

A 3D aerodynamic simulation of a train nose, showing streamlines and a red base. The train is white and grey, with a red base. The background is a light grey with a grid pattern.

# AeroEfficient - Optimized Train

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Trieste, May 27, 2010

Alexander Orellano  
Manager, Center of Competence for Aerodynamics & Thermodynamics  
Bombardier

**BOMBARDIER**

# Bombardier – Fields of Activity

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## Aerospace

Employees: 28,100\*



## Transportation

Employees: 31,485\*

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\*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 3.06**  
(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)

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## The climate is right for train

**Rail transportation is an eco-friendly concrete, global, and immediately available solution to today's challenges:**

- **climate change**
- **population growth**
- **highway congestion**
- **fuel costs**

**Bombardier Transportation's products and services are designed for sustainable mobility**



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# Aerodynamic Resistance - Motivation

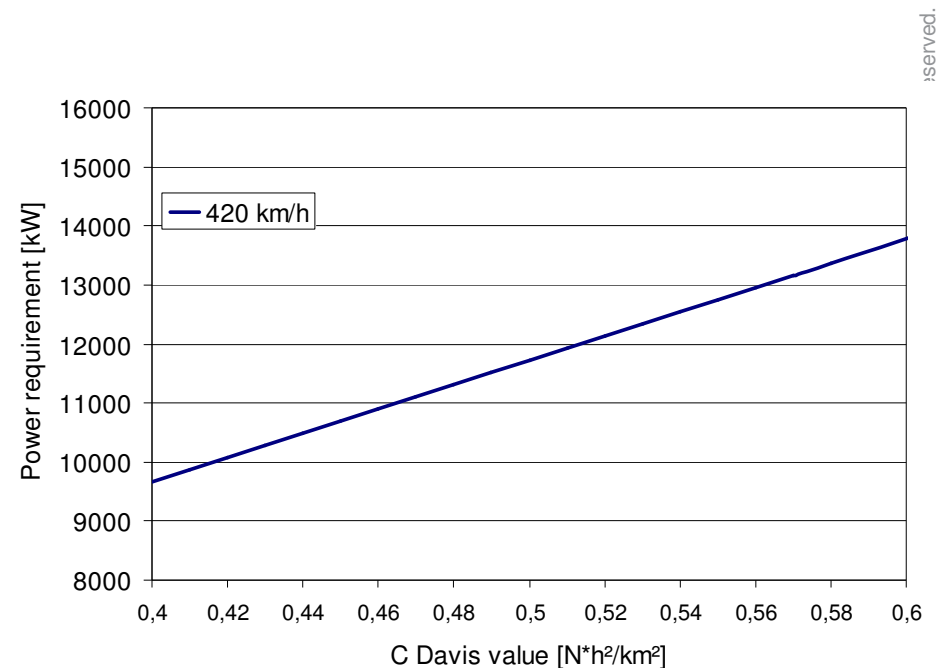
$$P_{\text{power traction}} = (c_w * A * \rho / 2) * v^3 + (m * a) * v$$

## ■ 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 by 20% reduces the energy consumption more or less by 10%



# Engineering Process

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## ■ Conventional development process:

- Iteration between engineering design and performance evaluation
- until all requirements and constraints of the train are satisfied
- This approach takes a long time to solution and the development is therefore very expensive.
- The conventional approach does not lead to the best solution in general

## ■ (Automated) optimisation:

- Controls a parameterised model that a-priori meets all constraints
- Automates and directs the iteration design - evaluation
- Aim is not just to fulfill all requirements but to deliver the best solution with given constraints related to pre-selected objectives

# Validation of Aerodynamic Drag Process for ZEFIRO

## R&D 2008

$c_D$ of the "BD" design	CFD (date Sept. 2008)	Experiment , HFI_CW38_2008	Exp / CFD	corrected measurement data
all 3 cars	0.425	0.430	1.01	0.430

### ■ Validation

- The drag of a 3 car model has been compared to the experiment of the same 3 car model
- The resulting difference of 1% is smaller then the error of the experiment

### ■ Conclusion:

- The CFD setup is validated

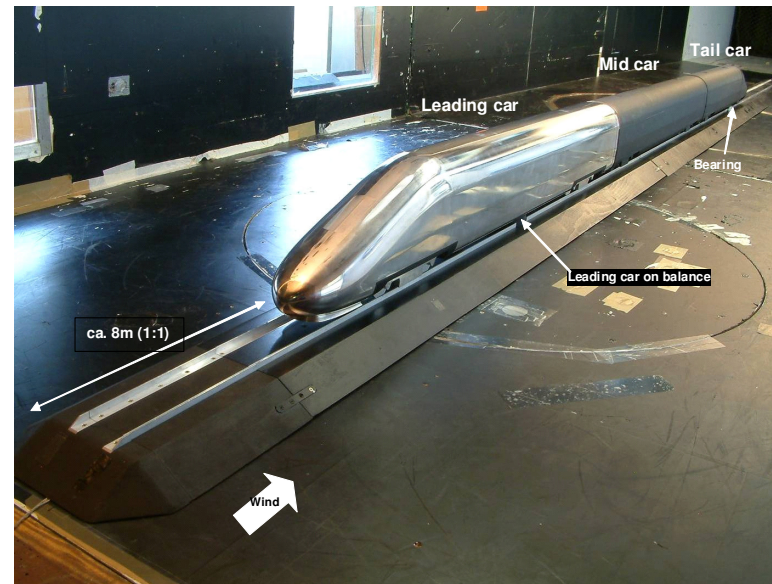
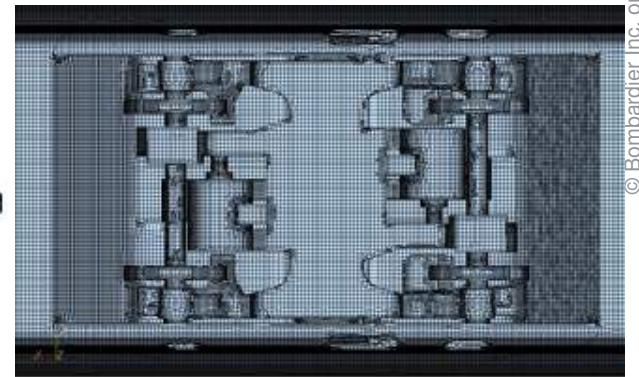
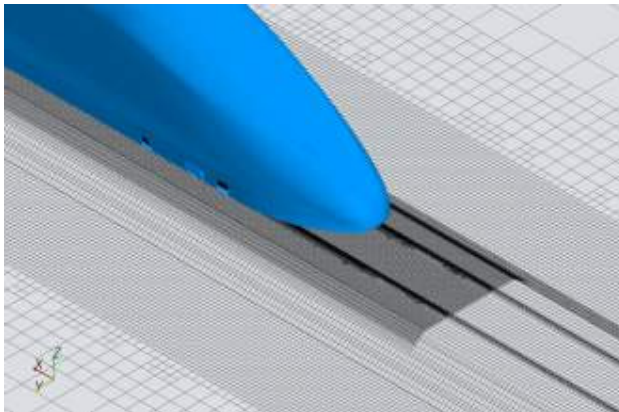
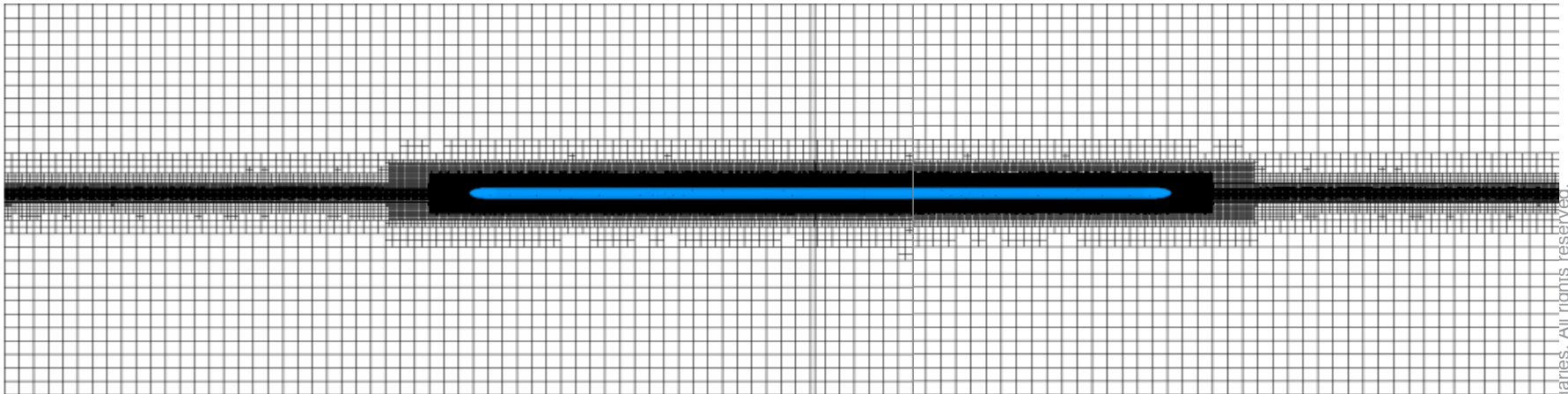


Figure 1, general view of drag measurement, first car on external balance, trailing cars coupled and supported on low friction steel wheels

# Computational Mesh and Domain: 289 mio. vertices

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# AeroEfficient - Computer Aided Optimisation

- **AeroEfficient Train Shape Optimization uses state-of-the-art computer-aided engineering (CAE) tools**

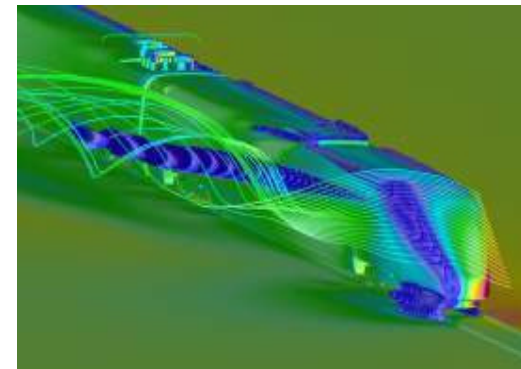
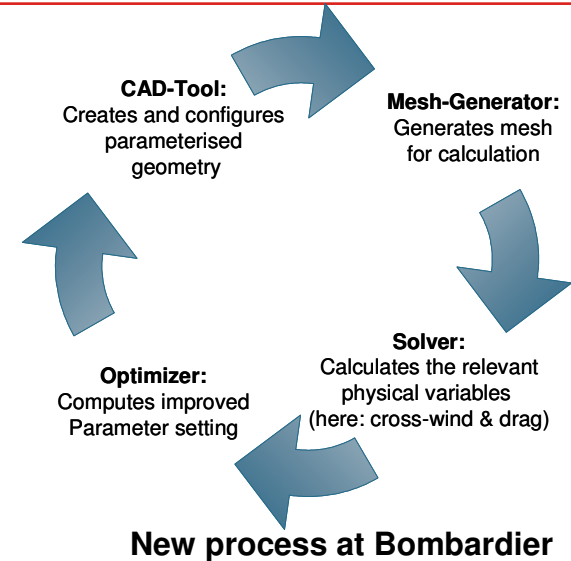
- Reducing aerodynamic drag saves up to 8 % of energy of regional trains and 15 % of high speed trains.
- Limiting drag and maximizing stability also increase acceleration, which reduces traveling time.

- **AeroEfficient train optimization is based on genetic algorithms that use**

- Parameterized, three-dimensional CAD models
- Simulation of aerodynamic drag and cross-wind stability
- Optimization software to determine Pareto optimal solutions

- **AeroEfficient technology takes into account constraints such as**

- crash structure
- industrial design
- ergonomic limits of the cab



**Zefiro China driving under cross-wind conditions**

# Optimisation - Details

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- **CAD – generation and manipulation of the model**
  - Digital 3D representation of the model (also used for windtunnel experiments)
  - CATIA V5 for explicit parameterization of the model
  
- **CFD – evaluation of the objective function**
  - Prepares the model for evaluation
  - Determines aerodynamics characteristics of the model
  - High computational costs
  - Accurate evaluation may take up to several days
  
- **Integrator and driver of the optimisation**
  - ModeFrontier – optimisation Software

# Optimisation Constraints

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## ■ Immediate restrictions by required

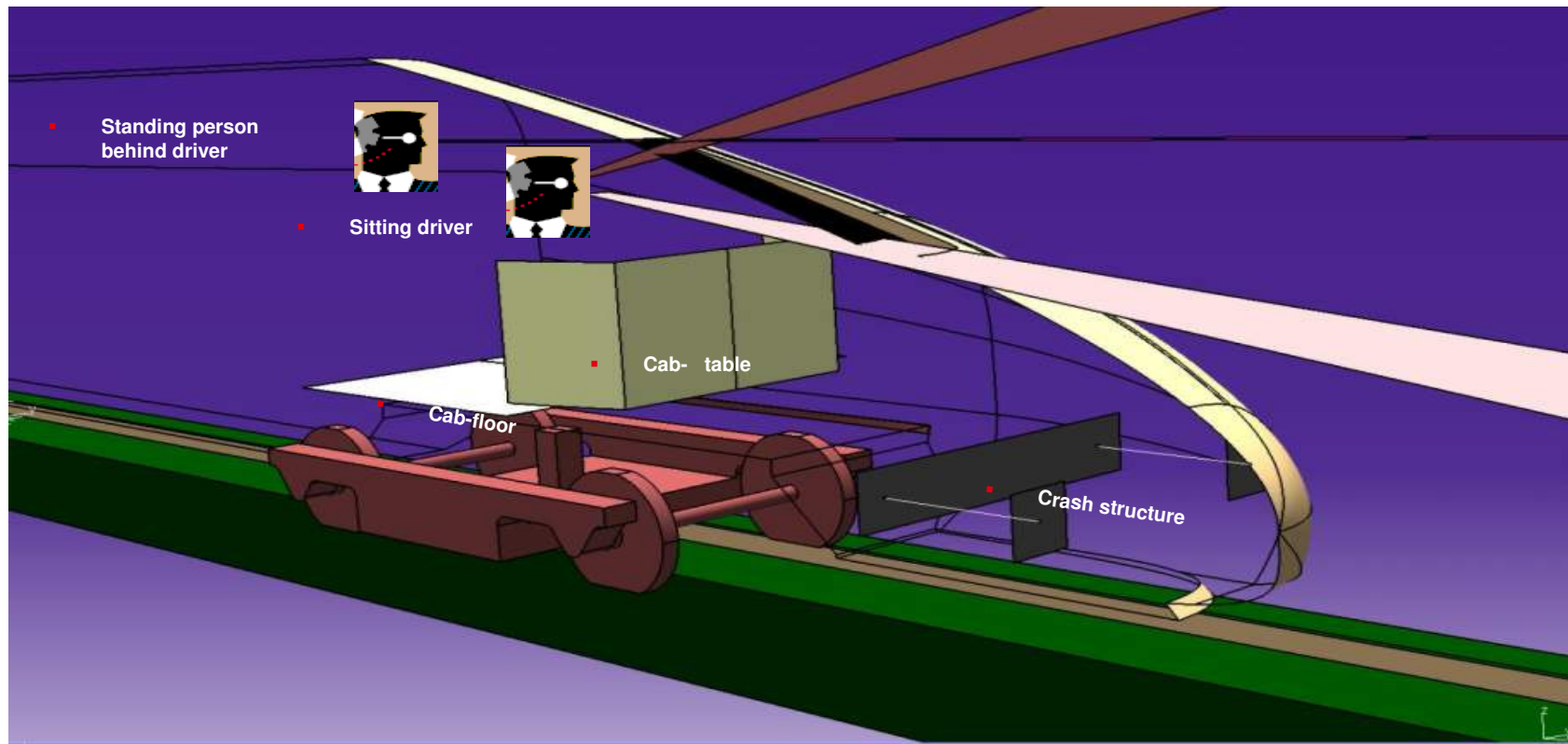
- integration of the crash structure and
- roof equipment like brake resistors, pantographs and clima comfort
- compliance with the predefined enveloping profile
- size and position of the windscreen to facilitate certain view angles

## ■ Further issues

- High passenger capacity conflicts with optimal aerodynamic shape
- Comfort of driver and passengers
- Elegancy vs. functionality ( designer vs. engineer )

# The Model

- A-priori integrates crash-structure and wind screen
- Further constraints met by restrictions on the parameters

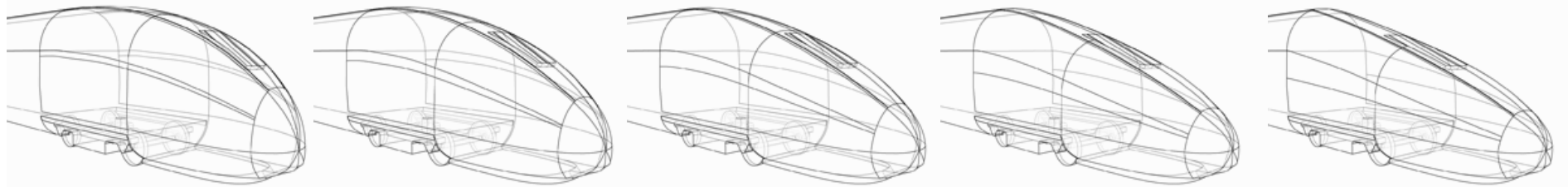


# The design variables

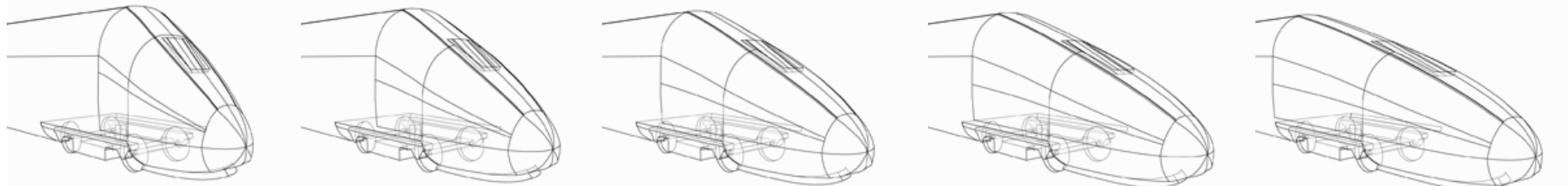
- 15 of 60 possible parameters were chosen to be optimised

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

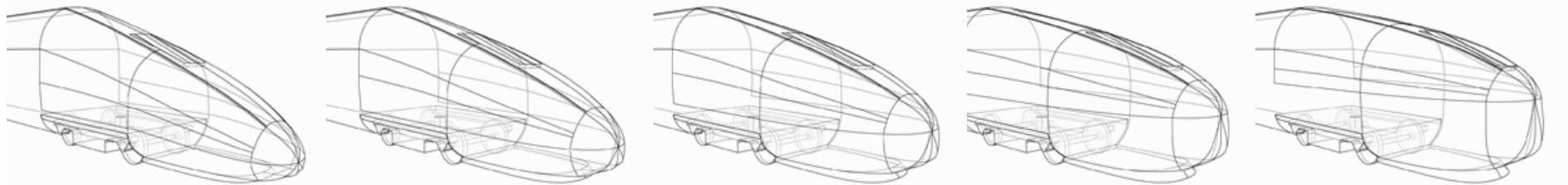
# Examples for Model Variability (3 parameters out of 60)



**bluff\_frontpart**



**nose\_shrinking**



**nosetip\_height**

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# Optimisation strategy for the Zefiro High Speed Train

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## 1. Optimise for drag

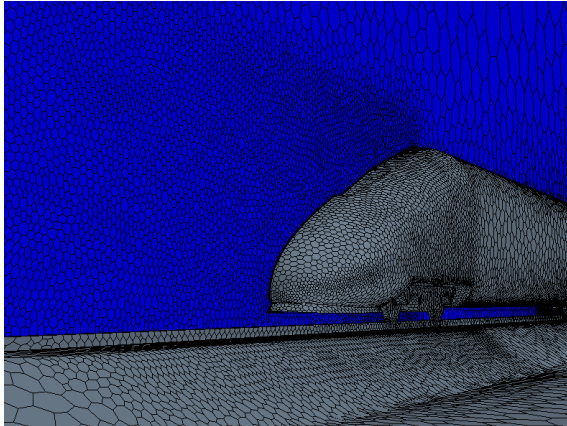
- Less aerodynamical drag means less energy consumption
- Drag sells – the less the better

## 2. Identify and fix the most dominant parameters

## 3. Optimise for cross wind stability

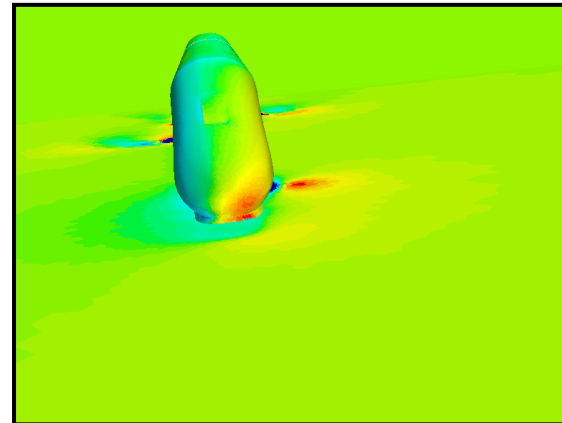
- Actually only the specifications have to be fulfilled and could be integrated into the drag optimisation loop as a constraint
- But the final masses of the train were not defined at that point of time
- If necessary a better cross wind performance requires less additional weight

# Drag and Cross-Wind Optimisation



## ■ Drag

- Setup: train cruising with 350 km/h in open field
- Objective function: drag coefficient
- Evaluated in CFD code (Star-CCM+)
- Using a grid of ~700 000 cells
- ~ 5 h per Iteration on 4 CPUs
- Optimised with MOGA2



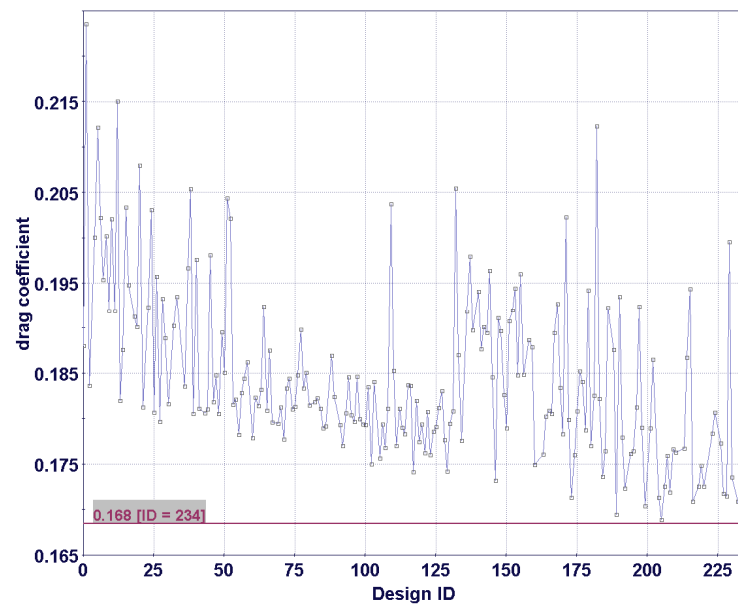
## ■ Cross-Wind

- Setup: train cruising with 300 km/h and a perpendicular crosswind of 109.2 km/h
- Goal function: Crosswind Stability
- Evaluated in an inhouse Matlab tool on the base of force coefficients estimated in StarCCM+
- 700 000 cells, ~ 6 h / iteration

# Optimisation History

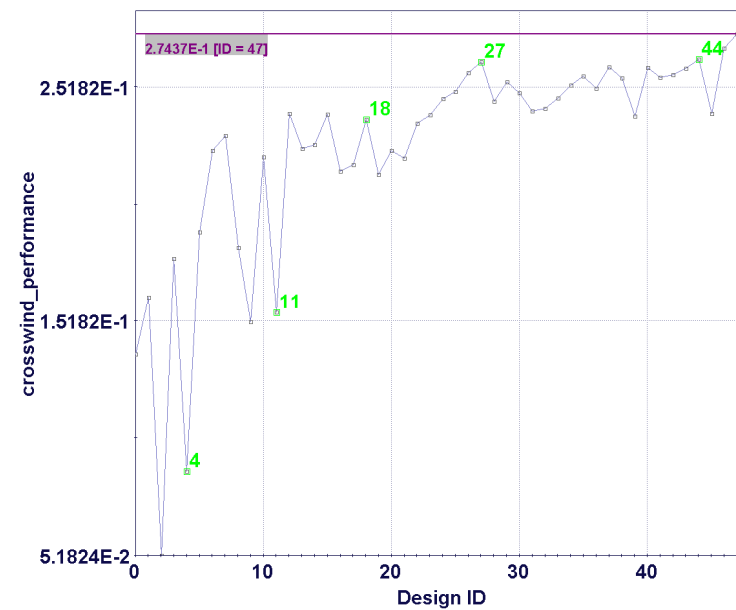
## ■ Drag

- 234 iterations
- Best to worst design: ~ 25 %



## ■ Cross-wind

- Best cross-wind design does not correspond with best drag design



# Single-objective optimisation

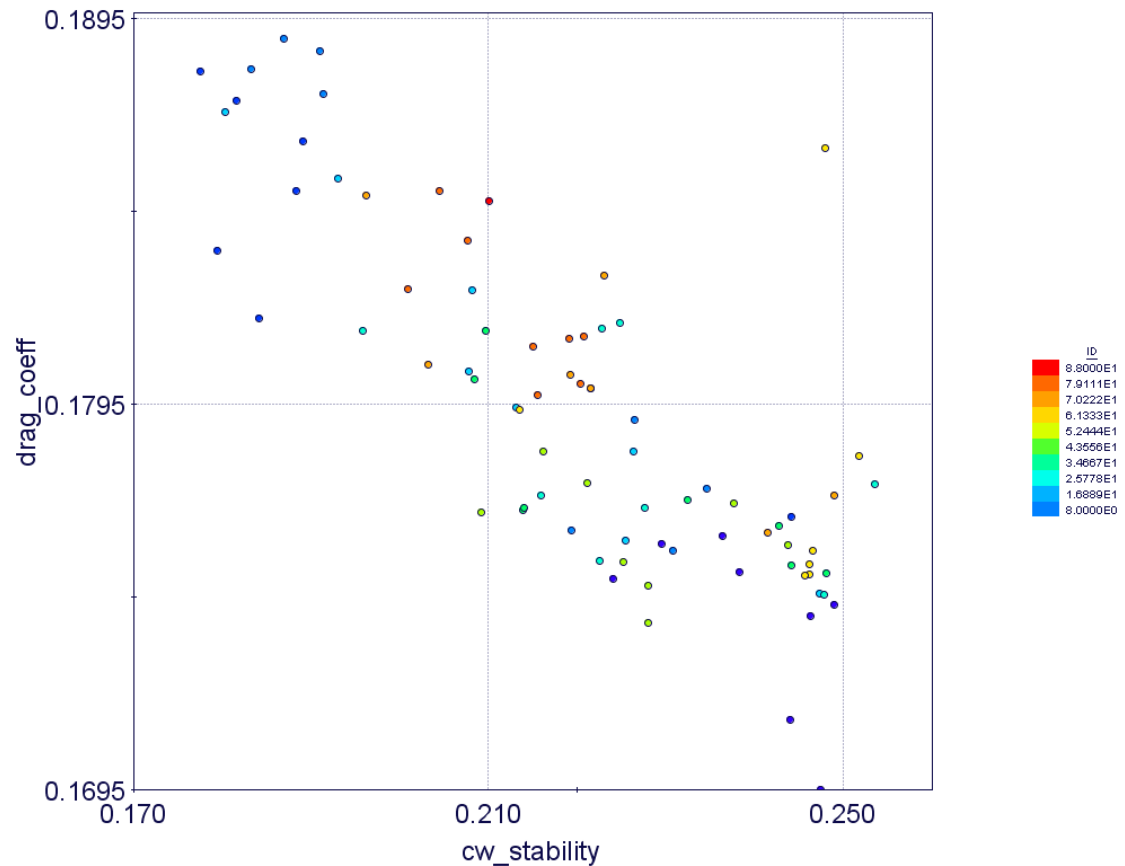
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- **Two single objective optimizations were run regarding drag and cross-wind performance**
- **Result: the best models for drag do not have a good crosswind stability, and vice versa**
- **Therefore: multi-objective optimization is necessary, that 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
- **And high computational costs ( ~7h per iteration on 7 CPUs )**

# Multi-Objective Optimisation

## ■ Multi-objective optimization means

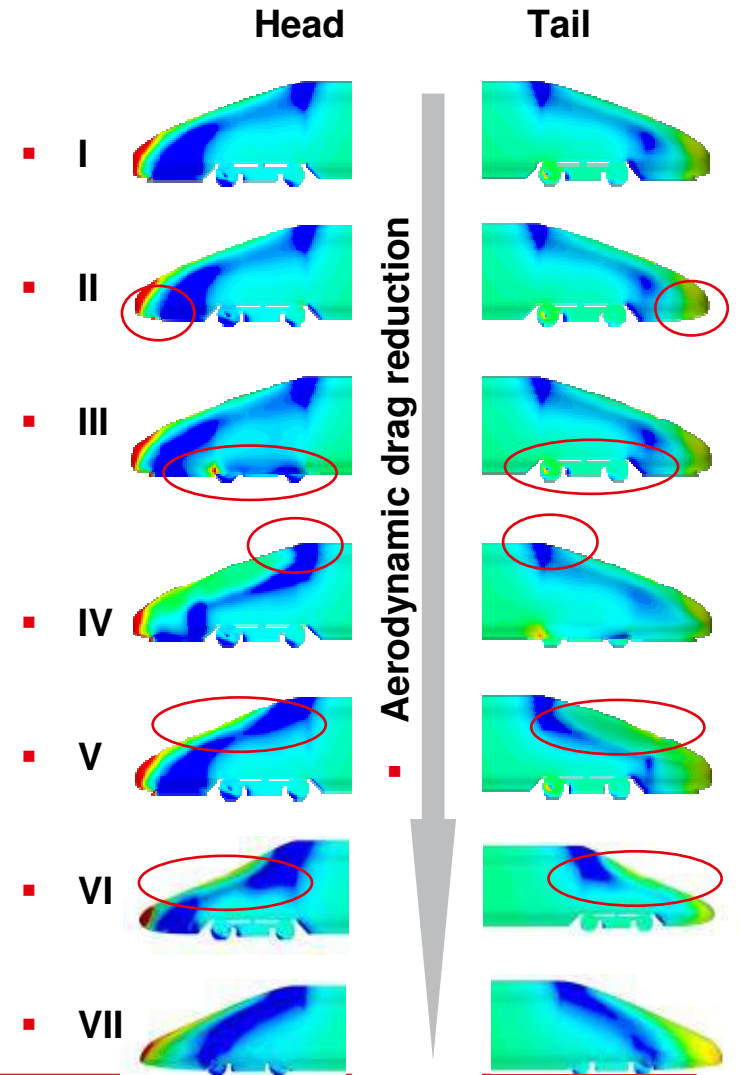
- Significant rise of the number of iterations
- Directed search algorithms like SIMPLEX or gradient methods are not applicable
- Generic algorithms are suitable
- Result is a cluster of pareto-optimal designs, but no unique solution
- $\sim 173 * 7 \text{ h} * 7 \text{ CPUs} = 8477 \text{ CPU hours}$



# High Performance Computation - Examples

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

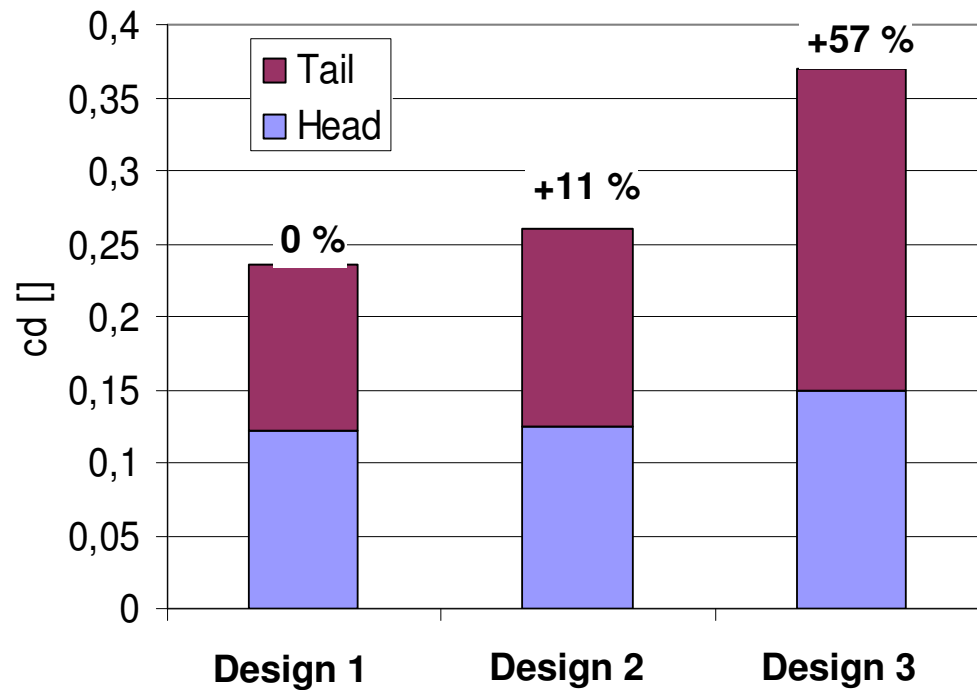
- I → II: spoiler variation
- I → III: bogie fairings
- I → IV: carbody front transition
- I → V: more slender nose
- I → VI: duck nose
- VII: ZEFIRO China Design



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# Benchmark of the Front Design – Internal Products



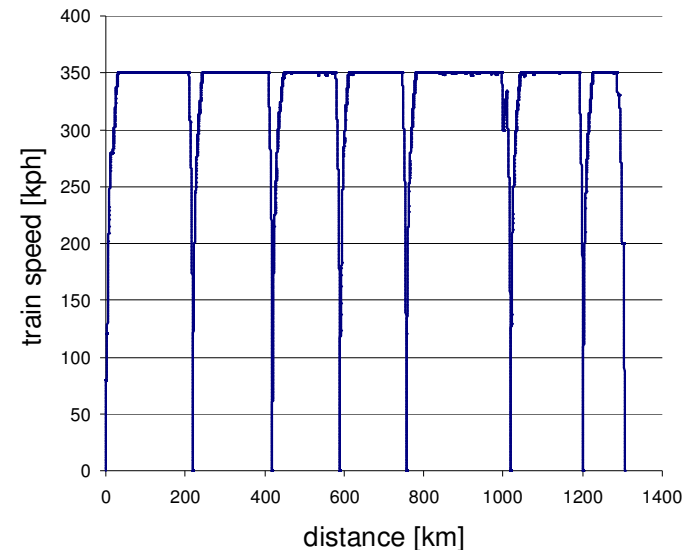
- **ZEFIRO Performance**
  - ZEFIRO exhibits the best aerodynamic performance of all high-speed trains world wide

# 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 [km]	Run Time [h:m:s]	Stop Time [h:m:s]	Total Time [h:m:s]	Avg Speed [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



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

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AeroEfficient Impact	without AeroEfficient	with AeroEfficient
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

# Conclusions

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- **New methods related to optimisation of aerodynamic performance are available**
- **Those methods are mature enough to be used in an industrial context**
- **The application of this method to Bombardiers high-speed trains leads to a competitive product related to**
  - Energy efficiency
  - Lower costs due to lower traction power dimensioning