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

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

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WP1 – Tire Modelling
WP2 – Heavy vehicle experiments
WP3 – Road network categorization
WP4 – Simulations
WP5 – PBS Assessment
WP6 – International cooperation and knowledge spreading
WP7 – Project management
How can HCT save CO$_2$?

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

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

typically 20% less CO2 per ton $\cdot$ km

...and even more reduction of CO2 per m$^3$ $\cdot$ km:

**TRANSPORTATION OF 600 M3 OF VOLUME LIMITED GOODS WITH THE SAME DENSITY (150KG/M$^3$)**

<table>
<thead>
<tr>
<th>Vehicles (and drivers)</th>
<th>6</th>
<th>4</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle length</td>
<td>16.5 m</td>
<td>25.25 m</td>
<td>32 m</td>
</tr>
<tr>
<td>Load per vehicle</td>
<td>100 m$^3$</td>
<td>150 m$^3$</td>
<td>200 m$^3$</td>
</tr>
<tr>
<td>Fuel consumption</td>
<td>3.5 ml/m$^3$km</td>
<td>3 ml/m$^3$km</td>
<td>2.5 ml/m$^3$km</td>
</tr>
<tr>
<td>CO2 emissions</td>
<td>100%</td>
<td>85% = -15%</td>
<td>73% = -27%</td>
</tr>
<tr>
<td>Road use</td>
<td>499 m</td>
<td>368 m</td>
<td>296 m</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</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>RA 3500 3750 4000 4250 4500</td>
</tr>
<tr>
<td>8108</td>
<td>200</td>
<td>2992</td>
<td>2.36</td>
<td>2.35 2.33 2.30 2.28 2.26</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>2992</td>
<td>2.33</td>
<td>2.32 2.30 2.28 2.26 2.22</td>
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<td>2192</td>
<td>2.29</td>
<td>2.28 2.26 2.24 2.22 2.22</td>
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<tr>
<td></td>
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<td>1992</td>
<td>2.26</td>
<td>2.25 2.23 2.21 2.21 2.21</td>
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<td>2.22 2.20 2.19 2.18 2.18</td>
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<td>2.19 2.17 2.15 2.15 2.13</td>
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<td>2.23 2.21 2.20 2.19 2.17</td>
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<td>400</td>
<td>2392</td>
<td>2.21</td>
<td>2.20 2.18 2.16 2.16 2.15</td>
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<td>2.18</td>
<td>2.16 2.15 2.13 2.13 2.11</td>
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<td>2.14</td>
<td>2.13 2.12 2.10 2.10 2.08</td>
</tr>
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<td>2.19</td>
<td>2.17 2.16 2.14 2.12 2.12</td>
</tr>
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<td>2.04</td>
<td>2.03 2.02 2.00 1.98 1.98</td>
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<td>2.08</td>
<td>2.07 2.06 2.04 2.02 2.02</td>
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<td>2.06</td>
<td>2.04 2.03 2.01 1.99 1.99</td>
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<td>2.03</td>
<td>2.01 2.00 1.98 1.96 1.96</td>
</tr>
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<td>2.00</td>
<td>1.99 1.97 1.95 1.93 1.93</td>
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<td>2992</td>
<td>2.04</td>
<td>2.02 2.01 1.99 1.97 1.97</td>
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<td>2.01</td>
<td>1.99 1.98 1.97 1.95 1.95</td>
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<tr>
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<td>2192</td>
<td>1.98</td>
<td>1.97 1.96 1.94 1.94 1.92</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td>1992</td>
<td>1.95</td>
<td>1.94 1.93 1.91 1.89 1.89</td>
</tr>
</tbody>
</table>

Open-loop lane change test according to ISO 14791 T = 0.40 s ja ν = 80 km/h
from Karel Kural, PhD thesis:

<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.)
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

https://www.trafikverket.se/contentassets/1160ae4fe6504bba8e3629eee4b60d7e/langre_lastbilar_pa_det_svenska_vagnatet_for_mer_hallbara_transporter.pdf

Vägmärke: F31.a Färdväg för långa fordonståg

[Map of Sweden]

Road wear
Air pollution
CO2
Accidents
Transport time

≈ $10^9€$

<table>
<thead>
<tr>
<th>Effektkategori</th>
<th>Samhällsekonomisk effekt</th>
<th>Effekt tidigare studie</th>
<th>Resultat, mkr</th>
<th>Känslighetsanalyse högt marknadsupptag, mkr</th>
<th>Känslighetsanalyse lägt marknadsupptag, mkr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Producert-/konsumenteffekter</td>
<td>Fordonsägare eller godstransport köpare</td>
<td>177 963</td>
<td>12 916</td>
<td>15 499</td>
<td>10 333</td>
</tr>
<tr>
<td>Budgeteffekter</td>
<td>Dieselskatt</td>
<td>-30 733</td>
<td>-2 231</td>
<td>-2 677</td>
<td>-1 784</td>
</tr>
<tr>
<td>Externa effekter</td>
<td></td>
<td>2 910</td>
<td>211</td>
<td>253</td>
<td>169</td>
</tr>
<tr>
<td></td>
<td></td>
<td>538</td>
<td>39</td>
<td>47</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8 382</td>
<td>608</td>
<td>730</td>
<td>487</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 040</td>
<td>221</td>
<td>265</td>
<td>177</td>
</tr>
<tr>
<td></td>
<td></td>
<td>835</td>
<td>61</td>
<td>73</td>
<td>48</td>
</tr>
<tr>
<td>Totalt</td>
<td></td>
<td>162 935</td>
<td>11 825</td>
<td>14 190</td>
<td>9 460</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/)

Present experiment implementation of the “Assessment front-end”

Computed PBS measures

A small “road vehicle register” (10-20 real units, fake reg numbers)
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

e.g.
- Rearward amplification $RA$ ratio of $\omega_z$ or $a_y$?
- and $RA = \frac{\text{max}_t(|\omega_{iz}|)}{\text{max}_t(|\omega_{1z}|)}$ or $\text{max}_f\left(\frac{|H_{\delta w \rightarrow \omega iz}(f)|}{|H_{\delta s w \rightarrow \omega iz}(f')|}\right)$
- 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 $\mu$?

**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. 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\textsubscript{2} be a PBS measure?

Euro1, Euro2, ...
Legal assessment of engines

CO\textsubscript{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\textsubscript{2}/ton.km</td>
</tr>
<tr>
<td>2</td>
<td>Carbon dioxide pollution - volume-wise</td>
<td>CO\textsubscript{2}/m\textsuperscript{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\textsuperscript{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\textsuperscript{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)</td>
<td>Object oriented modelling</td>
</tr>
<tr>
<td>(“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>Physical and strict models (for adding novelties)</td>
<td>DAE</td>
</tr>
<tr>
<td>Understandable and editable for engineers</td>
<td>Modelica =&gt; <em>R&amp;D front-end</em></td>
</tr>
<tr>
<td>Runnable for non-experts.</td>
<td>FMI =&gt; <em>Assessment front-end</em></td>
</tr>
<tr>
<td>Scriptable for experts.</td>
<td></td>
</tr>
<tr>
<td>Limited parameter editable for non-experts.</td>
<td>Modelica concepts Registry and Function</td>
</tr>
<tr>
<td>(In extreme: Only registration number on each of the units.)</td>
<td></td>
</tr>
</tbody>
</table>
Two tools in one...

Vehicle Specs

Vehicle Models

“R&D front-end”

“Assessment front-end”

FMI

PBSs

Modelica

export

RWA

LSSP

GA
Concepts selected

Here is the **parameterisation**!
Independent from model and manoeuvre

Vectorized models are used as far as possible.

**Manoeuvres** are the "simulatable models".

Each manoeuvre 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) are shown.
How does "R&D tool" look?
The "R&D tool" is a Modelica "package" (*.mo).
Here opened in the Modelica tool "Dymola":

Package browser

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:

\[
\begin{align*}
ay &= \text{der} (vy) + vx.*wz; \\
m.*ay &= Fy*\text{ones}(na,1) - [Fcy;0] \\
 & + [0;Fcx].*\text{sin}([0;\theta]) \\
 & + [0;Fcy].*\text{cos}([0;\theta]);
\end{align*}
\]

### Constitution:

\[
Fyw = -C.*alpha;
\]

### Compatibility:

```python
for i in 1:nu-1 loop
    vx[i+1] = vx[i]*\text{cos}(\theta[i])
    -(vy[i]+Bcog[i]*wz[i])*\text{sin}(\theta[i]);
    vy[i+1]+Acog[i+1]*wz[i+1] =
    (vy[i]+Bcog[i]*wz[i])*\text{cos}(\theta[i])
    +vx[i]*\text{sin}(\theta[i]);
end for;
```

...
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

- Tuutijärvi, Miro-Tommi, et.al., Method to provide simple tool for combination vehicle dimensioning, 2019, https://rd.springer.com/chapter/10.1007/978-3-030-20131-9_365


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Thanks for your attention. Questions?