Aerodynamics of High Speed Trains

Vehicle Aerodynamics Lecture

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Dr. Alexander Orellano

Director, Centre of Competence for Aerodynamics & Thermodynamics

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Bombardier
Overview

Aerospace and Transportation

Workforce of 65,400 people worldwide[1]

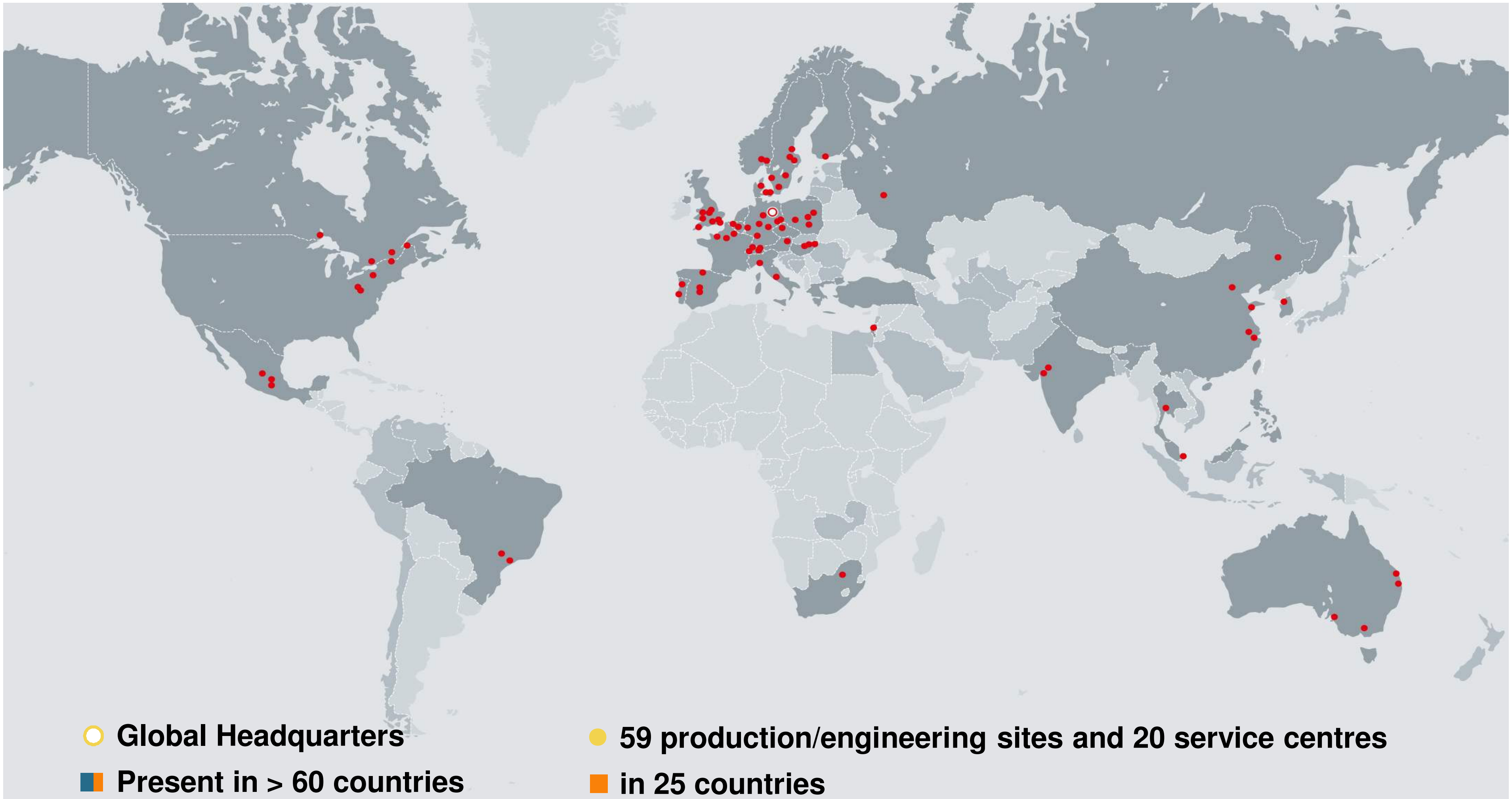
Revenues of $17.7 bn US[1]

Corporate office based in Montréal, Canada

Listed on Toronto Stock Exchange (BBD)

[1] for fiscal year ended January 31, 2011

Bombardier Transportation
Global expertise – Local presence



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Lecture Topics

Cross-Wind Stability **Head pressure pulse** **Tunnel Aerodynamics**

Basics **Running Resistance** **Slip stream** **Optimisation**

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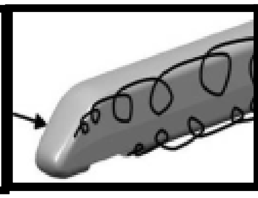

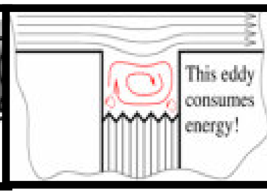

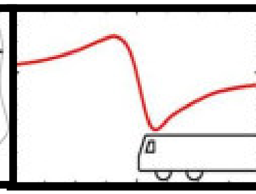

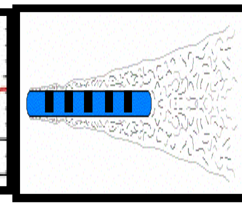

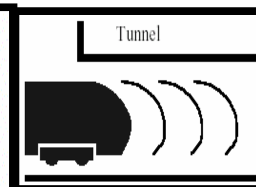

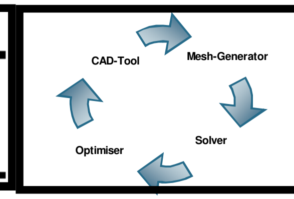

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Basics in Aerodynamics

Topic 1

Vehicle Aerodynamics Lecture

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Basic Parameters

- **Reynolds Number: ratio of inertia and viscosity**

characteristic velocity — **characteristic length**

$$\mathrm{Re} = \frac{cL}{\nu} = \frac{cL\rho}{\mu}$$

kinematic viscosity — **dynamic viscosity**

- **Mach Number: ratio of velocity of fluid to velocity of sound**

$$Ma = \frac{c}{a}$$

c = velocity of fluid
a = speed of sound

Basics in Continuums Mechanics

Energy and mass conservation applied to Finite Element/Volume

➡ Navier Stokes Equation **(x direction)**

$$\underbrace{\rho\frac{\partial u}{\partial t}+\rho u\frac{\partial u}{\partial x}+\rho v\frac{\partial u}{\partial y}+\rho w\frac{\partial u}{\partial z}}_{\text{Non-linear transport}}=-\frac{\partial p}{\partial x}+\underbrace{\frac{\partial}{\partial x}\left(2\mu\frac{\partial u}{\partial x}\right)+\frac{\partial u}{\partial y}\left[\mu\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right]+\frac{\partial u}{\partial z}\left[\mu\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right)\right]}_{\text{Viscous diffusion}}$$

Replace: ***u = U$_\infty$ * u', x = Lx', p = ρ/2 * v'^{2}*** **treat *v, w, y, z* analogous**

$$\underbrace{\frac{\partial u'}{\partial t'}+u'\frac{\partial u'}{\partial x'}+v'\frac{\partial u'}{\partial y'}+w'\frac{\partial u'}{\partial z'}}_{=\mathrm{O}(1)}=-\underbrace{\frac{\partial p'}{\partial x'}}_{\mathrm{O}(1)}+\underbrace{\frac{\mu}{\rho U_\infty L}\left[\frac{\partial}{\partial x'}\left(2\frac{\partial u'}{\partial x'}\right)+\frac{\partial}{\partial y'}\left(\frac{\partial u'}{\partial y'}+\frac{\partial v'}{\partial x'}\right)+\frac{\partial}{\partial z'}\left(\frac{\partial u'}{\partial z'}+\frac{\partial w'}{\partial x'}\right)\right]}_{=\mathrm{O}(1/\mathrm{Re})}$$

Re >> 1 → Euler equation

$$\rho\frac{\partial u}{\partial t}+\rho u\frac{\partial u}{\partial x}+\rho v\frac{\partial u}{\partial y}+\rho w\frac{\partial u}{\partial z}=-\frac{\partial p}{\partial x}$$

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Equations – Good to Know!

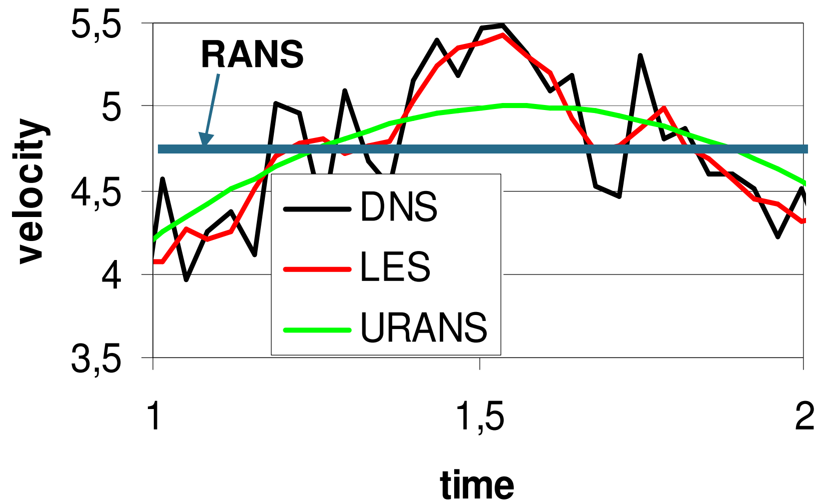
- **Navier Stokes**
  - Viscous, compressible/incompressible, rotational
- **Euler Equation**
  - inviscid
- **Potential Flow Theory – Laplace equation**
  - steady, irrotational incompressible flows but no-slip conditions (walls) not possible – therefore only valid with thin negligible boundary layers

$$\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} + \frac{\partial^2 \varphi}{\partial z^2} = 0$$

- **Bernoulli (Potential theory)**
  - Steady, irrotational, incompressible, along a streamline

$$\frac{\rho}{2} c^2 + \rho g h + p = \text{constant}$$

Common Numerical Viscid Methods (Grid Based)



- **Direct Numerical Simulation (DNS)**
  - Complete Navier-Stokes equation
  - No turbulence model required
- **Large Eddy Simulation (LES)**
  - Spatially filtered Navier Stokes equation
  - Turbulence model for sub grid scales
- **Reynolds Averaged Navier Stokes (RANS)**
  - Time averaged NS-equations leads to new terms called Reynolds stresses which are then modelled with eddy viscosity models (e.g. k-e model)
- **Detached Eddy Simulation**
  - LES in well resolved regions
  - RANS near walls and coarse grid regions

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Most common Turbulence Modelling – Eddy Viscosity

- **Turbulence models are based on engineering assumptions to predict turbulent stresses. These stresses emerge as a result of averaging or filtering of the non-linear convection terms of the governing flow equations. They may be regarded as an extra viscosity that for turbulent flows are sometimes several orders of magnitude larger than the molecular viscosity. However, no universal turbulence model exists.**
- **The chosen turbulence model for external aerodynamics simulation of trains shall resolve the following relevant physical phenomena:**
  - Non equilibrium flow – e.g. two equation models
  - Natural wall normal behaviour without wall functions – i.e. no k-ε models
  - Realizable turbulent stress – non-constant anisotropic coefficient
  - 3D flow structure with secondary flow effects – implicit or explicit Reynolds stress modelling
  - For other models or methods used in conjunction with LES or DES it is needed to show that the physical modelling assumptions are valid for the chosen setup.

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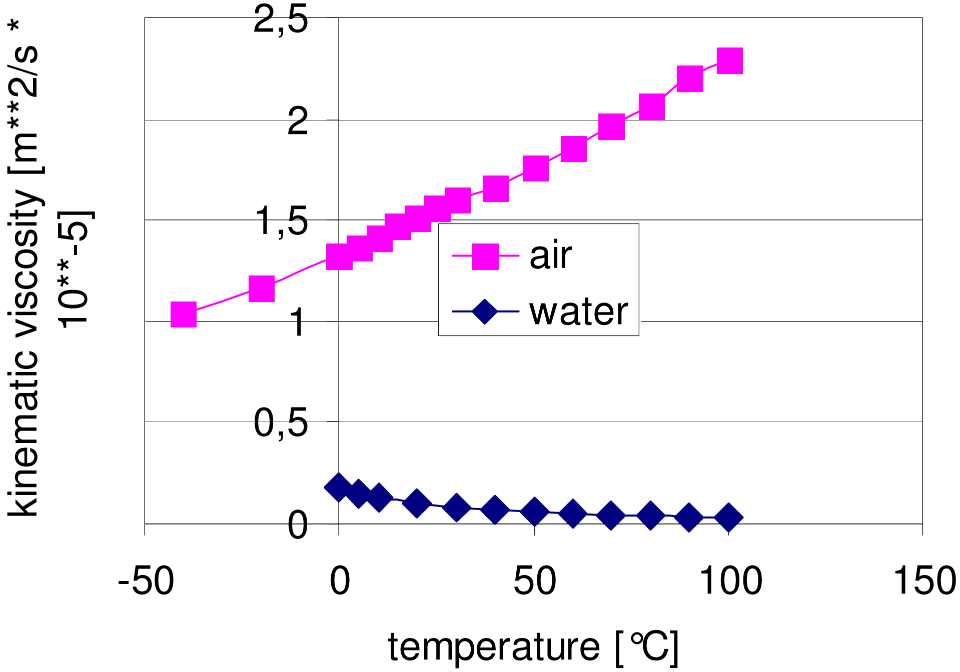
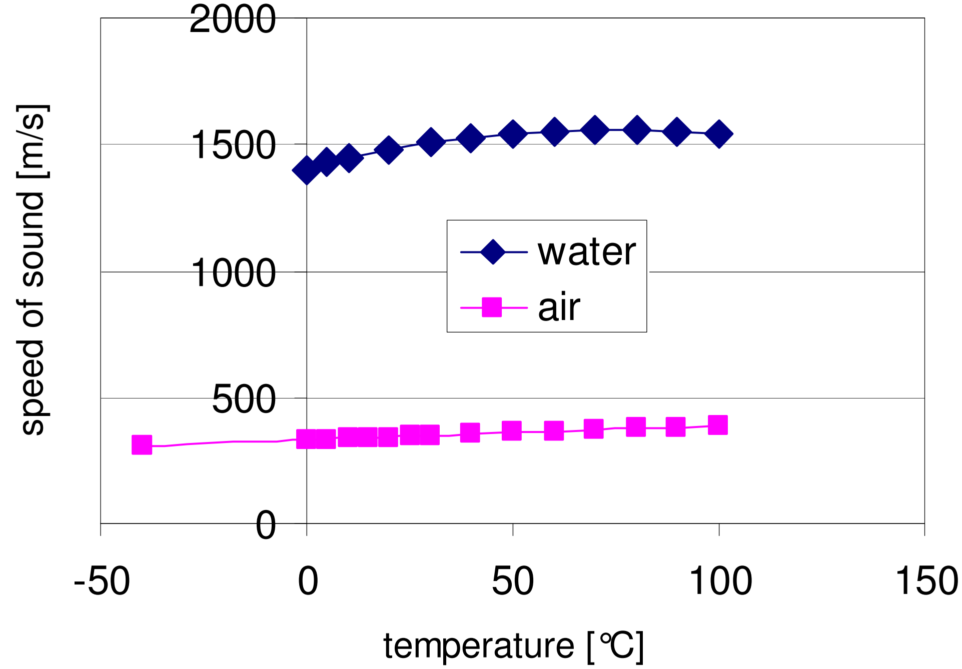
Properties of Air and Water (Reynolds and Mach Number)





- **Example:**
  - Flow problem with a characteristic length = 3m
    characteristic velocity = 100 m/s
    Temperature = 20°C

Air

- Re=2 000 000
- Ma=0.29

Water

- Re=29 800 000
- Ma=0.067

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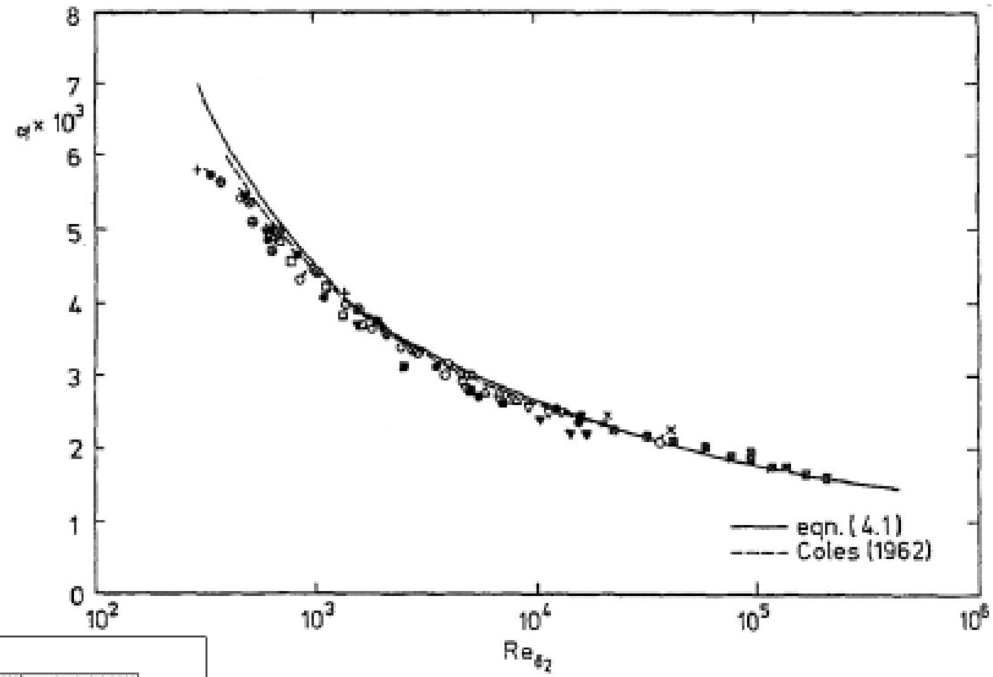
Scaled Experiments

- **Perfect Experiment**
  - Reynolds similarity
  - Geometrical similarity
  - Mach Number similarity

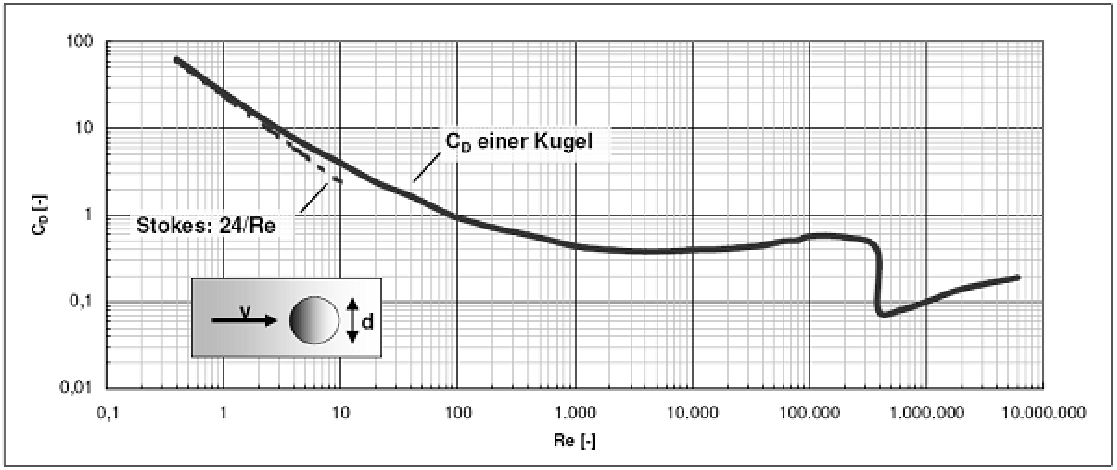
- **Compromises in experiments**
  - What about Reynolds Independency?
  - What about low Compressibility?
  - What about Geometrical simplification?

Reynolds Number Dependency

- **Skin Friction of a flat plate over the momentum loss thickness (right)**
- **Drag coefficient of a sphere over Reynolds number (below)**



Fernholz and Finley 1996



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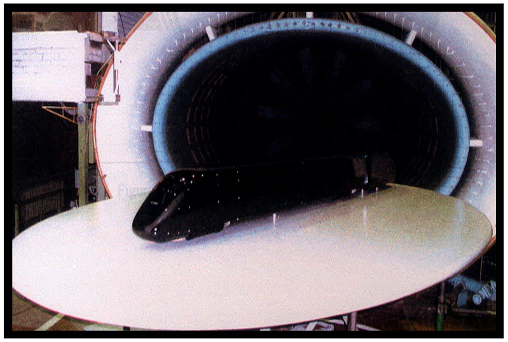
How to get high Reynolds Number in Wind Tunnels?

- **Big Models (Low Reynolds Number Wind tunnel, e.g. Audi up to 100 m/s)**



- **Low Temperature (Kryogenic Wind Tunnel, e.g. T=-173℃ in Köln)**

- **High Pressure (e.g. up to 100 Bar in HDG Göttingen)**

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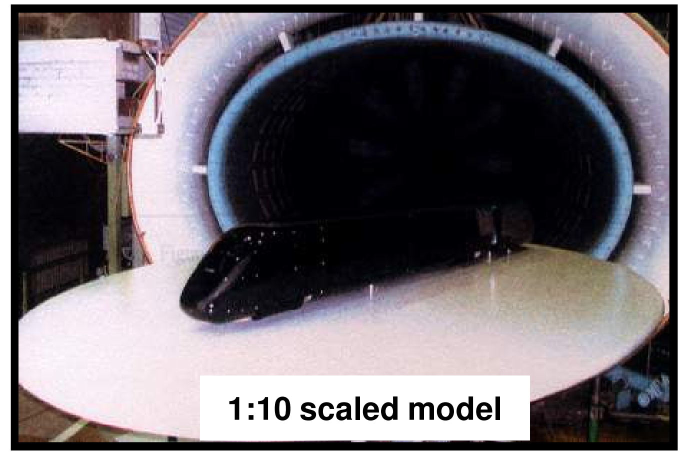
Scaled Model Testing

- **Preserve**
  - Reynolds Similarity
  - Geometrical similarity
  - Mach Number similarity



Re = (78 m/s * 3 m)/(1.5*10-5m**2/s)**

Re = 15 000 000

Ma = 78/335 = 0.23

Re = (78 m/s * 0.3 m)/(1.5*10-5m**2/s)**

Re = 1 500 000

Ma = 0.23

Do we have a problem now with Re?

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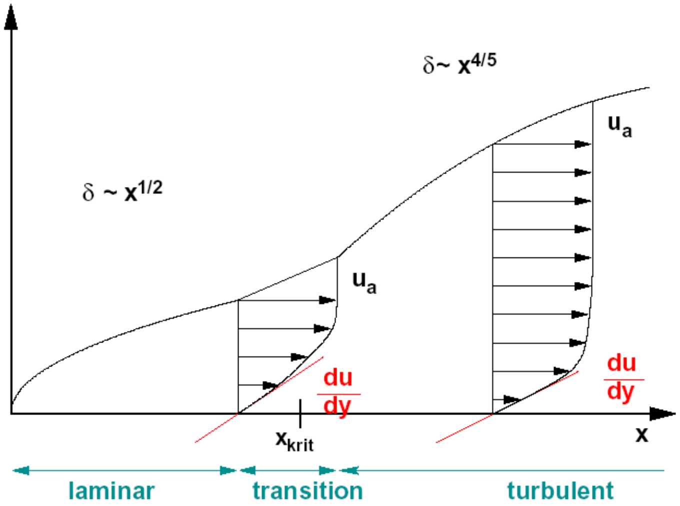
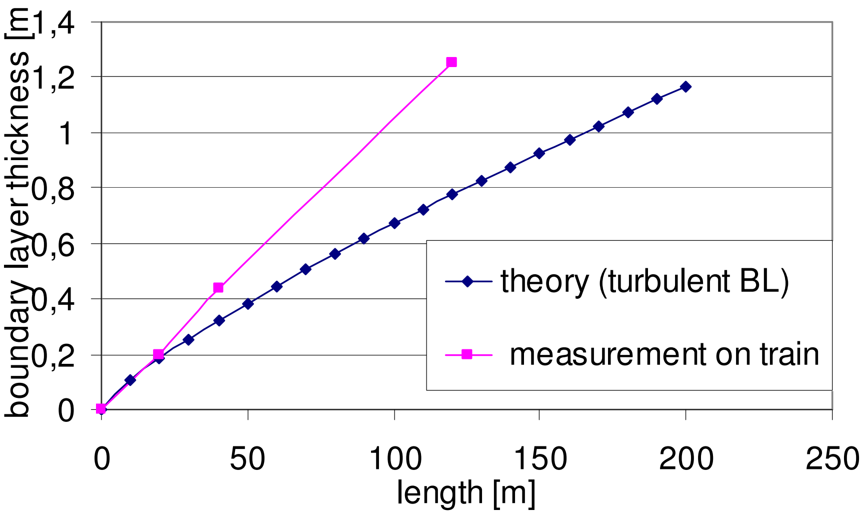
Turbulent Boundary Layer Development

Approximation out of experiments

$$\left(\frac{u}{u_\infty}\right) = \left(\frac{y}{\delta}\right)^{1/7} \Longrightarrow \frac{\delta}{x} = \frac{0.37}{\sqrt[5]{\mathrm{Re}_x}} \Longrightarrow \delta(x) \sim x^{4/5}$$





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Head Pressure Pulse

Topic 2

Vehicle Aerodynamics Lecture

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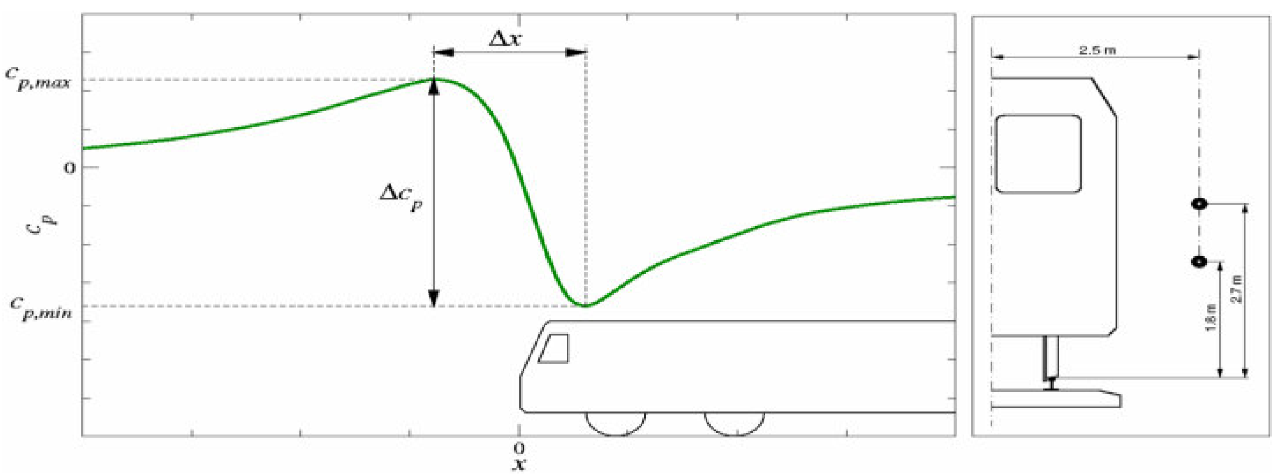
Head Pressure Pulse Problem

- A passing vehicle is accompanied with flow velocities and variations of the static pressure in its proximity
- This generates forces on persons and nearby objects
- Highest flow velocities are associated with the passing of the train tail $\Rightarrow$ slip stream effect
- Biggest pressure changes are associated with the passing of the train head $\Rightarrow$ head pressure pulse
- Head pressure pulse intensity mainly depends on the train speed and on the head shape and related details of the front configuration (spoilers, snow plough)
- Head pressure pulse implies danger to persons staying near the track and nearby objects $\Rightarrow$ threshold values defined by reference vehicles

Head Pressure Pulse - Requirements

- **European Level**
  - TSI requirement for trains with v_{max} > 190 kph
    - Criteria
      - A full length train, running at a given speed (reference case) in the open air shall not cause an exceedance of the maximum peak-to-peak pressure changes $\Delta p2\sigma$ over the range of heights 1,5 m to 3,3 m above the top of rail, and at a distance of 2,5 m from the track centre, during the whole train passage (including the passing of the head, couplings and tail).
    - Limit
      - 720 Pa for trains up to a maximum speed of 250 km/h
      - 795 Pa measured at 250 km/h for trains with a maximum speed of 250 km/h or higher
- **National Level**
  - Different criteria according to the specified load limit for infrastructure at the track directly stated in the contract.



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Head Pressure Pulse Assessment

- **Since the head pressure pulse amplitude depends quadratically on the train speed, pressures are normalised with the dynamic pressure:**

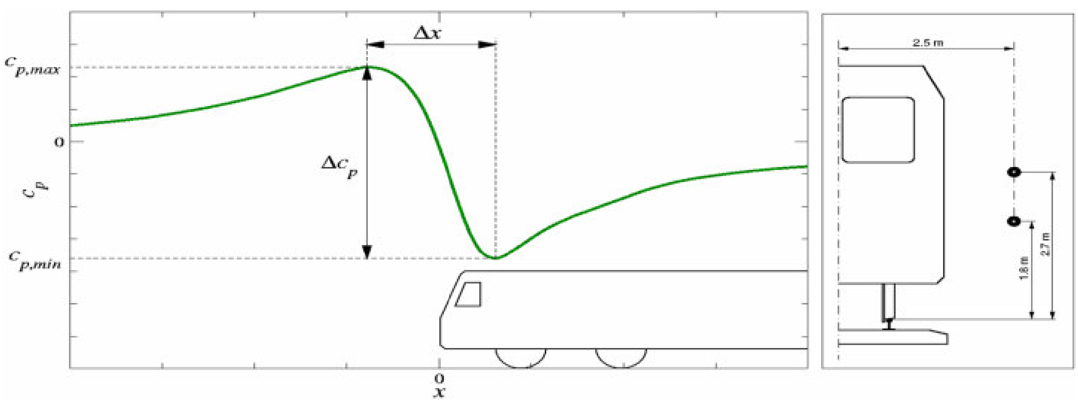
$$c_p = \frac{p - p_0}{q} \quad \text{with the dynamic pressure:} \quad q = \frac{1}{2}\rho v^2$$

ρ = air density ≈ 1.2 kg/m³, v = train speed

- **The relevant assessment criterion is the maximum (normalised) pressure change:**

$$\Delta c_p = c_{p,\max} - c_{p,\min}$$

as shown in the following figure ...



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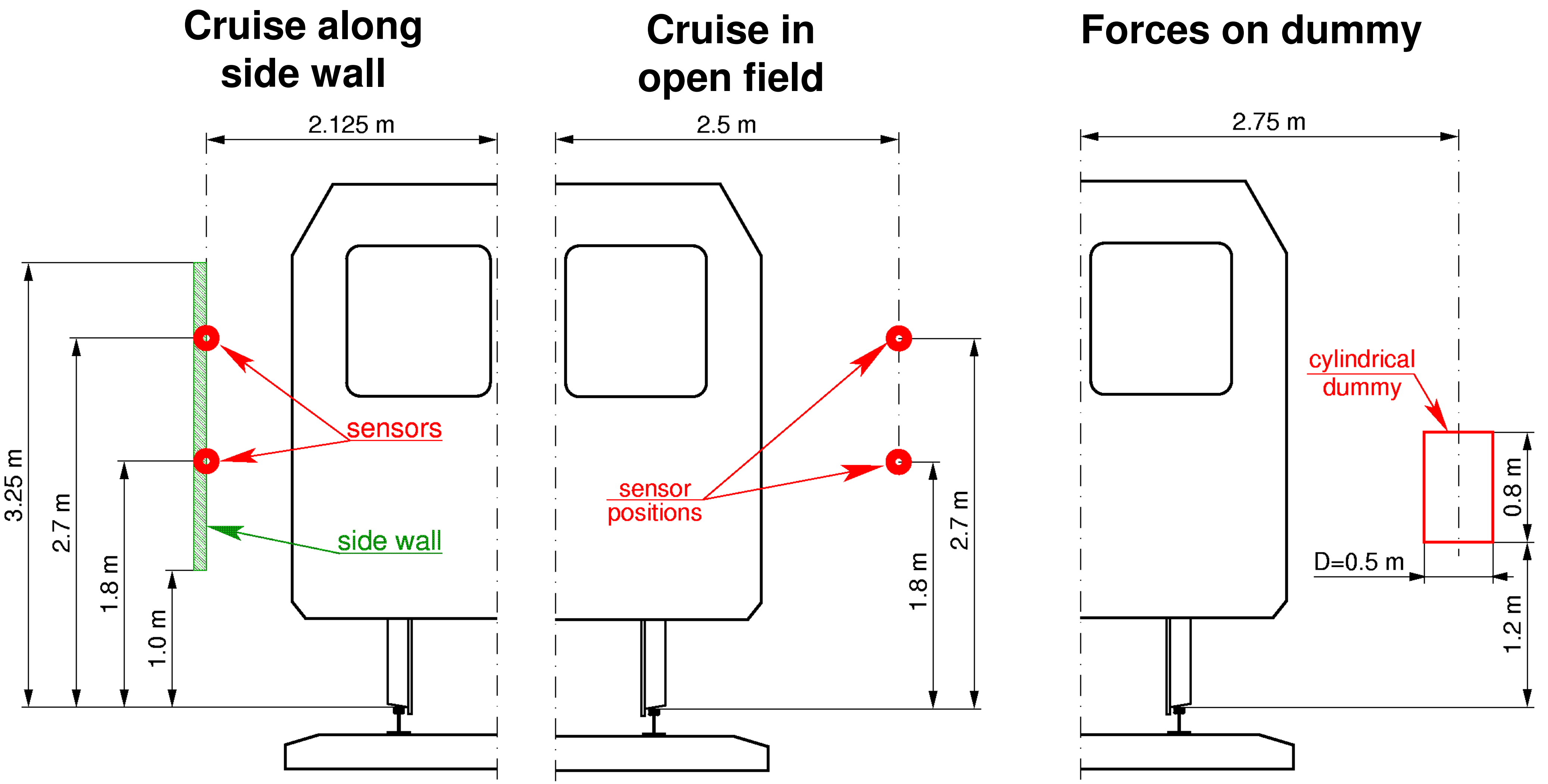
Test Setups used throughout Europe



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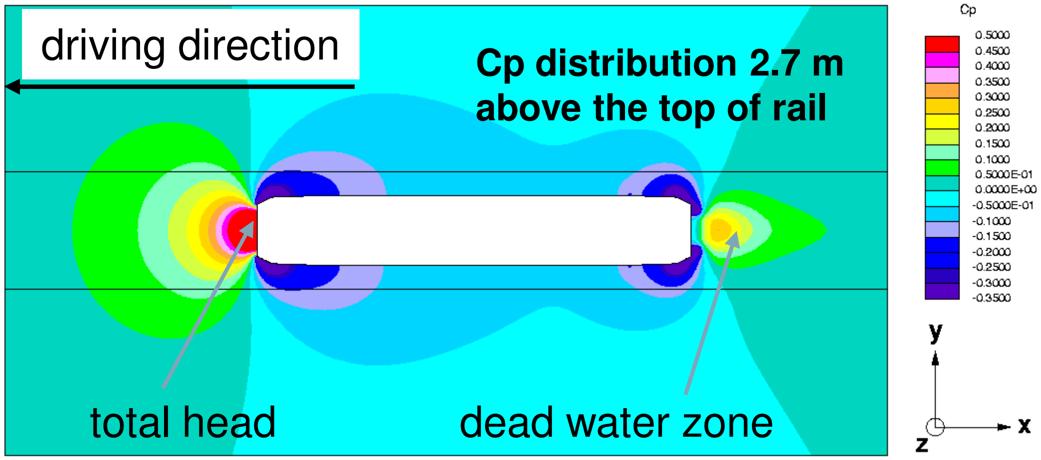
Head Pressure Pulse - Prediction

- The three-dimensional, high Reynolds number turbulent flow around a vehicle is usually characterised by the following: deceleration and acceleration, curved boundaries, separation, possible reattachment, recirculation and swirling properties. In general, sufficiently accurate solutions may be achieved by turbulence modelling through approaches such as: Large Eddy Simulation (LES), Detached Eddy Simulation (DES), Reynolds Averaged Navier-Stokes (RANS) and codes based on the Lattice Boltzmann Method. These methods require the volume containing the flow of interest to be discretised into sub-volumes or cells in which approximations to the physical equations are solved.
- All the above mentioned approaches are known by the generic name of computational fluid dynamic (CFD) methods. The chief challenge of CFD is the appropriate choice of an adequate combination of computational domain sub-division (mesh cells or grid points), boundary conditions, computational method and turbulence modelling.



BR185, CFD solution

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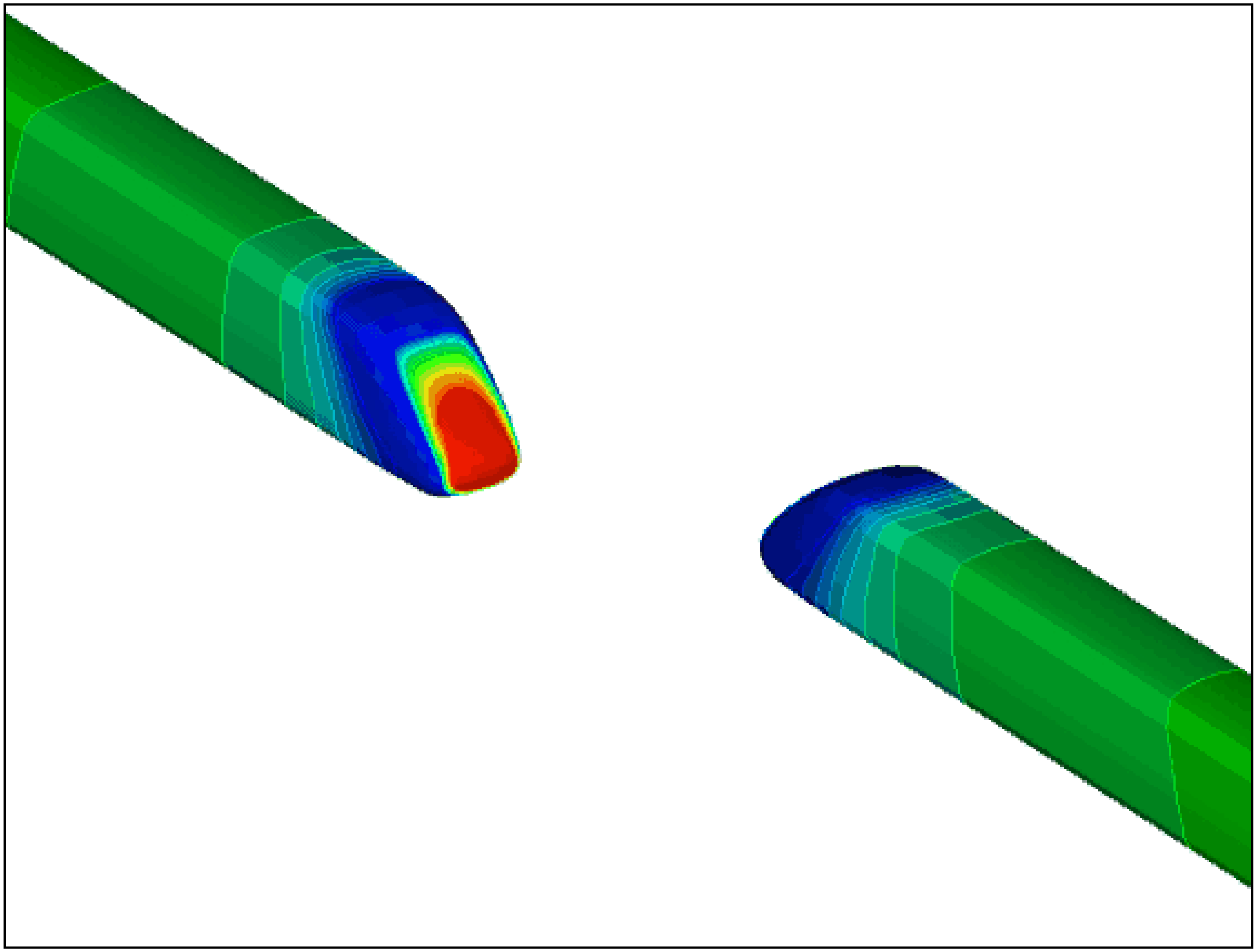
Head Pressure Pulse Impact on Trains Crossing



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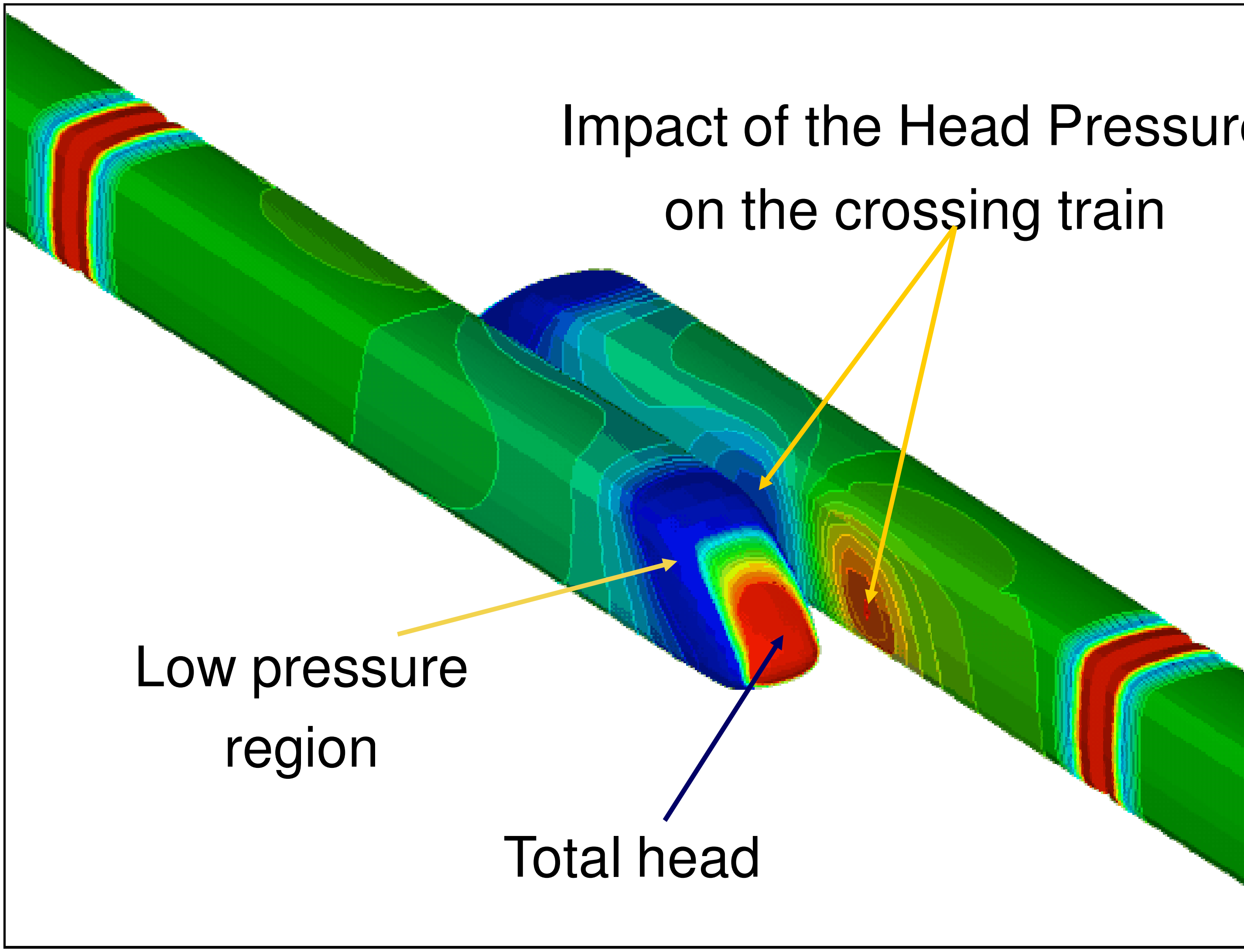
Head Pressure Pulse Impact on Trains crossing



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Tunnel Aerodynamics

Topic 3

Vehicle Aerodynamics Lecture

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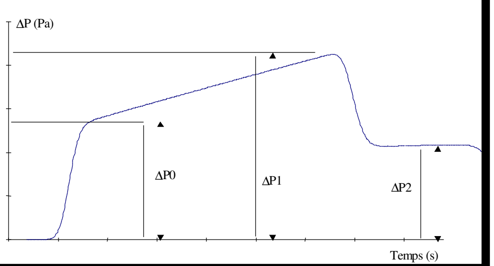
Tunnel Aerodynamics – Requirements

- **European Level**
  - TSI requirement for Safety reasons
- **Customer Level**
  - Criteria for pressure comfort

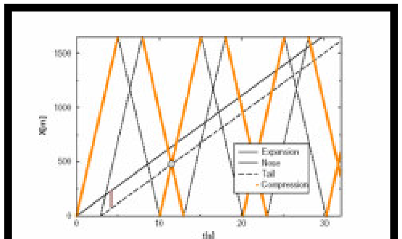
Tunnel pressure specification

Critère : les valeurs des variations de pression ΔP0, ΔP1 et ΔP2, **dans le cas d'une circulation isolée,** doivent respecter simultanément:

- **ΔP0≤1500Pa**
- **ΔP1≤2300Pa**
- **ΔP2≤1200Pa**



Degree of pressure tightness?



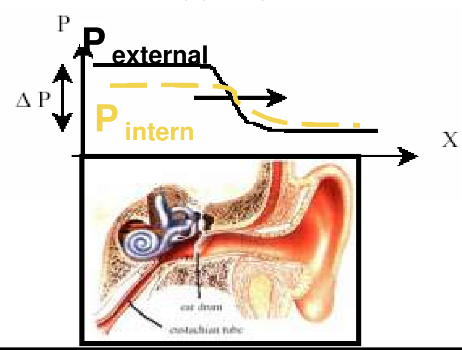
Cabin pressure specification

UIC 651:

- **90 m² Tunnel**
- **with Train encounter**

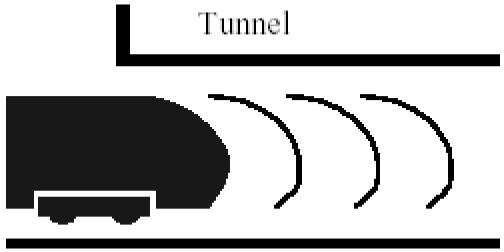
Permissible limits

- **< 1000 Pa**
- **< 400 within 1**

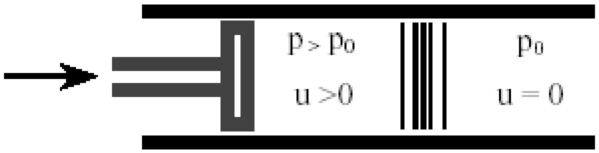


Pressure Comfort: Physics

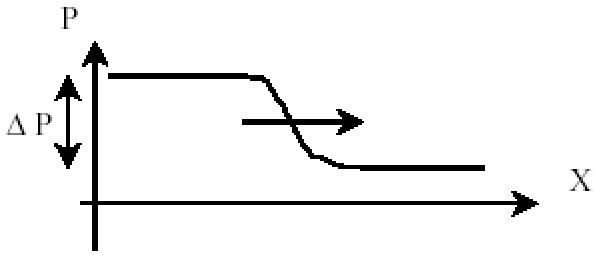
- **Train generates 3-D pressure wave upon tunnel entry**



- **Becomes 1-D wave travelling with the speed of sound, similar to moving piston**



- **Wave front moves through tunnel with speed of sound**



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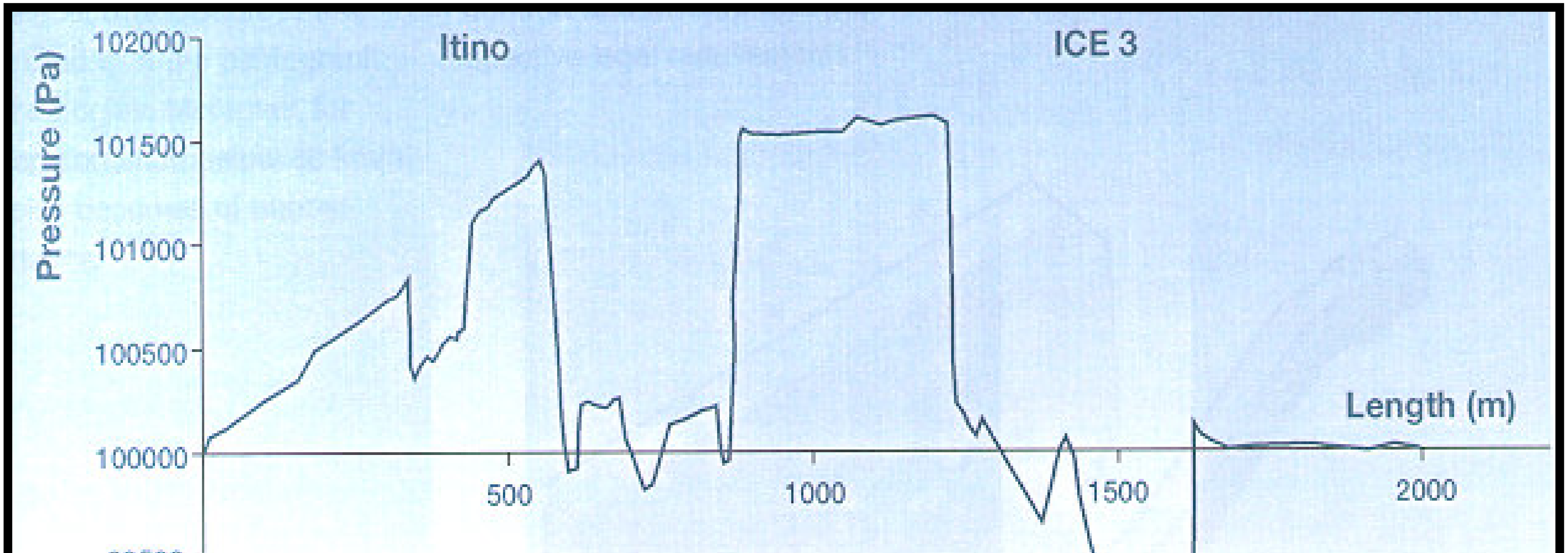
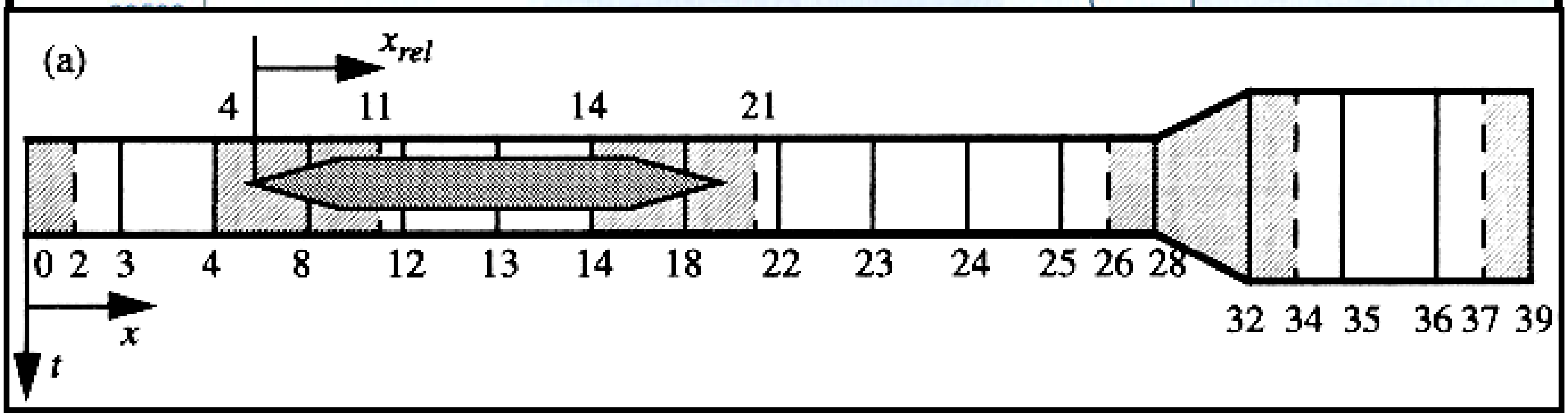
Pressure Comfort:





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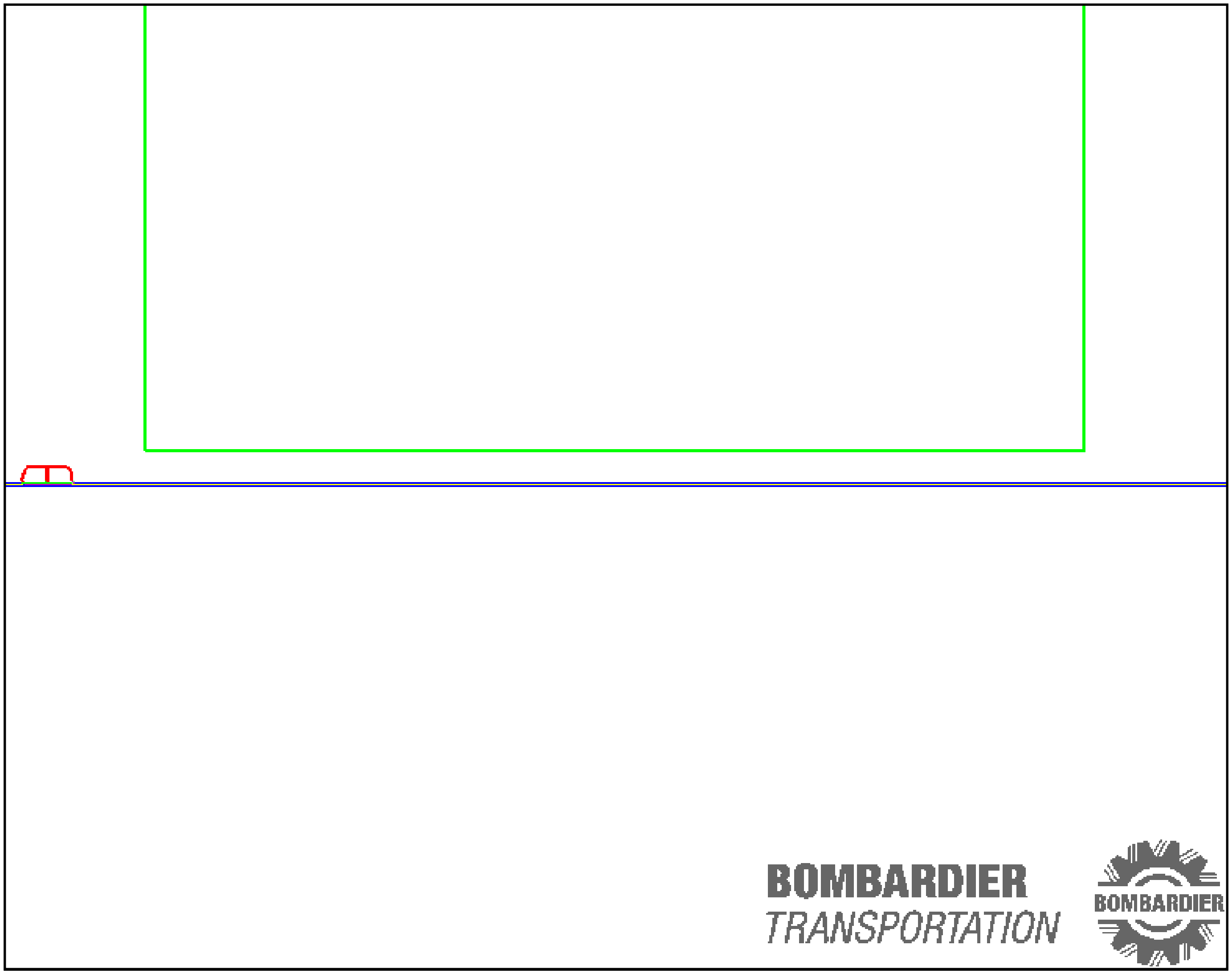
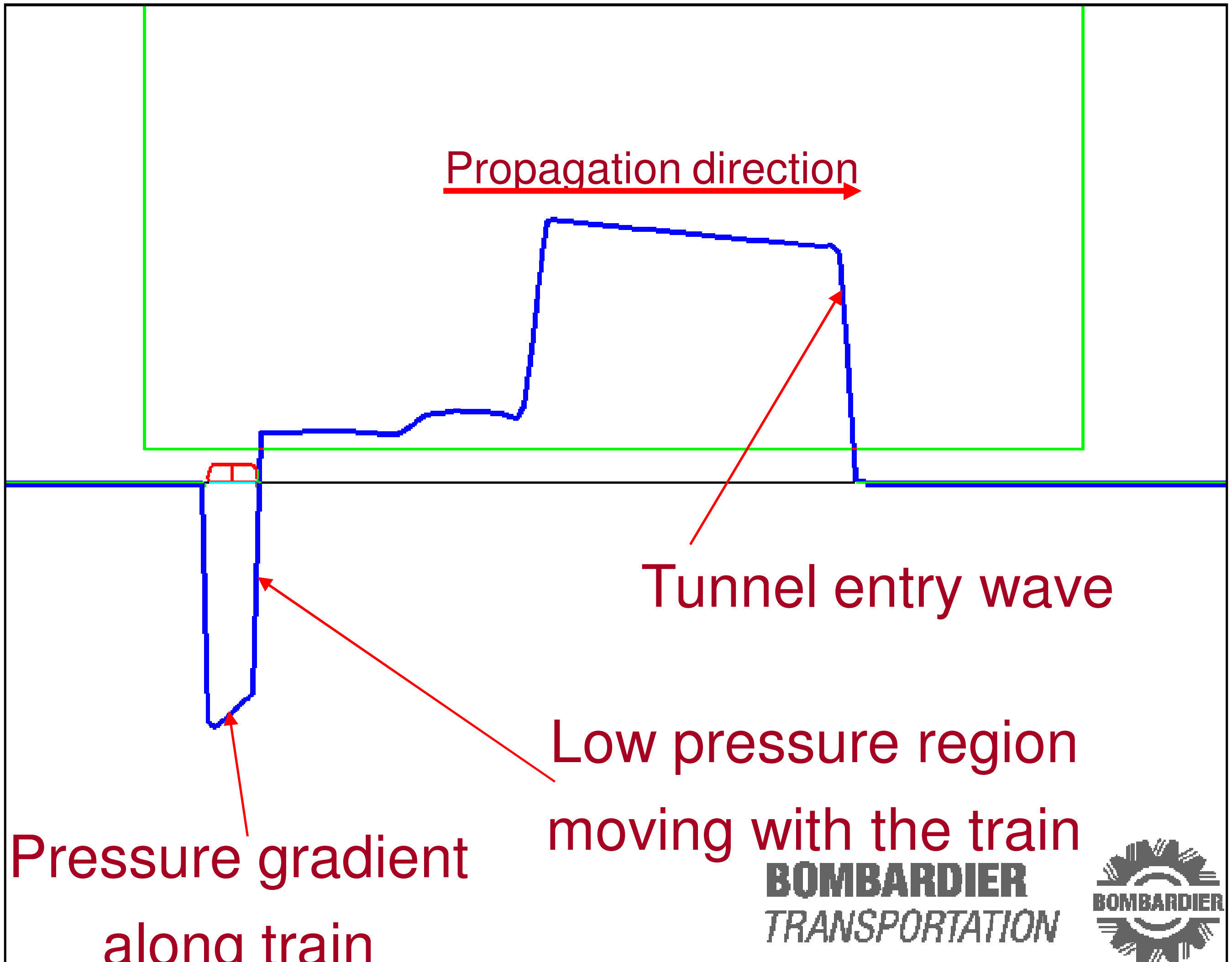
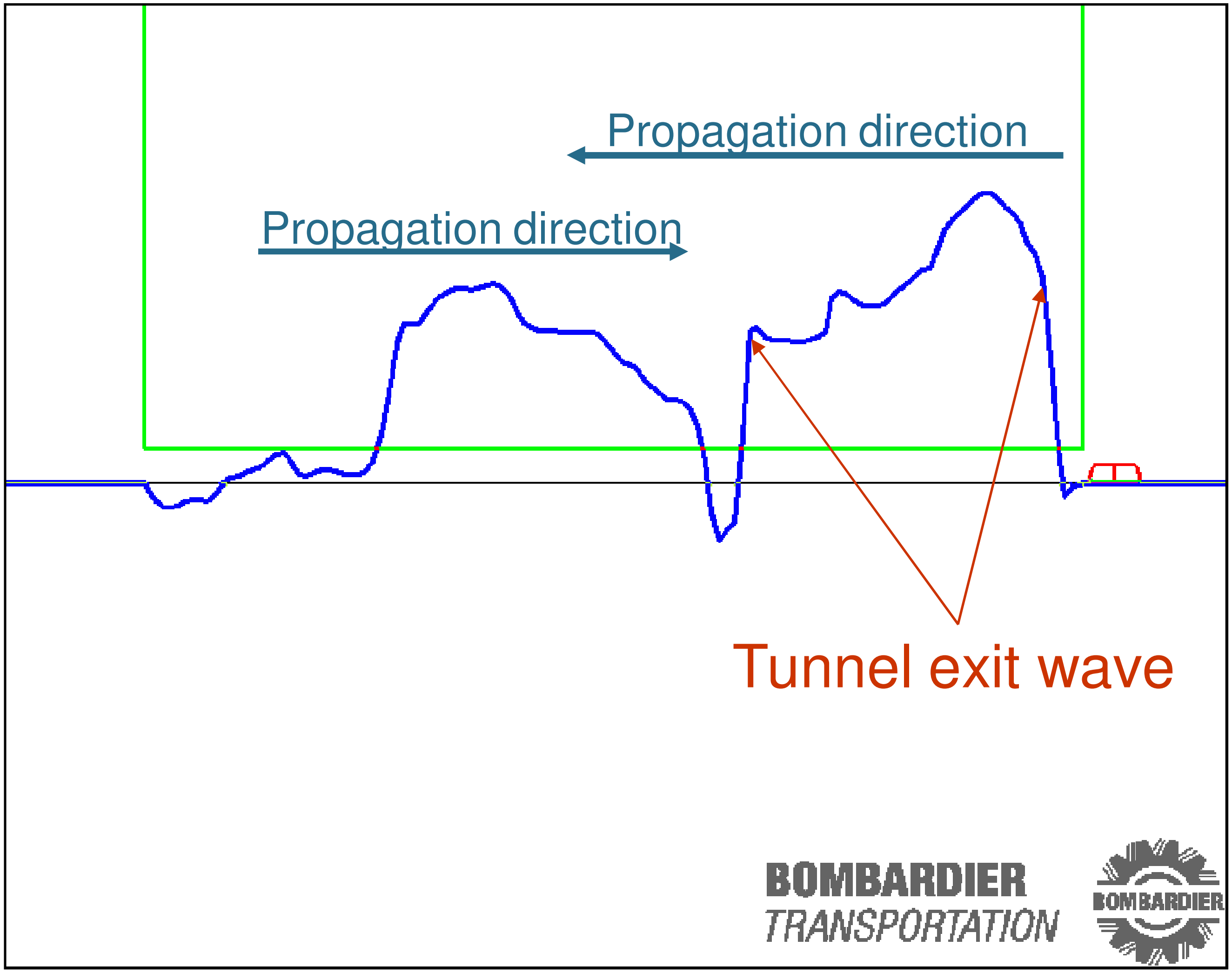
Propagation of pressure waves in a tunnel



Tunnel Aerodynamics - Prediction



Tunnel exit wave



Pressure Comfort: Cabin pressure variation

Cabin pressure depends on:

- external pressure
- leakage area - pressure tightness
- cabin volume
- cabin deformation

$$\frac{dp_i}{dt} = \frac{1}{\tau}[p_e(t) - p_i(t)]$$

τ : time constant [to decrease pressure to 63 % of initial value]

p_i : cabin pressure

p_e : tunnel pressure

Components affecting the pressure tightness

- HVAC, pressure protection, condensed water drain
- Car Body Shell
- Gangway
- Doors
- Windows
- Ducting & Cabling through shell
- WC

Cross-Wind Stability

Topic 4

Vehicle Aerodynamics Lecture

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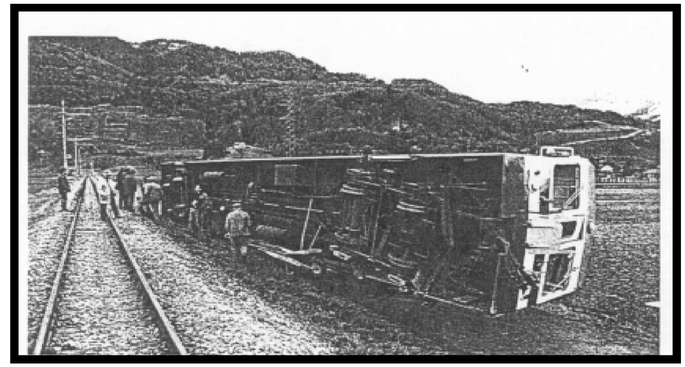
Cross-Wind Stability: Motivation

- Weight of trains decreases to improve energy consumption
- Speed of trains increases
- Trains shall operate under all weather conditions, e.g. storm
- Capacity of trains increases to reduce operating costs, double deckers are now common
- Old narrow gauge tracks enhance the problem



28.1.1994:Cross-wind accident

22.2.1994: Japan, Sanriku Railways

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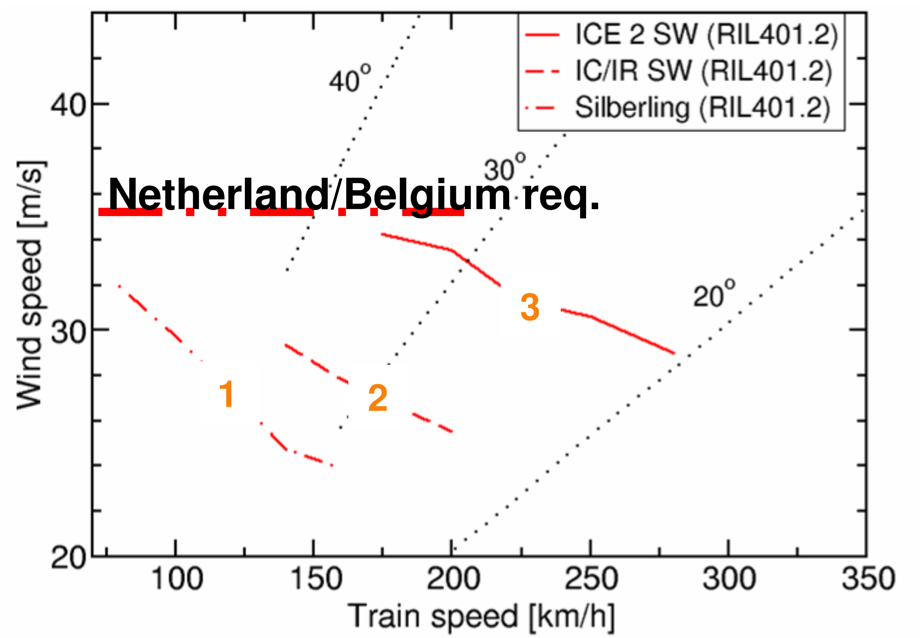
Cross-Wind Stability - Requirements

- **European Level for Homologation**
  - TSI requirement for trains with v_{max} > 250 kph (in approval process)
  - TSI requirement for trains with v_{max} < 250 kph (planned by ERA)
- **National Level for Homologation**
  - UK: Group Standard RSSB
  - Germany: Richtlinie RIL 807
  - Other countries like Belgium or the Netherlands have slightly different requirements which are based on the regulations for track access.



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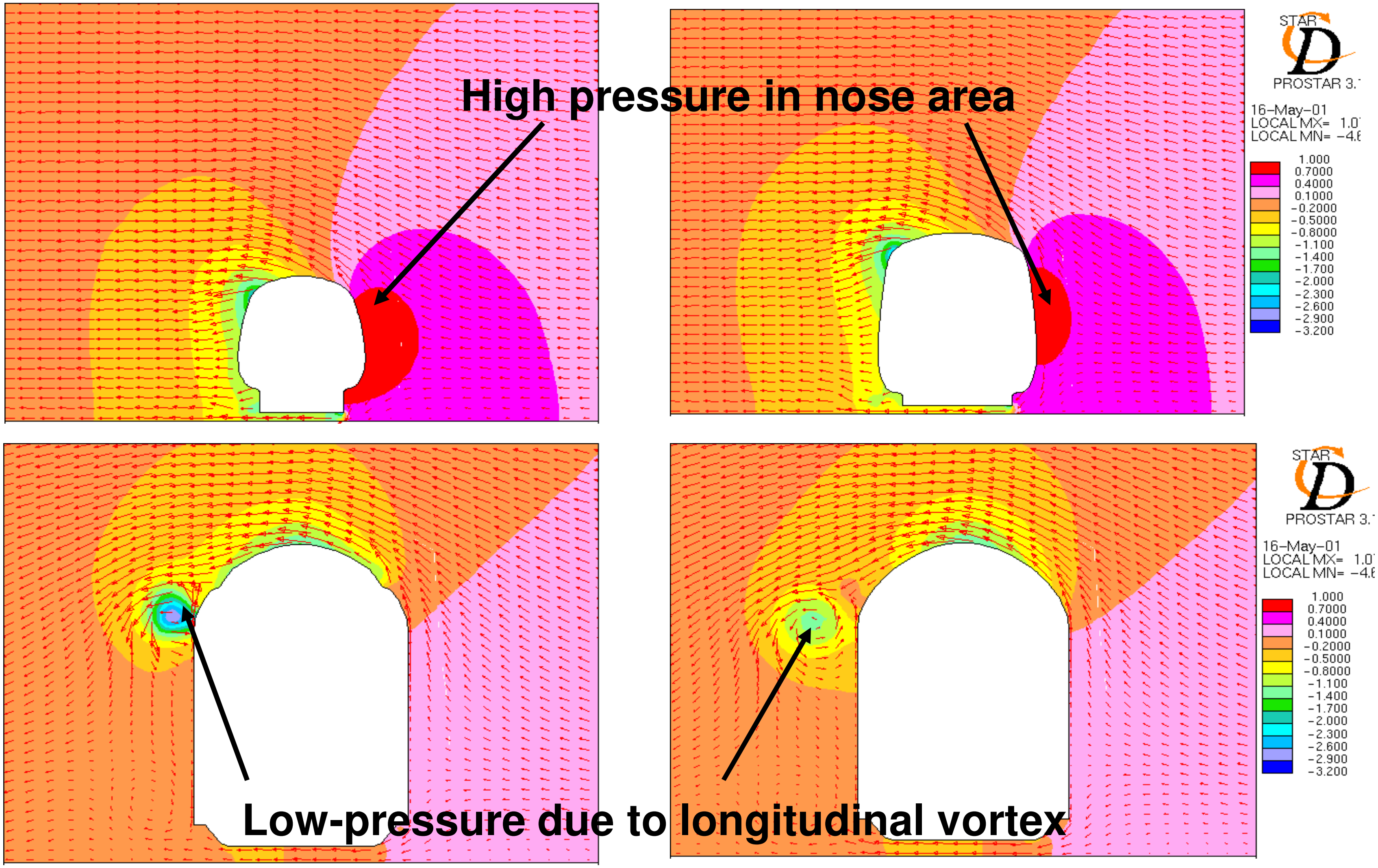
Flow Field Topology: CFD



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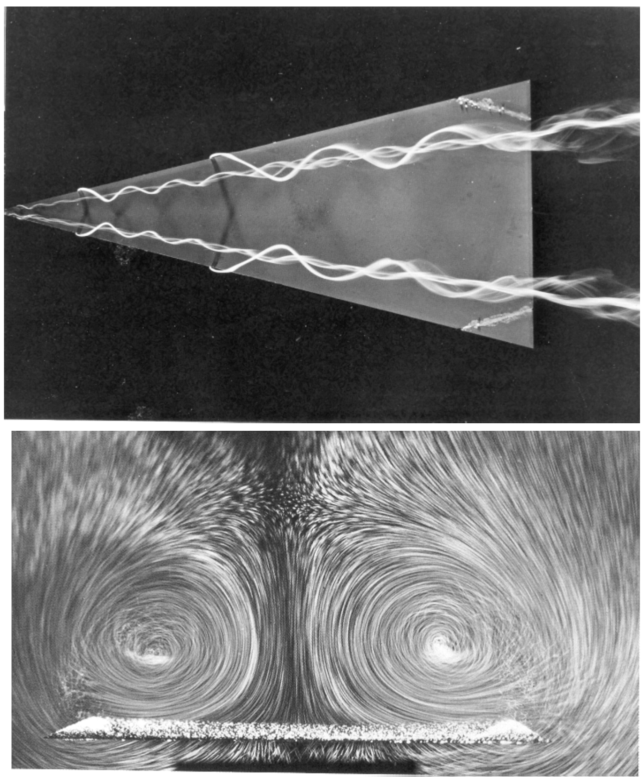
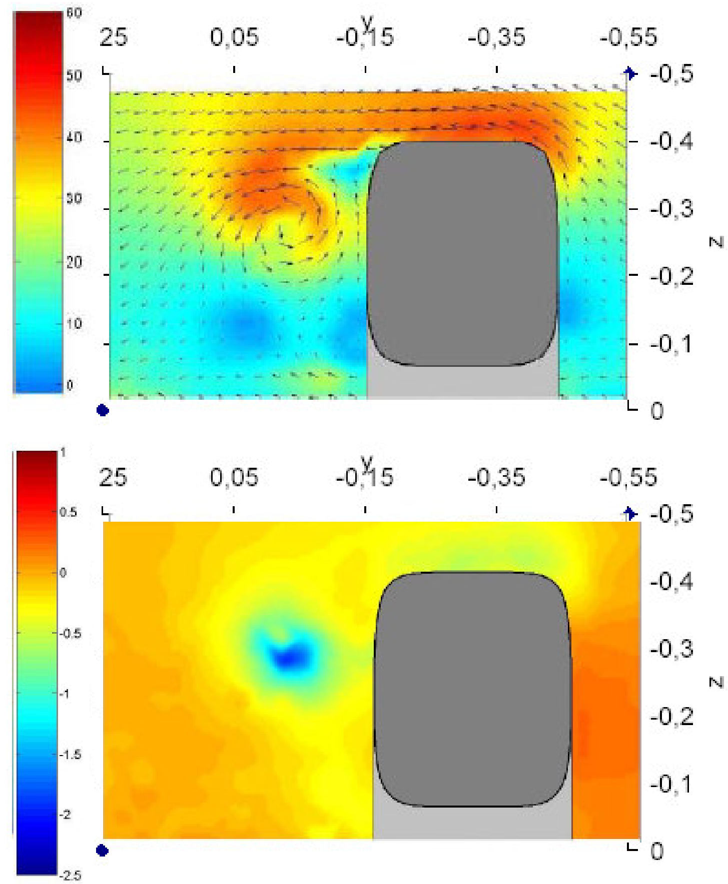
Flow Field

- **Longitudinal vortices present like displayed at delta wings causing low pressure region**



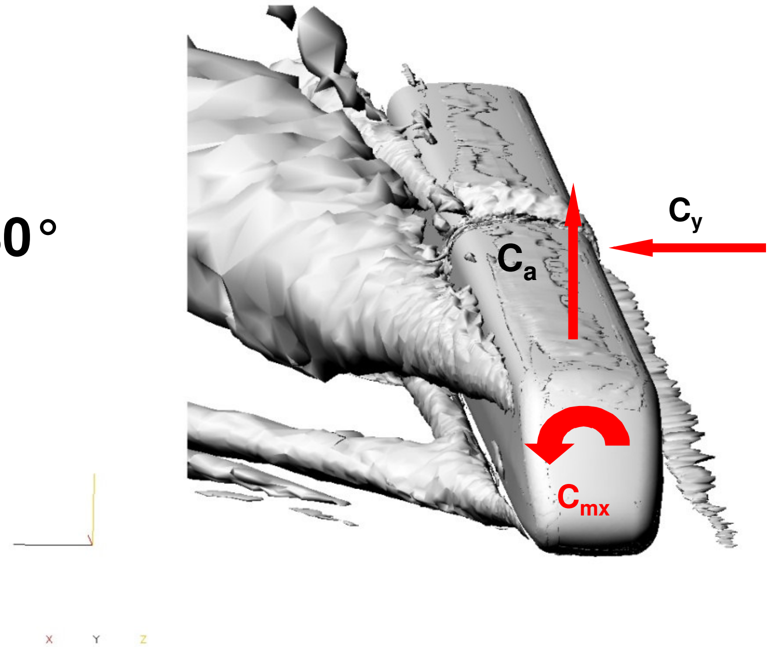
Werle, 1963

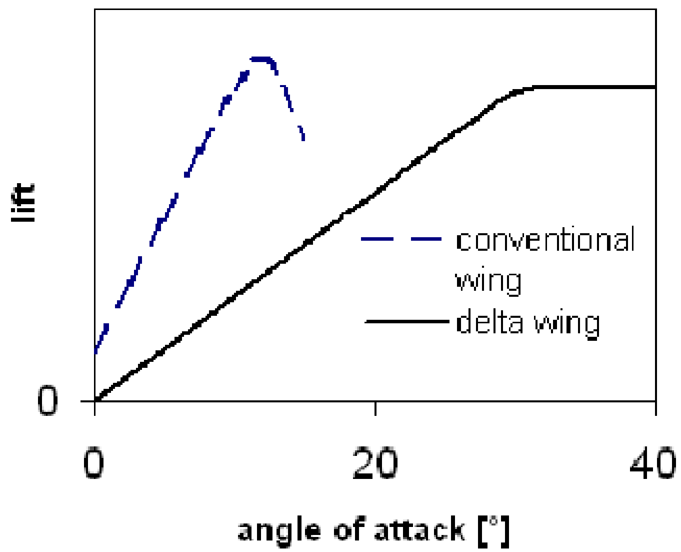


Velocity and pressure distribution at x=-0.134 and α=30° (experimental data)

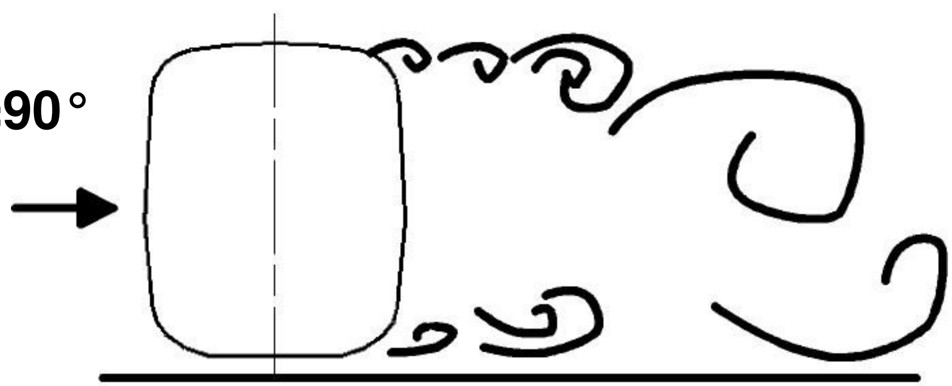
Flow Topology

Alpha=30°





Alpha=90°



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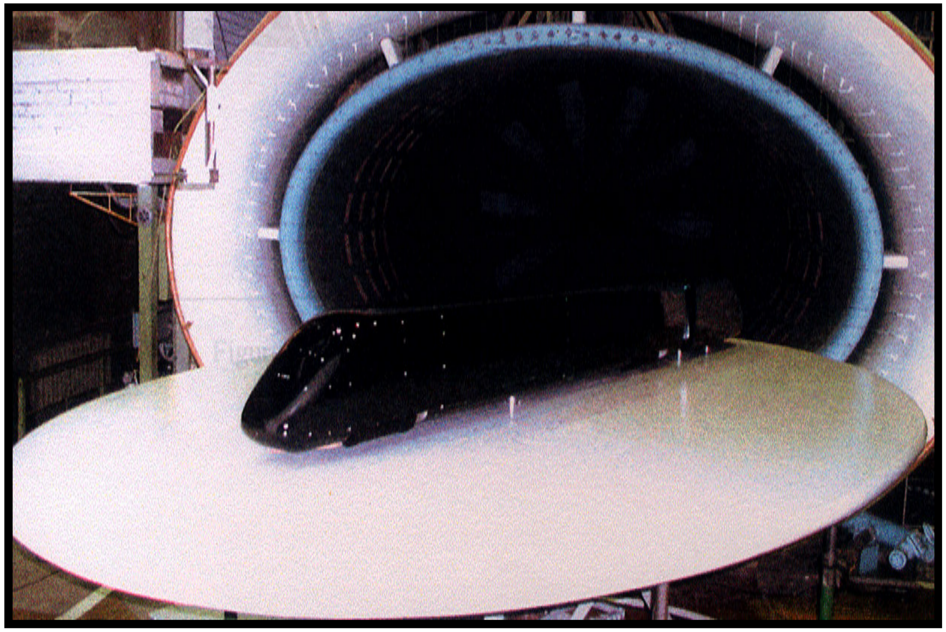
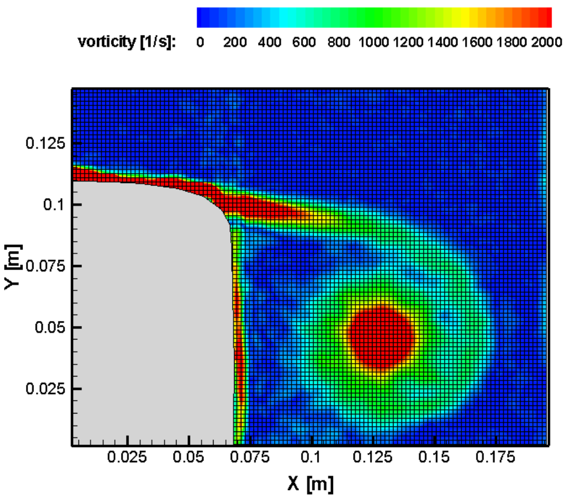
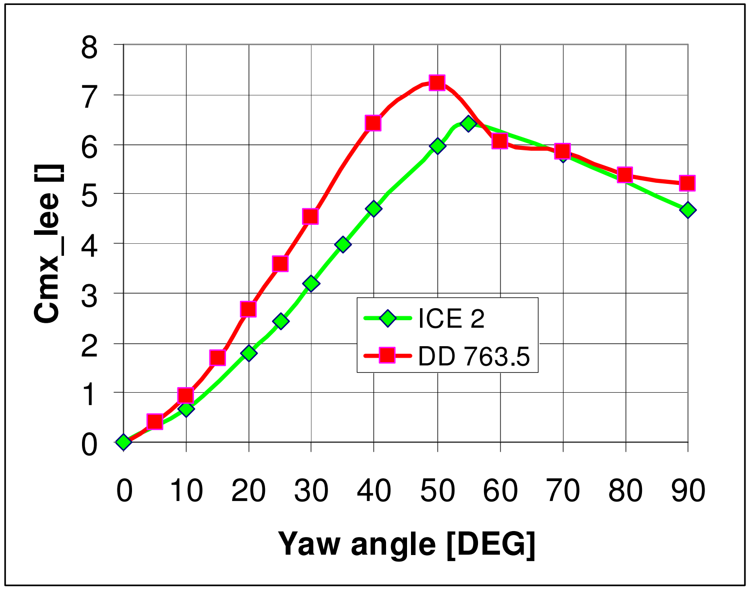
Behaviour of Roll Moment

- **The roll moment exhibits the maximum between 40° and 55°**
- **What is the reason that we do not have the maximum at 90°?**

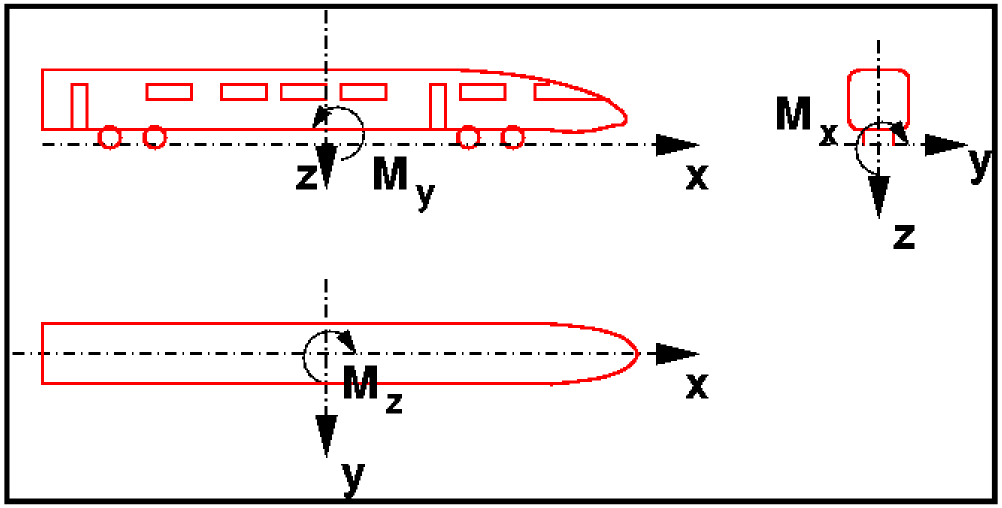






Cross-Wind Stability: Aerodynamic forces

- **Six aerodynamic coefficients**
  - Three aerodynamic forces
  - Three aerodynamic moments
- **All except drag influence side-wind stability**
- **Roll moment M_x has largest influence**



A=10m², l= 3m

$$c_i = \frac{F_i}{\rho/2 \cdot v^2 \cdot A} \Big|_{i=x,y,z}$$

$$c_{mi} = \frac{M_i}{\rho/2 \cdot v^2 \cdot A \cdot l} \Big|_{i=x,y,z}$$

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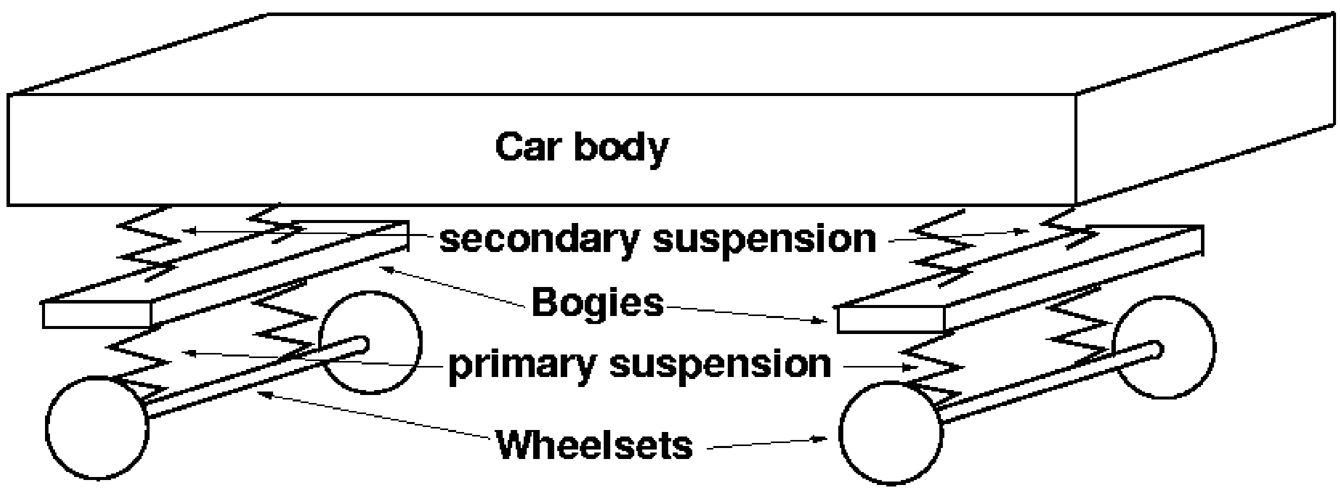
Cross-Wind Stability: Wheel-Rail Forces

Quasi Static Method

- In-house Code *Windsafety (Matlab)*
- Five body system
- 12 degrees of freedom
- Captures displacements
- Quasi static

Transient Method

- Multi Body Simulation
- n body system
- n*x degrees of freedom
- Captures all displacements
- transient



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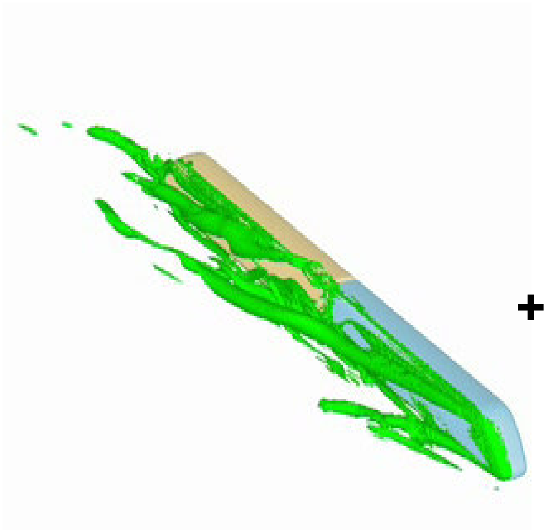
Cross-Wind Stability - Prediction



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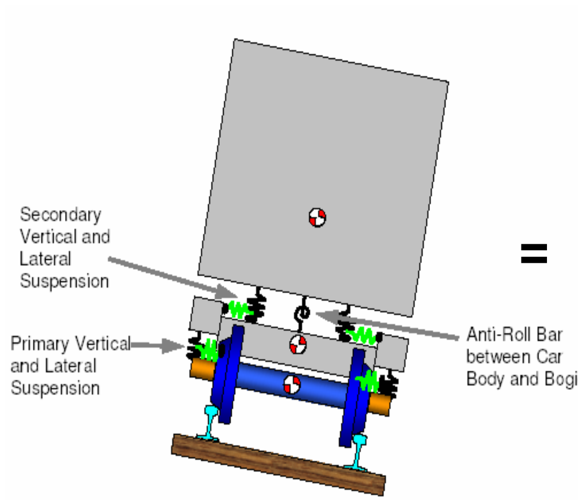

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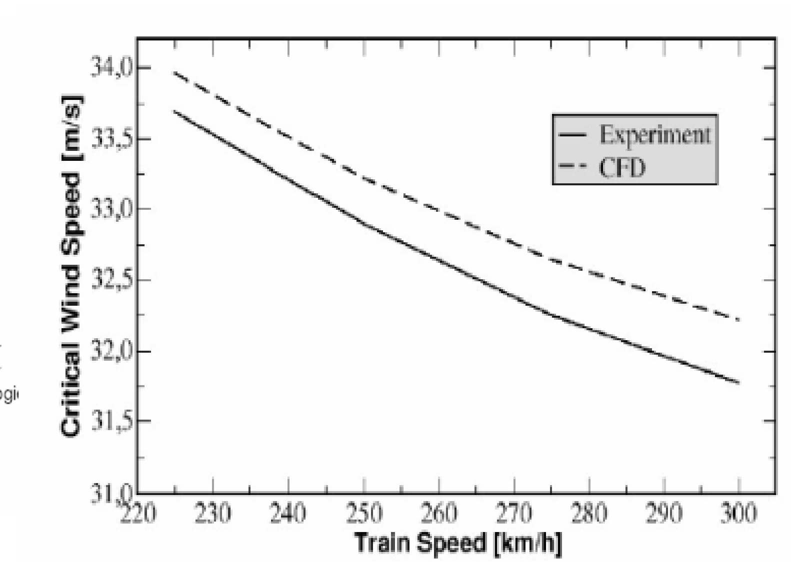

Computational Fluid Dynamics + Multi Body Simulation = Performance Prediction

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Counter Measures

- **Shape optimisation (aerodynamic coefficients)**
  - lower roof height
  - optimise roof radius and nose shape
- **Bogie**
  - restrict lateral displacement of car-body (springs)
  - lower vertical position of lateral stops
  - small effect only - spring stiffness increase
- **Mass distribution**
  - increase mass
  - shift centre of gravity to the front
  - lower vertical centre of gravity

Slip Stream Effect During Train Passing

Topic 5

Vehicle Aerodynamics Lecture

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Introduction

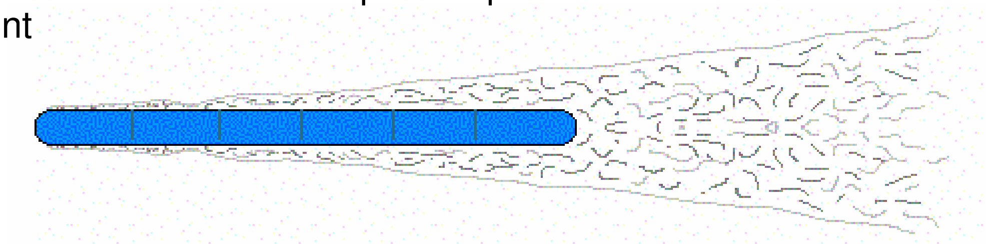
- **What is Slipstream?**
  - Air flow felt by a passenger waiting at a platform when a train passes
  - Air flow acting on trackside workers when a train passes
  - Slipstream generates fluctuating forces on nearby persons and objects
- **Persons and objects may be destabilised by a trains slipstream**
- **Slipstream can cause baby buggies and luggage trolleys to move and roll over**
- **Slipstream is a safety relevant issue and may cause injuries, fatalities and damage of objects**

Slipstream – Requirements

- **European Level**
  - TSI requirement for v_{max} > 190 kph
    - A full length train running in the open air at 300 km/h or at its maximum operating speed if lower shall not exceed the air speed $u_{2\sigma}$ at the trackside, at a height of 0,2 m above the top of rail and at a distance of 3,0 m from the track centre, during the passage of the whole train (including the wake, i.e. 10s after the train has passed).

Maximum speed (km/h)	Maximum permissible air speed, $u_{2\sigma}$ (m/s)
From 190 to 249	20
From 250 to 300	22

    - Example: Aerodynamic loads on track workers at the track side (TSI requirement)
      - A full length train running in the open air at 300 km/h or at its maximum operating speed if lower shall not exceed the air speed $u_{2\sigma}$ at the trackside, at a height of 0,2 m above the top of rail and at a distance of 3,0 m from the track centre, during the passage of the whole train (including the wake, i.e. 10s after the train has passed).
- **National Level**
  - Germany: similar to TSI requirement
  - Other countries like France or Spain require different scenarios like the so-called “dummy” requirement



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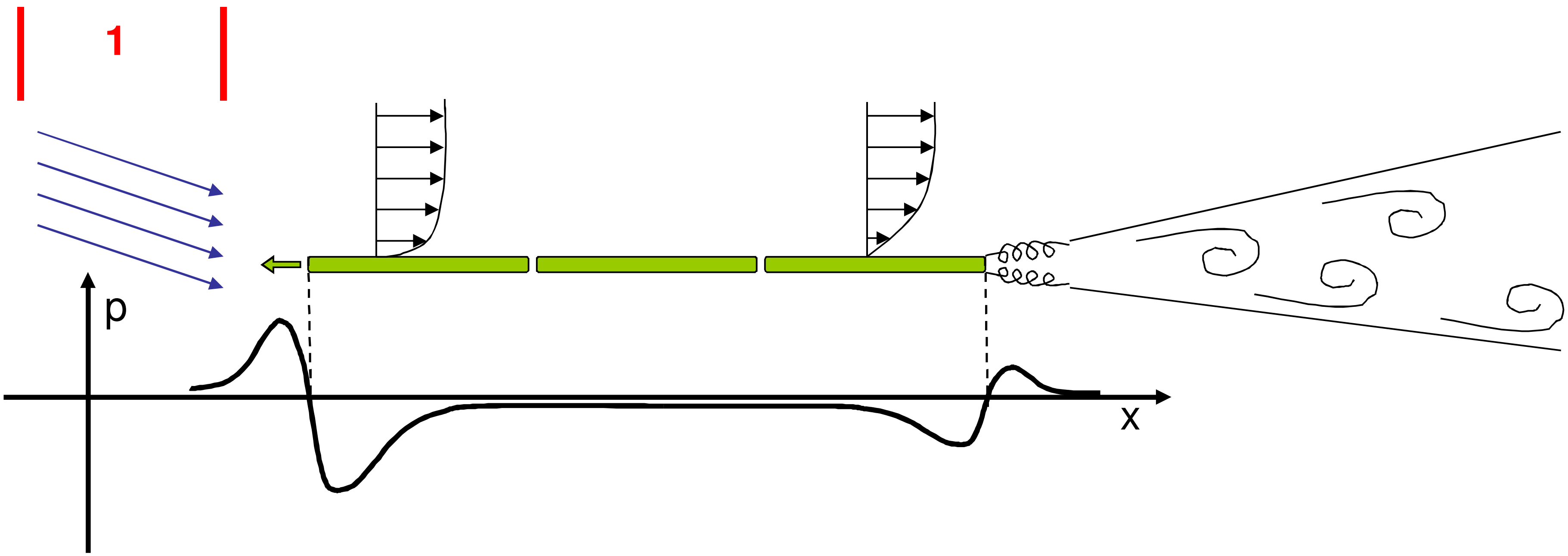
Physical Background



1. **Pre-Head Zone**
2. **Head Passage**
3. **Boundary Layer Zone**
4. **Near Wake**
5. **Far Wake**

- **Highest Slipstream Velocities usually occur:**
  - Cargo trains: During train passage
  - Passenger trains: In the wake region, after the train has passed

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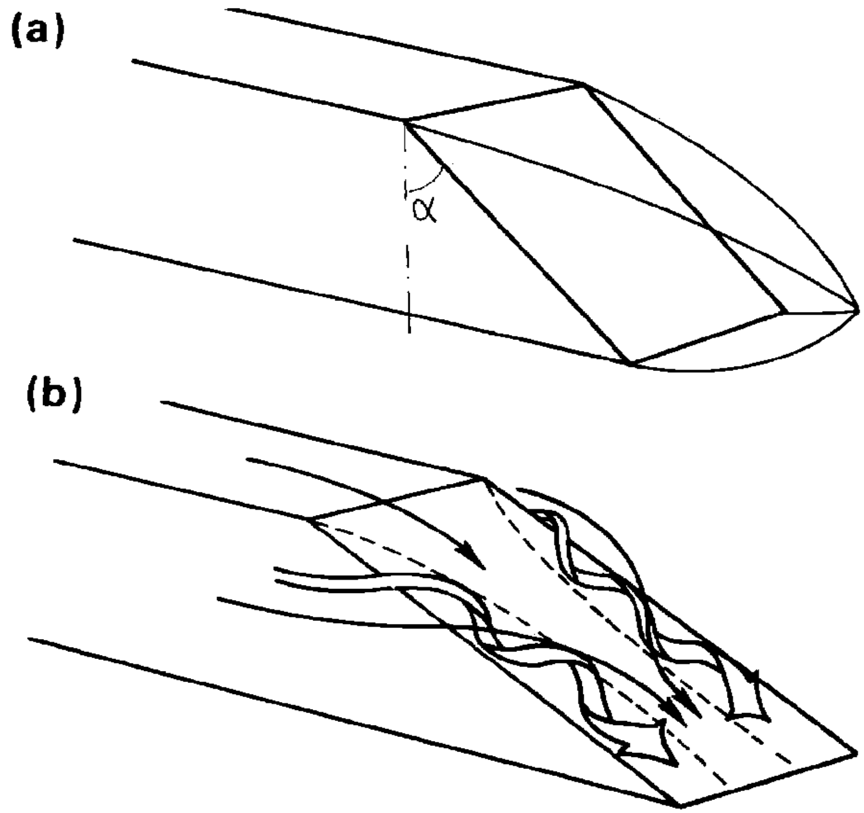
Physical Background

- **Looking at the slipstream performance of a train, the wake flow behind the tail has to be taken into account**
- **The flow pattern in the wake region strongly depends on the tail shape, e.g.:**
  a) Quasi axis-symmetric separation bubble
  b) Fully 3-D wake flow with characteristic vortex shedding
- **For simple geometries the dependency of the wake flow on few parameters can be studied**
- **This is not possible on complex tail shapes**



Source: Morel, Th., Effect of Base Slant on Flow in the near Wake of an axissymmetric Cylinder, *Aeronautical Quarterly*, May 1980, pp. 132-147

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Test Setups, Applied Methods

- **Ultrasonic anemometers have been applied to measure slipstream velocities on a platform**
- **2-D and 3-D sensors have been used**
- **Sampling rate: 10 Hz**
- **Latest commercially available ultrasonic sensors reach sampling rates up to 250 Hz**

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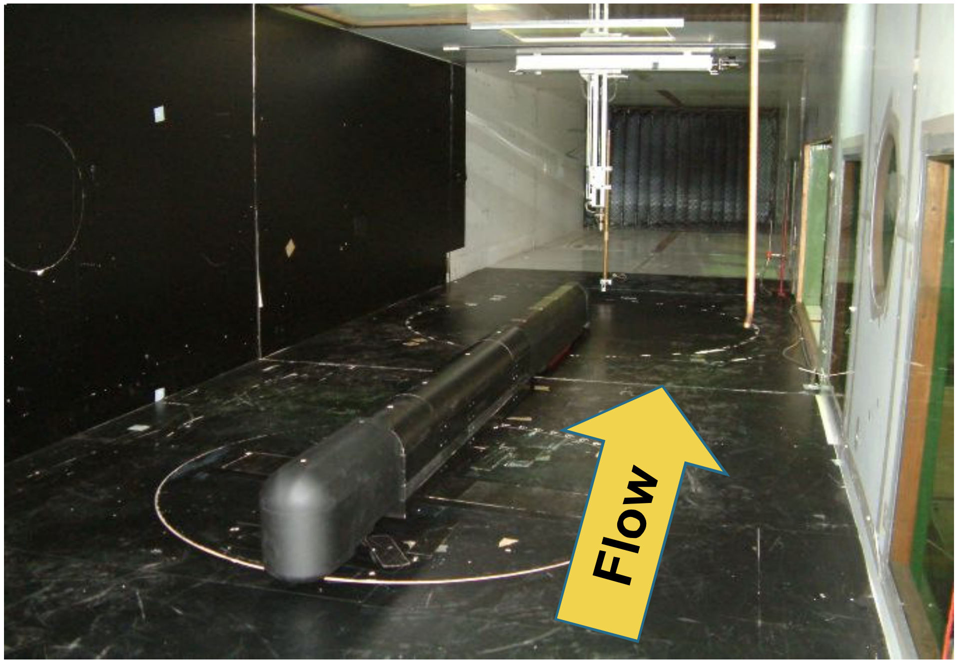
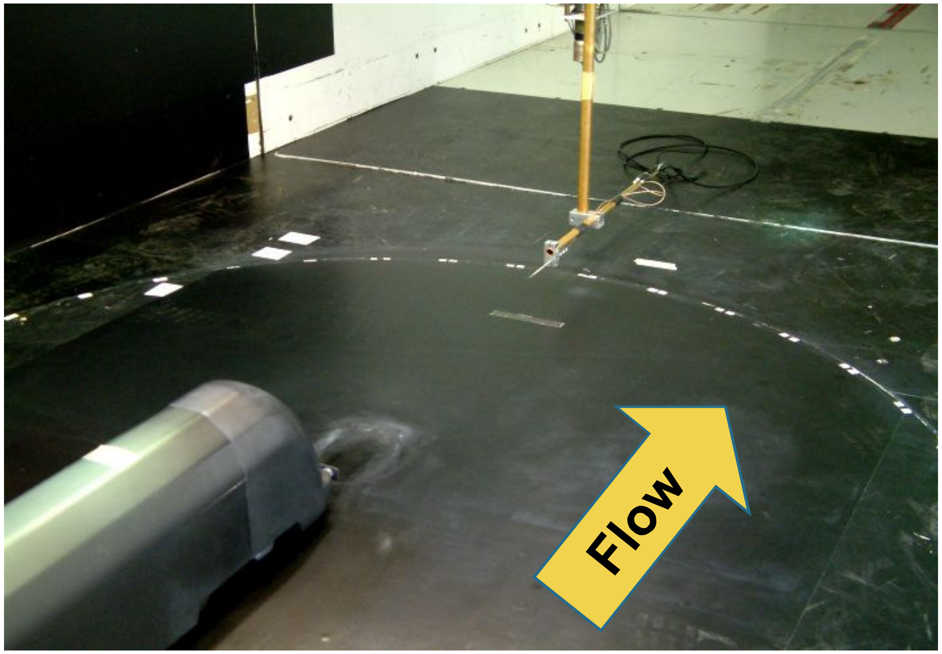
Test Setups, Applied Methods

- **Wind-tunnel setup:**
  - 2 ½ - car train set with upstream pre-body
  - X-wire probe traversed in the wake using a 2-D traverse (Y-Z-plane)
  - Oil paint and smoke visualisations





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Test Setups, Applied Methods

- **Comparison of Full Scale and Wind-Tunnel Conditions:**

	Full Scale Test	Wind-Tunnel Test
Probe Position	3 m beside Centre of Track, 1.2 m above Platform, longitudinal	14.2 m (full Scale) behind Vehicle tail (highest intensities in full scale), lateral and vertical traversing
Probe Orientation	Parallel to Ground (u+v Components)	
Ground Model	Relative Movement between Train and Ground	No moving Floor (Conveyor Belt), relative Movement not covered
Platform	Yes, 0.36m above Top of Rail	No, Flat Ground Configuration
Model Scale	1:1 real Vehicle	1:20 Model
Reynolds-Number Ref. Length l = 3m	Re = 8,900,000	Re = 250,000

Running Resistance

Topic 6

Vehicle Aerodynamics Lecture

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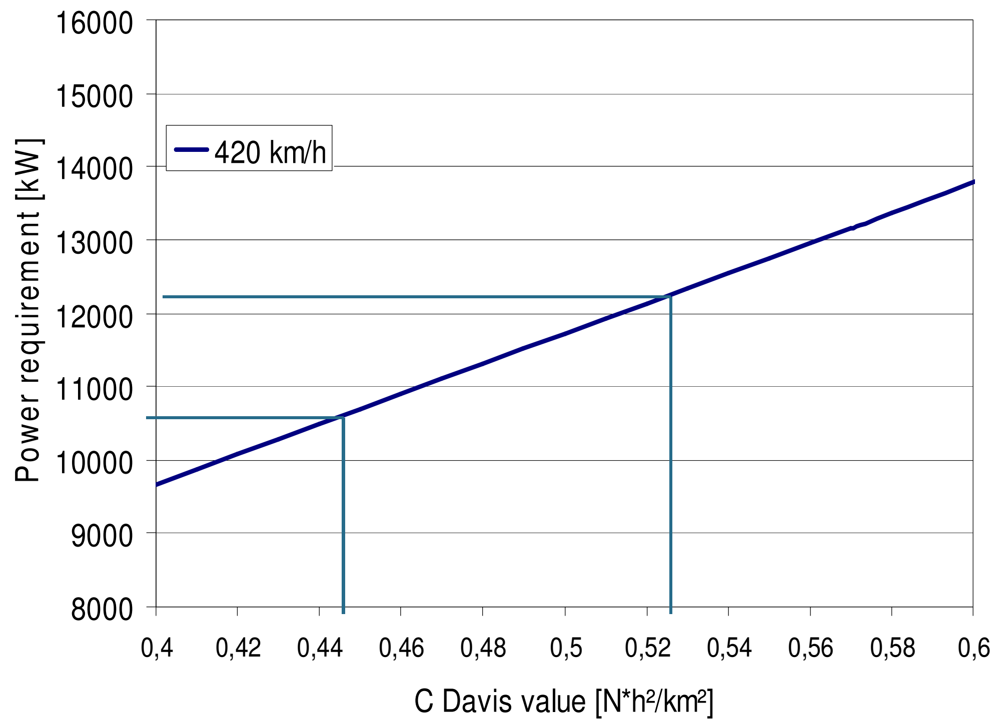
Aerodynamic Resistance - Motivation

$$P_{power\ traction} = (c_w * A * \rho/2) * v^3 + (m * a) * v$$

c_w	**aerodynamic resistance**
A	**reference area (10m²)**
ρ	**air density [kg/m³]**
v	**train velocity [m/s]**
m	**mass of train kg]**
a	**acceleration [m/s²]**

- **Installed Power**
  - The traction power is a function of the aerodynamic resistance
  - The traction power for a train should be as low as possible to reduce one off and LCC costs, weight and complexity

- **Energy Consumption - traction**
  - The energy consumption is a function of the aerodynamic resistance
  - Reducing the aerodynamic resistance of a high speed train by 20% reduces the energy consumption more or less by 10%



aerodynamic resistance

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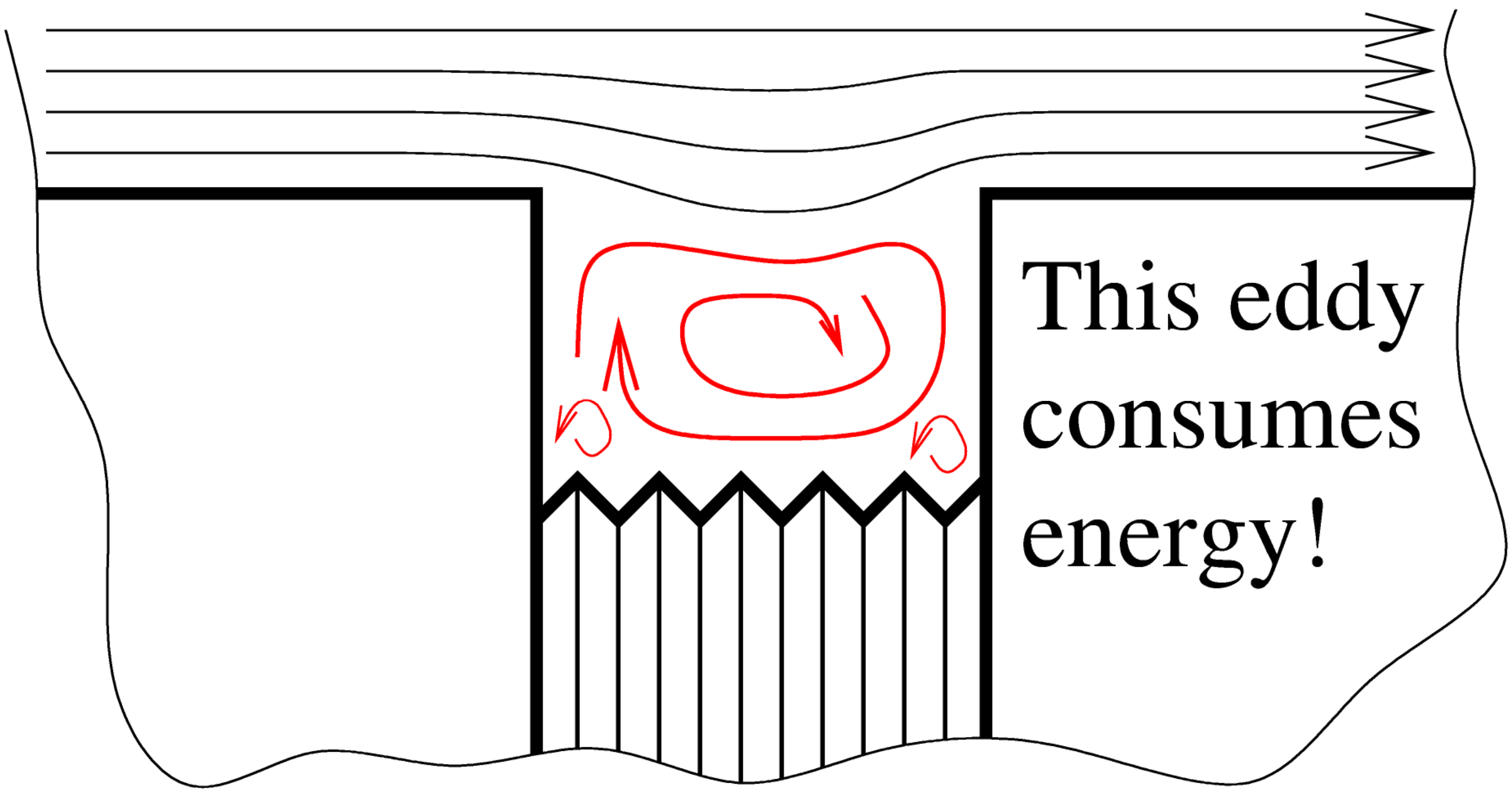
Physical background

- **Intercar gaps:**
  - A huge vortex within the gap is driven by the external flow ⇒ dissipation of energy



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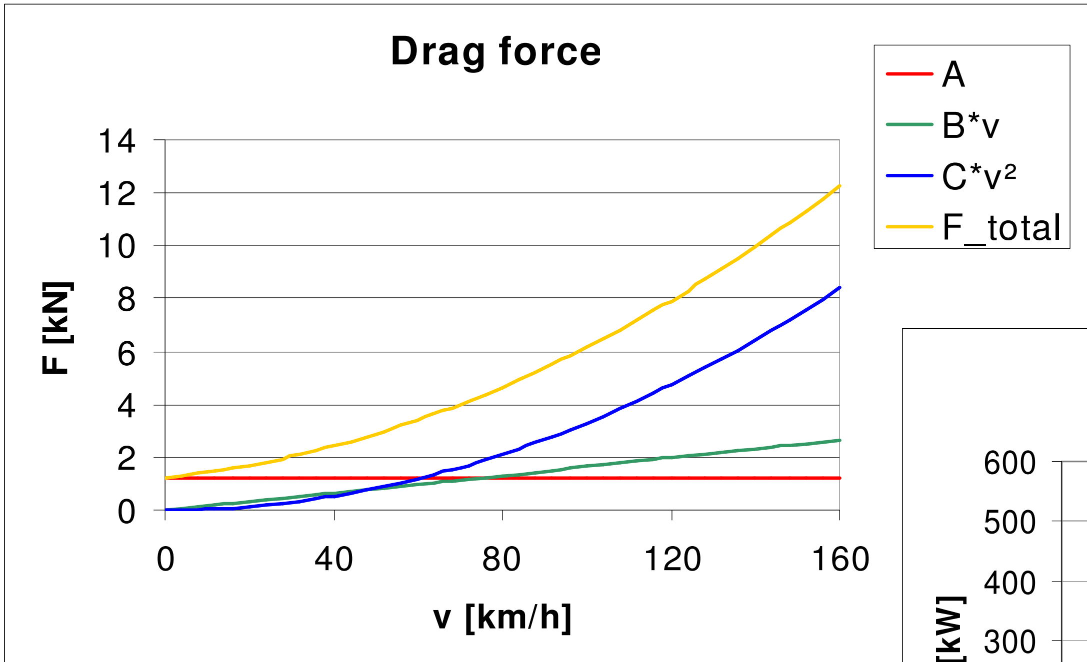
Davis Formula

$$F = F(v) = A + Bv + Cv^2$$

Parameters governing the train resistance

- **The total running resistance can be approximated by a quadratic approach, i.e. the Davis Formula F = A + B*v + C*v^2**
  - F [N] is the total running resistance in Deka Newton
  - v[km/h] is the train speed
  - A[N], B[Nh/km], C[Nh^2/km^2] are the Davis coefficients
- **The term A represents the mechanical rolling resistance.**
- **The term B is linearly dependent on the velocity and reflects the mechanical resistance and momentum losses due to air mass exchange of the train with the environment. The momentum losses are mainly associated with the power needed to accelerate the air taken in to the speed of the train.**
- **The term C represents the classical aerodynamic drag which consists of the skin friction and the pressure drag.**

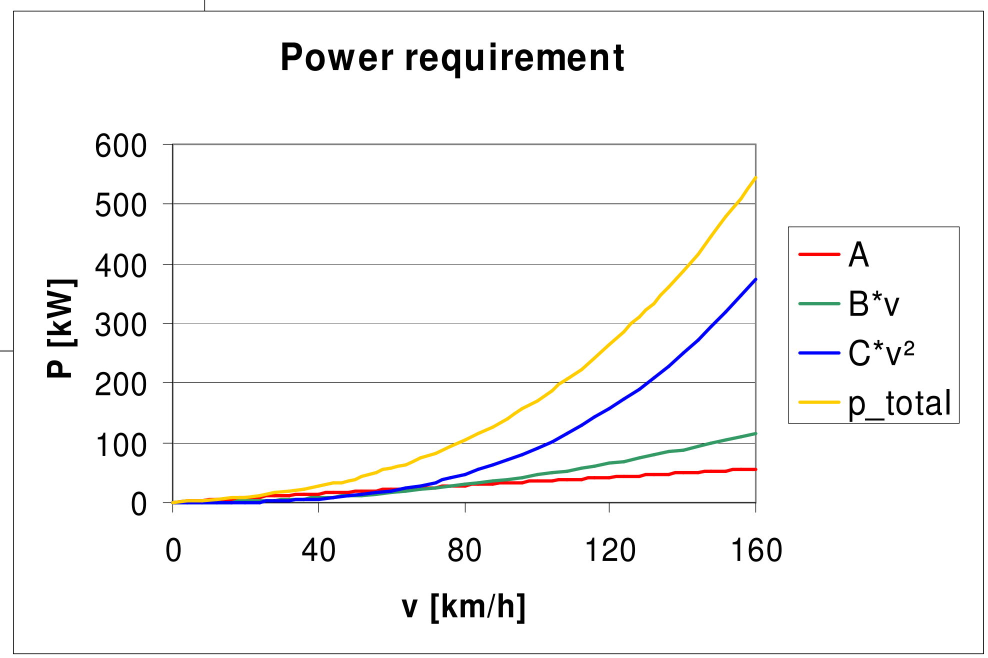
Drag contributions for a typical 3-car train



The aerodynamic contribution becomes dominant for train speeds exceeding v=60 km/h

What is the power needed?

$$P = F \cdot v$$



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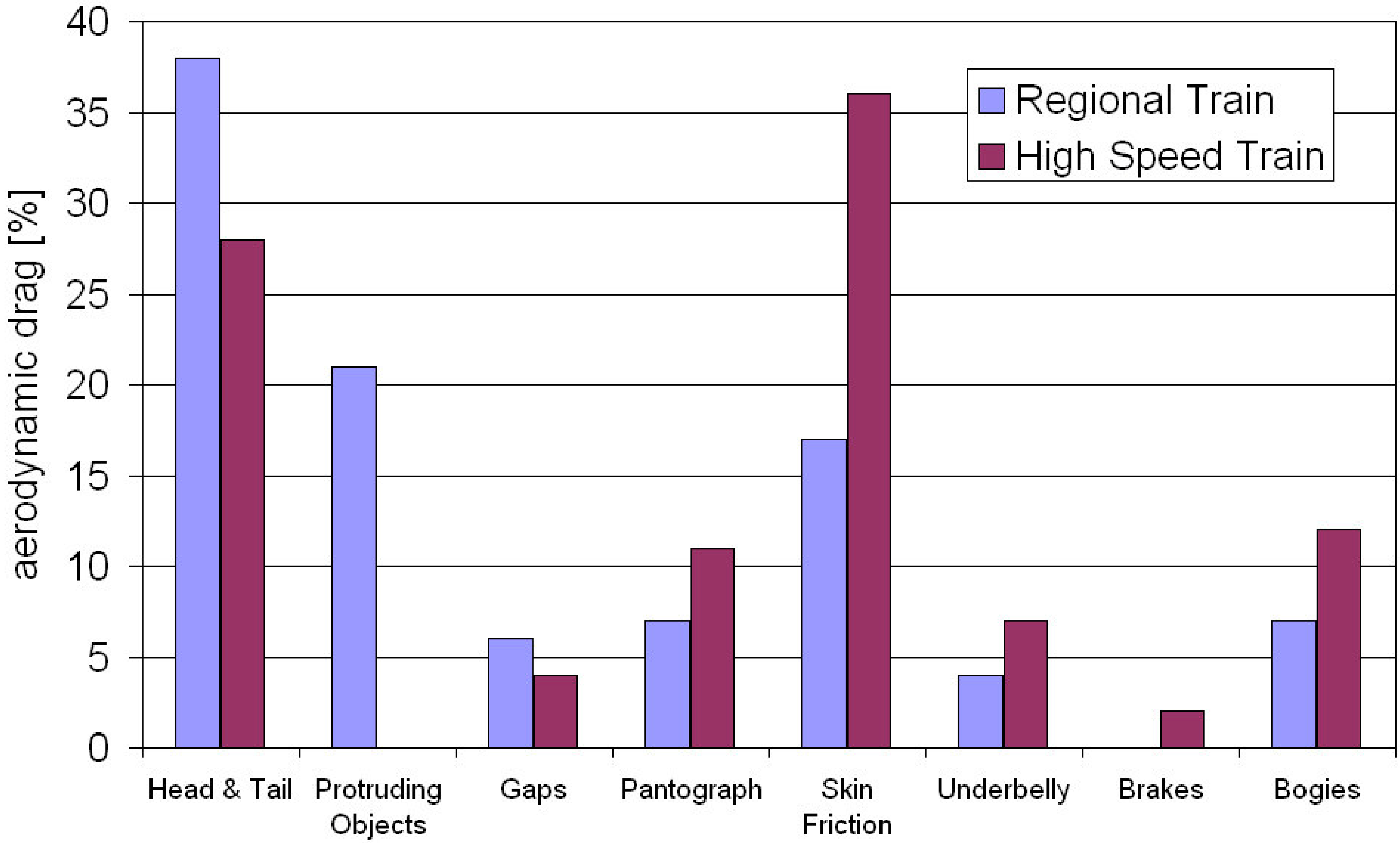
Typical Aerodynamic Drag Distribution



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Optimisation

Topic 7

Vehicle Aerodynamics Lecture

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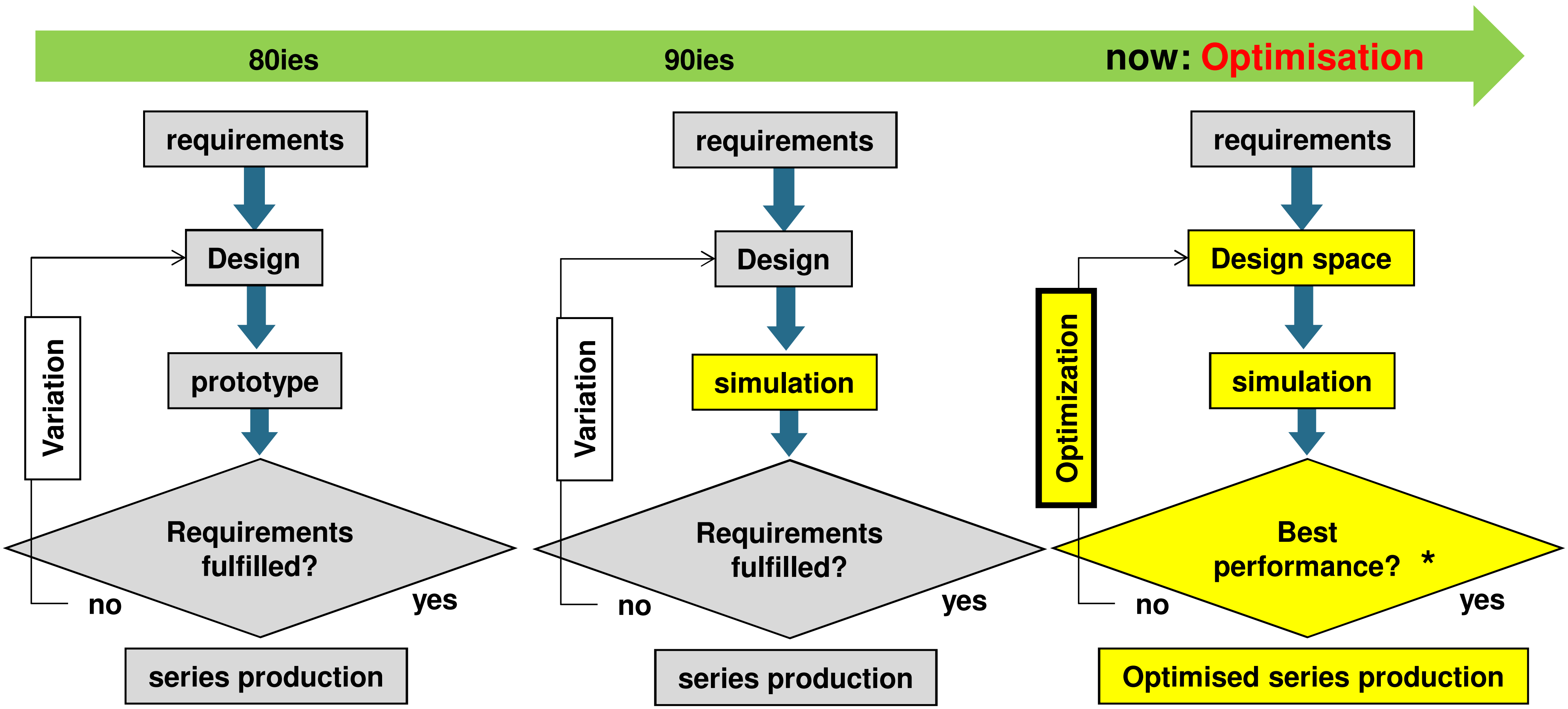
Train resistance example: ZEFIRO Very High Speed Train

- **Top Speed of 380 km/h**
- **Customer is the MOR in China**
- **Will begin service in October 2012**
- **Development in Europe / Production in China**

New Engineering Process

- **Conventional development process:**
  - Design iterations until required performance is fulfilled
  - Long lead time to solution results in expensive development
  - The conventional approach does lead to an acceptable but not best solution
- ***AeroEfficient* optimisation:**
  - Controls a parameterised model that a-priori meets all constraints
  - Automates and directs the iteration design - evaluation
  - Delivers best performance on pre-selected objectives with given constraints

New Engineering Process, contd.



* with given boundaries and costs

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Validation of the CFD Simulation Model

- **Wind tunnel Experiment**
  - Aerodynamic drag = 0.425
- **CFD simulation with 289 million vertices**
  - Aerodynamic drag = 0.430
- **Error is only around 1%**
  - The resulting difference of 1% is smaller then the error of the experiment

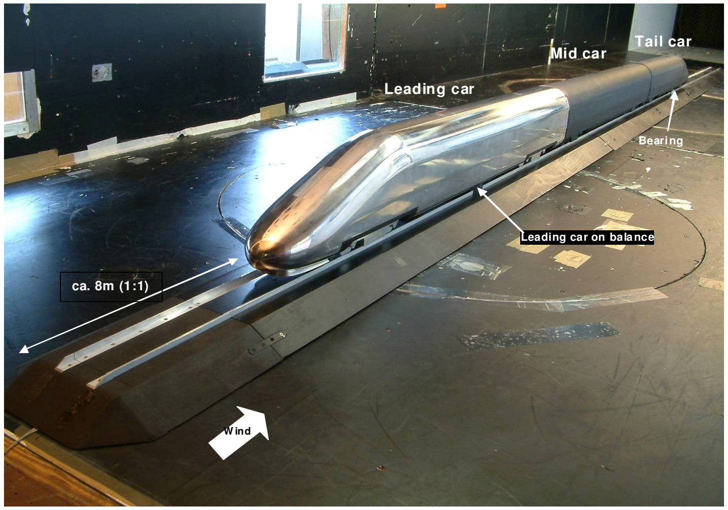
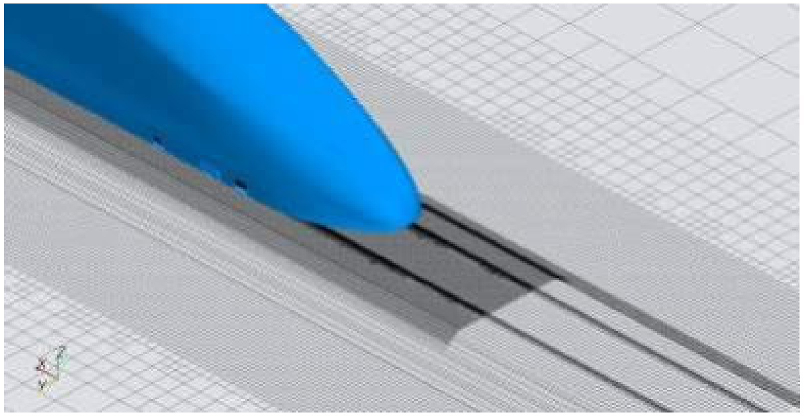


Figure 1, general view of drag measurement, first car on external balance, trailing cars coupled and supported on low friction steel wheels



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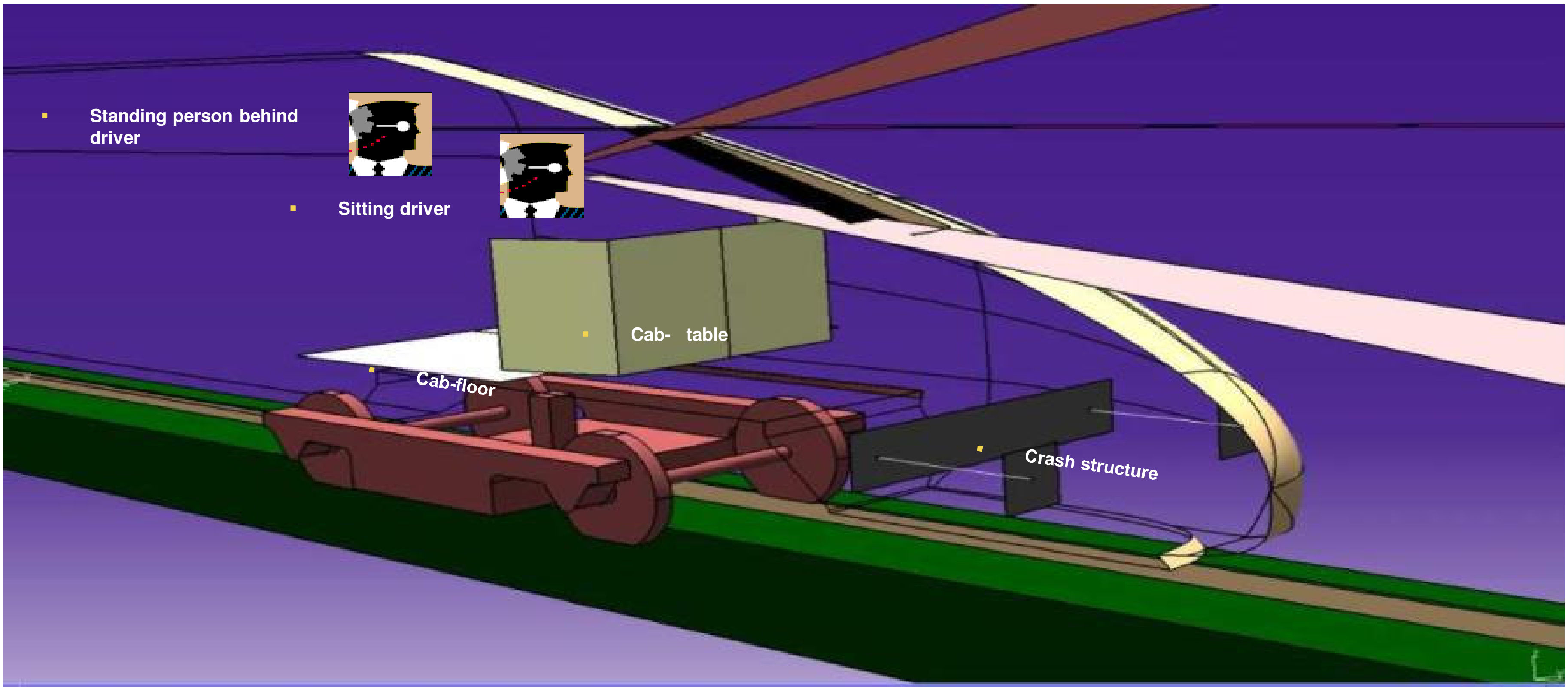
Optimisation Process

- **CAD – parameterise model**
  - Digital 3D representation of the model (also used for windtunnel experiments)
  - CATIA V5 for explicit parameterization of the model
- **CFD – evaluate objective**
  - Prepares the model for evaluation
  - Determines aerodynamics characteristics of the model
  - High computational costs
  - Accurate evaluation may take up to several days
- **Optimiser – suggest new design**
  - ModeFrontier – optimisation Software
  - Drives whole process with scripting

Optimisation Constraints

- Integration of the crash structure, brake resistors, pantographs and HVAC
- Compliance with the predefined enveloping profile
- Size and position of the windscreen to facilitate certain view angles



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The design variables

- **15 of 60 possible parameters were chosen to be optimised**

	Parameter	Description
1	**chamfer**	chamfering the edges of the bogie cut-out
2	**intercar_gaps**	height of the gap between the wagons
3	**nose_shrinking**	distance to maximal permissible nose length
4	**blunt_nosetip_down**	bluntness of the nose (side view)
5	**less_uppity**	controls how strong the nose front is directed to the ground
6	**blunt_nose_horizontal**	bluntness of the nose (top view)
7	**bluff_frontpart**	controls the inclination of the profile at the transition between nose and car body. A high value results in a bluff frontpart.
8	**nosetip_height**	vertical position of the nosetip
9	**skirt_reduction**	relative size of the skirts at the bogies
10	**spoiler_inclination**	inclination of the spoiler
11	**spoiler_nose_distance**	distance between nose tip and spoiler
12	**nose_start**	point of the transition between car body and nose, the lower the value the more space the nose actually occupies
13	**A-pillar_roundness**	roundness of the A-pillar, defined at the nose tip
14	**step_height**	height of the separation step
15	**roof_edginess**	curvature of upper edge of the wagon, also affects the A-pillar

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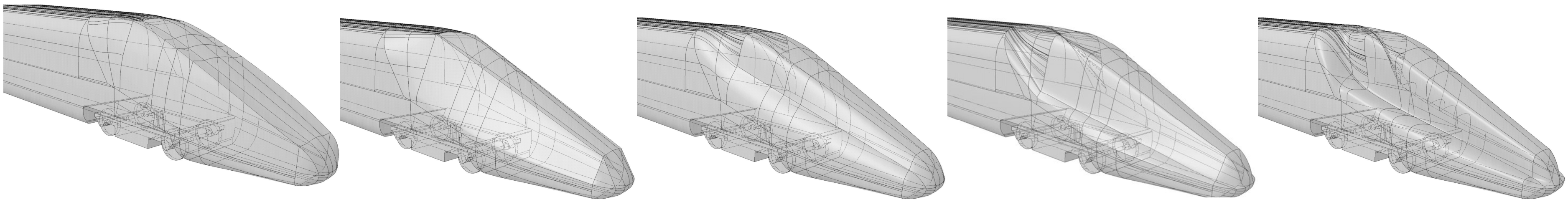
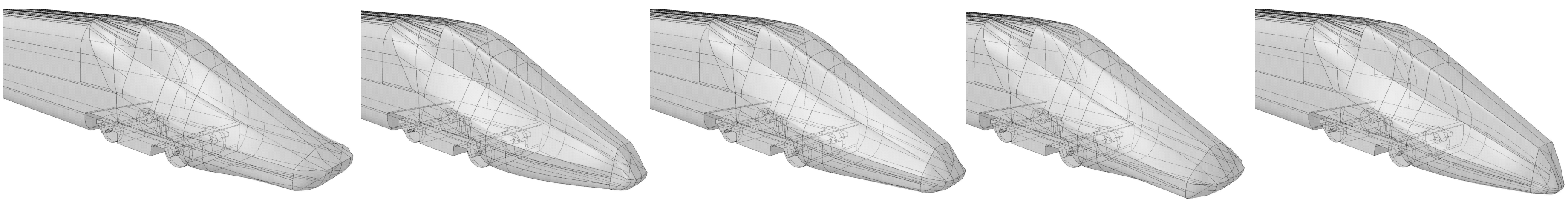
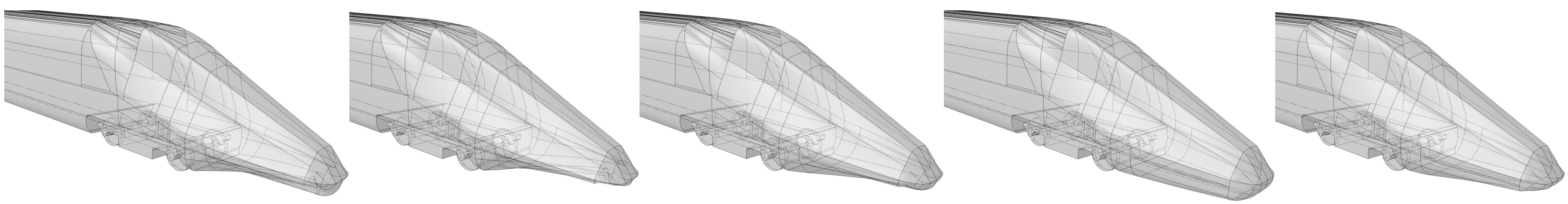
Examples for Model Variability (3 parameters out of 60)



A pillar edge



flatness of nose

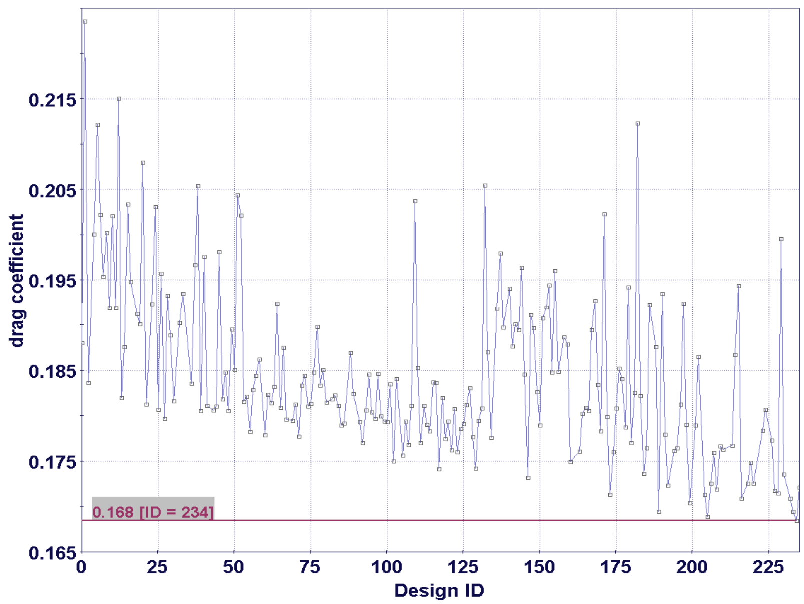


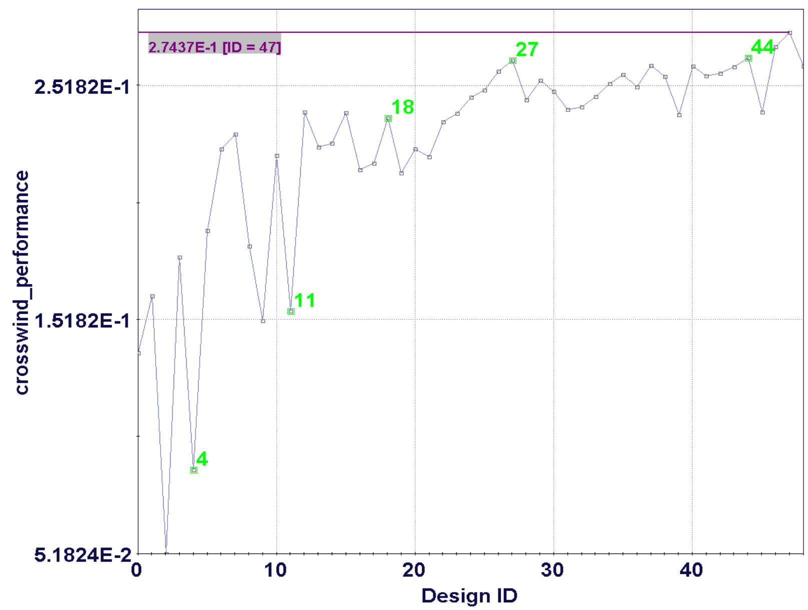
undercarriage keel

Single Objective Optimisation History

- **Drag**
  - 234 iterations
  - Drag reduction of ~ 25 %

- **Cross-wind**
  - – Best cross-wind design does not correspond with best drag design





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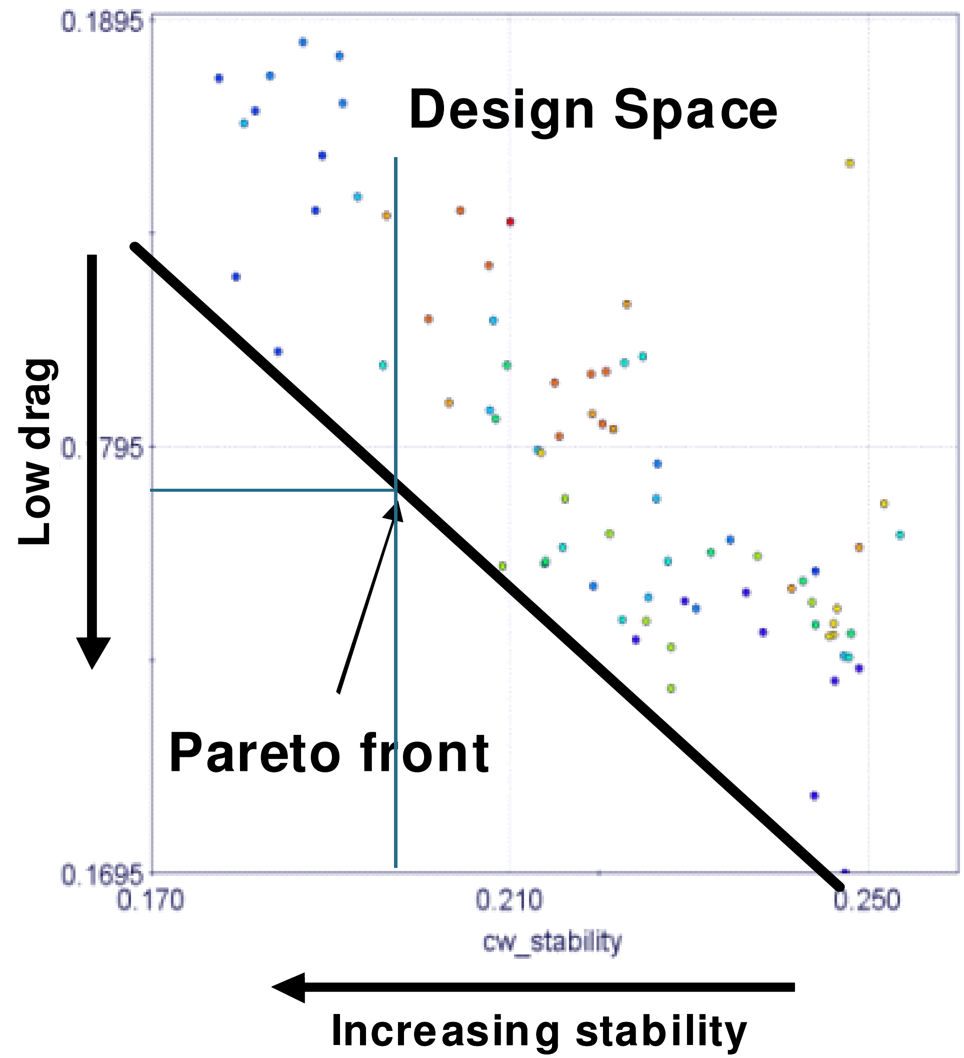
Multi-Objective Optimisation

- **Multi-objective optimization means**
  - Significant rise of the number of iterations
  - Directed search algorithms like SIMPLEX or gradient methods are not applicable
  - Generic algorithms are suitable
  - Result is a cluster of pareto-optimal designs, but no unique solution
  - ~ 173 * 7 h * 7 CPUs = 8477 CPU hours



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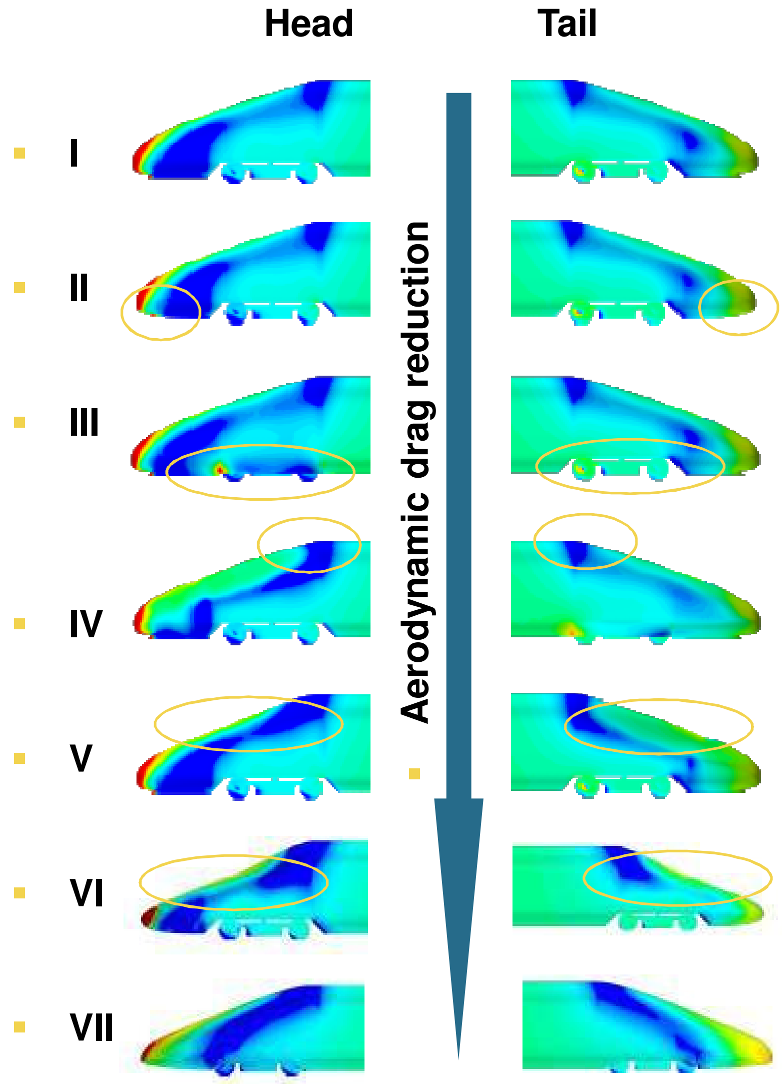
High Performance Computation - Example

- **Examples of variations in detailed design phase (pressure on surface is shown):**

  - I → II: spoiler variation
  - I → III: bogie fairings
  - I → IV: carbody front transition
  - I → V: more slender nose
  - I → VI: duck nose
  - VII: ZEFIRO China Design



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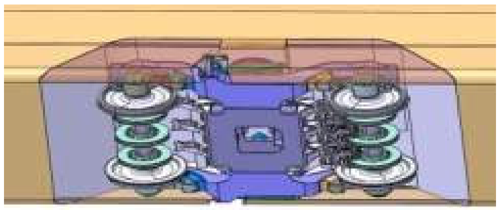
Superior Aerodynamic Resistance – Key Elements
Details of optimisation

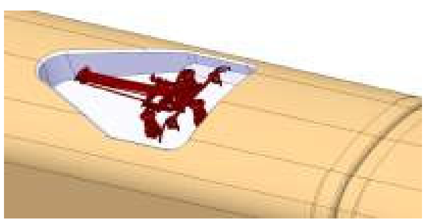
- Bogie skirts
- Aerodynamic optimized bogie design



Front / tail optimization with genetic algorithms

Minimized Protruding objects at the roof

- Low resistance pantograph integration
- High voltage equipment in one box aligned with the carbody



Inter car gap is minimized

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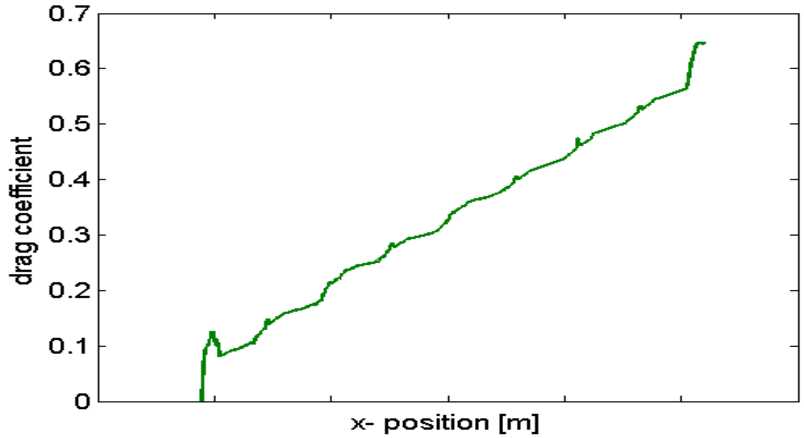
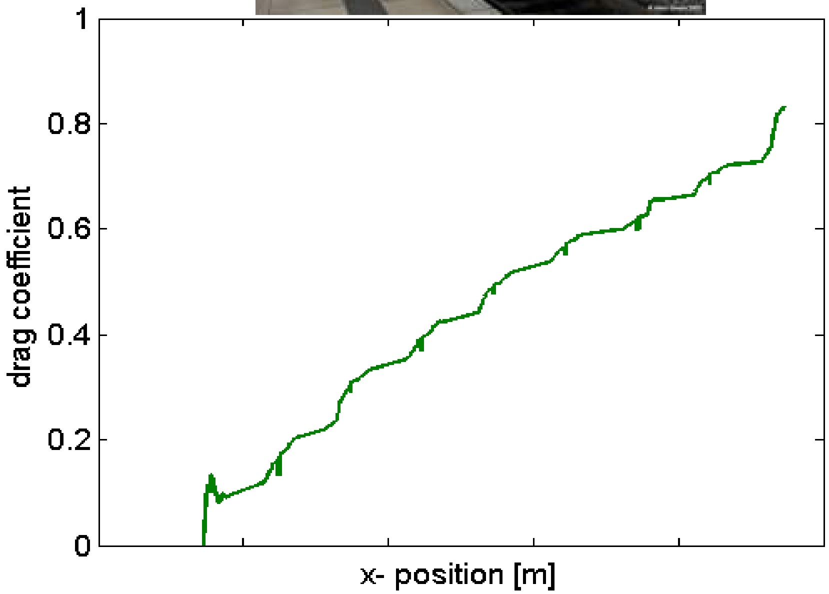
Comparison of ZEFIRO 380 with ICE3

Simulation of both trains with same setup





ZEFIRO 380 exhibits around 20% lower drag compared to ICE3 despite the fact that ZEFIRO 380 exhibits a considerably higher and wider cross section

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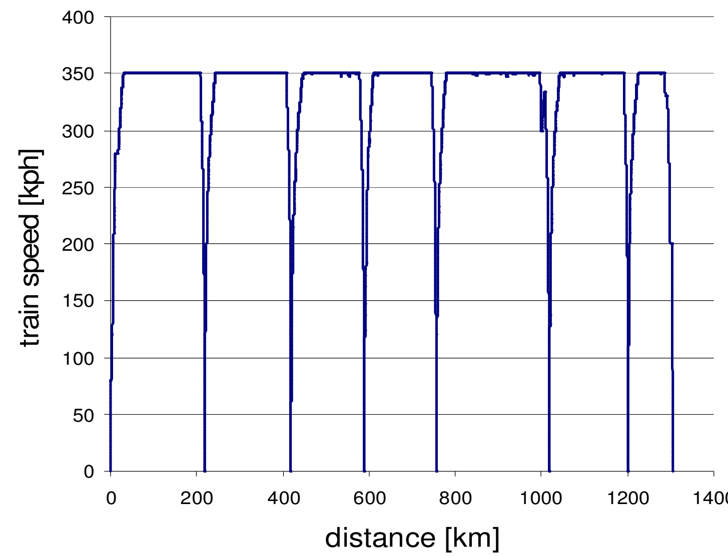
Beijing – Shanghai Line – Impact of *AeroEfficient*

- **The line Beijing – Shanghai has been taken to calculate the energy consumption**
- **The eco 4 technology "AeroEfficient Shape Optimisation" has been used to determine the shape of the train**
- **The time table and the speed profile below has been used for the investigation**

Station	Position	Run Time	Stop Time	Total Time	Avg Speed
	[km]	[h:m:s]	[h:m:s]	[h:m:s]	[km/h]
--					
South BeiJing	0.00	00:00:00	00:00:00	00:00:00	0.0
West CangZhou	219.20	00:42:22	00:01:00	00:43:22	310.4
West passenger station JiNan	419.40	00:37:50	00:01:00	01:22:12	317.5
East TengZhou	589.13	00:32:46	00:01:00	01:55:58	310.8
East SuZhou	756.43	00:32:15	00:01:00	02:29:13	311.2
South NanJing	1018.55	00:48:40	00:01:00	03:18:53	323.2
East WuXi	1201.15	00:34:49	00:01:00	03:54:42	314.7
Shanghai	1305.07	00:21:51	00:00:00	04:16:33	285.4



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9% Traction Energy Reduction with *AeroEfficient* Technology for ZEFIRO 380 for China

AeroEfficient Impact	without AeroEfficient [kWh]	with AeroEfficient [kWh]
Motoring energy at rail	29.670.000	27.320.000
Braking energy at rail	4.327.000	4.400.000
Regenerated energy to line	2.583.000	2.637.000

- **The ZEFIRO 380 for China will exhibit the best possible shape related to minimised aerodynamic resistance**
- **The ZEFIRO saves around 9 % of traction energy compared to current high speed train design**
- **This world class aerodynamic performance has been achieved by genetic algorithms**

High Competitiveness with Performance Engineering

Products developed with new approach

ZEFIRO 380 for MOR:
High-end aerodynamics convinced the Ministry of Rail (MOR)

TWINDEXX for SBB:
Crosss-wind stable light-weight high speed double decker

Icx for DB:
Bombardier is responsible for Aerodynamics → highest cross-wind stability facilitate light-weight end-car

V300ZEFIRO for Trenitalia:
Fulfills all TSI requirements with lowest energy consumption due to reduced resistance

Régio2N for SNCF:
Crosss-wind stable light-weight high performance double decker

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Quiz

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Drag: which head is the best / which one is the worst ??

- reference

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Drag: which head is the best / which one is the worst ??

- Head: -1%
- Tail: -8%

worst

best

- Head: 0%
- Tail: -22%

best tail

- Head: -2%
- Tail: -14%

- Head: -4%
- Tail: -14%

best head

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Contact

Bombardier

Alexander Orellano

Director, Center of Competence for Aerodynamics & Thermodynamics

Am Rathenaupark

16761 Hennigsdorf

Germany

alexander.orellano@de.transport.bombardier.com

Thank you for your attention!!