Assessment methods of High Capacity Transports

Bengt Jacobson, Vehicle Dynamics, Chalmers University of Technology, Göteborg, Sweden
1. We need goods transport. Some of it on roads.

2. HCTs is a “low-hanging fruit” for CO₂ savings.

3. Assessment of novel Long Combination Vehicles.

from Karel Kural, PhD thesis:
My present involvement in Assessment of HCT

[https://research.chalmers.se/en/project/8350](https://research.chalmers.se/en/project/8350)

project: **Performance Based Standards 2, PBS2, 2018-2020**

- Chalmers University of Technology, Gothenburg, Sweden
- Nokian Tyres, Finland
- Parator Industri, Bollnäs, Sweden
- Scania, Södertälje, Sweden
- Swedish Transport Administration, Borlänge, Sweden
- Swedish Transport Agency, Norrköping, Sweden
- Swedish National Road and Transport Research Institute (VTI), Linköping, Sweden
- University of Oulu, Oulu, Finland
- Volvo Group, Gothenburg, Sweden

<table>
<thead>
<tr>
<th>WP1 – Tire Modelling</th>
</tr>
</thead>
<tbody>
<tr>
<td>WP2 – Heavy vehicle experiments</td>
</tr>
<tr>
<td>WP3 – Road network categorization</td>
</tr>
<tr>
<td>WP4 – Simulations</td>
</tr>
<tr>
<td><strong>WP5 – PBS Assessment.</strong></td>
</tr>
<tr>
<td>WP6 – International cooperation and knowledge spreading</td>
</tr>
<tr>
<td>WP7 – Project management</td>
</tr>
</tbody>
</table>
How can HCT save CO₂?

\[ m \cdot \dot{v} = F_{\text{prop}} + F_{\text{brk}} - m \cdot g \cdot RRC + m \cdot g \cdot \varphi_{\text{grade}} - \frac{\rho A c_d}{2} \cdot v^2; \quad \text{where} \quad m = m_{\text{kerb}} + m_{\text{load}}; \]

- fewer kerb weights
- less grade and rolling resistance
- fewer front areas
- less air resistance

...and even more reduction of CO₂ per m³ ⋅ km:

<table>
<thead>
<tr>
<th>TRANSPORTATION OF 600 M³ OF VOLUME LIMITED GOODS WITH THE SAME DENSITY (150KG/M³)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vehicles (and drivers)</strong></td>
</tr>
<tr>
<td>Vehicle length</td>
</tr>
<tr>
<td>Load per vehicle</td>
</tr>
<tr>
<td>Fuel consumption</td>
</tr>
<tr>
<td>CO₂ emissions</td>
</tr>
<tr>
<td>Road use</td>
</tr>
</tbody>
</table>

Source: Cider L, Larsson L, HCT DUO2-project Gothenburg-Malmö in Sweden, 2019
Special HCT assessment? What “(Traffic) Risks” do we see?

Today: Each vehicle unit separately approved. Automatically OK to couple some, e.g. one Tractor + one SemiTrailer.

So, what can be “risks” when combining more of approved units?

Traffic Flow
- Stuck in uphill ⇒ Startability
- Slow in uphill ⇒ Gradeability
- Slow on entry/exit roads ⇒ Acceleration Capability)
- ...⇒ Low Speed Swept Path
- ...⇒ Frontal Swing
- ...⇒ Tail Swing
- ...⇒ Friction demand on Drive Tyres
- ...⇒ Friction demand on Steering Tyres
- ...⇒ Tracking Ability on a Straight Path

Traffic Safety
- ...⇒ High Speed Steady State Off Tracking
- ...⇒ Steady State Rollover Threshold
- ...⇒ Load Transfer Ratio
- ...⇒ High Speed Transient Off Tracking
- ...⇒ Yaw Damping
- ...⇒ Rearward Amplification
- ...⇒ Braking Stability in a Turn
- ...⇒ Coupling Forces

Each bullet is "Traffic Risk ⇒ PBS".

Each PBS is motivated by one Traffic Risk, which we think is not handled by approval of the single units.

We strictly define one (PBS) measure for each risk and set a numerical min/max requirement.
Different assessment methods and PBS
How can we assess HCT?

**PBS** (for all PBSes: $Measures_i > Requirement_i$):
- Strict agreements on measures
- Real vehicle test
  - Expensive, poor repeatability, difficult to vary operation parameters, such as road friction
- or Virtual test (computation, simulation)
  - Authorized “assessors” with their own models
  - or Anyone compute with agreed open models
- How to get parameter values?

**Prescriptive:**
- “Blue prints”
- Envelops in table format

**Statistics from real use:**
- Assess each Individual vehicle
- Assess each Transport operator

**Warning:** An assessment method can reduce incentive for technology developments!
January 2019, Finland allows: **34.5 m 76 ton**, on whole road network, except some bridges and intersection. Assessed by test and simulation. Using regression ⇒ “PBS-based envelope-table”.

**Table 6. Example of the parameter study results, measures in mm.**

<table>
<thead>
<tr>
<th>Semi-trailer wheel-base</th>
<th>Full trailer wheel-base</th>
<th>Coupling under hang</th>
<th>Coupling from the bogie</th>
<th>Yaw rate rearward amplification [RA] Drawbar length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Draws</td>
</tr>
<tr>
<td>8108</td>
<td>200 2592</td>
<td>2.36 2.35 2.33 2.31</td>
<td>2.29 2.28 2.26 2.25</td>
<td>2.22 2.21 2.20 2.19</td>
</tr>
<tr>
<td>8282</td>
<td>200 2592</td>
<td>2.30 2.29 2.27 2.25</td>
<td>2.23 2.22 2.20 2.19</td>
<td>2.16 2.15 2.13 2.11</td>
</tr>
<tr>
<td>8457</td>
<td>200 2592</td>
<td>2.24 2.23 2.21 2.19</td>
<td>2.18 2.16 2.15 2.13</td>
<td>2.11 2.10 2.08 2.06</td>
</tr>
<tr>
<td>8018</td>
<td>200 2592</td>
<td>2.19 2.17 2.16 2.14</td>
<td>2.12 2.11 2.10 2.08</td>
<td>2.06 2.05 2.04 2.03</td>
</tr>
<tr>
<td>8031</td>
<td>200 2592</td>
<td>2.15 2.14 2.13 2.11</td>
<td>2.10 2.09 2.08 2.06</td>
<td>2.04 2.03 2.02 2.01</td>
</tr>
<tr>
<td>8085</td>
<td>200 2592</td>
<td>2.13 2.12 2.11 2.09</td>
<td>2.07 2.06 2.05 2.03</td>
<td>2.01 2.00 1.99 1.97</td>
</tr>
<tr>
<td>8880</td>
<td>200 2592</td>
<td>2.08 2.07 2.06 2.04</td>
<td>2.03 2.02 2.01 1.99</td>
<td>1.97 1.95 1.93 1.91</td>
</tr>
<tr>
<td>9154</td>
<td>200 2592</td>
<td>2.04 2.02 2.01 1.99</td>
<td>1.97 1.95 1.93 1.91</td>
<td>1.89</td>
</tr>
</tbody>
</table>

High rearward amplification, RA > 2

Open-loop lane change test according to ISO 3471 F = 0.40 Hz ja v = 80 km/h
<table>
<thead>
<tr>
<th>No.</th>
<th>Australian PBS Measure</th>
<th>Current EU-Legislation</th>
<th>Proposed EU legislative principles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Startability</td>
<td>R No 1230/2012 - Min. slope</td>
<td>R No 1230/2012 - Min. slope</td>
</tr>
<tr>
<td>2</td>
<td>Gradeability</td>
<td>R No 1230/2012 - Min. engine power</td>
<td>R No 1230/2012 - Min. engine power</td>
</tr>
<tr>
<td>3</td>
<td>Acceleration capability</td>
<td>R No 1230/2012 - Min. engine power</td>
<td>R No 1230/2012 - Min. engine power</td>
</tr>
<tr>
<td>4</td>
<td>Tracking ability</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>5</td>
<td>Directional braking stability</td>
<td>R No 661/2009 - Braking stability</td>
<td>R No 661/2009 - Braking stability</td>
</tr>
<tr>
<td>6</td>
<td>Overtaking provision</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>7</td>
<td>Low-speed swept path width</td>
<td>D 97/27 EC - Max. swept area</td>
<td>D 97/27 EC - Max. swept area</td>
</tr>
<tr>
<td>8</td>
<td>Steer tyre friction demand</td>
<td>R No 1230/2012 - Min. steer axle load</td>
<td>R No 1230/2012 - Min. steer axle load</td>
</tr>
<tr>
<td>9</td>
<td>Frontal swing</td>
<td>N/A</td>
<td>Use Australian definition</td>
</tr>
<tr>
<td>10</td>
<td>Tail swing</td>
<td>D 97/27 EC - Tail swing</td>
<td>D 97/27 EC - Max. tail swing</td>
</tr>
<tr>
<td>11</td>
<td>Static rollover threshold</td>
<td>N/A</td>
<td>Use Australian definition</td>
</tr>
<tr>
<td>12</td>
<td>Rearward amplification</td>
<td>N/A</td>
<td>Use Australian definition</td>
</tr>
<tr>
<td>13</td>
<td>Yaw damping</td>
<td>N/A</td>
<td>Use Australian definition</td>
</tr>
<tr>
<td>14</td>
<td>Load transfer ratio</td>
<td>N/A</td>
<td>Use New Zealand definition</td>
</tr>
<tr>
<td>15</td>
<td>High-speed transient offtracking</td>
<td>N/A</td>
<td>Use Australian definition</td>
</tr>
<tr>
<td>16</td>
<td>Handling quality</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>17</td>
<td>Pavement vertical loading</td>
<td>D 96/53/EC - Max. axle load</td>
<td>D 96/53/EC - Max. axle load</td>
</tr>
<tr>
<td>18</td>
<td>Pavement horizontal loading</td>
<td>D 96/53/EC - Axle spacing vs. load</td>
<td>D 96/53/EC - Axle spacing vs. load</td>
</tr>
<tr>
<td>19</td>
<td>Tyre contact pressure distribution</td>
<td>D 96/53/EC - Air suspension required</td>
<td>D 96/53/EC - Air suspension required</td>
</tr>
<tr>
<td>20</td>
<td>Bridge formulae</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 2.11: Comparison of EU legislation with Australian legislation and proposal for future legislative principles.
Sweden introduced a web service (LBK) to assess individual combination vehicles when for 64 ton was allowed 2018. (Actually assesses individual “transport operations”, since $F_z$ per axle is input.)

[Image of the LBK website]

Input registration numbers of the units in order first to last.
The overall goal for 2030 is to provide the conditions so that 80% of the freight transport work on the road is carried out by HCT vehicles (the targets for 2020 are 5% and for 2025 45%) and that this means that energy consumption will be 10% lower per tonne meter than 2018.
Presently on remittance in Sweden

Vägmärke: F31.a Färdväg för långa fordonståg

Road wear
Air pollution
CO2
Accidents
Transport time

≈ 10^9€

Tabell 1. Resultat från förenklad samhällsekonomisk beräkning.

<table>
<thead>
<tr>
<th>Effektkategori</th>
<th>Samhällsekonomisk effekt</th>
<th>Effekt tidigare studie</th>
<th>Resultat, mkr</th>
<th>Känslighetsanalyt högt marknadsuppdrag, mkr</th>
<th>Känslighetsanalyt lägt marknadsuppdrag, mkr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fordonsägare eller godstransport köpare</td>
<td>177 963</td>
<td>12 916</td>
<td>15 499</td>
<td>10 333</td>
<td></td>
</tr>
<tr>
<td>Dieselskatt</td>
<td>-30 733</td>
<td>-2 231</td>
<td>-2 677</td>
<td>-1 784</td>
<td></td>
</tr>
<tr>
<td>Externa effekter</td>
<td>2 910</td>
<td>211</td>
<td>253</td>
<td>169</td>
<td></td>
</tr>
<tr>
<td></td>
<td>538</td>
<td>39</td>
<td>47</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8 382</td>
<td>608</td>
<td>730</td>
<td>487</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 040</td>
<td>221</td>
<td>265</td>
<td>177</td>
<td></td>
</tr>
<tr>
<td></td>
<td>835</td>
<td>61</td>
<td>73</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>Totalt</td>
<td>162 935</td>
<td>11 825</td>
<td>14 190</td>
<td>9 460</td>
<td></td>
</tr>
</tbody>
</table>
PBS2 project extends the LBK to longer than 24.5 m.

The initiative is called OpenPBS and has 2 front-ends:

- An “assessment front-end” with a simple user interface as in present LBK

- An “R&D front-end”, enabling download and editing of models (change any parameters, add equations and parameters to try e.g. extra propelled and steered axles).

Both front-ends are using the same dynamic models on the open format Modelica (https://modelica.org/).
So, what's the problem??

**Definition of PBSes:**
- ISO gives several selections and can be interpreted differently.
- Who agree and How?
- What more than PBSes is needed

**Model (equations):**
- How detailed is necessary? How simple is possible?

**Parameters (numeric values):**
- The vehicle registry does not include all parameters.

Consider: An assessment method can remove incentive for technology developments

- **Proposal:** First agree on which “risks”
  
  e.g. clash between unit bodies

  e.g. is roll important? is xy-planar motion enough?

  See: Santahuhta, thesis from University of Oulu, Finland, 2019.

- e.g. Rearward amplification $RA$ ratio of $\omega_z$ or $a_y$?
- and $RA = \frac{\max_t(|\omega_{iz}|)}{\max_t(|\omega_{1z}|)}$ or $\max_f\left(\frac{|H_{\delta sw-\omega_{iz}}(f)|}{|H_{\delta sw-\omega_{1z}}(f)|}\right)$?
- and is manoeuvre single sine (what $\Delta x$? what $\Delta y$?) or single lane change (what $\Delta x$? what $\Delta y$?)
- and what speed $v_x$? and what road friction $\mu$?

- e.g. suspension data, engine map, gear ratios, ...
- e.g. cornering coefficient=7.5 [N/N], ...
- e.g. should operator/driver input $F_z$ per axle or compute from max allowed gross weight and assumed CoG location
- e.g. steered axle on towed units
- e.g. control algorithm (IP!), ...
Could CO$_2$ be a PBS measure?

Euro1, Euro2, ...
Legal assessment of **engines**

CO$_2$ a future “PBS measure”? I.e., per **vehicle** (not per unit)?

...or per **operation**?

from Karel Kural, PhD thesis:

<table>
<thead>
<tr>
<th>No.</th>
<th>Societal Benefit Measure</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Carbon dioxide pollution - load-wise</td>
<td>CO$_2$/ton.km</td>
</tr>
<tr>
<td>2</td>
<td>Carbon dioxide pollution - volume-wise</td>
<td>CO$_2$/m$^3$.km</td>
</tr>
<tr>
<td>3</td>
<td>Fuel consumption - Load-wise</td>
<td>l/ton.km</td>
</tr>
<tr>
<td>4</td>
<td>Fuel consumption - Volume-wise</td>
<td>l/m$^3$.km</td>
</tr>
<tr>
<td>5</td>
<td>Transport costs - Load-wise</td>
<td>€/ton.km</td>
</tr>
<tr>
<td>6</td>
<td>Transport costs - Volume-wise</td>
<td>€/m$^3$.km</td>
</tr>
</tbody>
</table>

Table 2.12: Proposed societal benefit measures for future regulations
Design principles of “Open PBS”
Envisioned solution and top level Requirements on it

**An Open PBS Tool**
*(Open means: Free and Readable and Understandable)*

**Requirements:**
- PBSs independent of Vehicles
- Vehicles specifications (“parameters”) independent of Vehicle models (“equations”)
- Standardized format for dynamic models
## Requirements on ⇒ Concepts for an “Open PBS Tool”

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Conceptual solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Define these 3 independently from each other:</td>
<td></td>
</tr>
<tr>
<td>• PBSs (Manoeuvres &amp; Measures) (“equations &amp; parameters”)</td>
<td></td>
</tr>
<tr>
<td>• Vehicle Specs (“parameters”)</td>
<td></td>
</tr>
<tr>
<td>• Vehicle Models (“equations”)</td>
<td></td>
</tr>
<tr>
<td><strong>Physical</strong> and <strong>strict</strong> models (for adding novelties)</td>
<td><strong>DAE</strong></td>
</tr>
<tr>
<td><strong>Understandable</strong> and <strong>editable</strong> for engineers</td>
<td><strong>Modelica =&gt; R&amp;D</strong></td>
</tr>
<tr>
<td><strong>Runnable</strong> for non-experts. <strong>Scriptable</strong> for experts.</td>
<td><strong>FMI =&gt; Assessment</strong></td>
</tr>
<tr>
<td><strong>Limited parameter editable</strong> for non-experts. (In extreme: Only registration number on each of the units.)</td>
<td><strong>Modelica concepts Registry and Function</strong></td>
</tr>
</tbody>
</table>
Two tools in one...

Vehicle Specs

Vehicle Models

"R&D front-end"

"Assessment front-end"

Modelica

export

PBSs

FMI

RWA

LSSP

GA
Here is the parameterisation! Independent from model and manœuvre.

Vectorized models are used as far as possible.

Manœuvres are the “simulatable models”.

Each manœuvre is responsible to compute some of the PBSes.

Figure 2. Overview of how OpenPBS is structured.
Example: Manoeuvre “High Speed Lane Change”

- Front axle lateral acceleration is prescribed to exact sinus path.
- Steering angle is computed (but not of primary interest).
- All other variables, such as yaw rates are, of course, also computed.
- The PBSs associated with this manoeuvre is calculated. Here RearWardAmplification (RWA) and YawDamping (YD).
How does "R&D tool" look?

The "R&D tool" is a Modelica "package" (* .mo).
Here opened in the Modelica tool "Dymola":

---

[Diagram showing a Modelica package browser and a manoeuvre model for SingleLaneChange]
How does a “Vectorised VehicleModel” look?

Here, Vectorised Lateral Dynamics VehicleModel:

$\approx 1$ page declarations

$\approx 1$ page equations

(Dynamic) Equilibria:

\[
ay = \text{der}(vy) + vx.*wz;
\]

\[
m.*ay = F_y \times \text{ones}(na,1) - [F_{cy};0] + [0;F_{cx}].*\sin([0;\theta]) + [0;F_{cy}].*\cos([0;\theta]);
\]

Constitution:

\[
F_{yw} = -C.*\alpha;
\]

Compatibility:

\[
\text{for i in 1:nu-1 loop}
vx[i+1] = vx[i]*\cos(\theta[i]) - (vy[i]+B_{cog}[i]*wz[i])*\sin(\theta[i]);
vy[i+1]+A_{cog}[i+1]*wz[i+1] = (vy[i]+B_{cog}[i]*wz[i])*\cos(\theta[i]) + vx[i]*\sin(\theta[i]);
\text{end for;}
\]

...
Conclusions
Conclusions & Future work

• HCT seems to come on to the roads in EU soon. Already today in Finland!
• Assessment can be arranged based on PBS.
  • Two cooperating assessment tools in Sweden (Finland involved in same project.):
    • LBK (launched)
    • Open PBS, “experiment version” launched:
      • “Assessment front-end”: at web
      • “R&D fronte-end”: at github at web
      • “Open” means anyone is welcome to try it and contribute
• For sure, other similar tools are developed.
  • E.g. the “framework≈tool” within Karel Kural’s PhD thesis work presented later today.
References


- https://closer.lindholmen.se/sites/default/files/content/resource/files/fardplan_hct-vag_uppdaterad.pdf


Thanks for your attention. Questions?