Life cycle analysis of the energy consumption of a rail vehicle

Enhancing the environmental performance of rail transport – challenges, good examples, further tasks

Workshop of the Allianz pro Schiene, Hotel „Sylter Hof“, Berlin, September 19, 2006

Walter Struckl and Anton Stibersky
Siemens Transportation Systems GmbH & Co KG, Austria

Walter Gunselmann
Siemens AG, Germany
Contents

Stages of the energy life cycle of a metro vehicle
- Materials
- Technology
- Recycling

Potentials for the optimisation of the system design
- Optimisation of the speed profile
- Automatic train operation
- Energy storage

Potentials for the optimisation of the vehicle design
- Reduction of weight
- Materials
- Vehicle thermal insulation
- Direct motor

Conclusions
Energy efficiency for rail vehicles depends on …

- Vehicle design (electrical and mechanical equipment)
- Materials / raw materials
- Manufacturing
- Delivery to the customer
- Energy losses e.g. train resistance, traction system
- Maintenance
- Disassembling and recycling

.... considering the whole life cycle of a metro train.
Vehicle example: 3-car train MX for the Metro Oslo

Train configuration: MC1 + M + MC2
Car body material: aluminium
Tara weight: approx. 100 t
Max. axle load: 12.5 t
Length over couplers: 54.14 m
Width of car: 3.16 m
Number of seats: 122
Train capacity (6 pers./m²): 678 passengers
Energy consumption of a metro train. Description of the life cycle stages

- End of life
- Raw materials
- Manufacturing
- Energy expense
- Energy efficiency
- Delivery
- Training operation
- Maintenance
Energy consumption of the metro train MX for the overall life cycle and 30 years of operation

- Train operation: 90.10%
- Maintenance: 5.15%
- Delivery: 0.05%
- Raw materials: 4.23%
- Recycling: 0.41%
- Manufacturing: 0.06%
## Raw materials and their energy consumption

In this table the energy consumption for the production of the raw materials of the metro train MX (approximately 100 t of train weight) has been considered.

<table>
<thead>
<tr>
<th>Raw material</th>
<th>Energy consumption per kg raw material¹ [MJ/kg]</th>
<th>Percentage of vehicle mass</th>
<th>Energy consumption [MJ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel (low alloyed)</td>
<td>45</td>
<td>14 %</td>
<td>630 000</td>
</tr>
<tr>
<td>Steel (high alloyed)</td>
<td>70</td>
<td>37 %</td>
<td>2 590 000</td>
</tr>
<tr>
<td>Aluminium (50 % secondary)</td>
<td>96</td>
<td>31 %</td>
<td>2 976 000</td>
</tr>
<tr>
<td>Plastics (average)</td>
<td>90</td>
<td>7 %</td>
<td>630 000</td>
</tr>
<tr>
<td>Composite materials</td>
<td>100</td>
<td>3 %</td>
<td>300 000</td>
</tr>
<tr>
<td>Chemicals (average)</td>
<td>90</td>
<td>1 %</td>
<td>90 000</td>
</tr>
<tr>
<td>Glass</td>
<td>13</td>
<td>2 %</td>
<td>26 000</td>
</tr>
<tr>
<td>Copper</td>
<td>80</td>
<td>3 %</td>
<td>240 000</td>
</tr>
<tr>
<td>Wood</td>
<td>22</td>
<td>2 %</td>
<td>44 000</td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>100 %</td>
<td>7 526 000 (2.09 Mio. kWh)</td>
</tr>
</tbody>
</table>

¹ Energy values from the Department of Manufacturing Engineering, Technical University of Denmark, Lyngby, Denmark, 2000

The material percentage of the vehicle mass is derived from one car
Distribution of the raw materials for the metro vehicle MX

- Steel (low alloyed): 14%
- Aluminium: 31%
- Steel (high alloyed): 37%
- Copper: 3%
- Wood: 2%
- Grp: 3%
- Glass: 2%
- Chemicals: 1%
- Plastics: 7%
Energy consumption and percentage of mass for the raw materials

![Graph showing energy consumption and percentage of mass for various raw materials.](image)
Manufacturing

Energy consumption for manufacturing the metro train at the factory site in Vienna:

About 100,000 MJ per metro train

- Estimation per 3-car train
- Incl. utilities
- Heating
- Electricity
- Supplies

References:
Jahresbericht im Betrieblichen Umweltschutz, 2004/05, Siemens Transportation Systems, Vienna
Energy values from the Department of Manufacturing Engineering, Technical University of Denmark, Lyngby, Denmark, 2000
Delivery of the train to the customer

Energy consumption for transportation:

Per truck \(^1\): 0.5 MJ/t-km
Per train (diesel) \(^1\): 0.8 MJ/t-km
Per train (electrical) \(^2\): 0.51 MJ/t-km
Per ship \(^1\): 0.35 MJ/t-km

Example:
Distance Vienna – Oslo: 1800 km
3-car train per truck
= 90 000 MJ

\(^1\) Energy values from the *Department of Manufacturing Engineering, Technical University of Denmark, Lyngby, Denmark, 2000*

\(^2\) DB AG Umweltbericht 2002
Energy balance for the electrical equipment of the metro train MX

- Heating
- Auxiliary converter
- Auxiliary systems
- Train resistance
- Braking losses gearbox
- Braking losses motor
- Braking losses converter / impedance
- Driving losses gearbox
- Driving losses motor
- Driving losses converter / impedance
- Energy recovery
Use of the metro train MX in Oslo

Energy values according to the *Final Train Performance Metro Oslo MX (Simulation)*

- **Energy consumption per kilometre:**
  44.5 MJ

- **Energy consumption per year**
  (120 000 km):
  5 340 000 MJ

- **Energy consumption for the life-time period of 30 years:**
  160 200 000 MJ

---

1 Train weight with AW2 load =135 t; average value of summer and winter operation
Recycling behaviour of the metro train MX

<table>
<thead>
<tr>
<th>Raw material</th>
<th>Energy consumption for recycling (MJ/kg)</th>
<th>Total energy consumption for material recycling (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel (low alloyed)</td>
<td>12 material¹</td>
<td>168 000</td>
</tr>
<tr>
<td>Steel (high alloyed)</td>
<td>12 material¹</td>
<td>444 000</td>
</tr>
<tr>
<td>Aluminium (50 % secondary)</td>
<td>2.5 material (Hamburger-Aluminium Werk GmbH)</td>
<td>77 500</td>
</tr>
<tr>
<td>Glass</td>
<td>9 material (Swiss Recycling) / 50 % thermal recycling</td>
<td>9 000</td>
</tr>
<tr>
<td>Copper</td>
<td>12 material¹</td>
<td>36 000</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>734 500</td>
</tr>
</tbody>
</table>

¹ Energy values from the Department of Manufacturing Engineering, Technical University of Denmark, Lyngby, Denmark, 2000.

The material percentage of the vehicle mass is derived from one car.

The material use has been reduced to 82 % due to losses which are related to the material recycling technology.

Recycling rate = recyclable train mass / total train mass

Recycling rate = approx. 90 %

Potentials for the optimisation of the system design.
Energy-optimised speed profiles

Example: distance = 490 m, travelling time = 53 s, stopping time = 15 s

<table>
<thead>
<tr>
<th></th>
<th>Travelling time</th>
<th>Stopping time</th>
<th>Energy consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>48 s</td>
<td>20 s</td>
<td>6.0 MJ</td>
</tr>
<tr>
<td>Optimised</td>
<td>53 s</td>
<td>15 s</td>
<td>4.3 MJ</td>
</tr>
</tbody>
</table>

With this optimised speed profile an energy saving of up to 25 % would result.
Potentials for the optimisation of the system design. Automatic train operation

Benefits from an operational concept of an automated metro can be:

- Implementation of an optimised speed profile.
- Flexible adaptation of the transport capacity on demand.
- Higher line capacity due to shorter distances between trains.
Potentials for the optimisation of the system design. Energy storage with Sitras SES

- Optimised recovery of the braking energy of the vehicles
- Well balanced power consumption
- Stabilisation of traction voltage
- Reduction of power peaks
- References in Germany, Spain and in the United States

Energy exchange between vehicles using a storage unit

Energy storage unit absorbs energy
Potentials for the optimisation of the vehicle design. 
Vehicle example: 3-car train for the Metro Kaohsiung

Train configuration: DM + T + DM
Car body material: stainless steel
Tara weight: 117.3 t
Max. axle load: 16.1 t
Length over couplers: 65.45 m
Width of car: 3.15 m
Number of seats: 126
Train capacity (6 pers. / m²): 771 passengers
Potentials for the optimisation of the vehicle design. Comparison of vehicles in use (3-car trains)

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Oslo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car body material</td>
<td>Stainless steel</td>
<td>Aluminium profile, open</td>
<td>Aluminium profile, closed</td>
<td>Aluminium profile, closed</td>
</tr>
<tr>
<td>Tara weight [t]</td>
<td>117</td>
<td>107</td>
<td>109</td>
<td>100</td>
</tr>
<tr>
<td>Maximum speed [km/h]</td>
<td>80</td>
<td>90</td>
<td>120</td>
<td>70</td>
</tr>
<tr>
<td>Distance between bogies [m]</td>
<td>14.8</td>
<td>15.8</td>
<td>12.6</td>
<td>11.0</td>
</tr>
</tbody>
</table>

For the comparison of vehicles also the different requirements have to be considered (e.g. crashworthiness).

However, in general it can be stated that the material aluminium enables lighter car body structures.

In recent years GTO technology has been followed by IGBT converters for traction application. For the metro vehicle MX the use of IGBT technology leads to a remarkable weight reduction.
Potentials for the optimisation of the vehicle design.
Examples of the energy consumption of raw materials

For the vehicles compared it can be stated:
The raw material for car body structures made out of stainless steel is about 54 % more energy efficient compared to aluminium.

If secondary aluminium with a content of 50 % primary aluminium is used for the car body structure, this advantage of stainless steel is reduced to 5 % difference in energy consumption of raw materials.
Potentials for the optimisation of the vehicle design.
Vehicle example: 4-car train for the Vienna Underground

Train configuration: TR + MC + MC + TR  
Car body material: aluminium  
Tara weight: 109.2 t

Max. axle load: 11.5 t  
Length over couplers: 74.72 m  
Width of car: 2.85 m  
Number of seats: 172  
Train capacity (6 pers. / m²): 782 passengers
Potentials for the optimisation of the vehicle design.
Vehicle thermal insulation (1)

Metro vehicles (stainless steel structure): calculated k-values

<table>
<thead>
<tr>
<th>Metro vehicle</th>
<th>Heat transition coefficient [W/(m²K)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel, typical values</td>
<td>1.9 – 2.2</td>
</tr>
<tr>
<td>Kaohsiung</td>
<td>approx. 2</td>
</tr>
</tbody>
</table>
Vehicle thermal insulation (2)

Metro vehicles (aluminium structure): measured k-values (climatic wind tunnel)

<table>
<thead>
<tr>
<th>Metro vehicle</th>
<th>Heat transition coefficient [W/(m²K)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium, typical values</td>
<td>2.4 – 3.25</td>
</tr>
<tr>
<td>Oslo MX, measured</td>
<td>2.95</td>
</tr>
</tbody>
</table>

General statements:

- The k-value of aluminium vehicles is higher than the k-value for vehicles made of stainless steel.
- Critical components: doors, windows, gangways between cars

Source: Oslo Sporveier
Potentials for the optimisation of the vehicle design.
Direct motor

**State-of-the-art**
Asynchronous motor with gearbox

- Efficiency factor: 93 %
- Mass: 100 %
- Noise: 105 dB(A)
- Gearbox: lubricated

**Innovation**
Gearless permanent magnet motor

- Efficiency factor: 96 %
- Mass: -30 %
- Motor: -10 %
- Gear / coupling: -20 %
- Noise: 90 dB(A)
- Gearbox: not necessary
Conclusions

- Siemens products and solutions are distinguished by high energy efficiency, helping to protect both environment and health.

- We have set ourselves the target of designing, developing, manufacturing and operating our trains so as to protect the environment and human health to the highest possible extent.

- The stages of the energy life cycle and their share of the overall consumption have been given for the new metro vehicle MX for Oslo as an example. Environmental performance indicators for the metro train and its operation have been presented.

- Future potentials for the optimisation of the vehicle design and operational concept have been discussed.