AeroEfficient - Optimized Train

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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 3.06** (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)
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
Aerodynamic Resistance - Motivation

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

- **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

- 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

<table>
<thead>
<tr>
<th>$c_D$ of the “BD” design</th>
<th>CFD (date Sept. 2008)</th>
<th>Experiment, HFI_CW38_2008</th>
<th>Exp / CFD</th>
<th>Corrected measurement data</th>
</tr>
</thead>
<tbody>
<tr>
<td>all 3 cars</td>
<td>0.425</td>
<td>0.430</td>
<td>1.01</td>
<td>0.430</td>
</tr>
</tbody>
</table>

- 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 than 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
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

New process at Bombardier

Zefiro China driving under cross-wind conditions
Optimisation - Details

- **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

- 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>chamfer</td>
<td>chamfering the edges of the bogie cut-out</td>
</tr>
<tr>
<td>intercar_gaps</td>
<td>height of the gap between the wagons</td>
</tr>
<tr>
<td>nose_shrinking</td>
<td>distance to maximal permissible nose length</td>
</tr>
<tr>
<td>blunt_nosetip_down</td>
<td>bluntness of the nose (side view)</td>
</tr>
<tr>
<td>less_uppity</td>
<td>controls how strong the nose front is directed to the ground</td>
</tr>
<tr>
<td>blunt_nose_horizontal</td>
<td>bluntness of the nose (top view)</td>
</tr>
<tr>
<td>bluff_frontpart</td>
<td>controls the inclination of the profile at the transition between nose and car body. A high value results in a bluff frontpart.</td>
</tr>
<tr>
<td>nosetip_height</td>
<td>vertical position of the nosetip</td>
</tr>
<tr>
<td>skirt_reduction</td>
<td>relative size of the skirts at the bogies</td>
</tr>
<tr>
<td>spoiler_inclination</td>
<td>inclination of the spoiler</td>
</tr>
<tr>
<td>spoiler_nose_distance</td>
<td>distance between nose tip and spoiler</td>
</tr>
<tr>
<td>nose_start</td>
<td>point of the transition between car body and nose, the lower the value the more space the nose actually occupies</td>
</tr>
<tr>
<td>A-pillar_roundness</td>
<td>roundness of the A-pillar, defined at the nose tip</td>
</tr>
<tr>
<td>step_height</td>
<td>height of the separation step</td>
</tr>
<tr>
<td>roof_edginess</td>
<td>curvature of upper edge of the wagon, also affects the A-pillar</td>
</tr>
</tbody>
</table>
Examples for Model Variability (3 parameters out of 60)

- bluff_frontpart
- nose_shrinking
- nosetip_height
Optimisation strategy for the Zefiro High Speed Train

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

- 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 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
- \( \sim 173 \times 7 \text{ h} \times 7 \text{ CPUs} = 8477 \text{ CPU hours} \)
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

Aerodynamic drag reduction
Benchmark of the Front Design – Internal Products

- **ZEFIRO Performance**
  - ZEFIRO exhibits the best aerodynamic performance of all high-speed trains worldwide.
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

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>South BeiJing</td>
<td>0.00</td>
<td>00:00:00</td>
<td>00:00:00</td>
<td>00:00:00</td>
<td>0.0</td>
</tr>
<tr>
<td>West CangZhou</td>
<td>219.20</td>
<td>00:42:22</td>
<td>00:01:00</td>
<td>00:43:22</td>
<td>310.4</td>
</tr>
<tr>
<td>West passenger station JiNan</td>
<td>419.40</td>
<td>00:37:50</td>
<td>00:01:00</td>
<td>01:22:12</td>
<td>317.5</td>
</tr>
<tr>
<td>East TengZhou</td>
<td>589.13</td>
<td>00:32:46</td>
<td>00:01:00</td>
<td>01:55:58</td>
<td>310.8</td>
</tr>
<tr>
<td>East SuZhou</td>
<td>756.43</td>
<td>00:32:15</td>
<td>00:01:00</td>
<td>02:29:13</td>
<td>311.2</td>
</tr>
<tr>
<td>South NanJing</td>
<td>1018.55</td>
<td>00:48:40</td>
<td>00:01:00</td>
<td>03:18:53</td>
<td>323.2</td>
</tr>
<tr>
<td>East WuXi</td>
<td>1201.15</td>
<td>00:34:49</td>
<td>00:01:00</td>
<td>03:54:42</td>
<td>314.7</td>
</tr>
<tr>
<td>Shanghai</td>
<td>1305.07</td>
<td>00:21:51</td>
<td>00:00:00</td>
<td>04:16:33</td>
<td>285.4</td>
</tr>
</tbody>
</table>
9% Traction Energy Reduction with AeroEfficient Technology for Zefiro 380 for China

<table>
<thead>
<tr>
<th>AeroEfficient Impact</th>
<th>without AeroEfficient</th>
<th>with AeroEfficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motoring energy at rail</td>
<td>29.670.000</td>
<td>27.320.000</td>
</tr>
<tr>
<td>Braking energy at rail</td>
<td>4.327.000</td>
<td>4.400.000</td>
</tr>
<tr>
<td>Regenerated energy to line</td>
<td>2.583.000</td>
<td>2.637.000</td>
</tr>
</tbody>
</table>

- 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

- 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