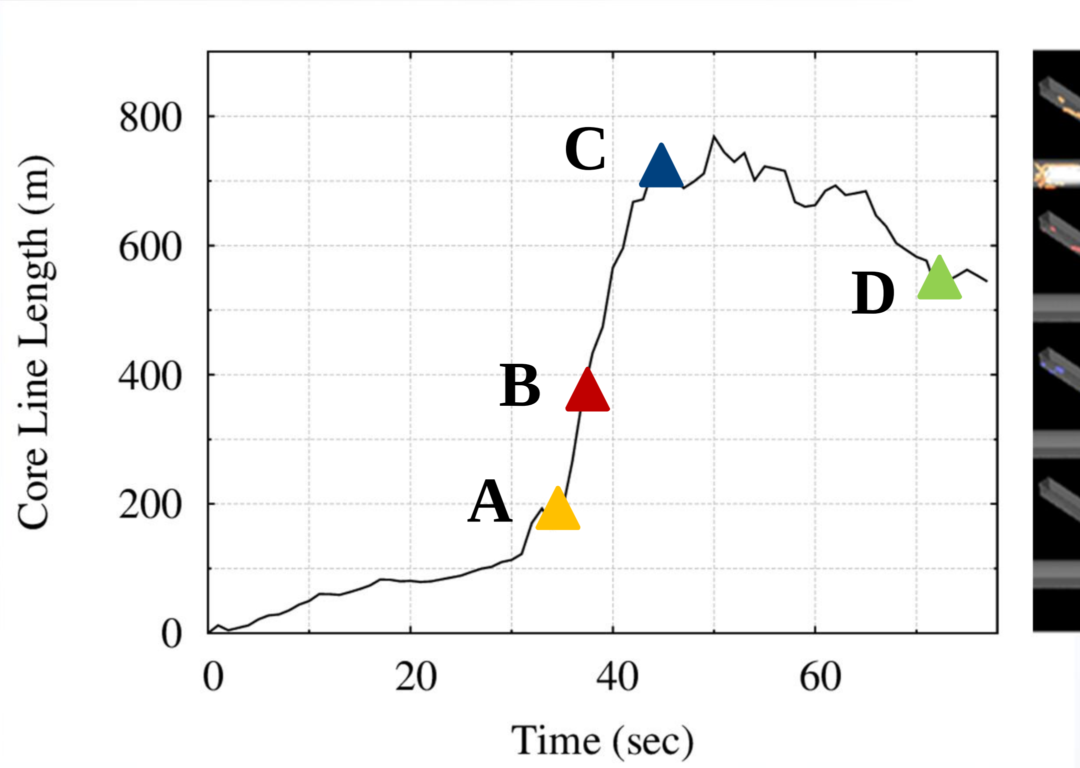


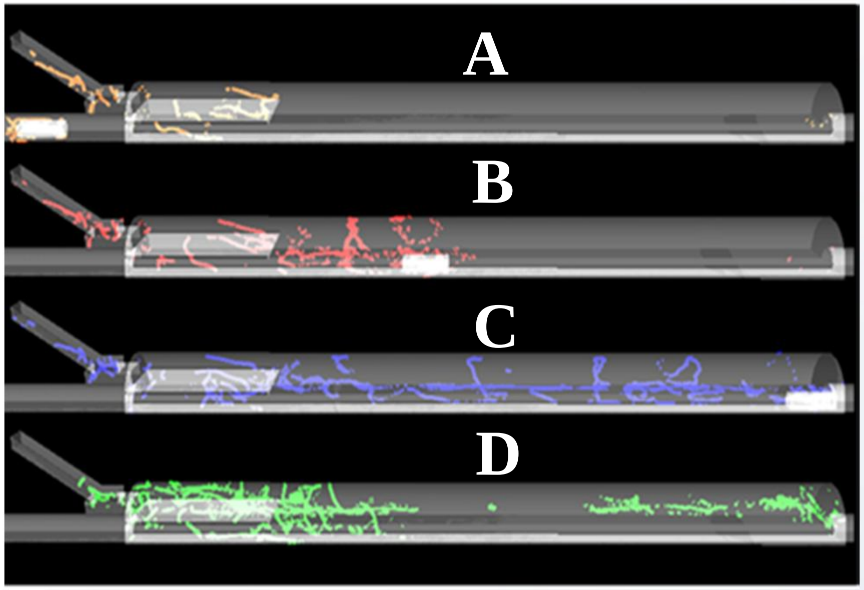


Vortex Core Lines in Station 2

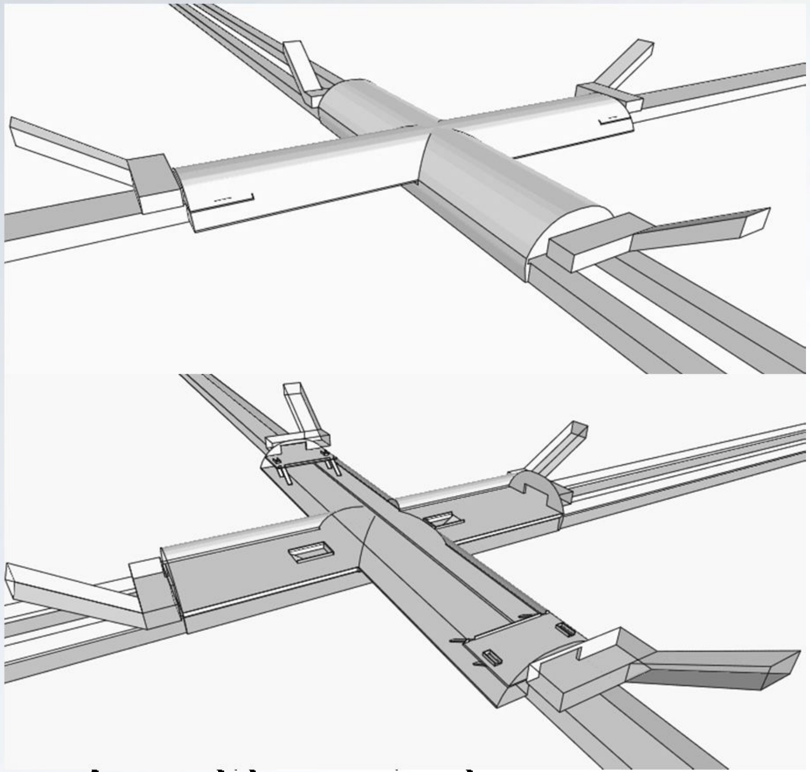


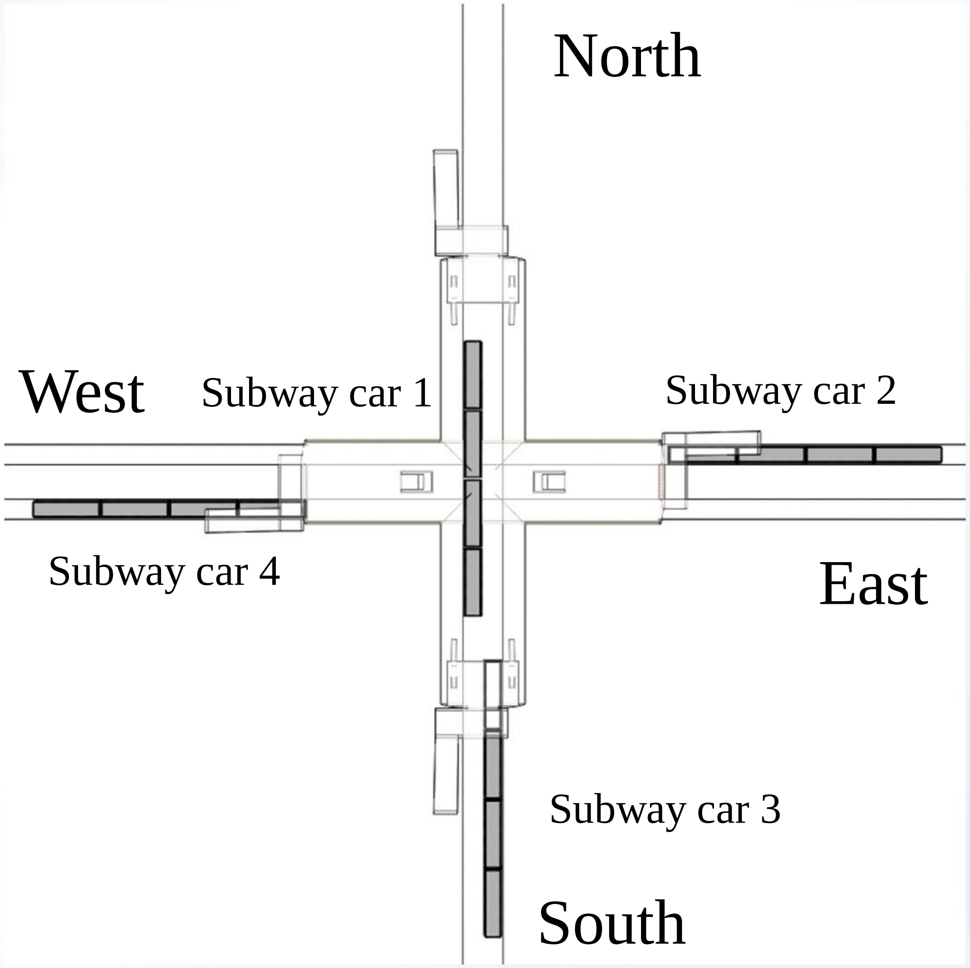
Spatial Flow Complexity in Station 2





Two-level Subway Station (Metro Center)





- 4 multi-car trains
- Realistic scheduling
- Multi-platform levels
- Stairwells connections between levels and the street

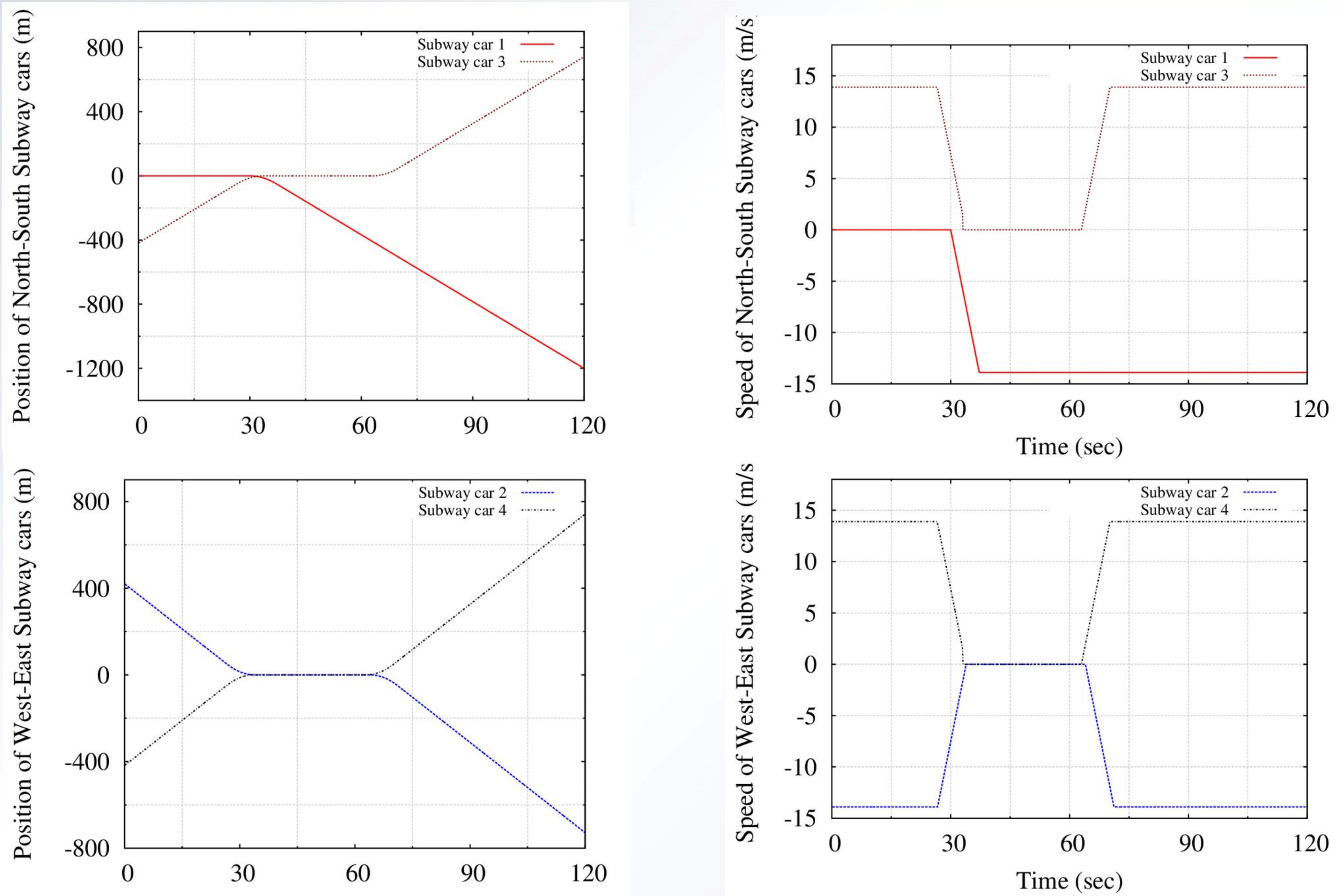
Conditions

- Ambient temperature 20°C
- Temperature at bottom of subway 50°C
- Temperature on subway walls 25°C
- Initial wind speed in tunnels and station is zero

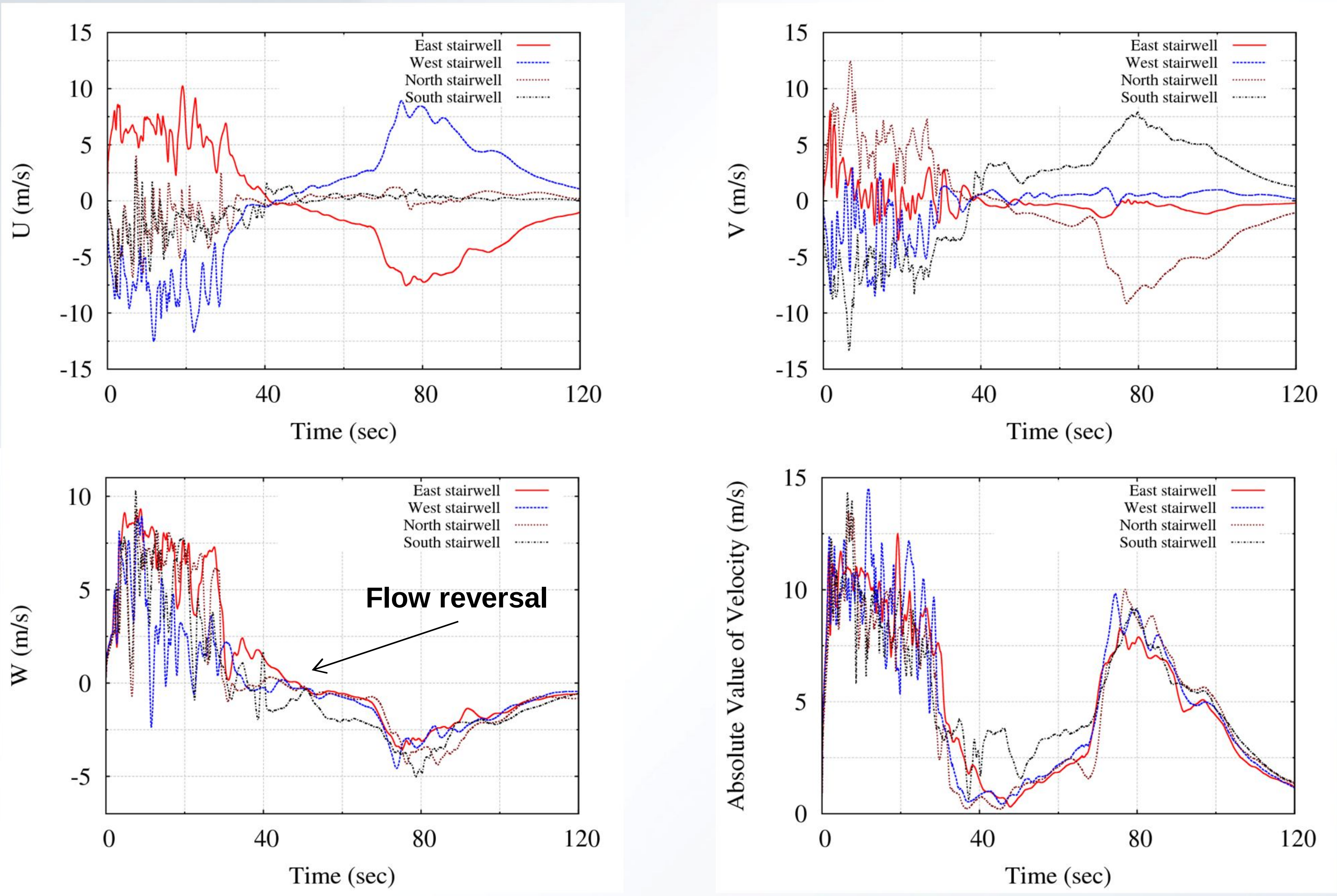
Governing Equations

Continuity	$\nabla \cdot \vec{u} = 0$
Navier-Stokes	$\rho \frac{D\vec{u}}{Dt} = \rho \vec{f}_e + \rho \vec{g}[1 - \beta(T - T_0)] - \nabla p + \mu \nabla^2 \vec{u}$
Temperature	$\rho c_p \left[\frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T \right] = \nabla \cdot (\kappa \nabla T)$
Concentration	$\frac{\partial c}{\partial t} + \vec{u} \cdot \nabla c = \nabla \cdot (D \nabla c) + S$

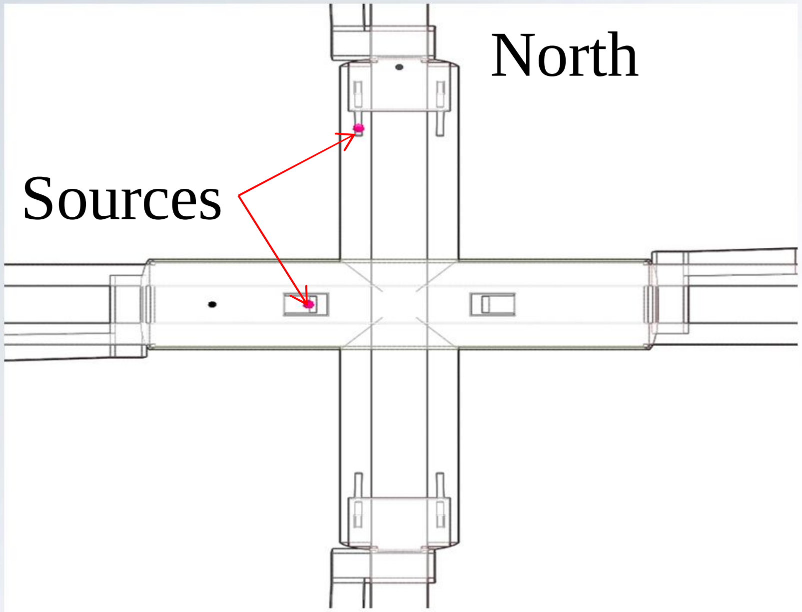
Train Schedules

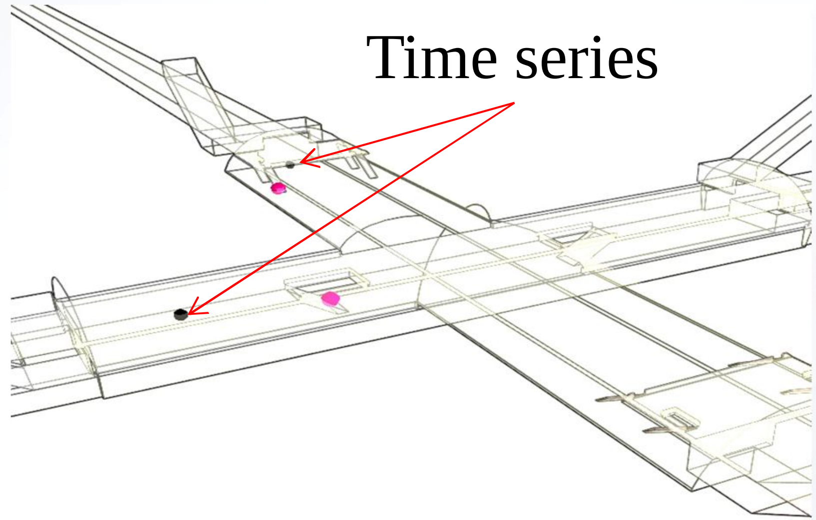


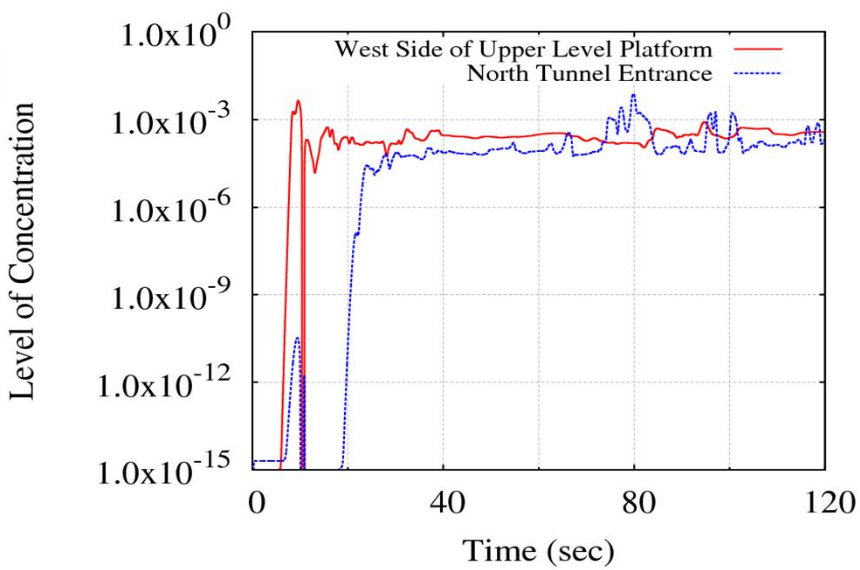
Velocity Measurements

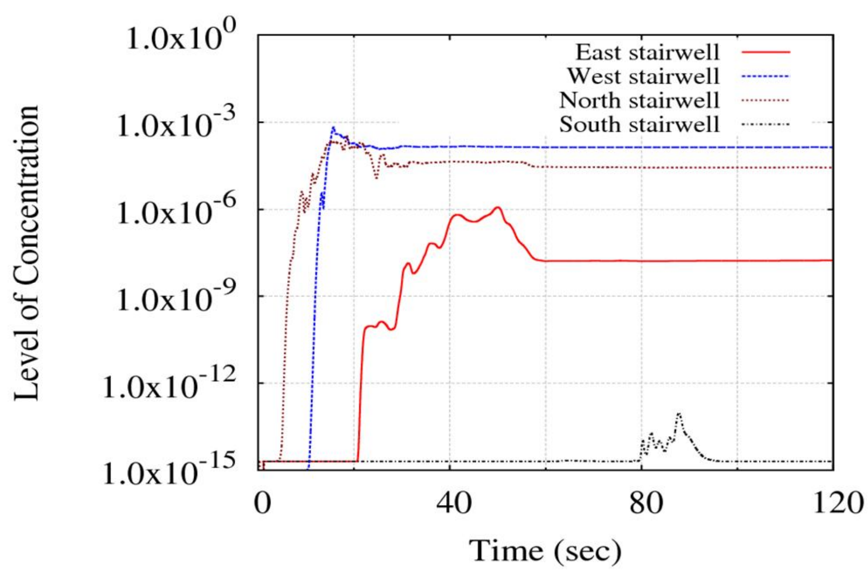


Contaminant Release

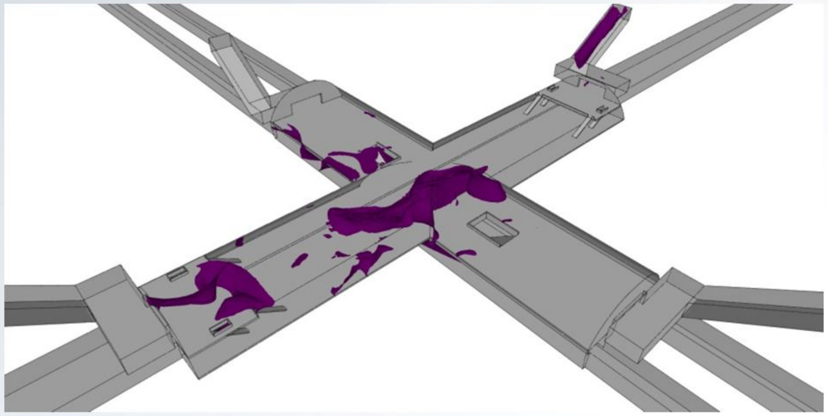




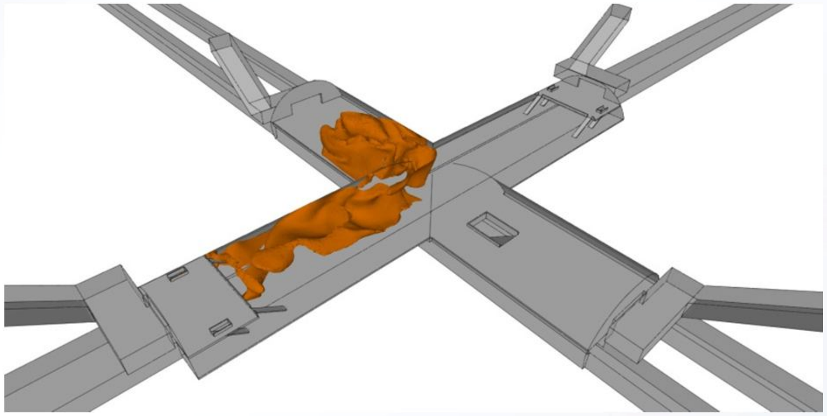




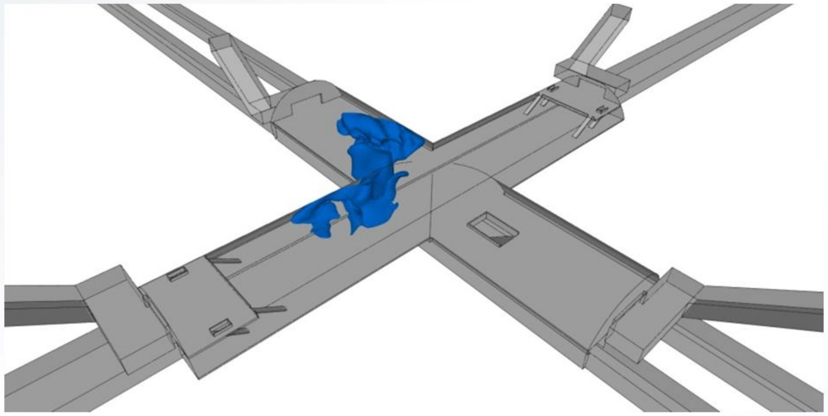
Iso-surfaces 70 Seconds After Relsease



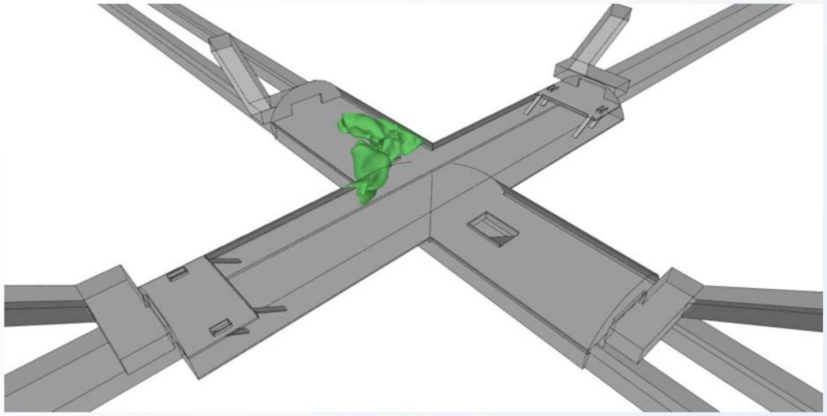
Concentration level of 1.0×10^{-5} ppm.



Concentration level of 3.4×10^{-4} ppm..

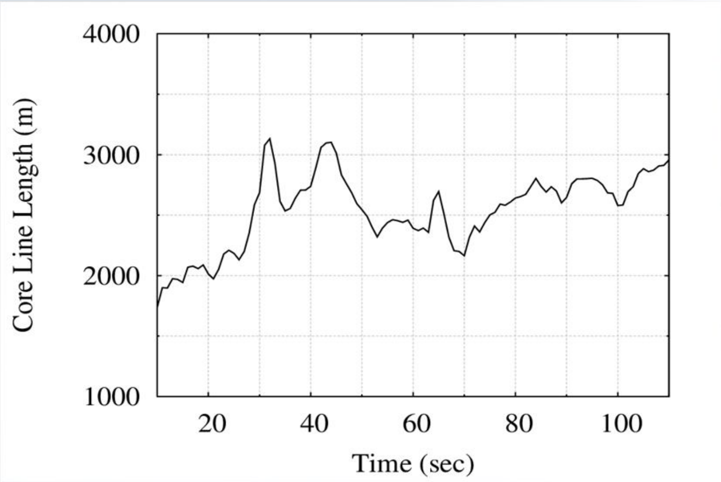


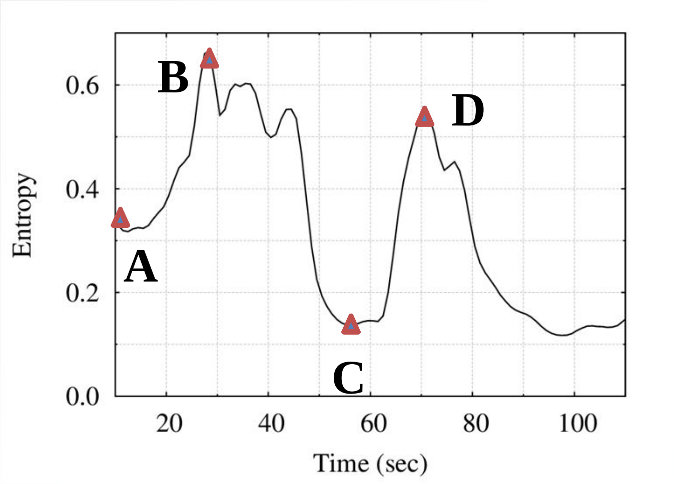
Concentration level of 6.7×10^{-4} ppm.

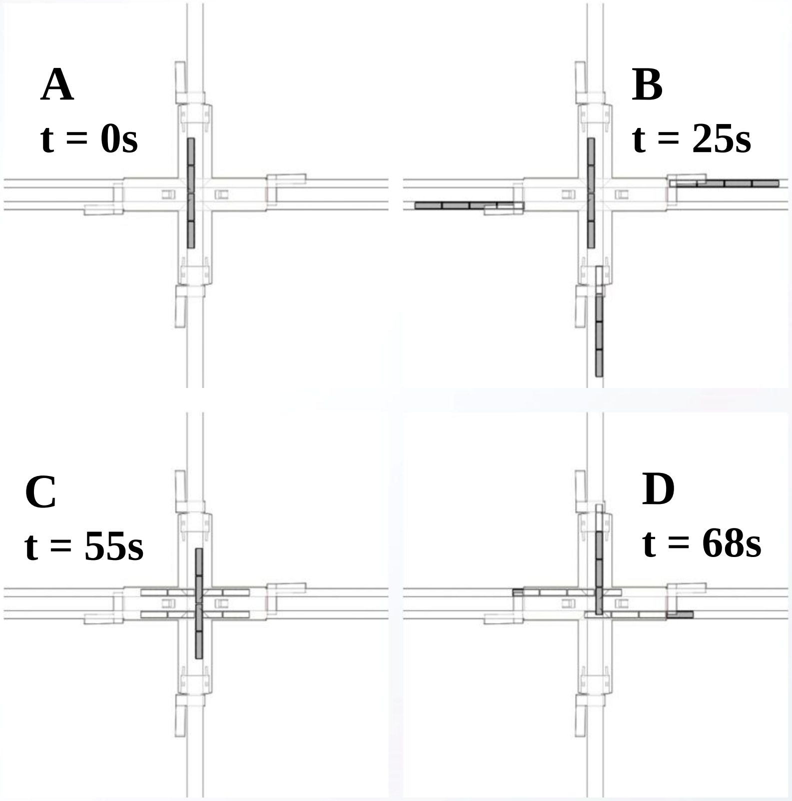


Concentration level of 1.0×10^{-3} ppm..

Flow Characterization







- Spikes in the flow variables pinpoint complex spatiotemporal flow patterns.

Conclusions

- We develop a more realistic CFD approach to model air flow in subway tunnels and stations.
- Simulations using the immersed body approach were validated against experimental data.
- The approach was extended for realistic station geometries, multi-car trains with schedules, street coupling and temperature profiles.
- Spatiotemporal flow structures were quantified within the station to study conditions leading to enhanced station contamination.

Outlook

- Experimental data from a subway station in Dortmund, Germany. Unresolved B.C.
- In search of controlled experimental data (e.g. wind tunnel) for detailed comparisons.