Aerodynamics of High Speed Trains

Vehicle Aerodynamics Lecture

Stockholm, KTH, May 12th 2010

Dr. Alexander Orellano

Manager, Centre of Competence for Aerodynamics & Thermodynamics

BOMBARDIER

Bombardier – Fields of Activity

Aerospace
Employees: 28,100*

Transportation
Employees: 31,485*

*As at January 31, 2008

Bombardier Transportation - Products

Light Rail Vehicles

***FLEXITY* Outlook**
(Bruxelles, Belgium)

***FLEXITY* Classic**
(Dresden, Germany)

Metros

C20
(Stockholm, Sweden)

MOVIA
(Shanghai, China)

Regional Trains

EMU *SPACIUM* 3.O6
(Paris, France)

***TALENT* 2**
(Germany)

Intercity / High-speed Trains

***TURBOSTAR* DMU**
(UK)

ZEFIRO

Locomotives

***TRAXX* P160 AC**
(Deutsche Bahn, Germany)

***TRAXX* F140 DC**
(RENFE, Spain)

Total Transit Systems

***CX-100* Beijing Airport** (China)

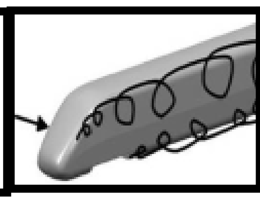
Gautrain
(South Africa)

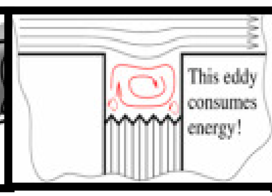
Lecture Topics

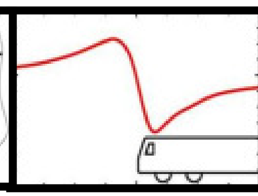
Cross-Wind Stability **Head pressure pulse** **Tunnel Aerodynamics**

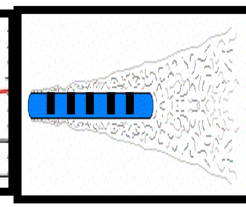
Basics **Running Resistance** **Slip stream** **Optimisation**

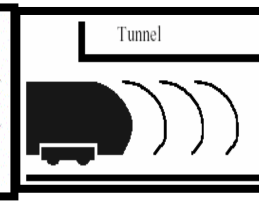
$$\frac{\partial^2\varphi}{\partial x^2}+\frac{\partial^2\varphi}{\partial y^2}+\frac{\partial^2\varphi}{\partial z^2}=0$$

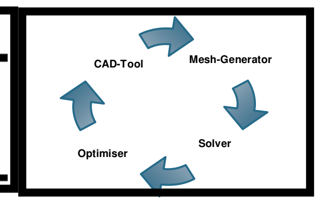












Basics in Aerodynamics

Topic 1

Vehicle Aerodynamics Lecture

BOMBARDIER

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

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

Re >> 1 → Euler equation $\rho\frac{\partial u}{\partial t}+\rho u\frac{\partial u}{\partial x}+\rho v\frac{\partial u}{\partial y}+\rho w\frac{\partial u}{\partial z}=-\frac{\partial p}{\partial x}$

BOMBARDIER

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

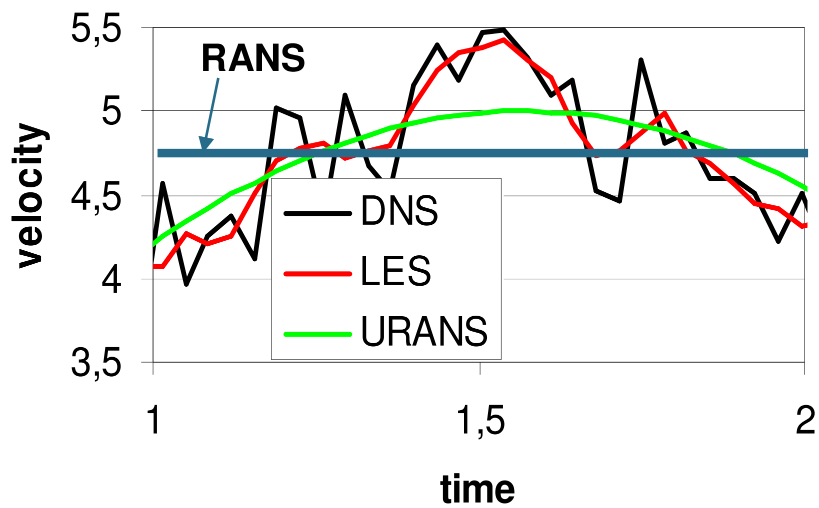
$$\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} + \frac{\partial^2 \varphi}{\partial z^2} = 0$$

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

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

BOMBARDIER

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

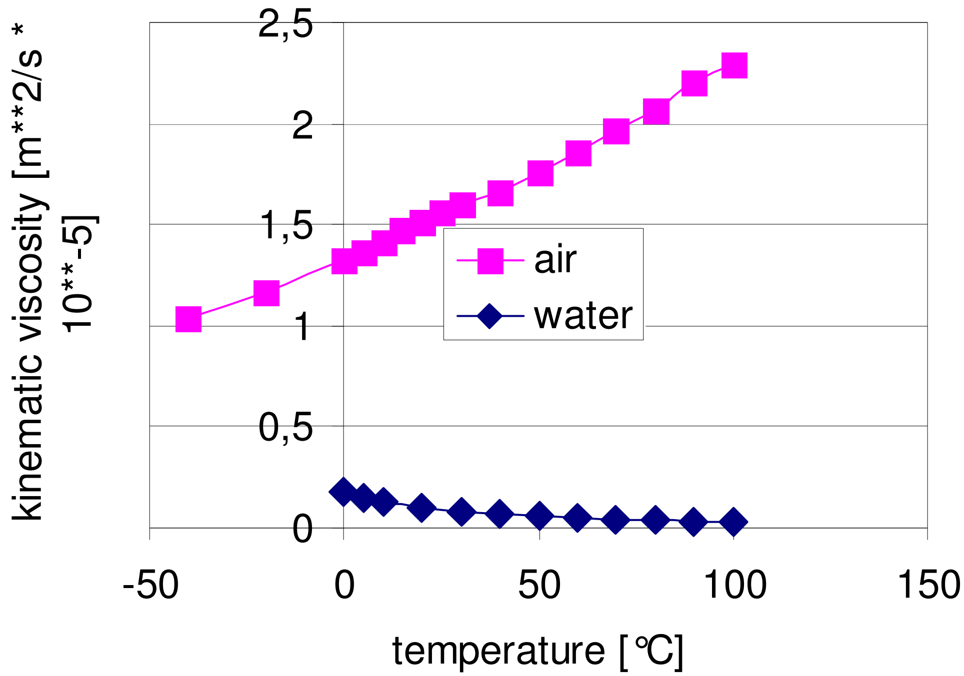
BOMBARDIER

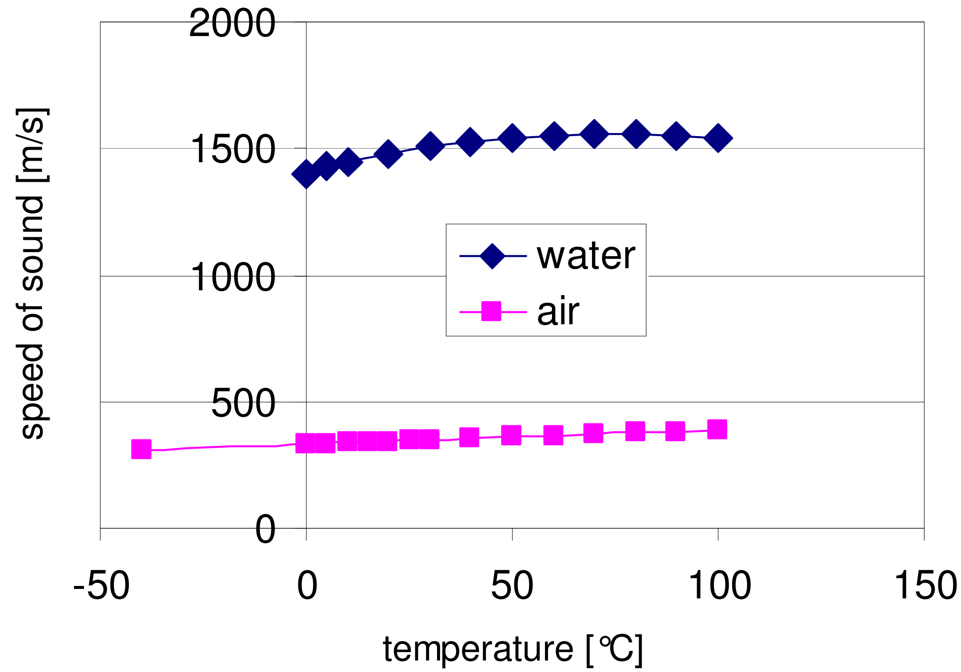
Most common Turbulence Modelling – Eddy Viscosity

- **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.

BOMBARDIER

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

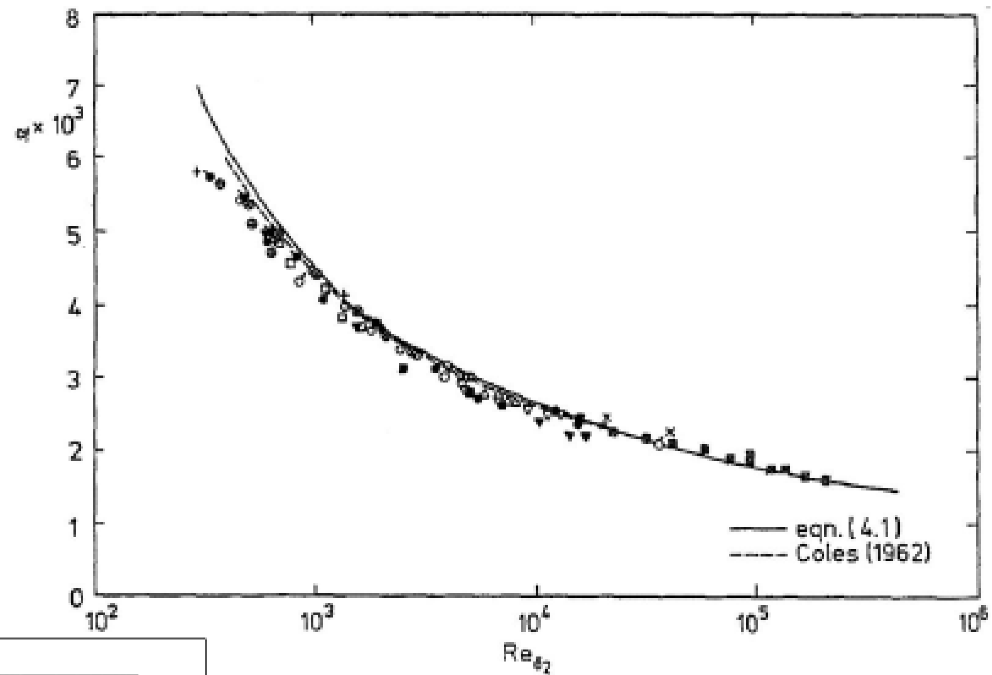
Scaled Experiments

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

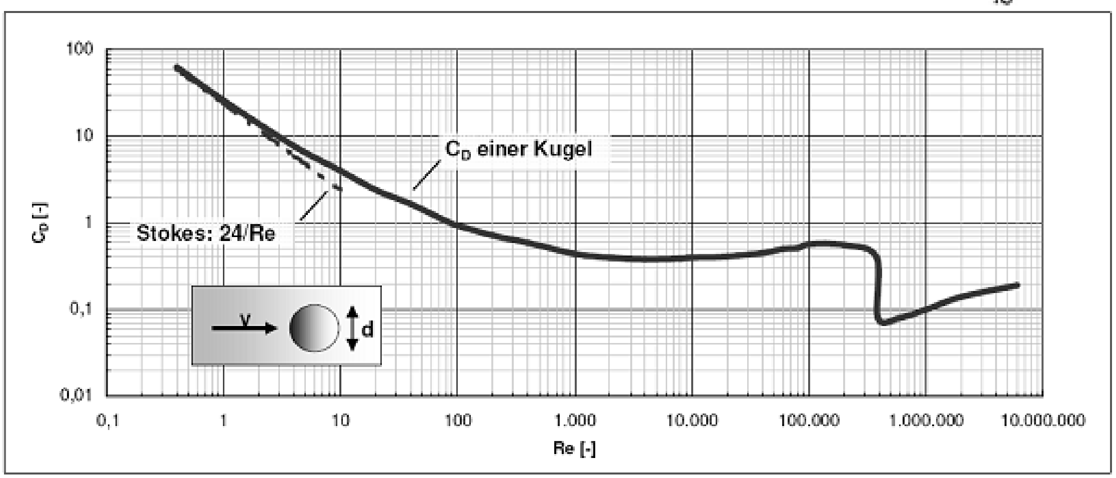
- **Compromises in experiments**
  - What about Reynolds Independency?
  - What about low Compressibility?
  - What about Geometrical simplification?

Reynolds Number Dependency

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



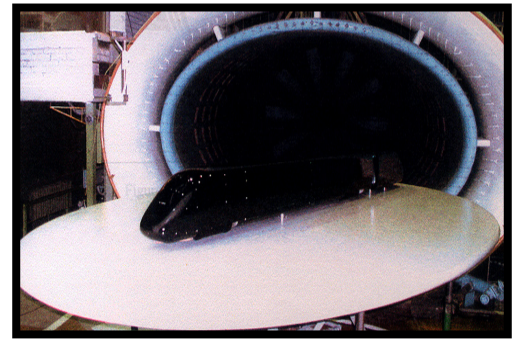
Fernholz and Finley 1996



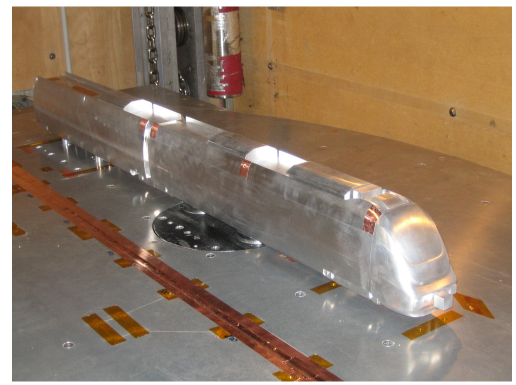
BOMBARDIER

How to get high Reynolds Number in Wind Tunnels?

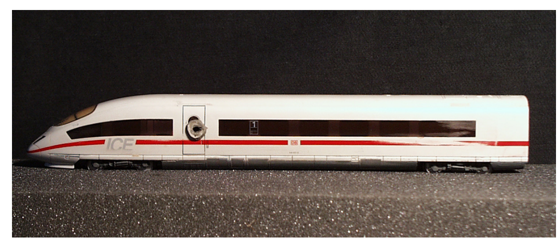
- **Big Models (Low Reynolds Number Wind tunnel, e.g. Audi up to 100 m/s)**



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

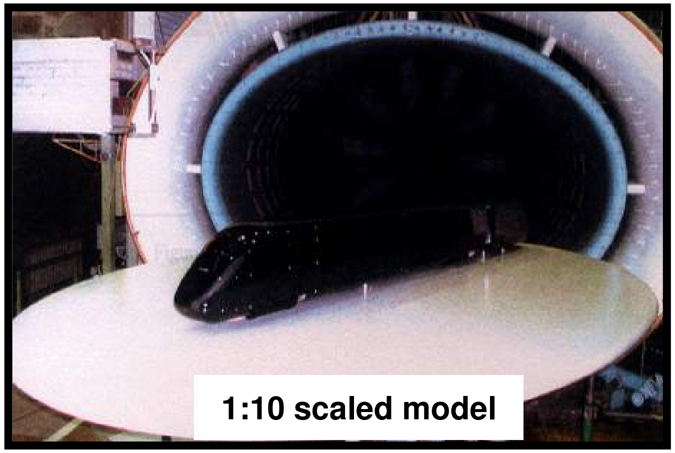


- **High Pressure (e.g. up to 100 Bar in HDG Göttingen)**



Scaled Model Testing

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



1:10 scaled model

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

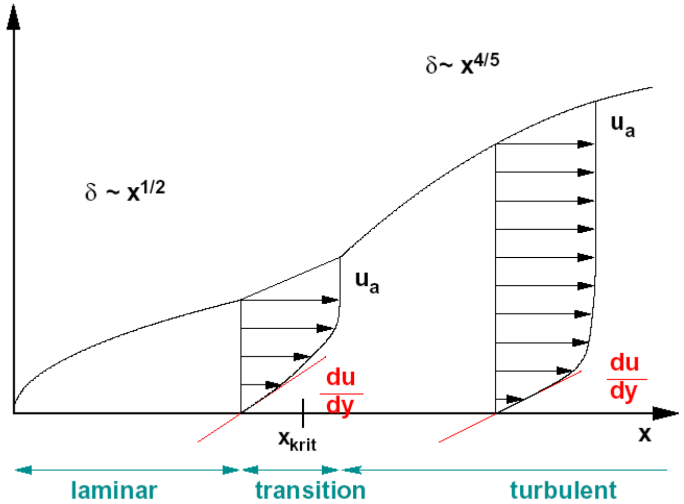
Ma = 0.23

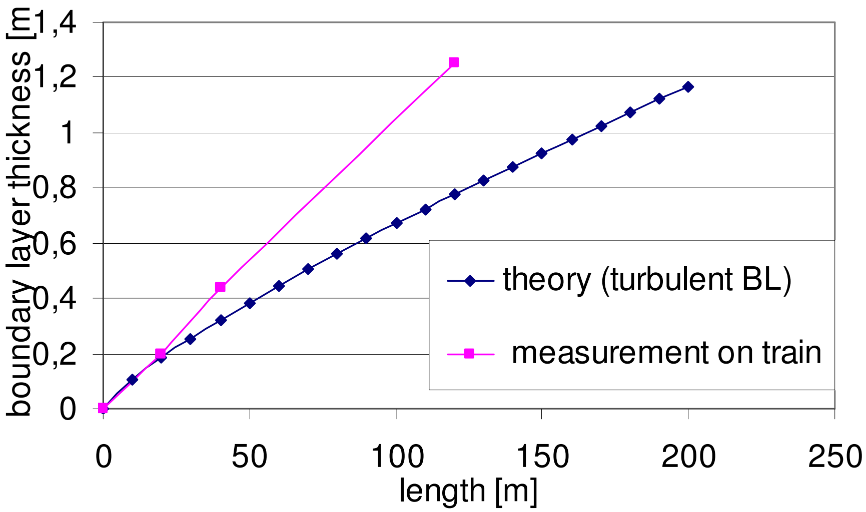
Do we have a problem now with Re?

Turbulent Boundary Layer Development

Approximation out of experiments

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





IER

Head Pressure Pulse

Topic 2

Vehicle Aerodynamics Lecture

BOMBARDIER

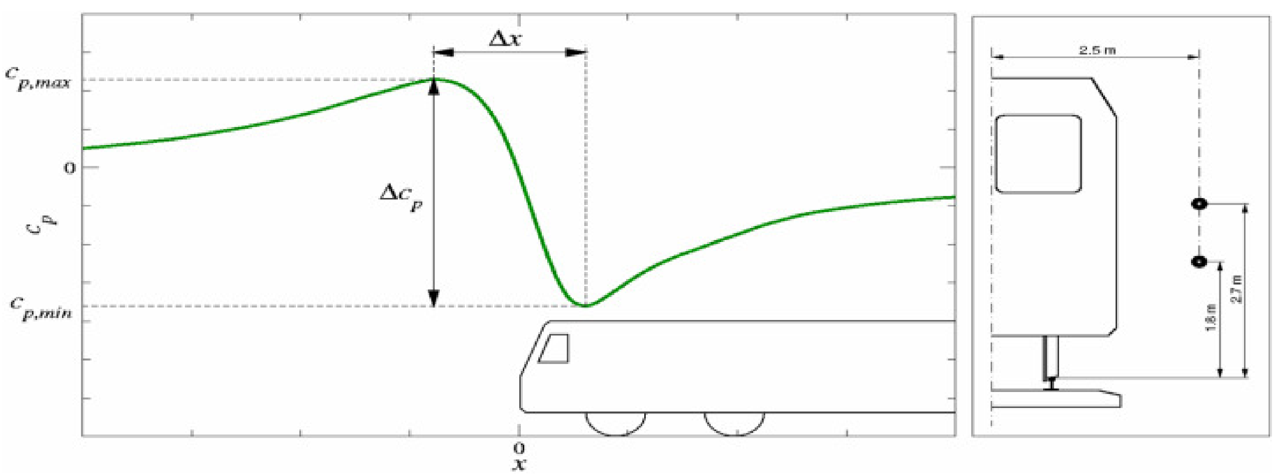
Head Pressure Pulse Problem

- 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 ⇒ slip stream effect
- Biggest pressure changes are associated with the passing of the train head ⇒ 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 ⇒ threshold values defined by reference vehicles

BOMBARDIER

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.



BOMBARDIER

Head Pressure Pulse Assessment

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

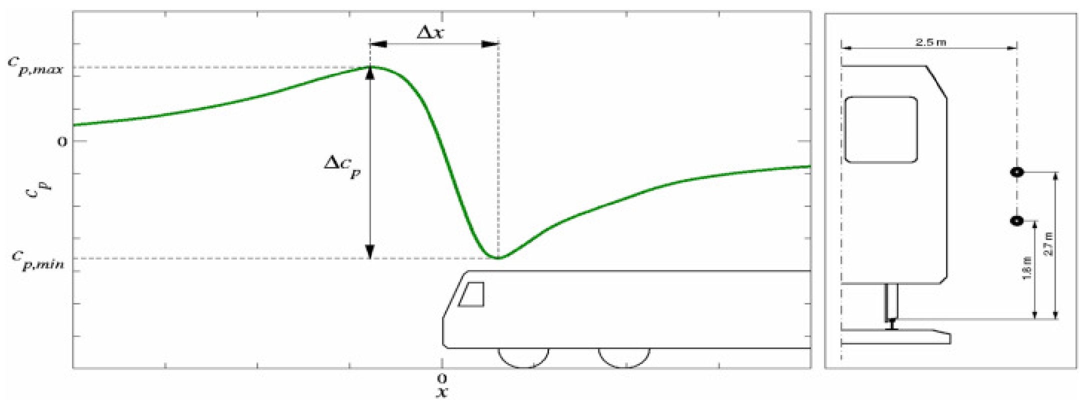
$$c_p = \frac{p - p_0}{q} \quad \text{with the dynamic pressure:} \quad q = \frac{1}{2}\rho v^2$$

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

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

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

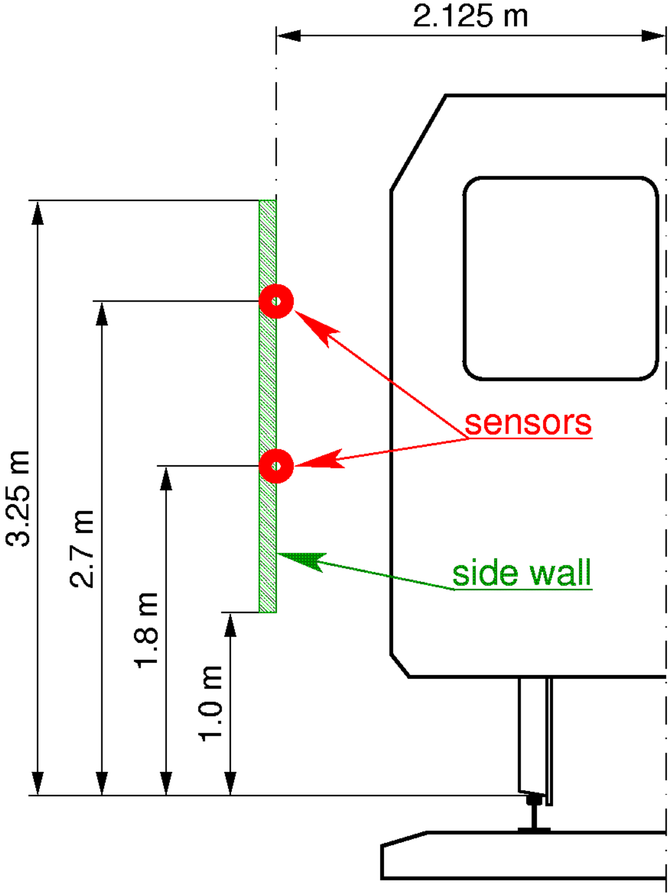
as shown in the following figure ...



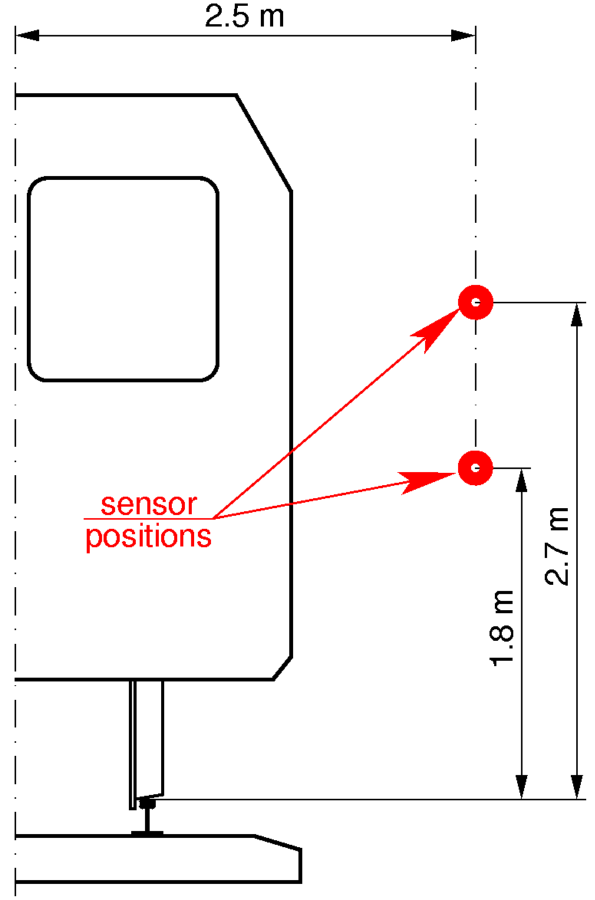
BOMBARDIER

Test Setups used throughout Europe

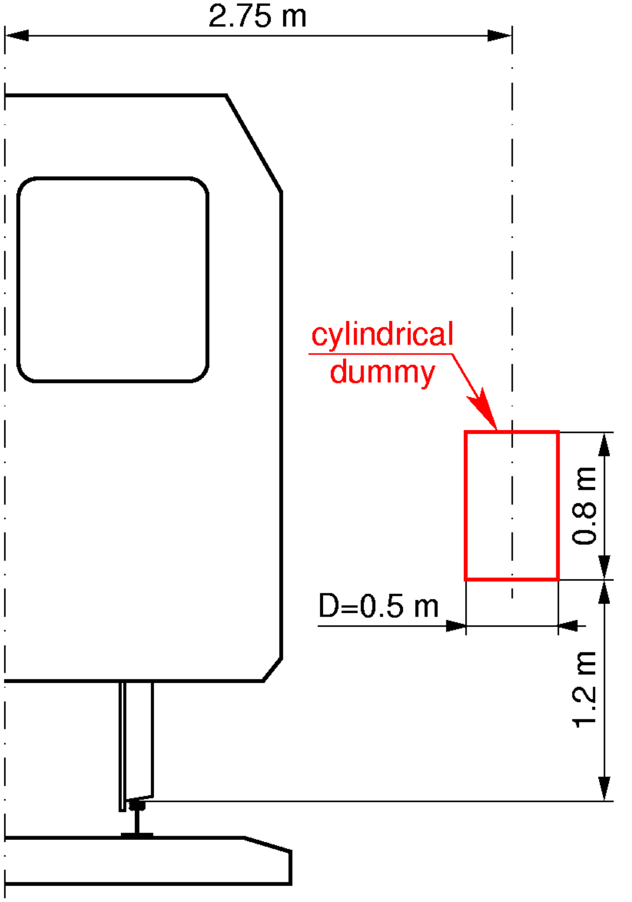
Cruise along side wall



Cruise in open field



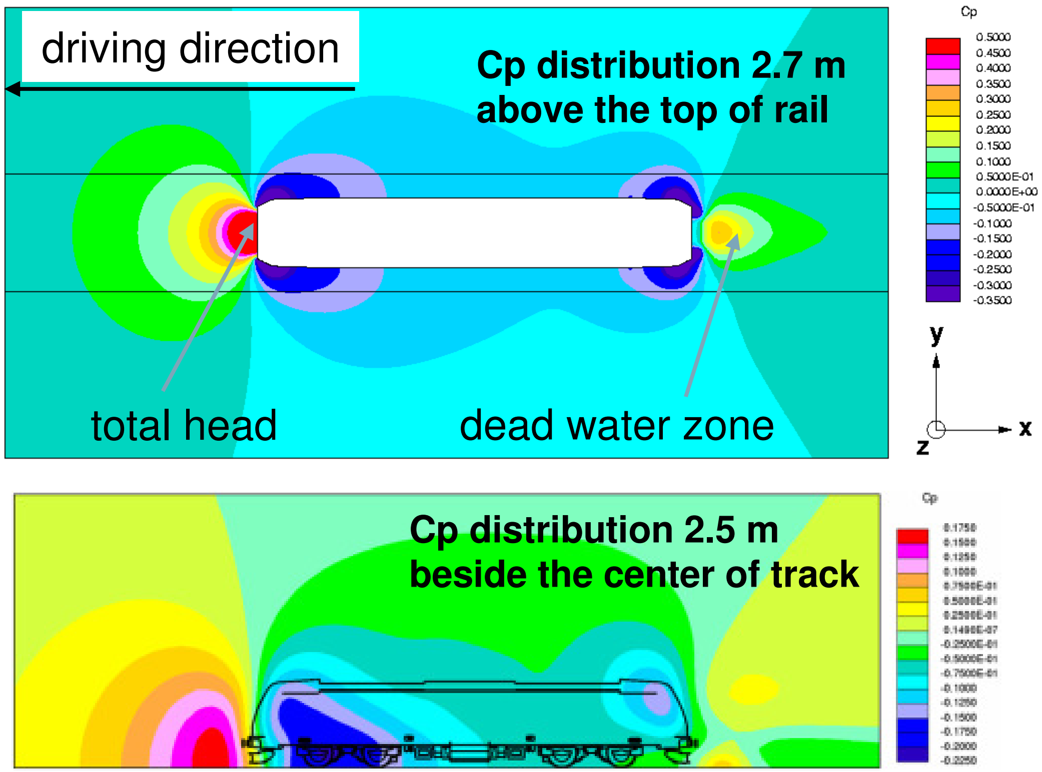
Forces on dummy



BOMBARDIER

Head Pressure Pulse - Prediction

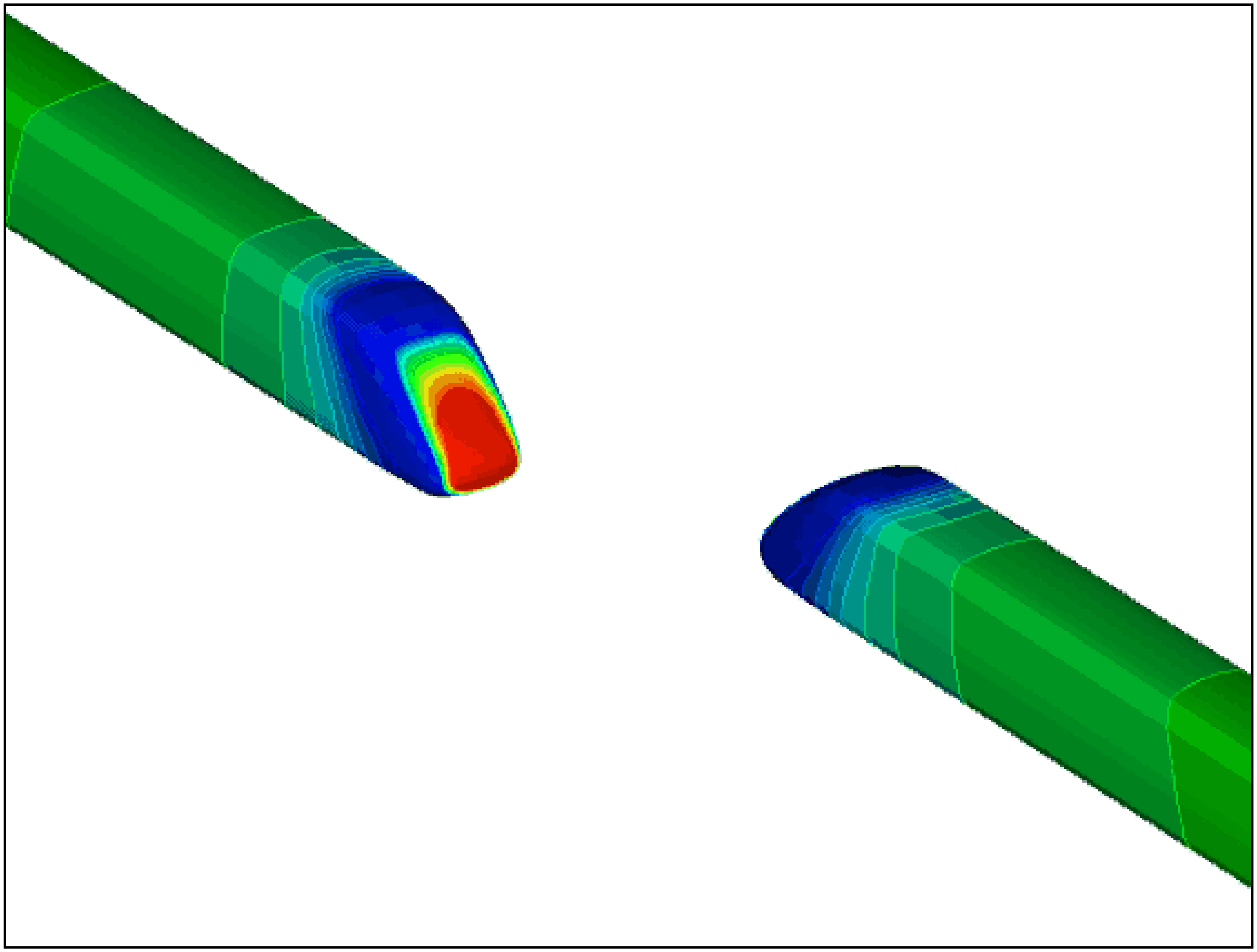
- The three-dimensional, high Reynolds number turbulent flow around a vehicle is usually characterised by the following: deceleration and acceleration, curved boundaries, separation, possible reattachment, recirculation and swirling properties. In general, sufficiently accurate solutions may be achieved 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

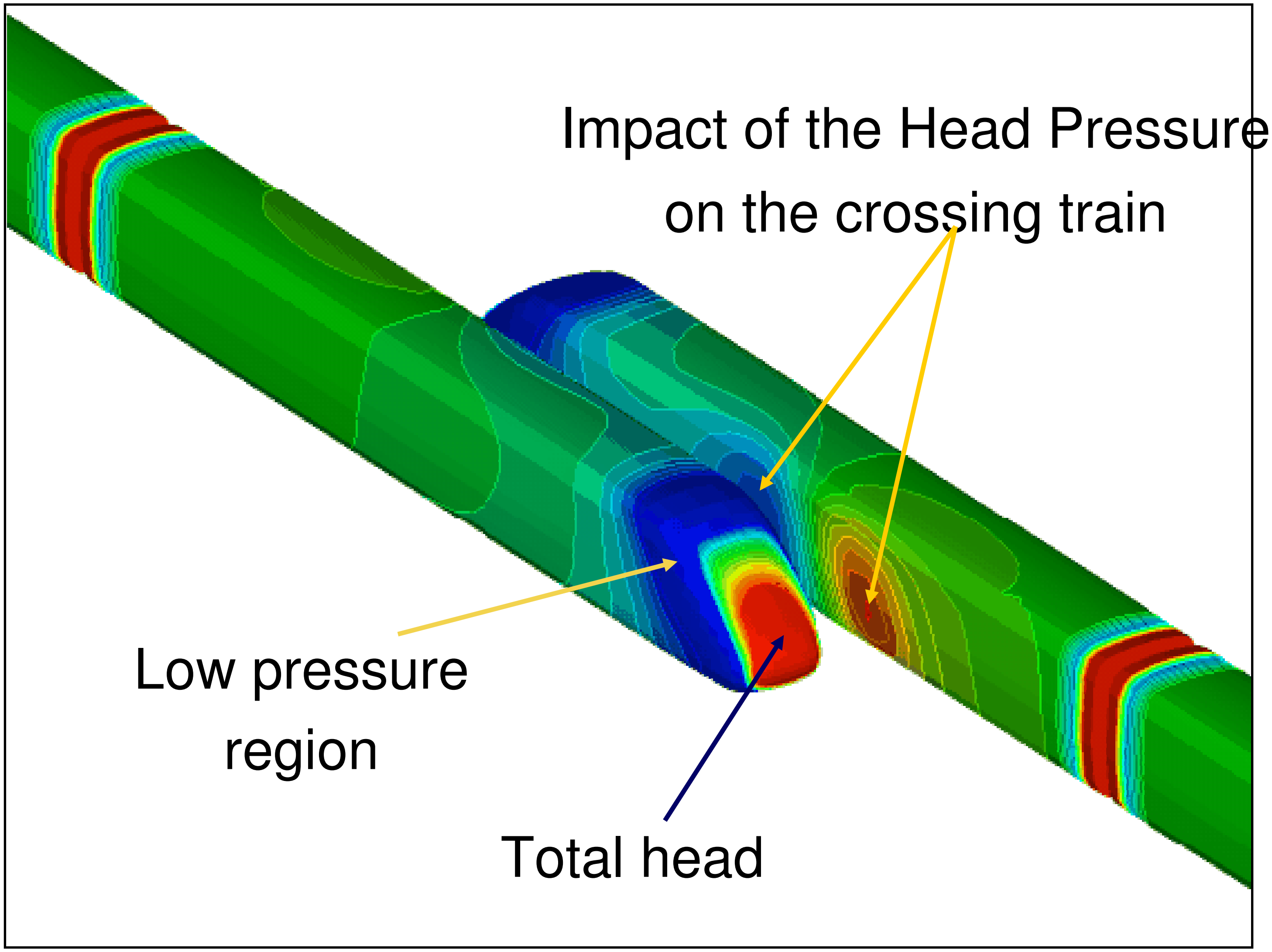
BOMBARDIER

Head Pressure Pulse Impact on Trains Crossing



BOMBARDIER

Head Pressure Pulse Impact on Trains crossing



BOMBARDIER

Tunnel Aerodynamics

Topic 3

Vehicle Aerodynamics Lecture

BOMBARDIER

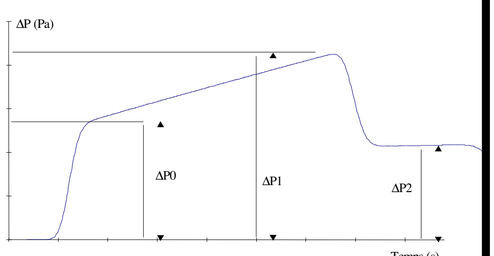
Tunnel Aerodynamics – Requirements

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

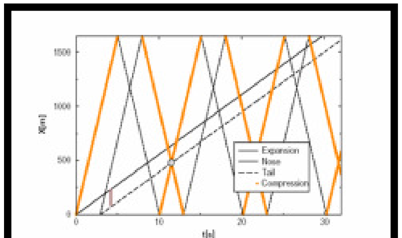
Tunnel pressure specification

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?



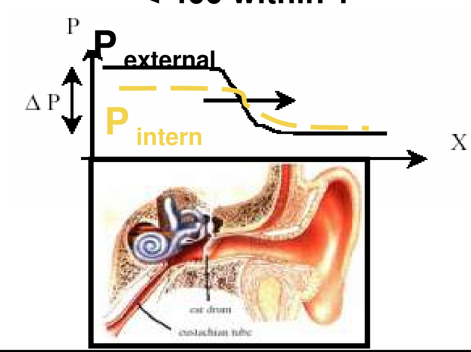
Cabin pressure specification

UIC 651:

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

Permissible limits

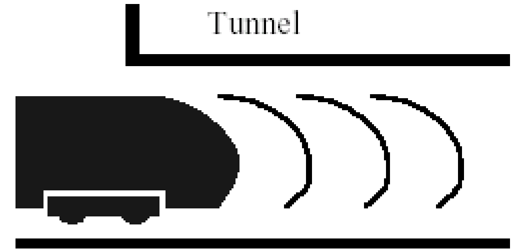
- **< 1000 Pa**
- **< 400 within 1**



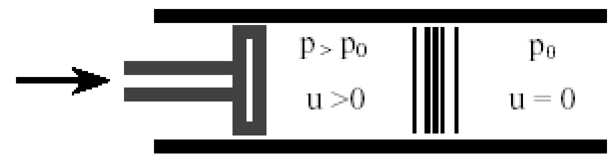
BOMBARDIER

Pressure Comfort: Physics

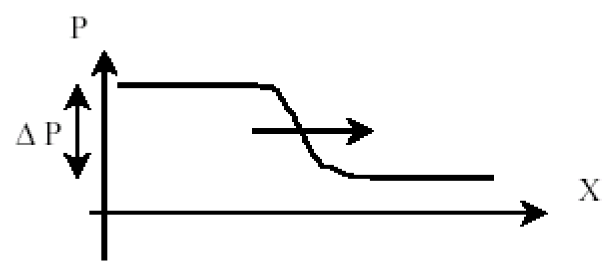
- **Train generates 3-D pressure wave upon tunnel entry**



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

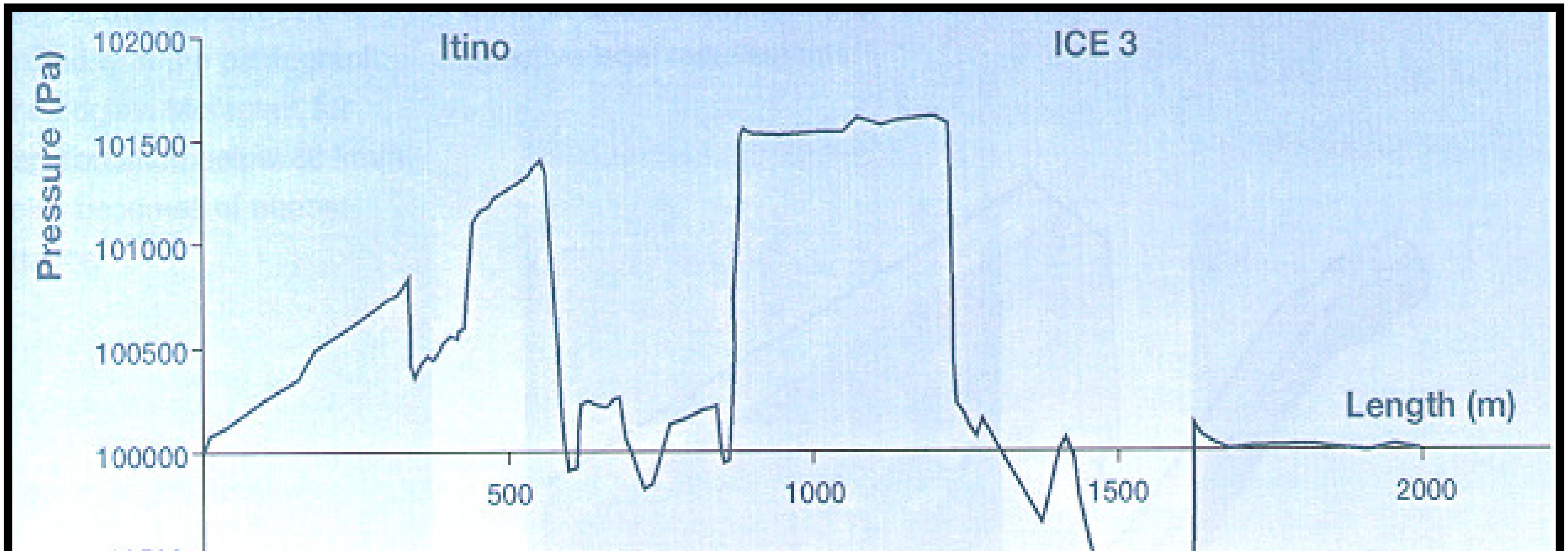


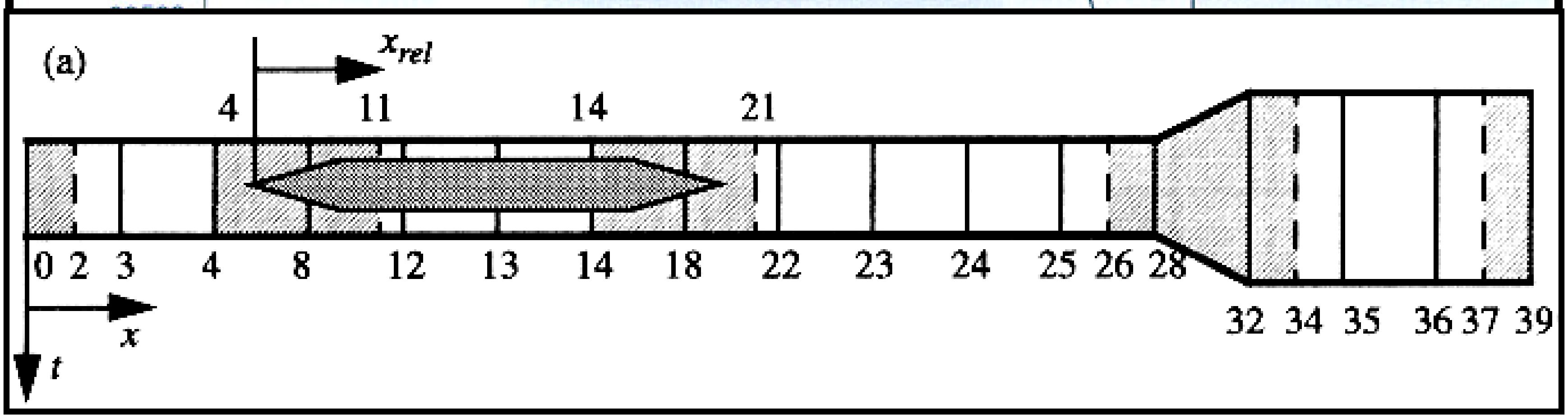
- **Wave front moves through tunnel with speed of sound**



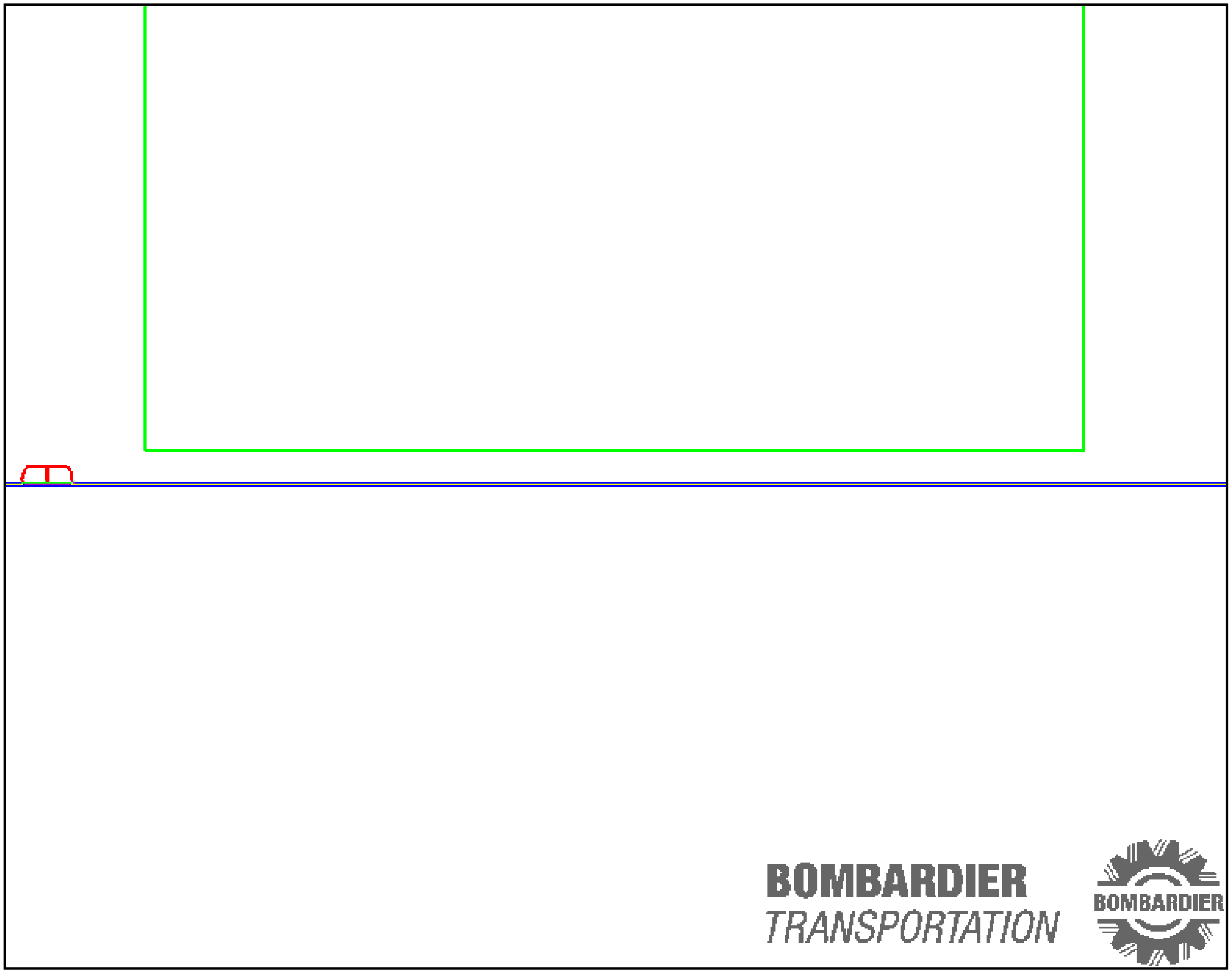
BOMBARDIER

Pressure Comfort:

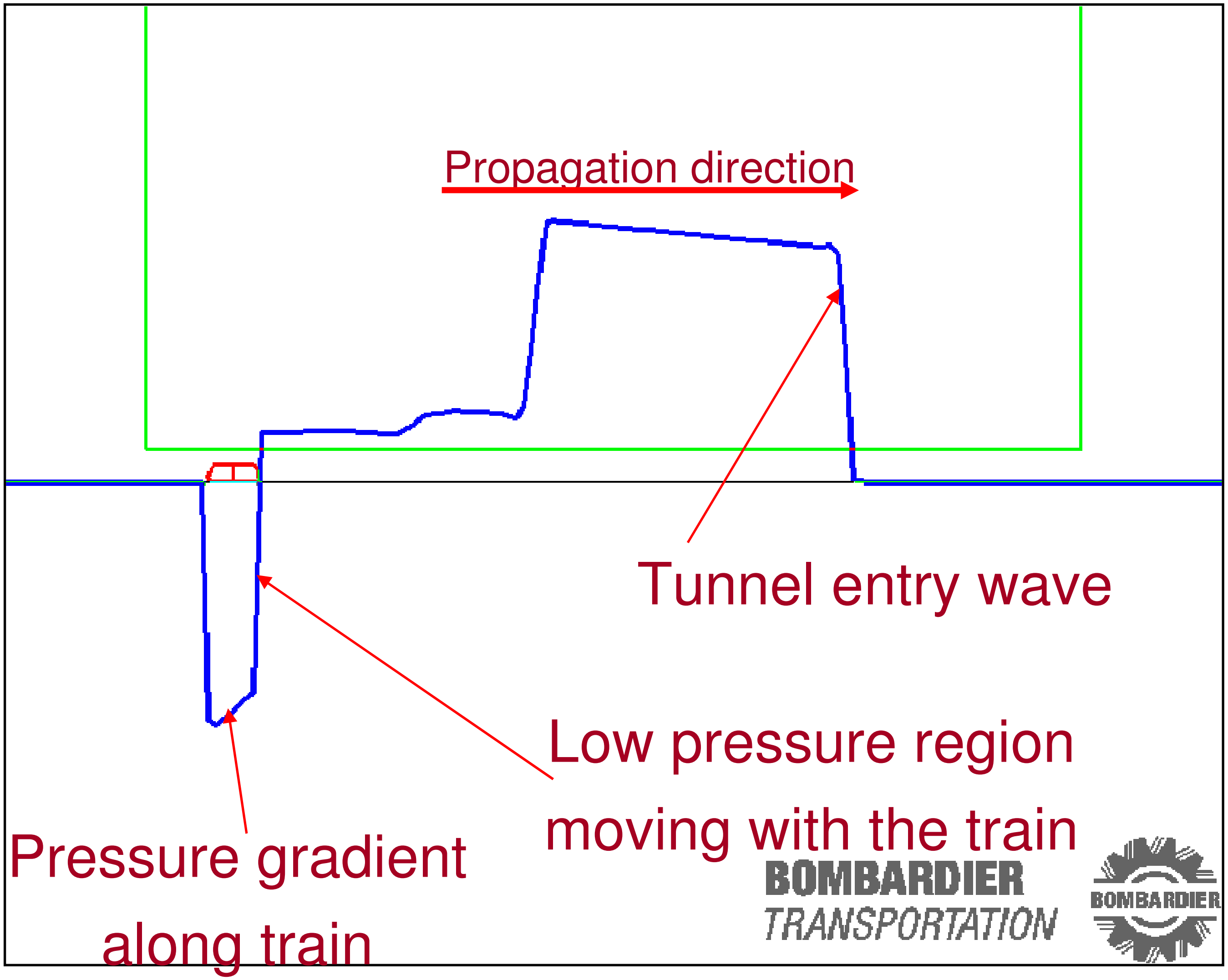




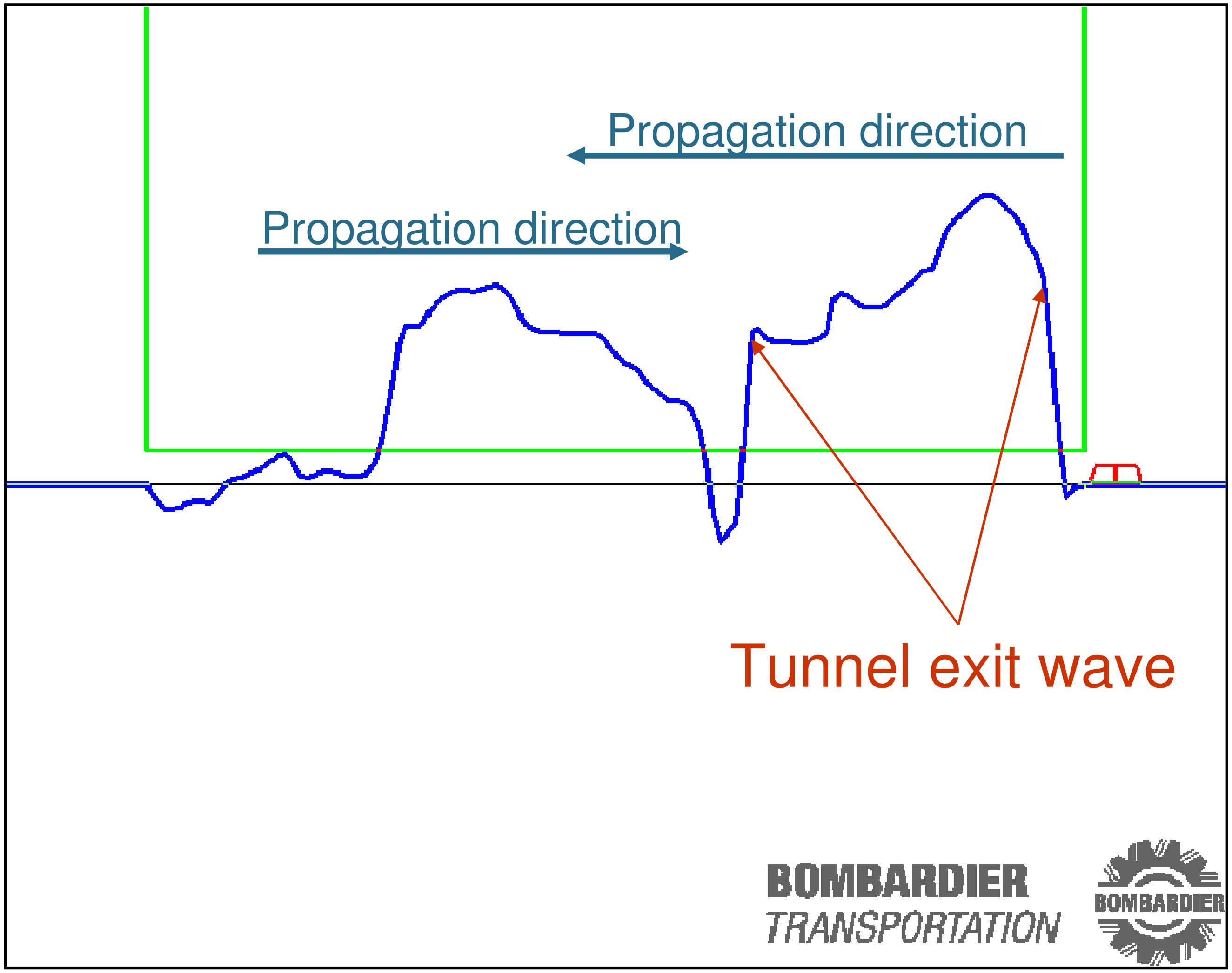
Propagation of pressure waves in a tunnel



Tunnel Aerodynamics - Prediction

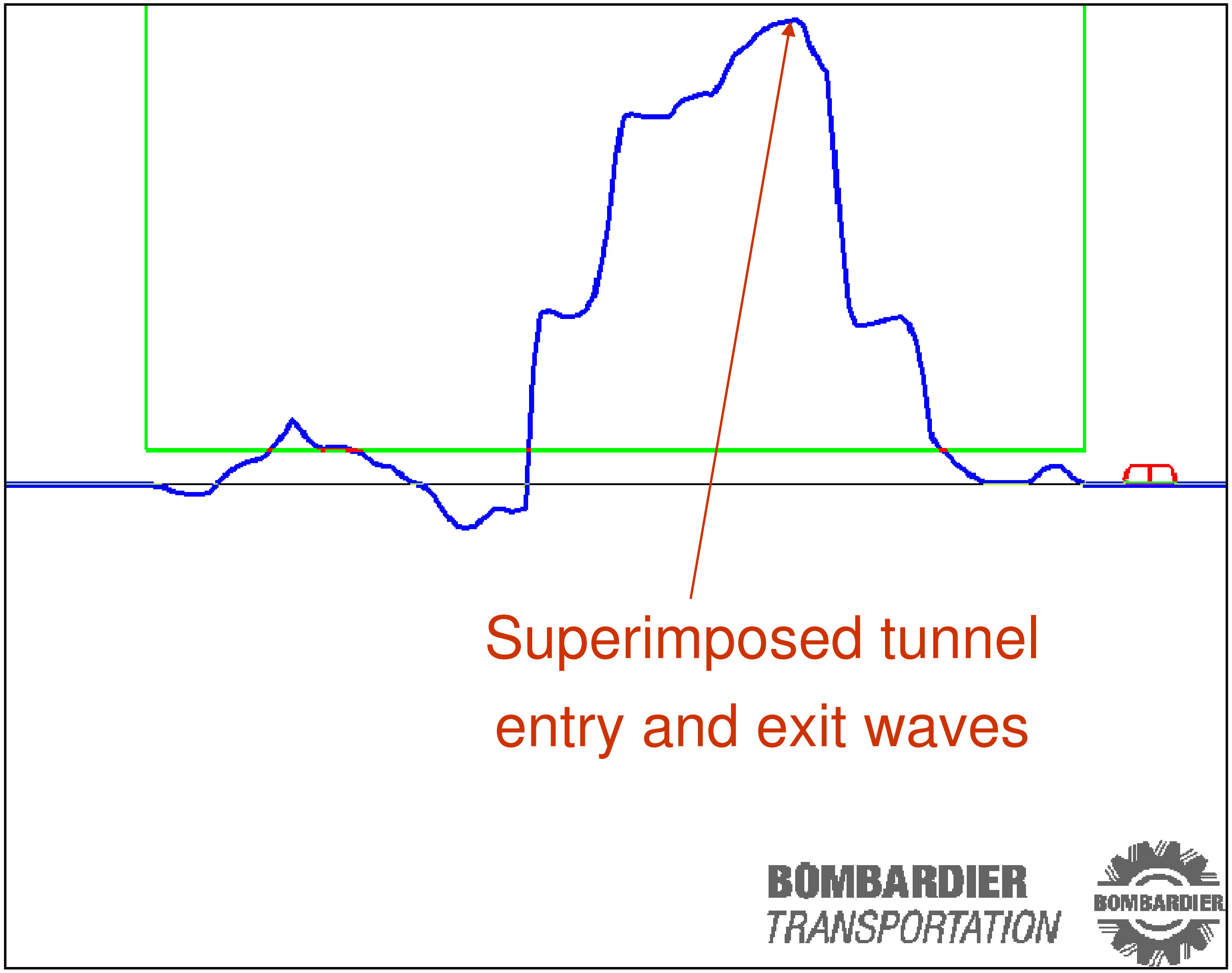


Tunnel exit wave



BOM

High pressure intensities due to superposition



⇒ Highest pressure intensities occur after train exit

⇒ Crossing trains are exposed to much higher pressure changes

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

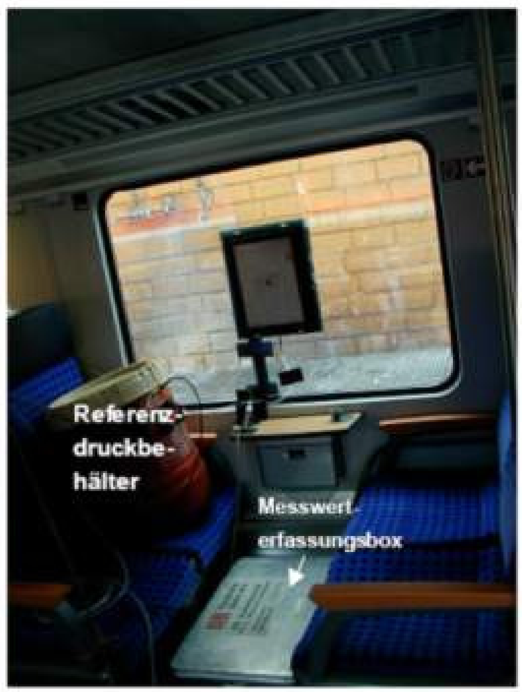
BOMBARDIER

Components affecting the pressure tightness

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

Tunnel Aerodynamics – Verification and Testing

- **Differential Pressure Sensors**
  - Outside sensor PDCR22 (+/-10k Pa measurement range)
  - Inside sensor PDCR 4160 (+/-7 k Pa measurement range)
  - Accuracy about +/-20 Pa based on +/-10k Pa meas. range
  - Sampling rate around 250Hz



Pressure comfort and pressure loads for Double Deck coaches

BOMBARDIER

Cross-Wind Stability

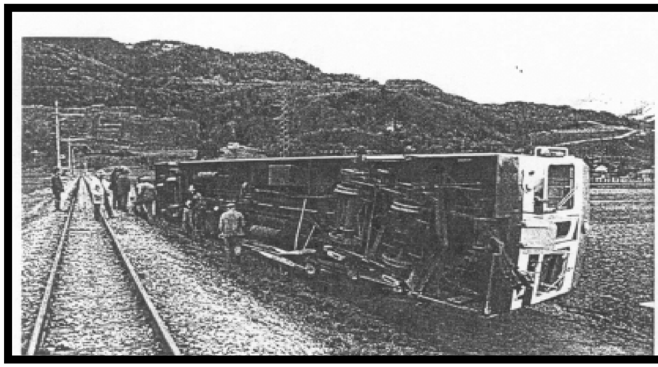
Topic 4

Vehicle Aerodynamics Lecture

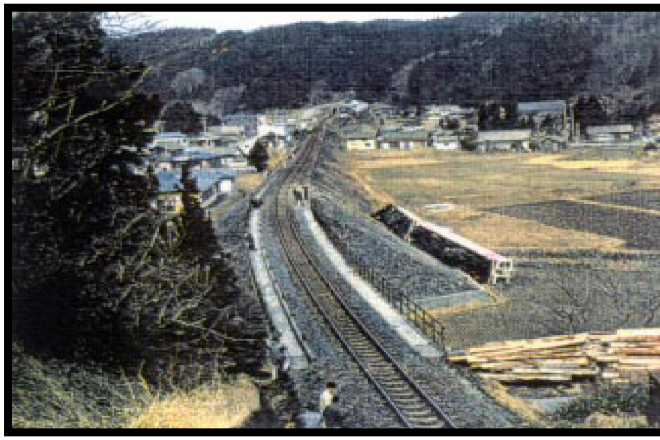
BOMBARDIER

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: France / Villy
Cross-wind accident

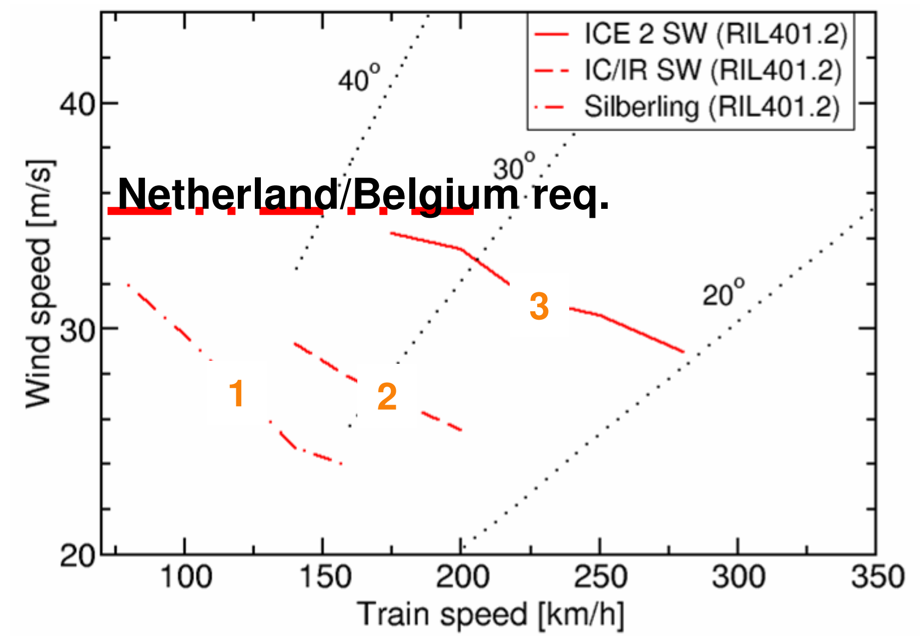


22.2.1994: Japan,
Sanriku Railways

BOMBARDIER

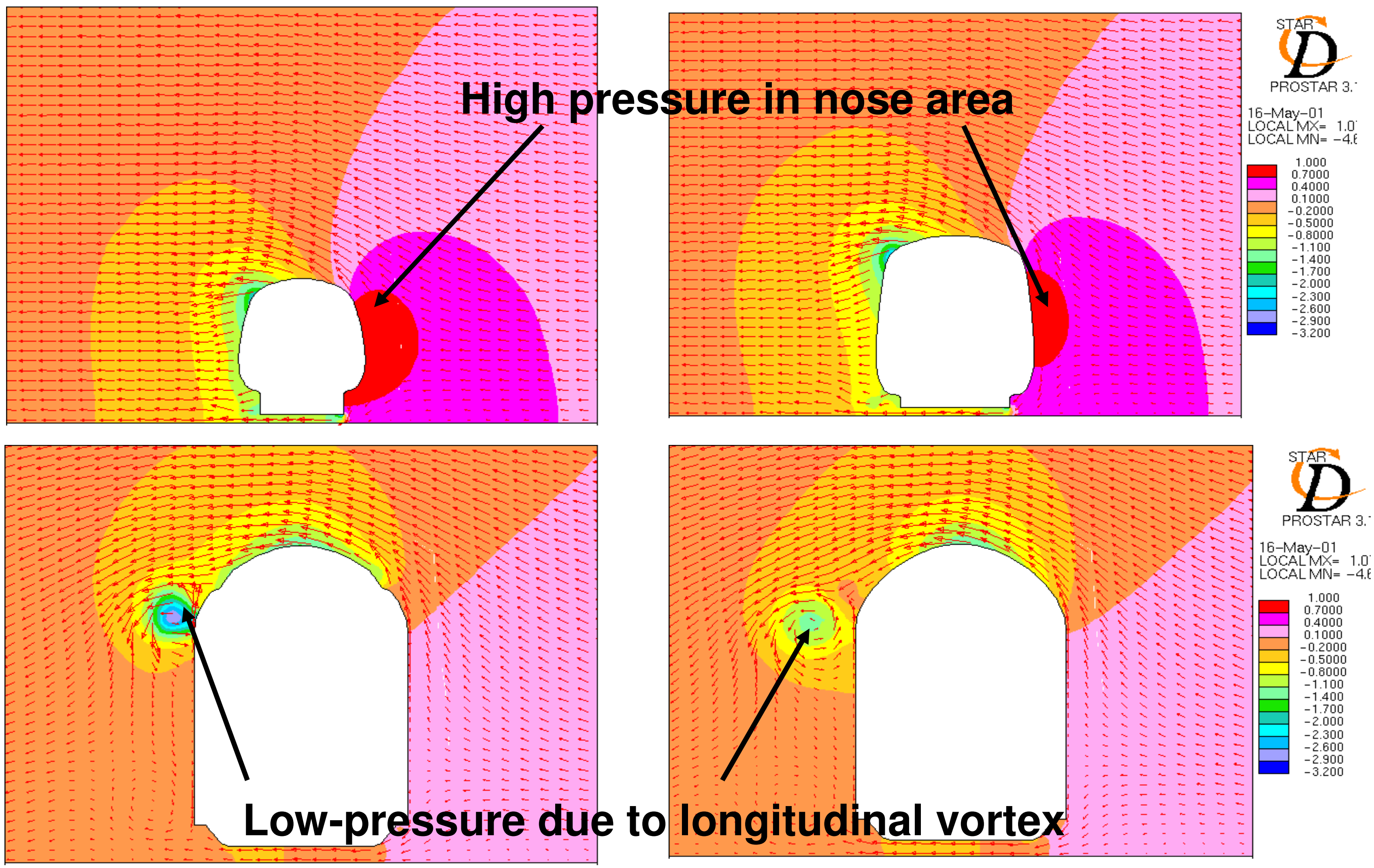
Cross-Wind Stability - Requirements

- **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.



BOMBARDIER

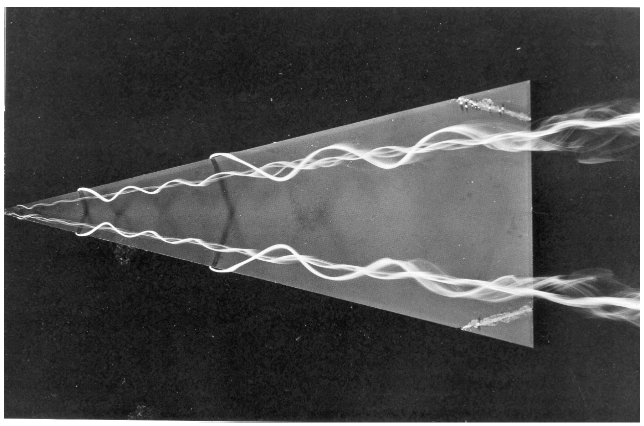
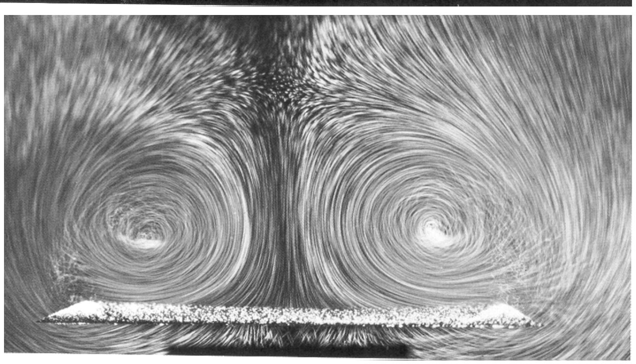
Flow Field Topology: CFD



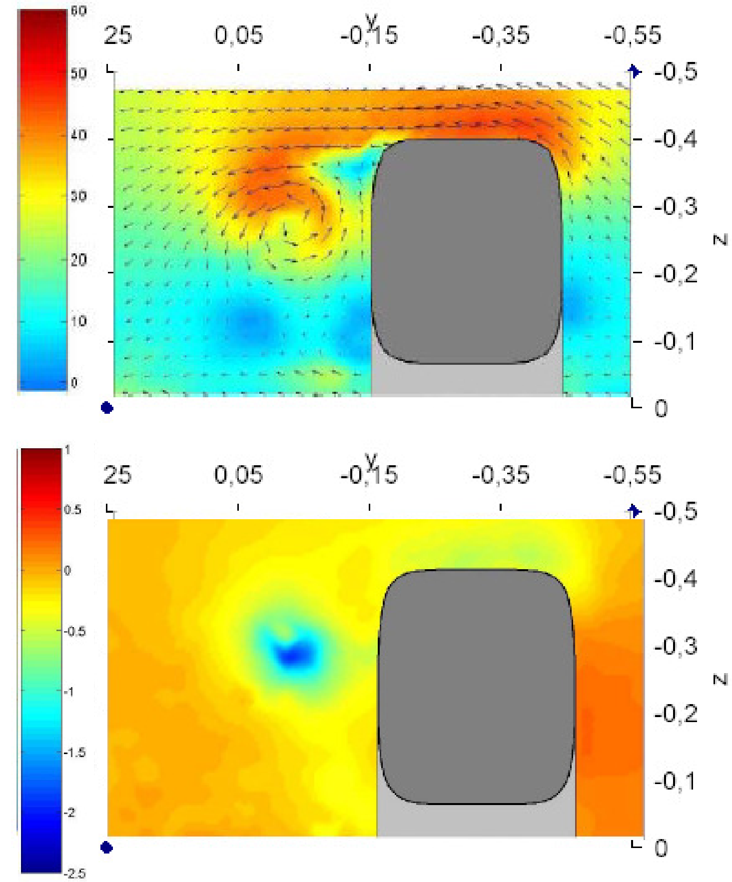
BOMBARDIER

Flow Field

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

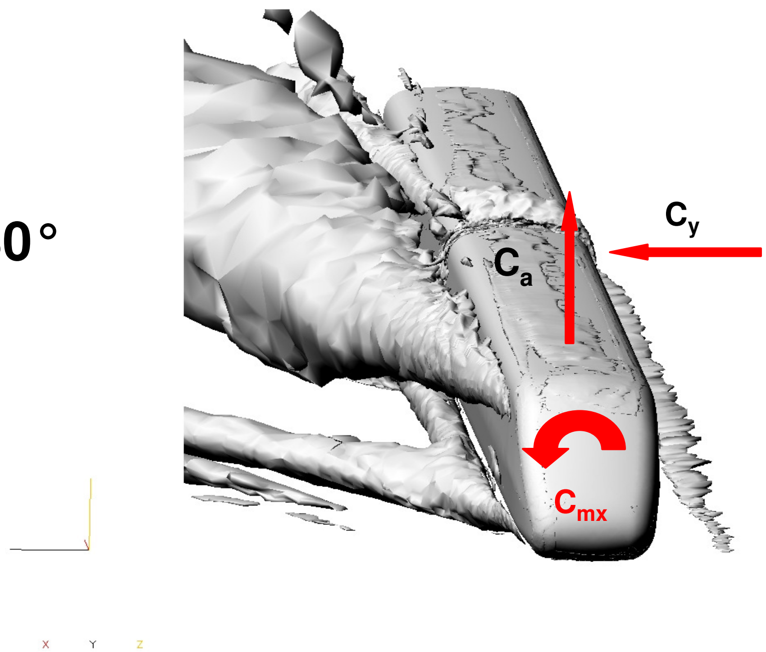
Werle, 1963

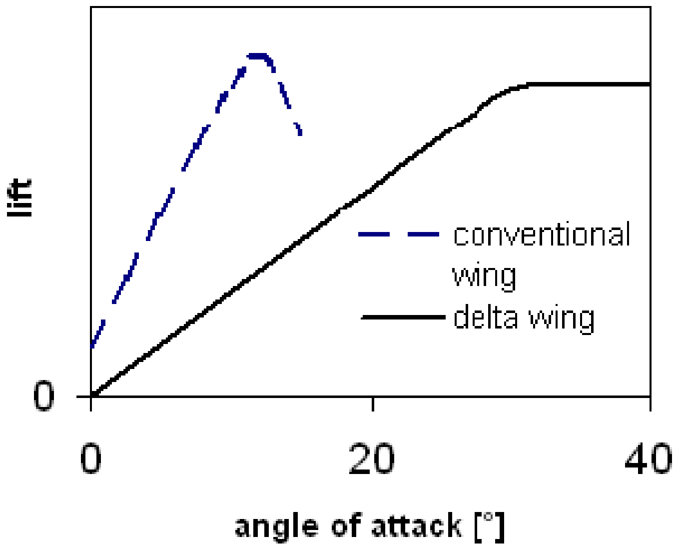


Velocity and pressure distribution at x=-0.134 and α=30° (experimental data)

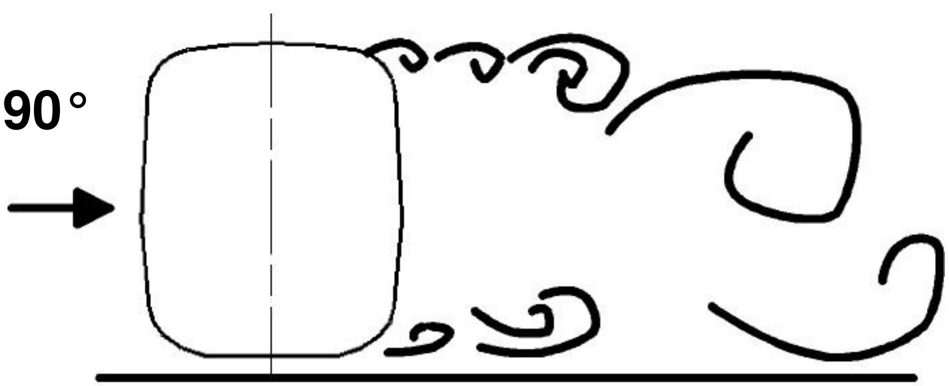
Flow Topology

Alpha=30°





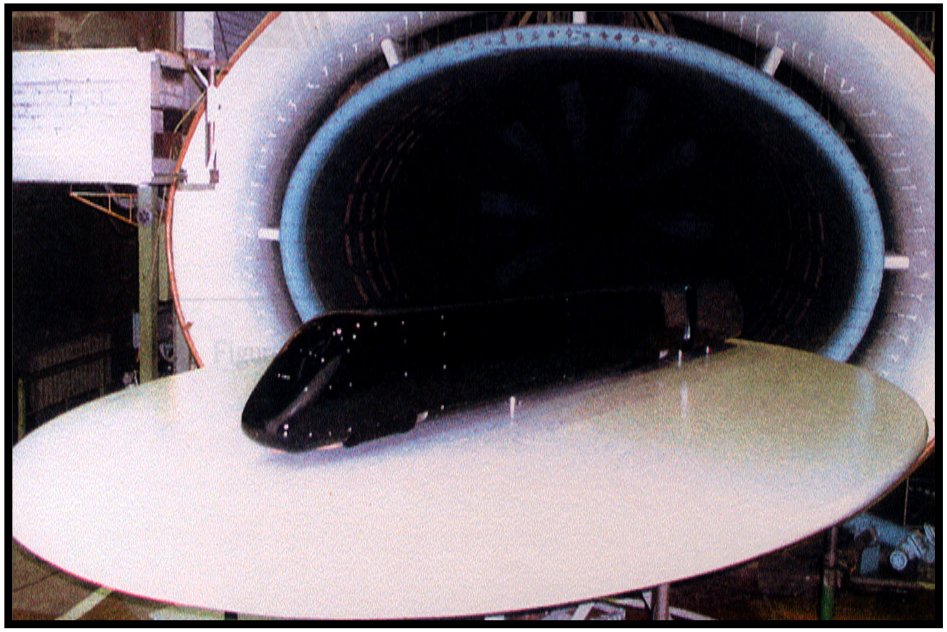
Alpha=90°

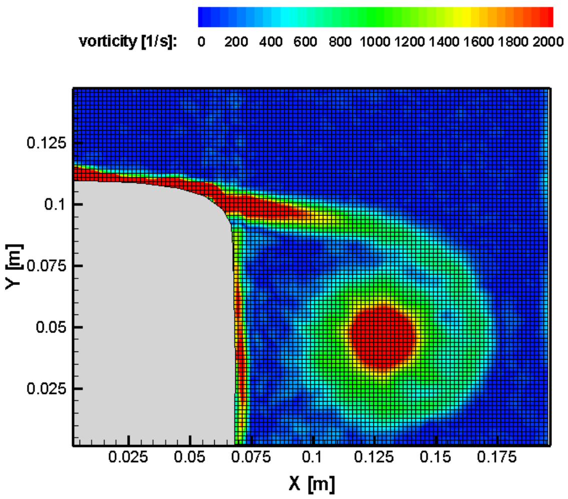


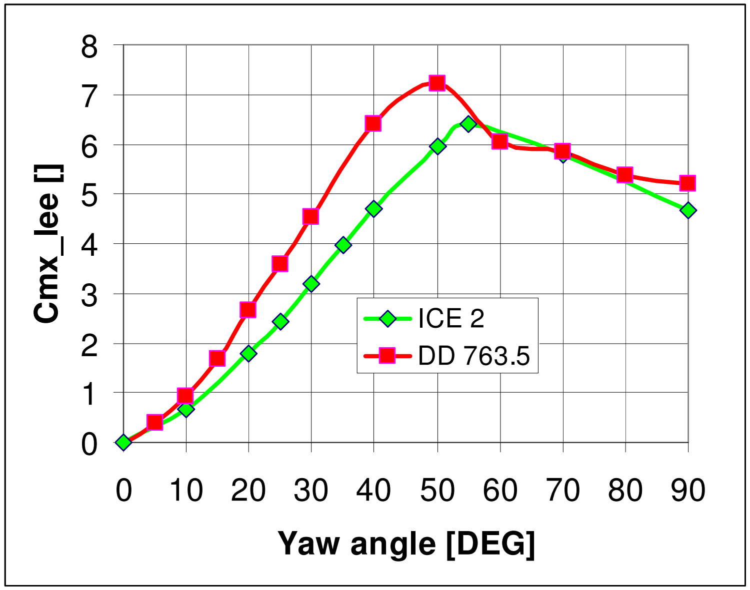
BOMBARDIER

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°?**

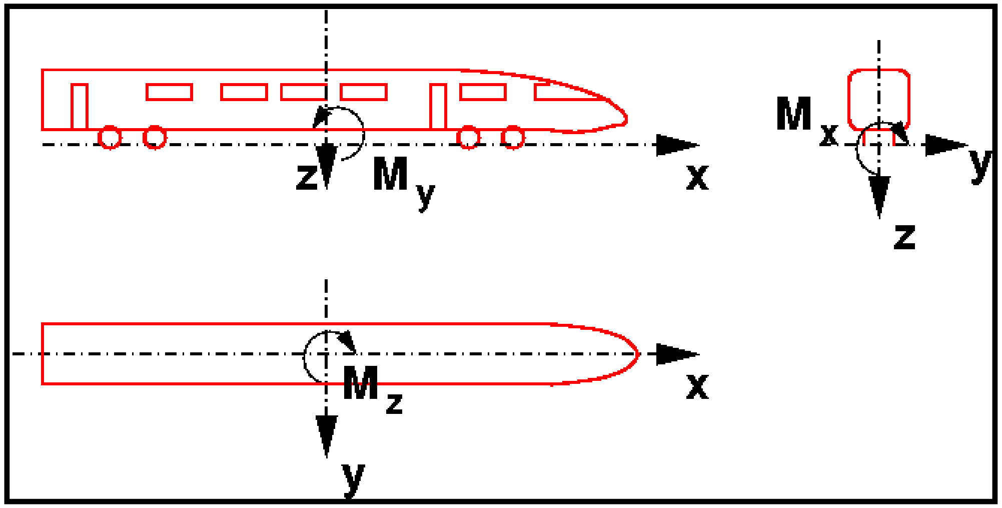






Cross-Wind Stability: Aerodynamic forces

- **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

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

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

BOMBARDIER

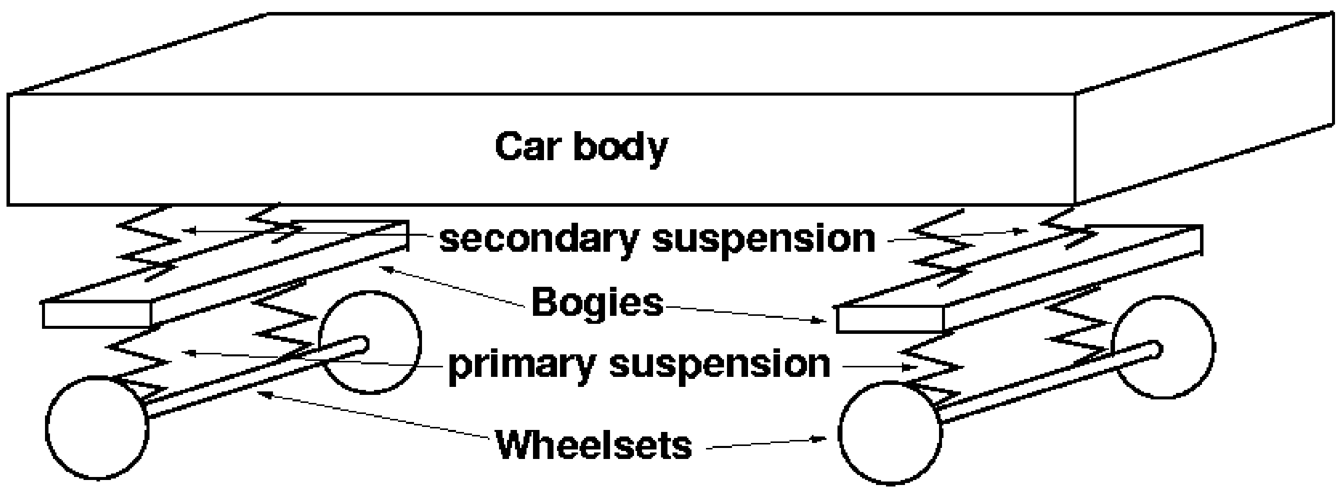
Cross-Wind Stability: Wheel-Rail Forces

Quasi Static Method

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

Transient Method

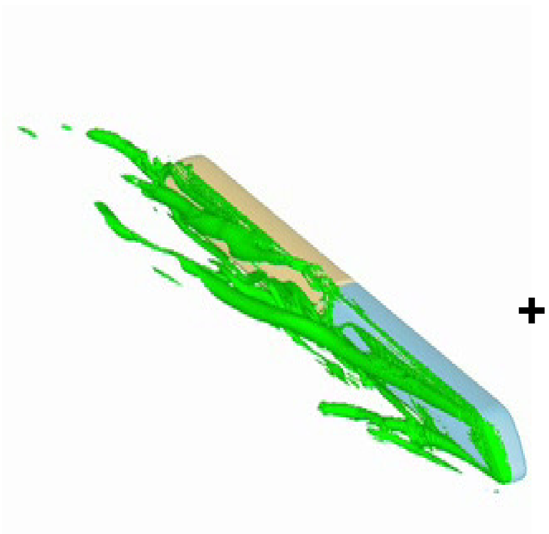
- Multi Body Simulation
- n body system
- n*x degrees of freedom
- Captures all displacements
- transient



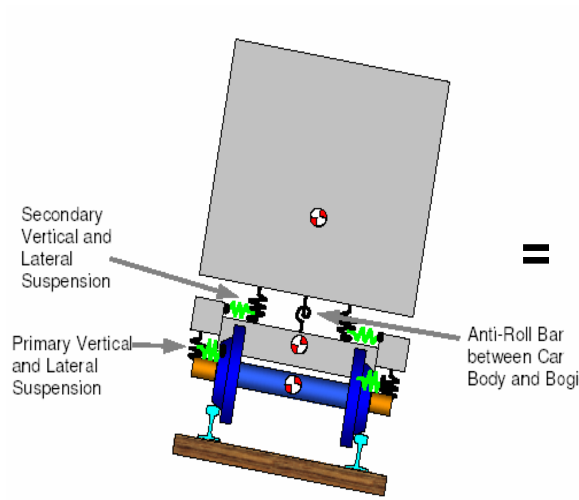
BOMBARDIER

Cross-Wind Stability - Prediction

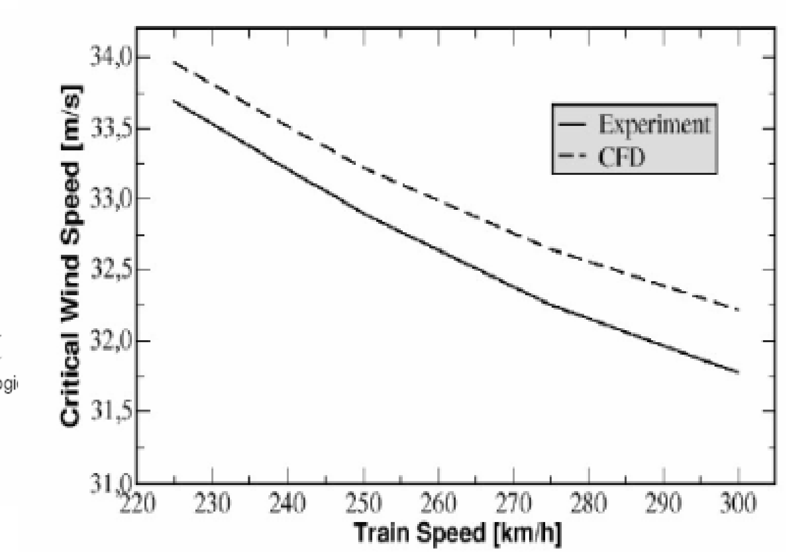
Requirements
Prediction
Verification and Testing



+



=



Computational Fluid Dynamics + Multi Body Simulation = Performance Prediction

BOMBARDIER

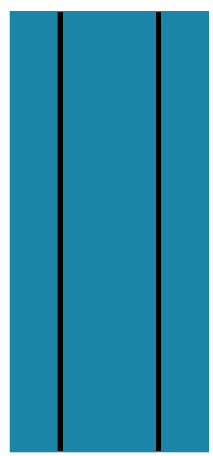
Counter Measures

- **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

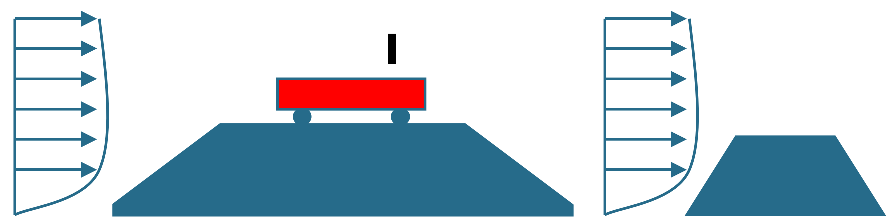
Problems to be Addressed in the Future – Moving Ground

Reality

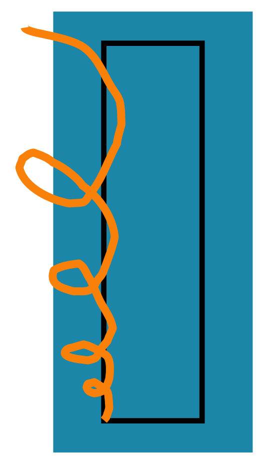
- 2 dimensional
- Train is moving
- No longitudinal vortex



Wind Tunnel



- 3 dimensional
- Train is not moving
- Strong longitudinal vortex



BOMBARDIER

Slip Stream Effect During Train Passing

Topic 5

Vehicle Aerodynamics Lecture

BOMBARDIER

Introduction

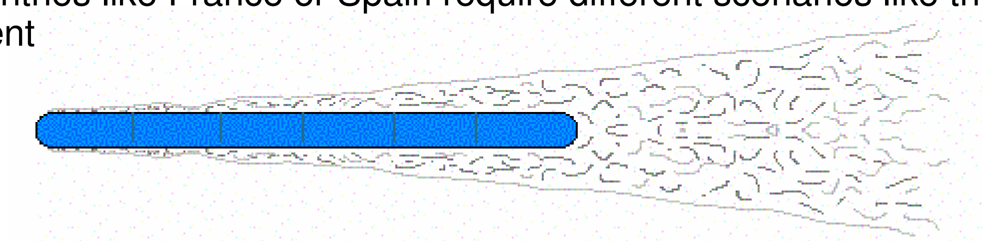
- **What is Slipstream?**
  - Air flow felt by a passenger waiting at a platform when a train passes
  - Air flow acting on trackside workers when a train passes
  - Slipstream generates fluctuating forces on nearby persons and objects
- **Persons and objects may be destabilised by a trains slipstream**
- **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).

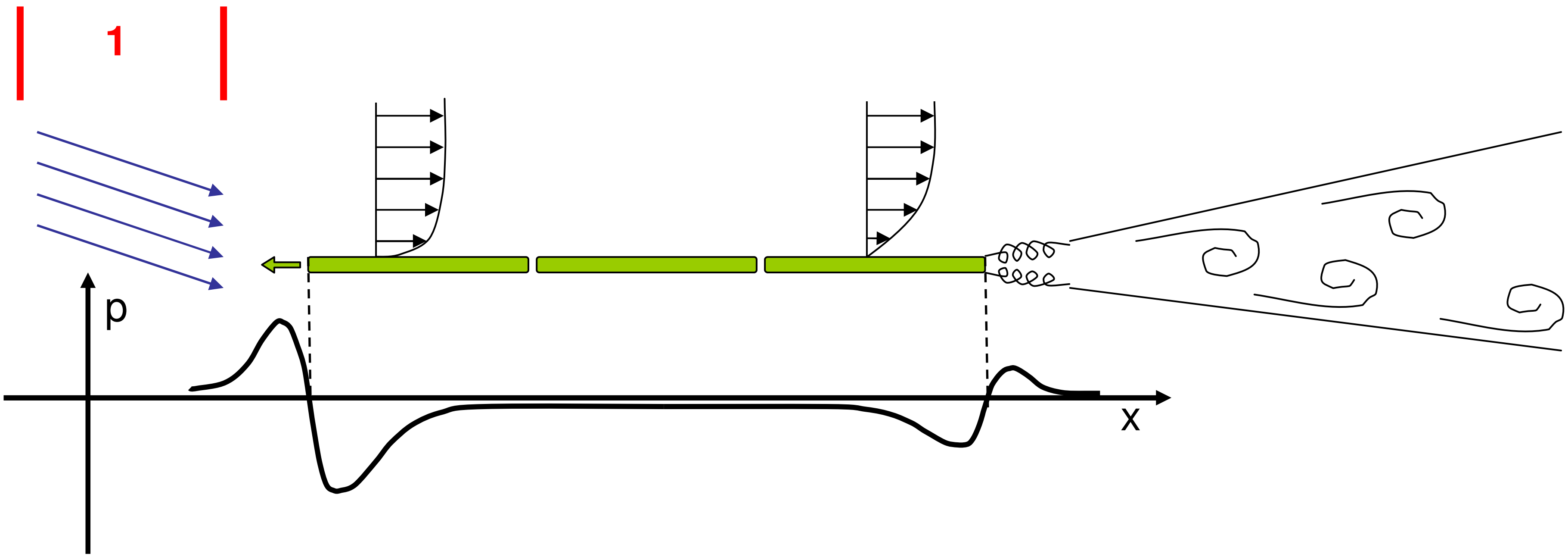
Maximum speed (km/h)	Maximum permissible air speed, $u_{2\sigma}$ (m/s)
From 190 to 249	20
From 250 to 300	22

    - 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



BOMBARDIER

Physical Background



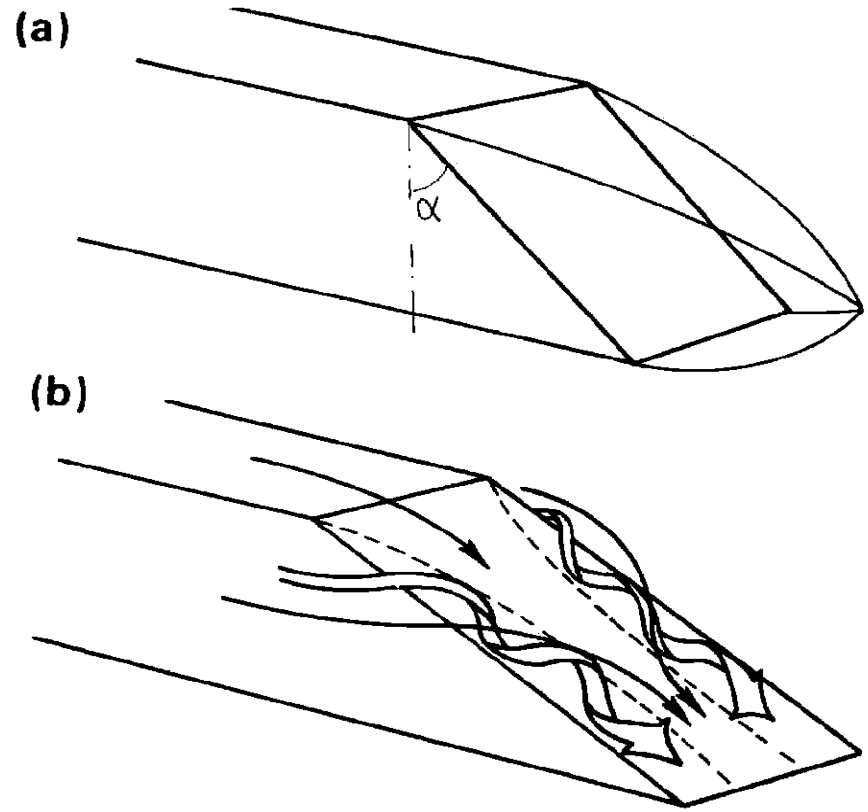
1. **Pre-Head Zone**
2. **Head Passage**
3. **Boundary Layer Zone**
4. **Near Wake**
5. **Far Wake**

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

BOMBARDIER

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

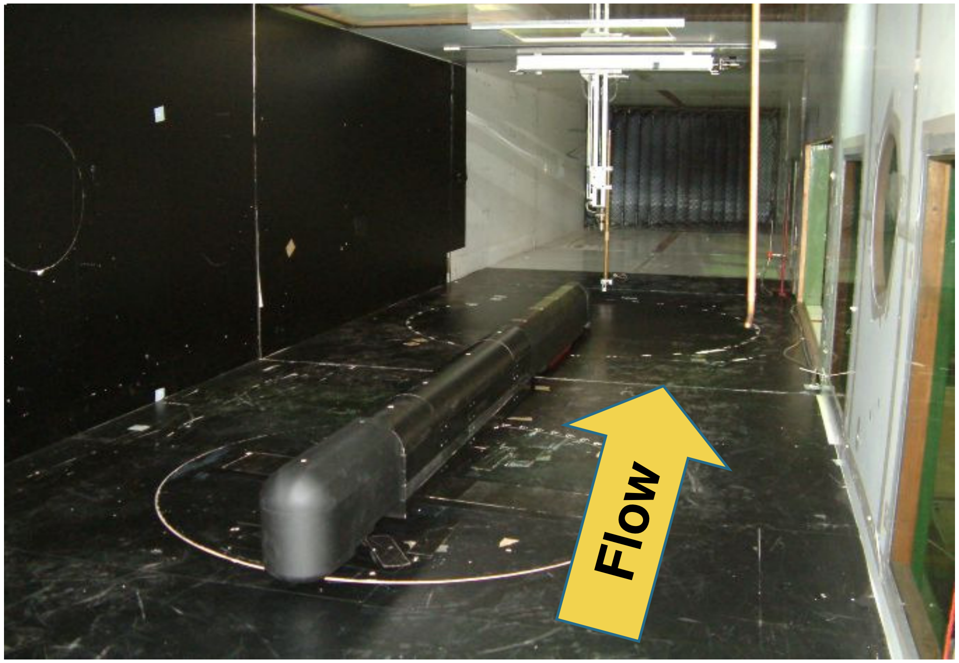
BOMBARDIER

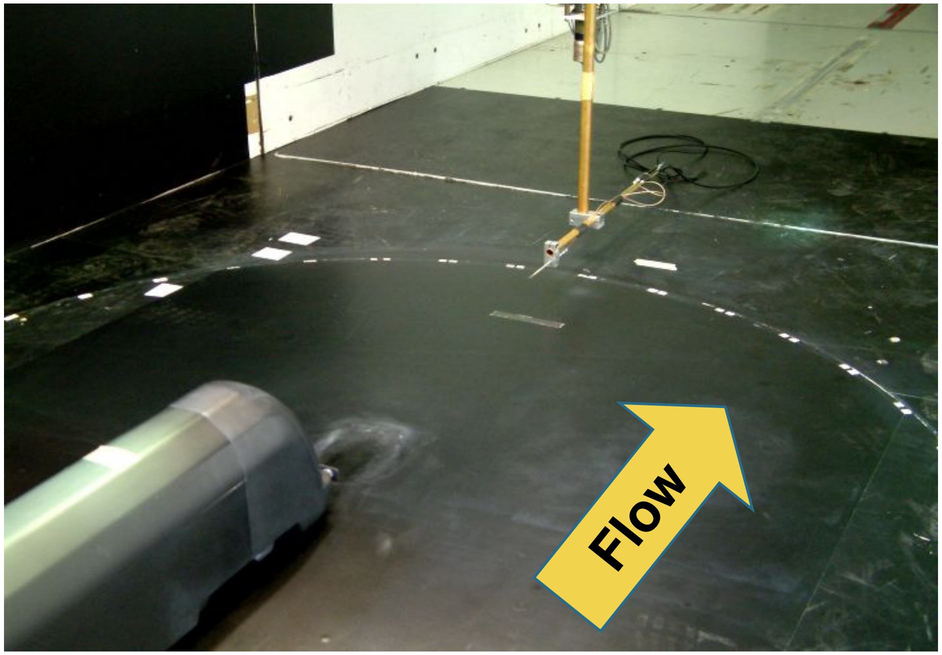
Test Setups, Applied Methods

- **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**

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





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

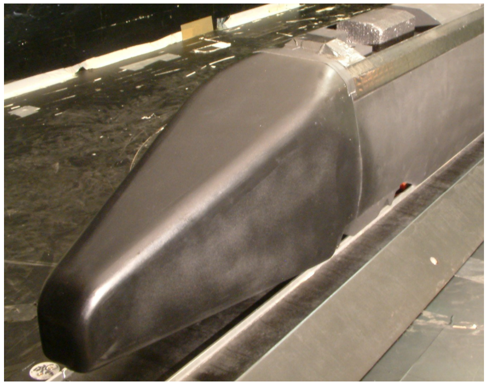
Vehicle Aerodynamics Lecture

BOMBARDIER

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

1

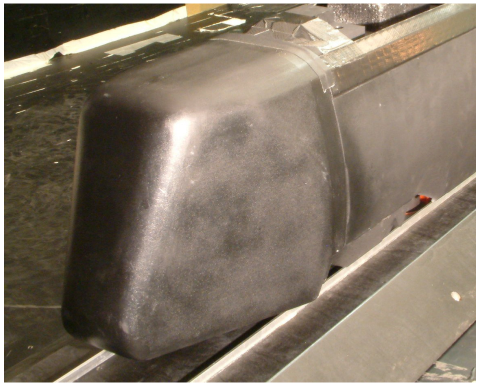
2



reference

0

3



4

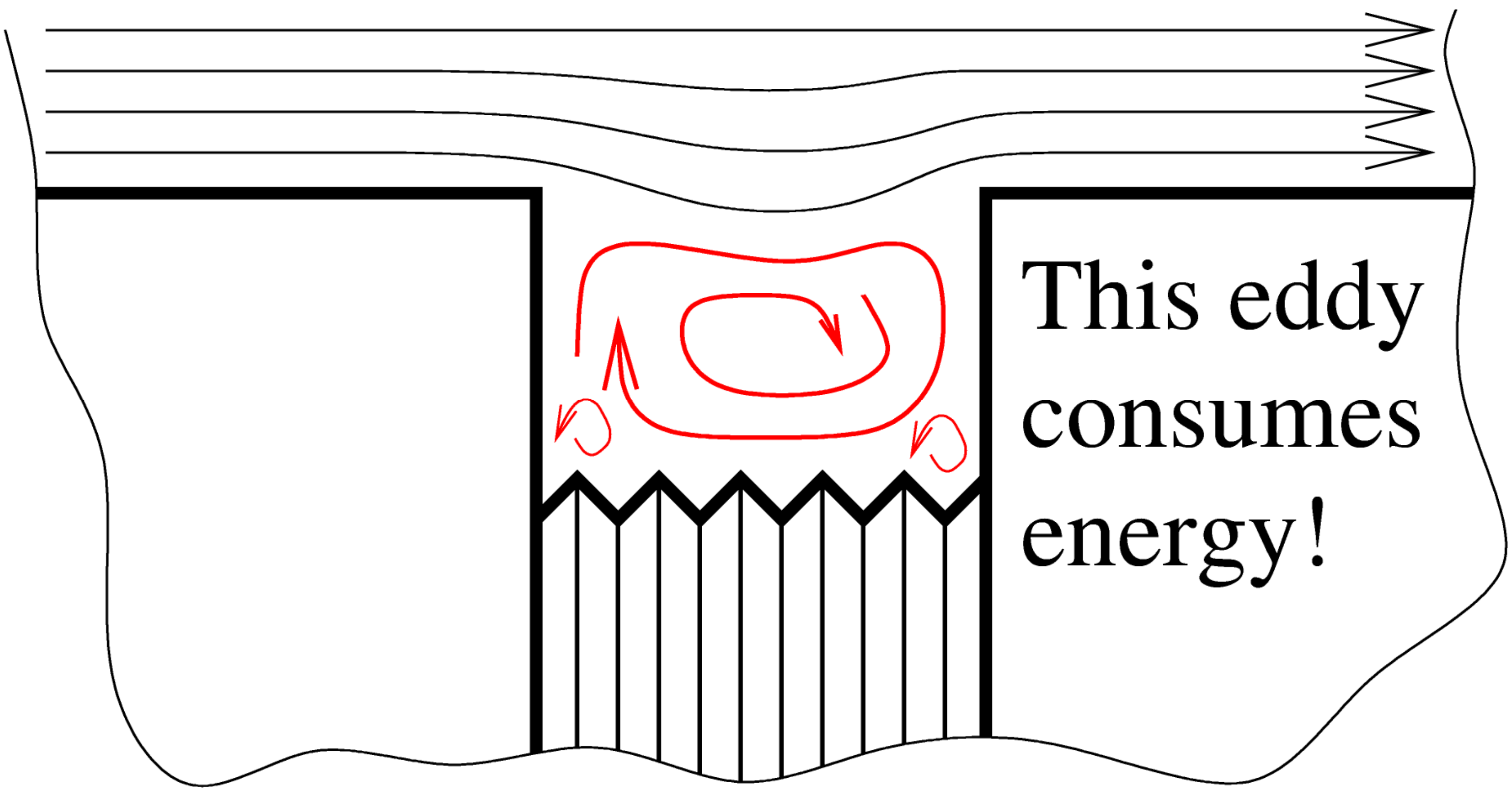
BOMBARDIER

Running Resistance - Requirements

- **Requirements can be direct and/or indirect**
  - Direct requirement to be equal or better than an existing reference vehicle or a given value defined by the customer.
  - Indirect by requirements on the JTC (Journey Time Capability).
- **The running resistance is required for**
  - Correct dimensioning of the propulsion unit, i.e. to assure the top speed of the train and to fulfil the run times required on the specified line.
  - Estimation of the energy consumption of the train.
  - Assessment of measures to reduce the power requirement.

Physical background

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



Physical background

- **Ventilated disc brakes:**
  - act as radial blowers and thus consume energy
- **Bogies:**
  - are normally not faired and therefore not aerodynamically shaped
  - interference occurs between bogies (dead water effect)
- **Underbelly design:**
  - Dead water zones occur downstream of obstacles
  - Within dead water zones energy dissipation is high
  - Therefore, surface roughness (distributed obstacles) increases friction

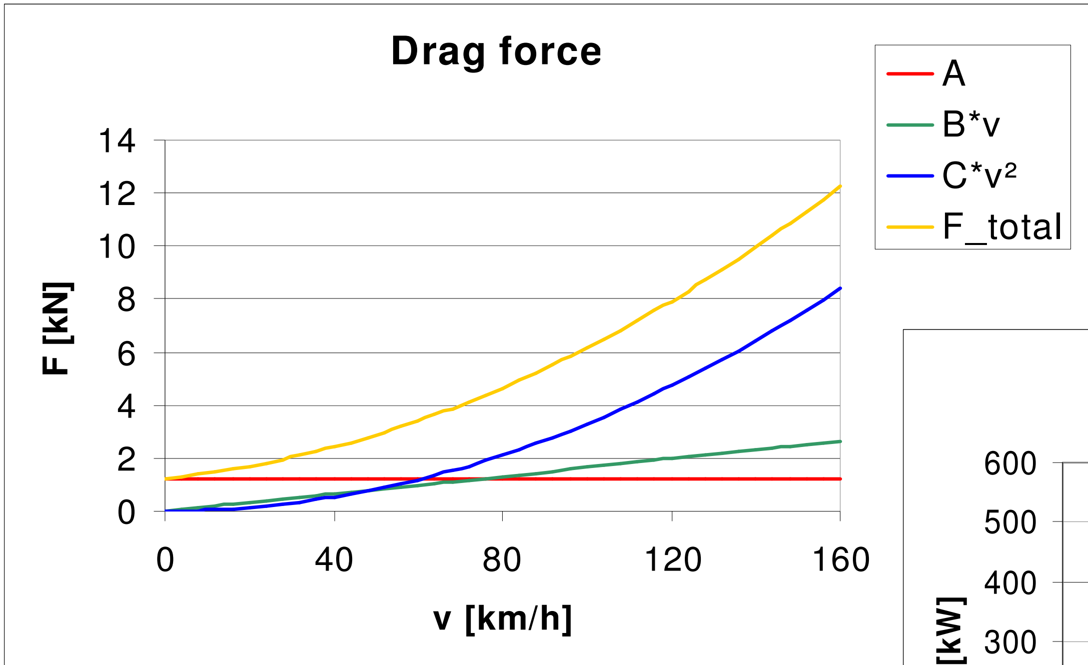
Davis Formula

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

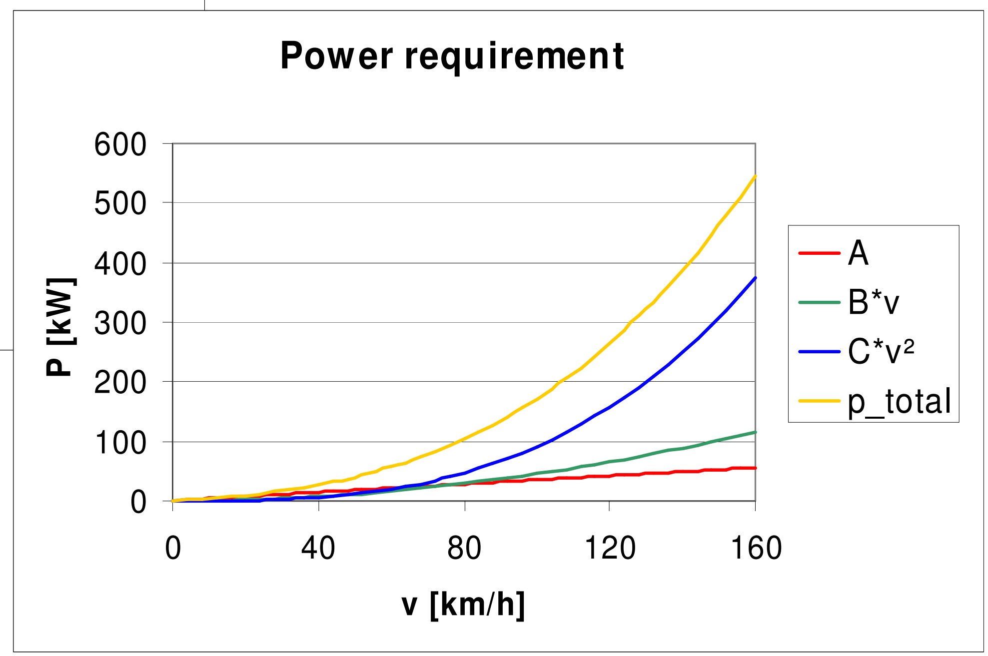
Parameters governing the train resistance

- **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

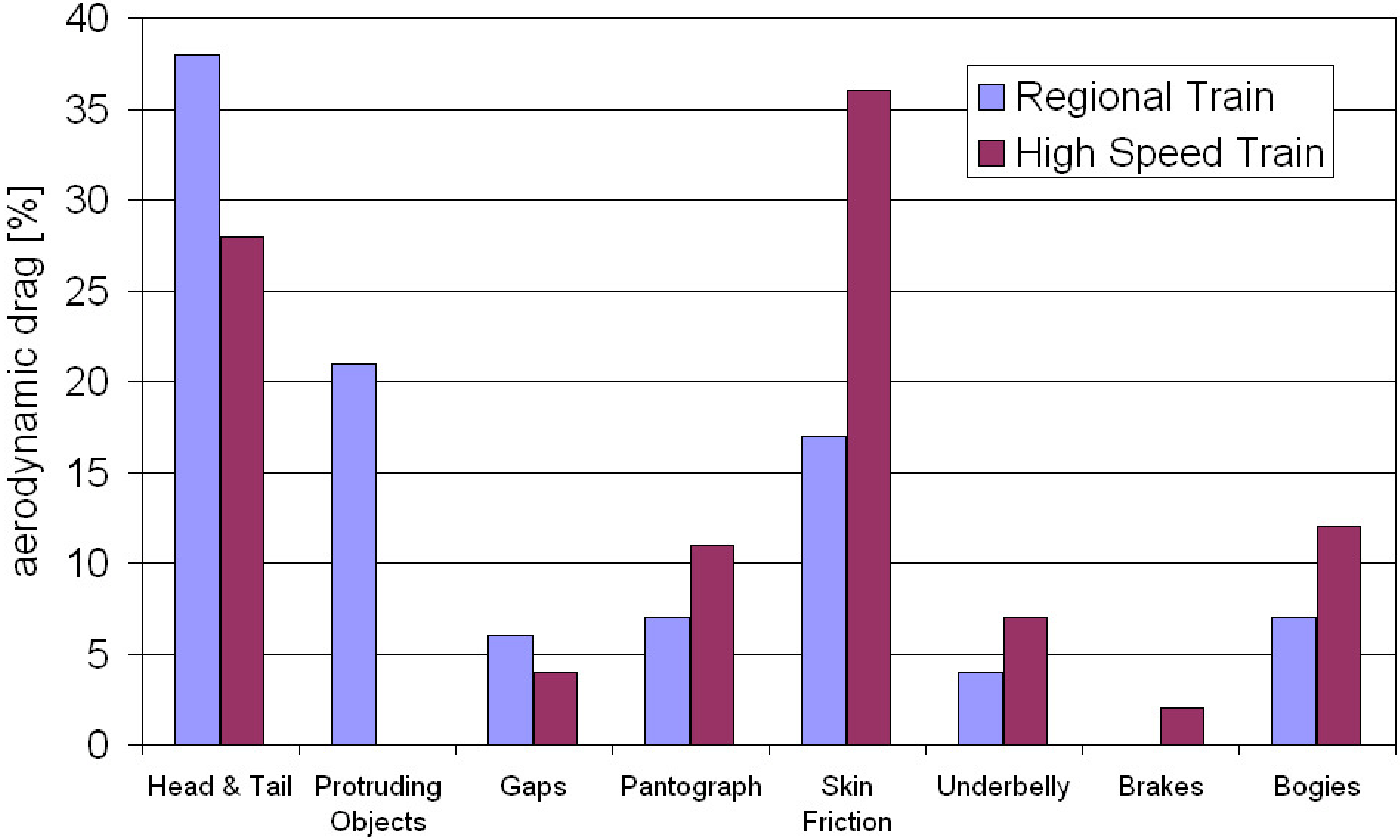


What is the power needed?

$$P = F \cdot v$$

BOMBARDIER

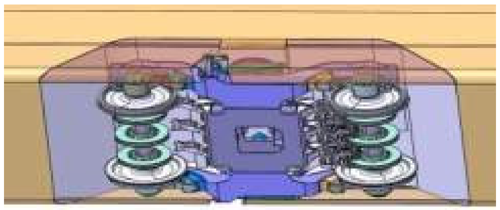
Typical Aerodynamic Drag Distribution



BOMBARDIER

Superior Aerodynamic Resistance – Key Elements
ZEFIRO 380 for China – operational speed of 380 / top speed of 420

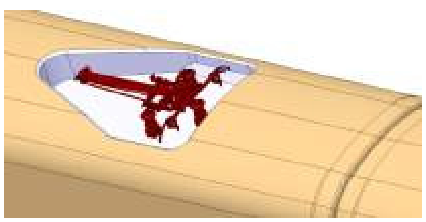
- Bogie skirts
- Aerodynamically optimized bogie design



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

Optimisation

Topic 7

Vehicle Aerodynamics Lecture

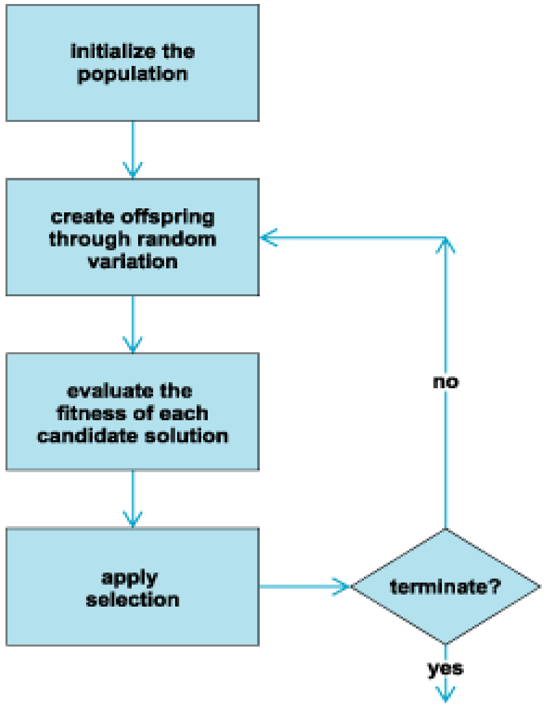
BOMBARDIER

Multiobjective optimization for very high speed trains

- **Trains should be as efficient as possible (*AeroEfficient*)**
- **Objectives:**
  - Reducing aerodynamic drag saves energy demand of trains and reduces costs
  - Limiting drag and maximizing stability also increase acceleration, which reduces traveling time.

AeroEfficient Optimisation

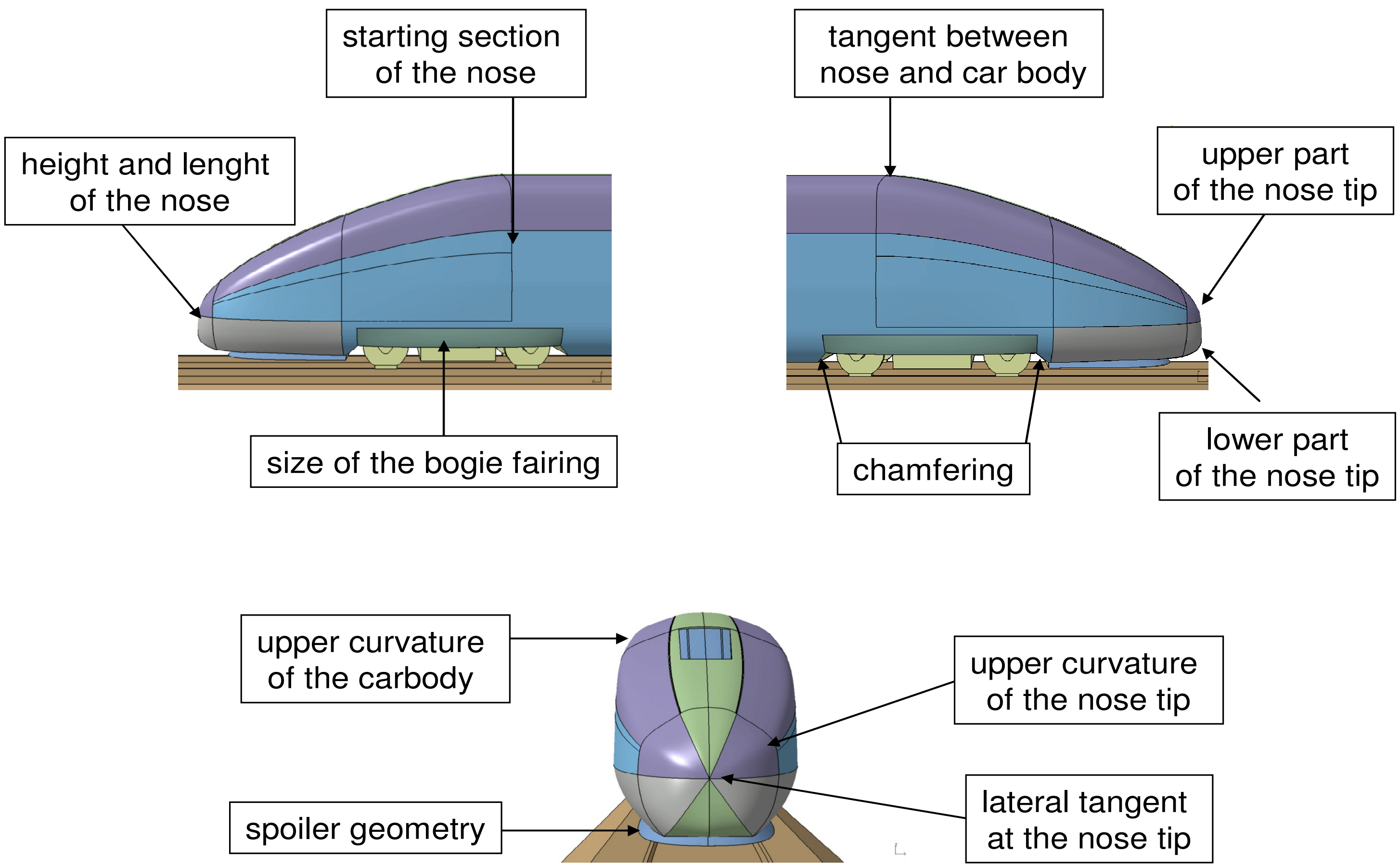
- ***AeroEfficient* train optimisation is based on genetic algorithms that use**
  - Parameterized, three-dimensional CAD models
  - Simulation of aerodynamic drag and cross-wind stability (STARCCM+)
  - Optimization software to determine Pareto optimal solutions



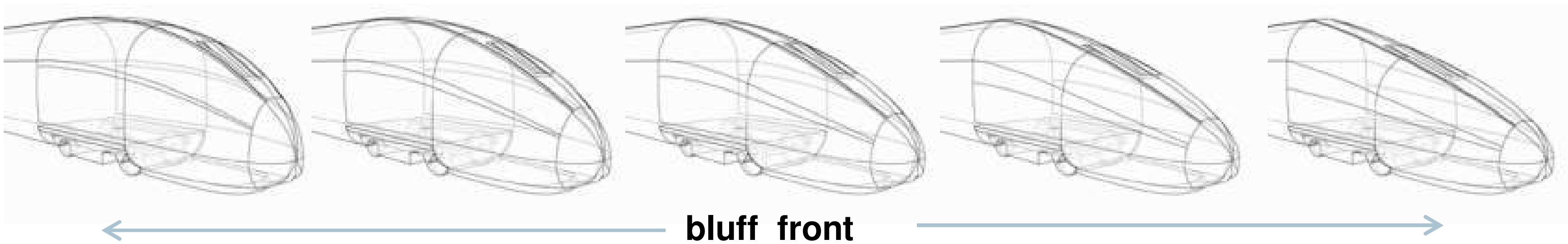
Typical flowchart for an evolutionary algorithm
Source: www.answers.com

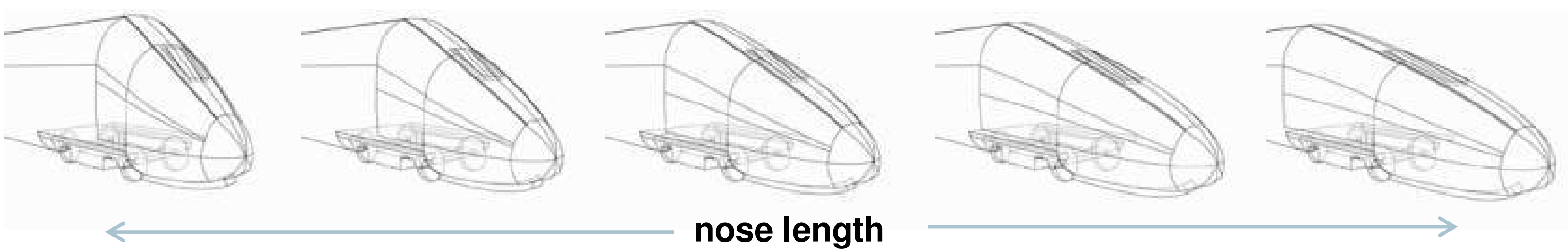
BOMBARDIER

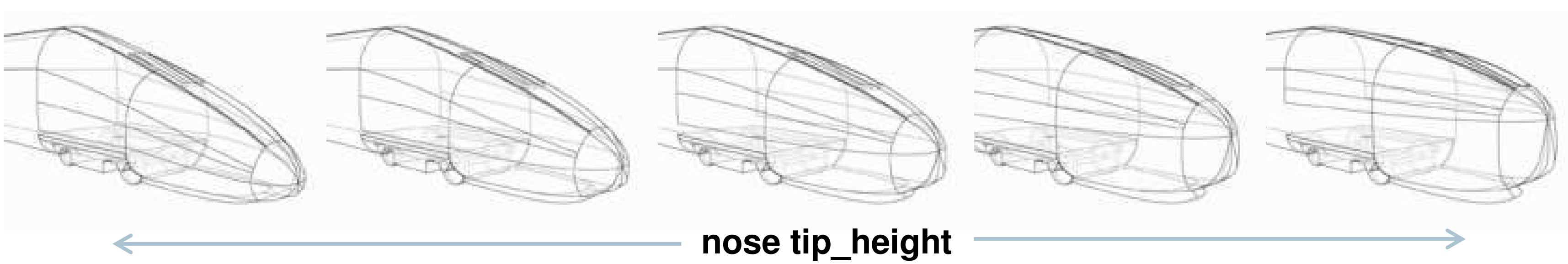
Parameterized model



Parameterized model







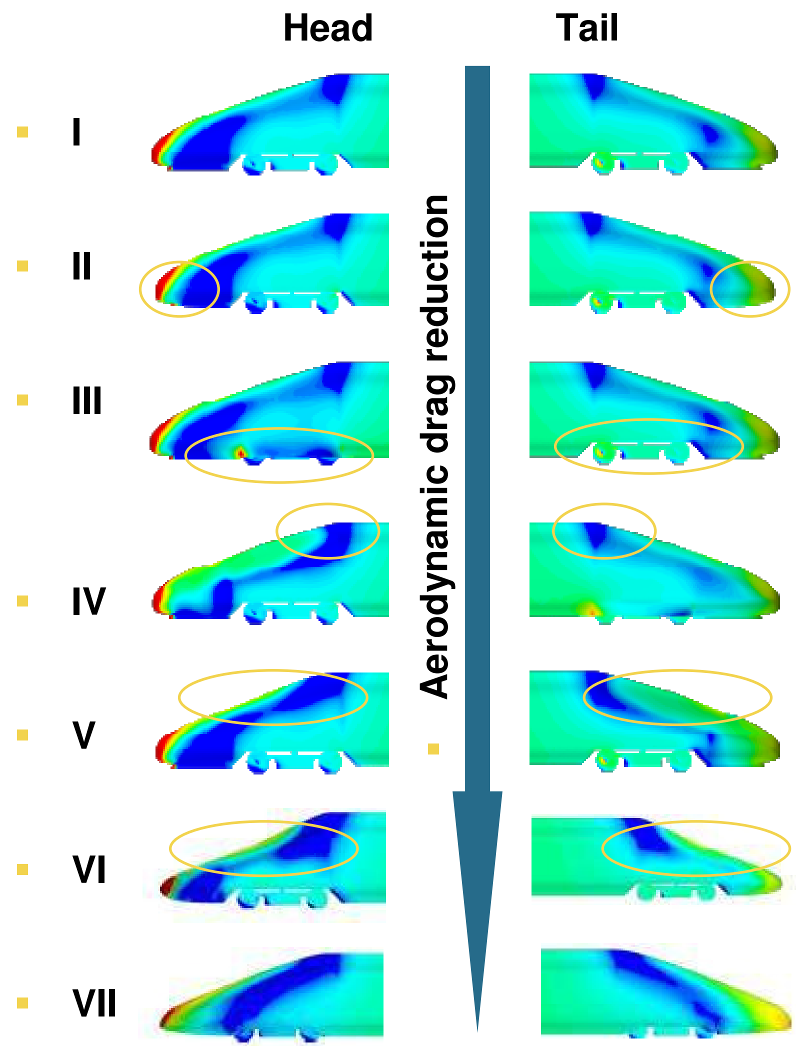
Constraints on the Optimisation of a High-Speed Train

- **Core restrictions**
  - Integration of the crash structure and
  - roof equipment like brake resistors, pantographs and clima comfort
  - Compliance with the predefined enveloping profile
  - Size and position of the windscreen to facilitate certain view angles

- **Mediate and further issues**
  - Weight and mass distribution affect the objective function
  - High passenger capacity conflicts with optimal aerodynamic shape
  - Comfort of driver and passengers
  - Elegancy vs. functionality (designer vs. engineer)

High Performance Computation - Examples

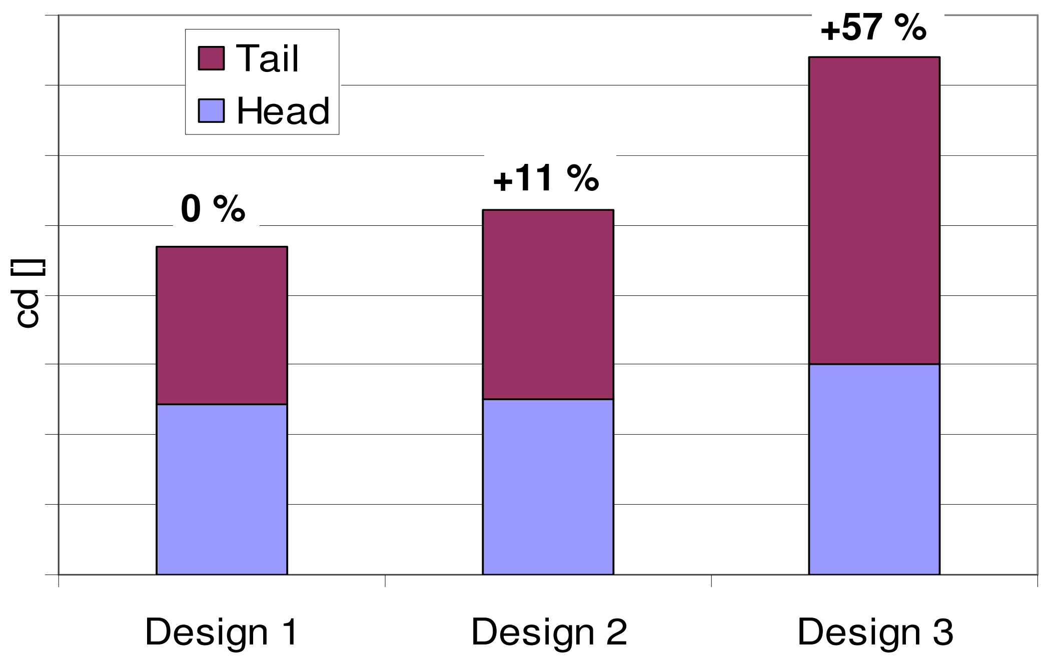
- **Examples of variations in detailed design phase (pressure on surface is shown):**
  - I → II: spoiler variation
  - I → III: bogie fairings
  - I → IV: carbody front transition
  - I → V: more slender nose
  - I → VI: duck nose
  - VII: optimised shape

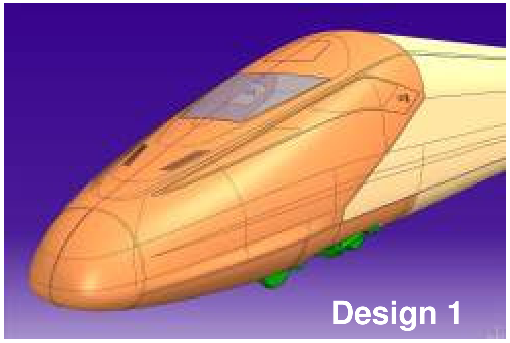


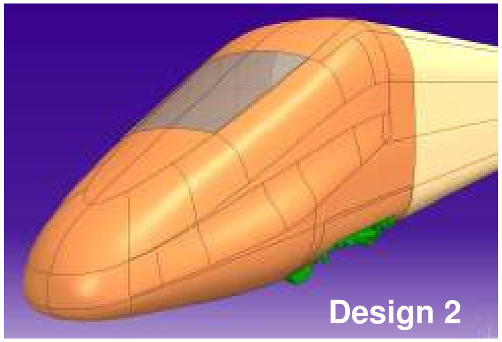
BOMBARDIER

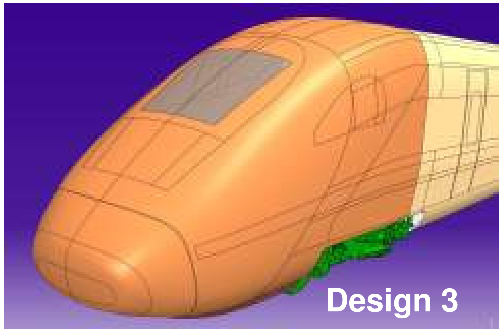
Benchmark of the Front Design – Internal Products

- **Note: Design 3 front is driven by design department**









- **Design 1 exhibits the best aerodynamic performance**

BOMBARDIER

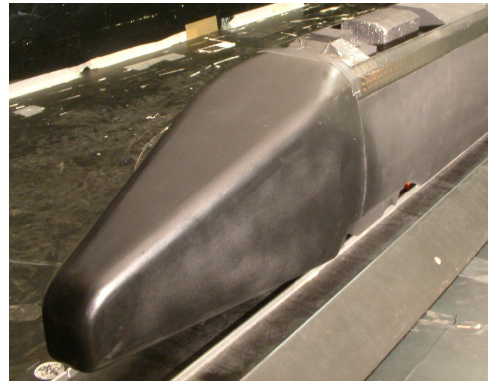
Quiz

BOMBARDIER

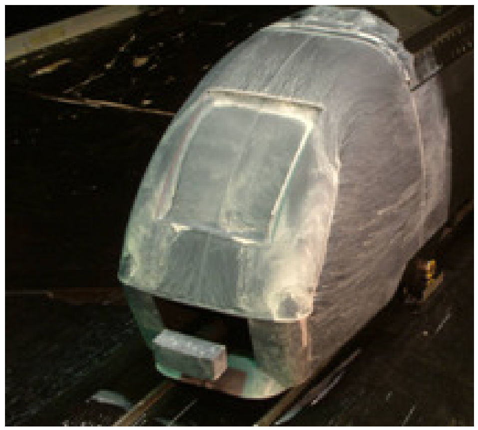
Drag: which head is the best / which one is the worst ??

1

2

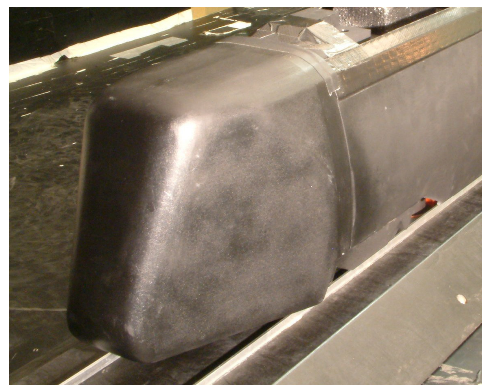


reference



0

3



4

BOMBARDIER

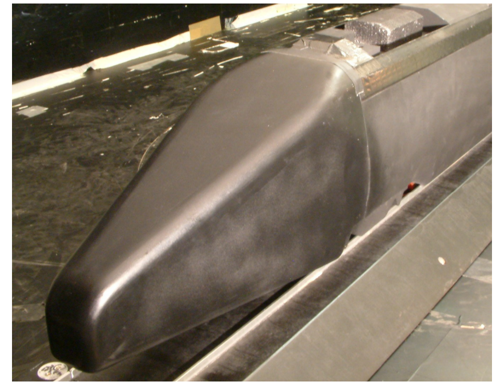
Drag: which head is the best / which one is the worst ??

1

Head: -1%

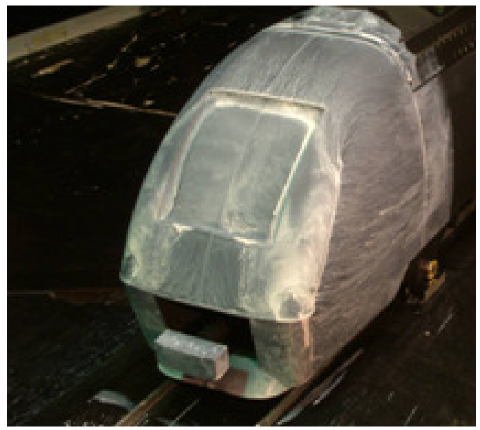
Tail: -8%

2



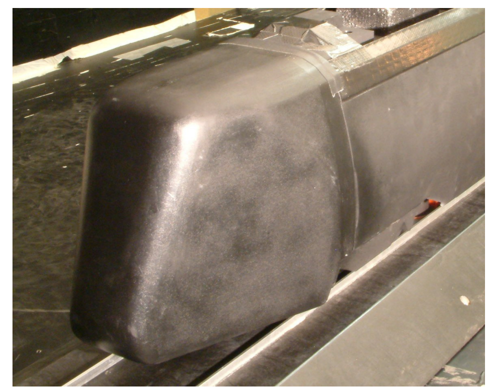
Head: 0%
Tail: -22%

reference



0

3



Head: -4%
Tail: -14%

4

Head: -2%
Tail: -14%

Contact

Bombardier

Alexander Orellano

Manager, Center of Competence for Aerodynamics & Thermodynamics

Am Rathenaupark

16761 Hennigsdorf

Germany

alexander.orellano@de.transport.bombardier.com

Thank you for your attention!!