AN OPEN ASSESSMENT TOOL FOR STANDARDIZED PERFORMANCE MEASURES OF LONG COMBINATION VEHICLES

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Abstract

Long Combination Vehicles (LCV) are transport efficient. However, allowing any combination of, individually legal, loaded vehicle units which when connected become LCV, can lead to traffic risks.Therefore, ways to assess LCVs are developed.

The paper proposes an open tool which can assess a certain LCV for a certain load distribution. The tool could be a base for a digital service for such assessment. The assessment is done with Performance-Based Standards (PBS). PBS measures, computed through dynamic models and simulations, can be compared to numerical requirements. The vehicle parameters are selected to be as easy as possible to find values on, e.g., from available data in a vehicle unit registry. Also, the loading is defined by giving the static vertical force for each axle and the load height for each vehicle unit.

A PBS based assessment method, as opposed to simply prescribing certain vehicle design parameters, would encourage novel combination vehicle designs. That would continuously drive the development towards even better transport efficiency, including energy efficiency.

Keywords: High-capacity transports, Long combination vehicles, Performance based standards, Open source, Assessment tool, Modelica

1 Introduction

1.1 Background

Long Combination Vehicles (LCV) are transport efficient. In EU, 18 m long combination vehicles are generally allowed. Finland allows 34.5 m since 2019 and Sweden is planning to follow during 2023.

1.2 Problem description

Allowing any combination of, individually legal, loaded vehicle units, summing up to a certain long length, can lead to traffic risks. Therefore, ways to assess LCVs are developed.

For single investigations one can build, load, and test real LCVs on test tracks, but this is not practical for a wider introduction of LCVs. More efficient ways to assess combination vehicles are needed. To avoid real testing, one could prescribe vehicle design parameters, such as axle and coupling positions, within a narrow envelop. However, such prescriptions would discourage development of novel vehicle designs.

PBS is the base for assessment in many countries and facilitates novel vehicle designs. Table 1 shows examples of a set of PBS measures.

Table 1 – Examples of a set of PBSs. Note that the requirement levels are only numerical examples, not suggested.

Traffic risk	PBS measure		**Short, approximate definition.** If not else stated: flat road, road friction 0.8.		Typical re-quirement
	Name	Abbre-viation	Measure	**Manoeuvre** (with some manoeuvre parameters exemplified)	
Transport efficiency	Startability	SA	Uphill grade	Combination vehicle start from 0 to slow forward. Road friction 0.35.	$SA = \frac{\Delta z}{\Delta x} \geq 0.12 \left[\frac{m}{m}\right]$
Transport efficiency	Gradeability	GA	Uphill grade	Combination vehicle drive in 70 km/h	$GA = \frac{\Delta z}{\Delta x} \geq 0.01 \left[\frac{m}{m}\right]$
Transport efficiency	Acceleration Capability	AC	Time	Combination vehicle accelerates from 0 to 80 km/h	$AC = t \leq 20\ [s]$
Safety	Braking Stability in a Turn	BST	EBS on all units	<No manoeuvre defined since no real performance PBS measure is defined.>	$BST = TRUE\ [bool]$
Safety, yaw stability	RearWard Amplification	RWA	Yaw Velocity amplification from first to last unit	Single lane change in 80 $\frac{km}{h}$ as in ISO14791, amplitude lateral acceleration on first axle 2 m/s^2	$RWA \leq 2.4 \left[\frac{rad/s}{rad/s}\right]$
Safety	Yaw Damping	YD	Yaw Angle damping over oscillations on worst unit	Single lane change in 80 $\frac{km}{h}$ as in ISO14791, amplitude lateral acceleration on first axle 2 m/s^2	$YD \geq 0.15 \left[\frac{rad/s}{rad/s}\right]$
Safety	High Speed Transient Off-tracking	HSTO	Off-tracking between first and last axle in ISO lane change	Single lane change in 80 $\frac{km}{h}$ as in ISO14791, amplitude lateral acceleration on first axle 2 m/s^2	$HSTO \leq 0.8\ [m]$
Safety	High Speed Steady State Off-tracking	HSSO	Off-tracking between first and last axle	Steady state cornering at radius 100 m and lateral acceleration 3.5 m/s^2	$HSSO \leq 0.6\ [m]$
Safety, roll-over	Lateral Load Transfer	LLT	Lateral difference in vertical force per total vertical axle force	Single lane change in 80 $\frac{km}{h}$ as in ISO14791, amplitude lateral acceleration on first axle 2 m/s^2	$LLT \leq 0.5 \left[\frac{N}{N}\right]$
Safety, roll-over	Steady state Rollover Threshold	SRT	Lateral acceleration	Steady state cornering at radius 100 m. Slowly increasing longitudinal speed until all inner wheels on one roll-stiff unit has lifted.	$SRT \geq 3.5 \left[\frac{m}{s^2}\right]$
Transport efficiency	Low Speed Swept Path	LSSP	Path width between the wheels' outer edges	Low speed 90 deg turn with 12.5 m radius path for outer edge of first unit body	$LSSP \leq 8.5[m]$
Transport efficiency	Tracking Ability on a Straight Path	TASP	Off-tracking between first and last axle	Constant speed on straight road with constant cross-fall of 5 deg. Road friction coefficient 0.35.	$TASP \leq 0.4[m]$
Transport efficiency	Frontal Swing	FS	First unit front body reaching distance outside defined path	Low speed 90 deg turn with 12.5 m radius path for outer edge of outer front tyre	$FS \leq 8.5\ [m]$
Transport efficiency	Tail Swing	TS	Last unit rear body reaching distance outside defined path	Low speed 90 deg turn with 12.5 m radius path for outer edge of outer front tyre	$TS \leq 8.5\ [m]$
Transport efficiency	Friction demand on Steering Tyres	FDST	Force in ground plane under steered axles	Low speed 90 deg turn with 12.5 m radius path for outer edge of first unit body	$FDST \leq 0.2 \cdot GCW\ [N]$
Transport efficiency	Friction demand on Drive Tyres	FDDT	Force in ground plane under driven axles	Low speed 90 deg turn with 12.5 m radius path for outer edge of first unit body	$FDDT \leq 0.25 \cdot GCW\ [N]$

However, there are not widely accepted and unambiguous definitions of neither PBS manoeuvres, PBS measures nor sets of PBSs. Internationally agreed definitions, such as (ISO14791, 2000), are written as non-executable prose with multiple alternatives.

1.3 Envisioned and presented solution

The present paper presents the result of the assessment tool work in the projects (Vinnova, Performance Based Standards for High Capacity Transports in Sweden, 2013-2017) and (Vinnova, Performance Based Standards II, 2018-2021).

An executable and unambiguous definition of PBS measures is proposed through dynamic models. Therefore, the standardised model format Modelica is selected. The proposal is delivered in the form of an open Modelica `package` (=collection of models) and some scripts for setting numerical parameters. It is called OpenPBS.

OpenPBS can be a base for a digital service, e.g., enabled via a web interface. One example of a similar digital service is Lastbilskalkylatorn LBK (Transportstyrelsen, 2017). LBK is in use in Sweden, but only for combination vehicles up to 25 m, 2 articulation points, and with a limited number of PBS measures. It is typically used by transport operators and traffic police. It was introduced to facilitate the increase of allowed gross combination weight to 74 tonnes in 2015. For the introduction of 34.5 m in 2023, a next version of LBK could be developed.

Besides, and even without, a digital service, OpenPBS can be useful for truck and trailer manufacturers as an engineering tool and/or a sales tool, see Figure 1-1.

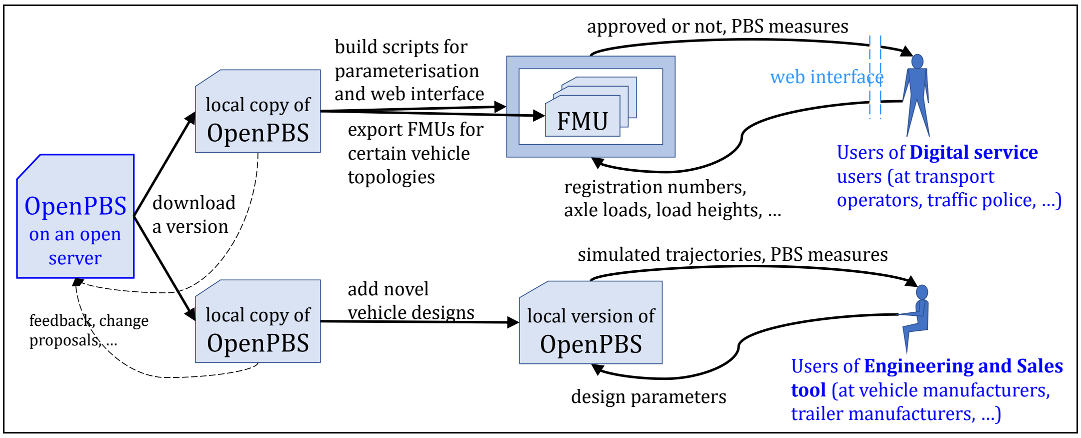

Figure 1-1: OpenPBS as base for digital service and as engineering and sales tool.

Generally, in cases where the digital service is limited, see section 4.1, the fall-back solution would be today's approval methods with real combination vehicle tests, possibly complemented with non-public simulations from manufacturers; compare to ESC regulation for passenger cars is today partly made through simulations.

A demonstrator of a digital service using OpenPBS is available at http://192.36.94.52:8000/.

1.4 Objectives

The objective of present paper is to describe the tool OpenPBS.

PBS for LCV has been studied and developed in many projects and publications, but compiling it to an executable and open tool, based on the standard format for dynamic models, is novel.

1.5 Nomenclature

In present paper, the word *combination vehicle* is used as for a combination of several *vehicle units*. One vehicle unit can be, e.g., a truck, a full-trailer, a semi-trailer, a centre-axle-trailer, or a converter dolly. The word *vehicle* is avoided unless as a general word is motivated, not distinguishing between combination vehicle or vehicle unit. (There is, at least, one alternative terminology, which instead uses *vehicle combination* and *vehicle*, respectively.)

2 Performance Based Standards PBS

All vehicle units are assumed to, individually, comply to regulations. So, PBSs for LCVs should only check additional identified *traffic risks* appearing from connecting multiple units to each other. To avoid redundancy between PBSs, one should compile a whole set of PBSs, where each PBS is motivated by a unique traffic risk. Adding a new PBS should only be made if motivated by a new identified traffic risk. See Table 1. Each PBS has to be defined both by a manoeuvres and a (scalar) measure. Multiple measures can use the same manoeuvre.

In the very end of this chain, the authorities can set numerical requirements levels for each PBS measure, potentially different between different road network and different times.

3 Modelling

3.1 Format selection

The tool OpenPBS is based on the standard format for dynamic models on mathematical form, Modelica (Modelica association, 2016). A Modelica model is **acausal** (uses symbolic equations, as opposed to assignments statements). So, a vehicle model becomes directly useful for a larger variation of manoeuvre definitions, such as prescribing either the steering angle or the vehicle path. The models can be simulated in Modelica tools. The models can also be exported as files `*.fmu`, i.e., on the standard form for dynamic models on **explicit (causal)** form, FMI (Functional Mock-up Interface, 2016). FMI is useful also in many other simulation tools and programming environments than Modelica tools, which can be important if implementing the OpenPBS in a digital service.

Modelica has a well-developed concept for adding descriptive text to models, parameters, and equations. A complete html documentation can often be automatically generated. A drawback is that Modelica has no integrated graphical description format.

For readers with interest in the dynamic modelling, a small example of a Modelica model is given in Eq [3.1]. It is a body with mass `m` and velocity `v`, suspended by a spring with stiffness `c` and force `F`. Note that a `parameter` is constant during a simulation.

```
model ExampleModel
  parameter Real m, c;
  Real v, F;
equation
  m*der(v) + F = 0;
  der(F) = c*v;
end ExampleModel;
```

Eq [3.1]

3.2 Overall modelling strategies

One overall modelling strategy is to model the *combination vehicle* independently from models of *PBS manoeuvres* and *PBS measures*. This follows the main idea behind PBS assessment. Each combination vehicle will be assessed in the same way, and the same combination vehicle will be assessed for all PBSs.

Another overall modelling strategy is to declare *vehicle parameters* independently from *vehicle model equations*. This is made by declaring only one parameter set (a `record`) for a combination vehicle. The record is instantiated in each vehicle model.

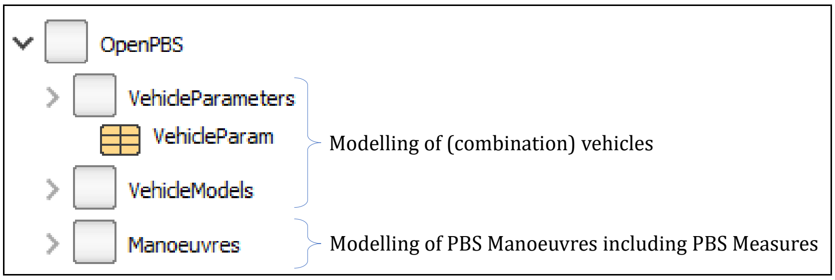

Figure 3-1: Vehicles are defined independently from PBS manoeuvres and PBS measures. Vehicles are parameterized independently from model equations.

3.3 Models of PBS manoeuvres and PBS measures

PBS measure *Low Speed Swept Path, LSSP*, will be used as an example, see Figure 3-2.

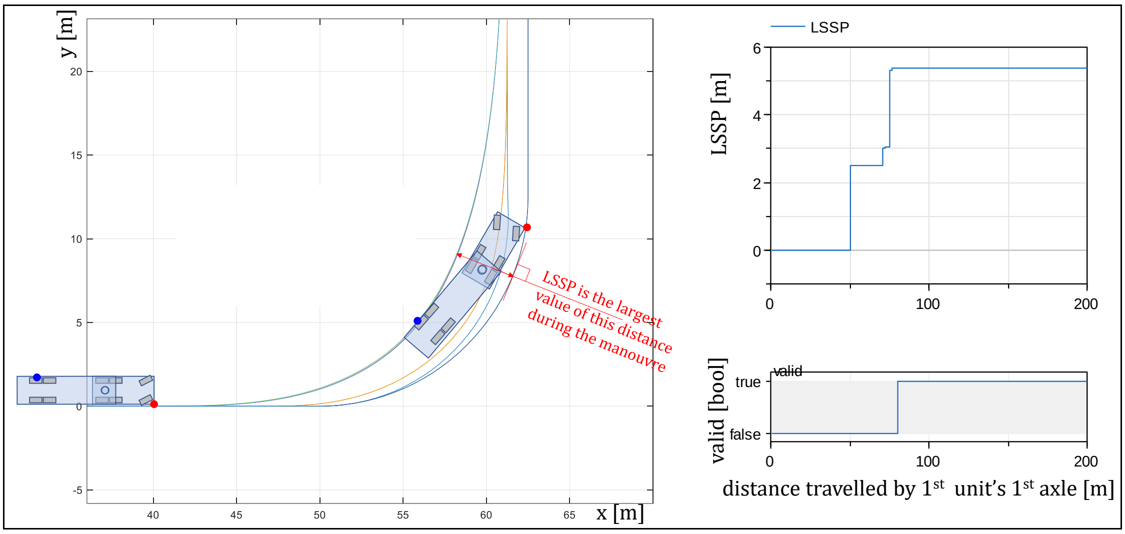

Figure 3-2: Graphical explanation of PBS measure, *Low Speed Swept Path, LSSP*.

The traffic risk motivating the *LSSP* is that LCVs might sweep laterally outside the lane in a roundabout or a tight curve. It can lead to LCVs has to stop and thereby block traffic, or to damages.

First, a typical curve path (radius and angle) needs to be defined. Then, the way of negotiating the roundabout or curve is *low speed driving* with the *front outer corner* following the curve path. The *LSSP* can then be defined, e.g., as the largest width between the curve path and the *rear-most inner wheel*. A valid flag is also defined in each manoeuvre because it is important to get a confirm that the calculated PBS measures are relevant. Conceptual Modelica code, with comments in “” and after //, for this is seen in Eq [3.2].

```
model LowSpeedCurve "This is one PBS manoeuvre"
  //Maneuver parameters:
  parameter Modelica.Units.SI.Length curve_radius=12.5;
  parameter Modelica.Units.SI.Position curve_start=50
            "Position where curve starts";
  parameter Real degOfTurn = 90 "Degree of turn";

  //Declarations for PBS measure(s) and valid flag:
  Modelica.Units.SI.Length LSSP "Low speed swept path width [m]";
  Boolean valid "True if the maneuver successful";

  // Combination Vehicle model parameters:
  replaceable parameter VehicleParamparamSet constrainedby VehicleParam;

  //Select one Vehicle model (equations):
  VehicleModel1 vehicle(paramSet = paramSet, DynOpCond=1);

initial equation
  valid=false;
equation
  //Here goes equations that prescribes the vehicle to follow the curve. E.g.
  vehicle.front.outer.v_x/vehicle.front.outer.v_y=PathDirection;
  //We also goes equations which computes the PBS measure(s) and valid flag.
  LSSP = ... ;
  valid = if ... then true else false;
end LowSpeedCurve;
```

Eq [3.2]

The parameter set `paramSet` is instantiated as a `replaceable parameter` in the manoeuvre model, which makes it easy to parameterize from outside, see Figure 3-3.

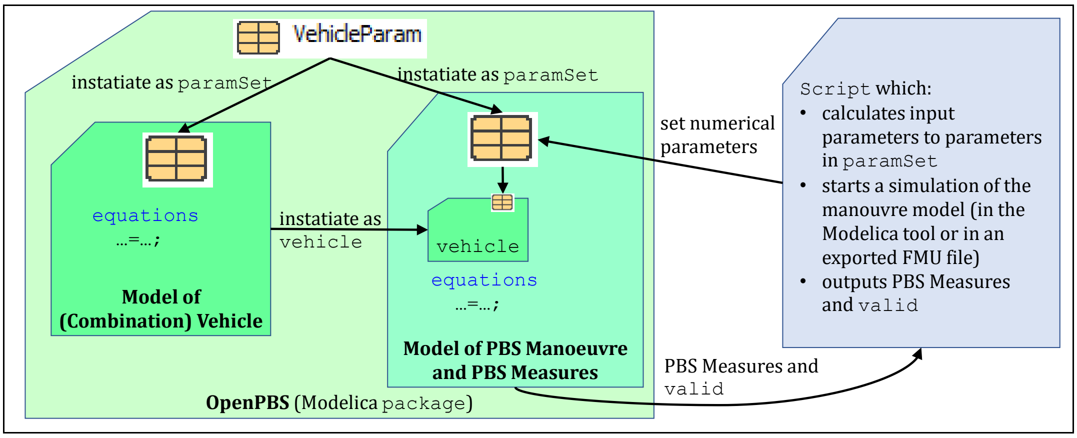

Figure 3-3: Using the parameter set for Vehicle model parameters.

3.4 Vehicle models

Eq [3.2] also shows how the (combination) vehicle is defined: The vehicle model (equations and some fixed parameters) is included through the statement with `VehicleModel1`. The vehicle is defined through the parameter set (or `record`) called `paramSet`. This means that very few vehicle models must be defined in OpenPBS, which makes the maintenance more efficient and less error prone.

Note that `VehicleModel1` in Eq [3.2] includes, e.g., the parameter `nu`, which is the number of vehicle units. This indicates that the multiplicity of units in a LCV is captured in a vectorized approach, see (Sundström, Jacobson, & Laine, 2014). The maximum number of axles on one unit is `na`. The concept is further developed, and most parameters are either a vector with `nu` or `nu-1` components, or a `nu×na` matrix. Eq [3.3] shows approximately 1/3 of the parameters proposed to be declared in the `record VehicleParam`.

```
record VehicleParam "(Combination) Vehicle model parameter set"
  parameter Integer nu "Number of units";
  parameter Integer na "Max number of axles per unit";
  parameter Modelica.Units.SI.Position[nu,na] L "Axles' positions …";
  parameter Modelica.Units.SI.Length[nu,na] W "Track width per axle";
  parameter Modelica.Units.SI.Position[nu] hRC "Units Roll Centre height";
  parameter Modelica.Units.SI.Position[nu - 1] hC "Coupling heights";
  parameter Modelica.Units.SI.Position[nu] A "Front coupling position …";
  parameter Modelica.Units.SI.Length[nu] B "Rear coupling position …";
  parameter Boolean[nu, na] driven "True for driven axle";
  parameter Modelica.Units.SI.Mass[nu] mk "Kerb masses";
  parameter Modelica.Units.SI.Force[nu,na] Fz "Vertical axle forces";
  parameter Modelica.Units.SI.Length[nu] FOH "Front overhang …";
  parameter Modelica.Units.SI.Length[nu] ROH "Rear overhang …";
  parameter Real drag_coefficient "Drag coefficient";
  parameter Modelica.Units.SI.Dimensionless rolling_resistance_coefficient;
  parameter Modelica.Units.SI.Power max_engine_power "Max engine power";
  parameter Modelica.Units.SI.Force max_thrust_force_vx0 "Max thrust force";
  parameter Modelica.Units.SI.Force[nu,na] FZT0 "Tyre static load per axle";
  parameter Real[nu, na] uy0 "Tyre: Nominal maximum lateral force coefficient";
  parameter Real[nu, na] uyg "Tyre: Maximum lateral force gradient";
  parameter Real[nu, na] CCy0 "Tyre: Cornering coefficient per axle";
  parameter Real[nu, na] R0 "Tyre radius";
  parameter Real[nu, na] C "Tyre shape factor";
  parameter Real[nu, na] CZT "Tyre normal stiffness";
  parameter Real[nu, na] CYT "Tyre lateral stiffness ";
  parameter Boolean[nu-1] vffc "Defines vertical force free couplings";
  parameter Boolean[nu,na] Lowspeed_Steered_axle "True for each Steered axle";
  …
end VehicleParam;
```

Eq [3.3]

The vehicle models' equations are expressed in the parameters declared in `VehicleParam`. Parameters declared in the vehicle model itself should be avoided unless they are universal, such as gravity, or defined to select between different modelling assumptions. Example of the latter is the parameter `DynOpCond`, see Eq [3.4] in section 3.4.1.1, which shows the lateral force equilibrium for all the units.

The numerical values of the parameters in `VehicleParam` must be set in a script outside the Modelica model. In a digital service as LBK, the units' registration numbers and each axles vertical load would be needed as input through a web-HMI to that script. The usage parameters, such as vertical load `Fz`, must be set by the user. The remaining would, ideally, be possible to read from the vehicle (unit) registry. However, many of them is not in the registry, so default values are carefully selected, such as tyre parameters to represent a common tyre, such as cornering coefficient at nominal inflation and load `CCy0`.

3.4.1 Lateral model

The concepts of vectorised model and use of `for` loops and `if` clauses are mentioned before. Additional use of `if` clauses is for such as modelling zero forces in the rear coupling of the last unit, because it is not coupled to anything.

The discrete parameter `DynOpCond` switches one single model between whether the lateral dynamics is modelled as Low speed (`DynOpCond`=1), Steady state cornering (`DynOpCond`=2), or Transient dynamic manoeuvre (`DynOpCond`=3). This would be far more difficult in an explicit form model. See Eq [3.4] and Figure 3-4.

```
for i in 1:nu then
  if DynOpCond==3 then
    m[i]*(der(v_y[i])+v_x[i]*w_z[i])=sum(F_ay[i,:])+F_cRy[i]+F_cFy[i];
  else if DynOpCond==2 then
    m[i]*(            v_x[i]*w_z[i])=sum(F_ay[i,:])+F_cRy[i]+F_cFy[i];
  else  // if DynOpCond==1 then
    0                              =sum(F_ay[i,:])+F_cRy[i]+F_cFy[i];
  end if;
end for;
```

Eq [3.4]

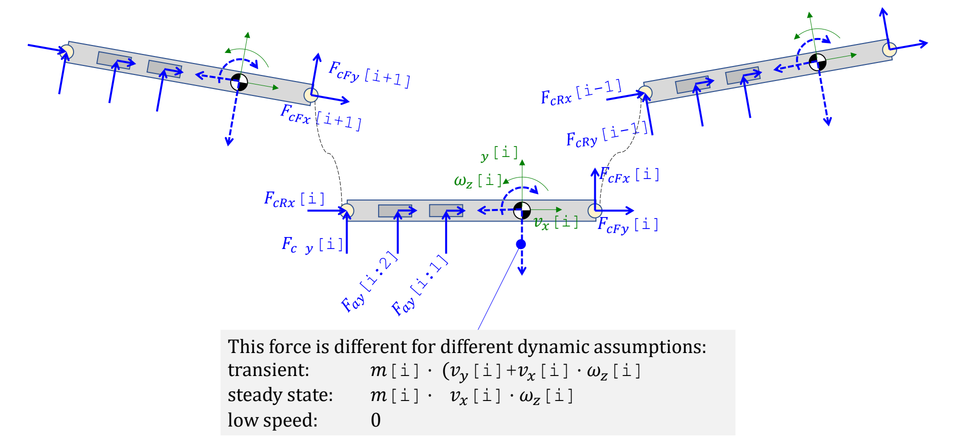

Figure 3-4: This figure is supporting Eq [3.4]. Vectorized vehicle model for motion in the xy plane. Subscripts: *a*=axle, *c*=coupling, *R*=rear, *F*=Front. The `i` means unit number `i`.

The `DynOpCond==3` is used in the manouvres for PBS measures RearWard Amplification RWA, Yaw Damping YD, High Speed Transient Off-tracking HSTO, and Lateral Load Transfer LLT. The `DynOpCond==2` is used in the manouvres for PBS measures High Speed Steady state Off-tracking HSSO. The `DynOpCond==1` is used in the manouvres for PBS measures Low Speed Swept Path LSSP.

3.4.1.1 Roll dynamics in lateral dynamics

During the projects where OpenPBS was developed, the importance of the roll dynamics was identified for high-loaded LCVs and *RWA*, *YD*, *HSTO*, and *LLT*, see (Islam, Fröjd, Kharrazi, & Jacobson, 2019). So, the vehicle model for these PBS measures uses a model with `DynOpCond==3` in Eq [3.4], but extended with roll dynamics. This also leads to introduction of a vehicle parameter for height of centre of gravity, and a boolean vector telling whether each coupling is roll-rigid or roll-moment free. These were defined as input parameters, while other new parameters such as roll-stiffness and roll-damping for each axle were given as default values.

3.4.2 Vertical model

OpenPBS has a special vertical model, including mainly the vertical and pitch equilibria for each unit. A common way to model is to declare the mass and the position of centre of gravity for each unit as (known) parameters, and the vertical forces under each axle as a (unknown) variables to solve for. But, since the assessment is for a certain load, the projects declared the vertical (static) force under each axle as (known) parameters, and instead solve for each unit's mass and position of centre of gravity. The same model equations (vertical and pitch equilibria and a suspension model for each axle group) are used but with another causality.

The total system of equations for a combination vehicle with many vehicle units is quite complex, so it is very advantageous to model in Modelica for these kind of causality variations.

A take-away from this part study was that the acausal way of modelling makes it easy to change what is known and unknown.

3.4.3 Steady state roll-over model

The model for the PBS measure *Steady state Roll-over Threshold, SRT*, is different since it is based on (ISO22135, 2023). That ISO standard is, in turn, based on the regulation ECE 111, but also includes the effect of tires lateral stiffness. Hence, it is more an algorithm than a physical dynamic model. If the legacy to the ISO and ECE 111 would not have been prioritized, Modelica could have been used to model rollover threshold in a more physical way, sweeping the lateral acceleration, and modelling the changed axle roll-stiffness due to wheel-lift of each axle's inner wheel with *discrete dynamics* and `if` and `when` statements. An example of such modelling is given in Figure 3-5.

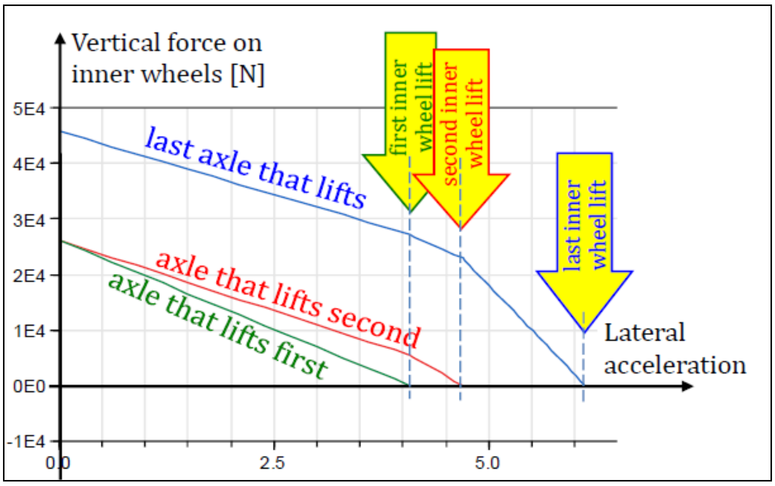

Figure 3-5: Physically modelled steady state roll-over in Modelica. The lateral acceleration is used as independent variable. Wheel-lifts are handled with *discrete dynamics*, using `if` and `when` clauses. From (Jacobson & al., 2022)

4 Results and Outro

The model package is developed for the following key concepts:

- Manoeuvres are defined in which the PBS measures are calculated from the simulation results.
- The vehicle definitions (parameters) are independent from definitions of PBS measures and PBS manoeuvres. Also, vehicle definitions are independent from vehicle model equations.
- A minimum of vehicle unit parameters and payload data is carefully selected. Of these, the user only must give a few, while the rest are either fixed or calculated from the given ones. Examples of fixed parameters are the cornering coefficients (=each axle's lateral slip stiffness, normalized with vertical load) and the axles' roll stiffness. The user can be given the choice to change other parameters.
- The parameterization should be made in Modelica format as far as possible, but there must be an opening to scripts in conventional programming language, such as Python or C. It must handle the parameters that the user should put in, collect information

from vehicle register, start simulation, and relay the resulting PBS measures and approval or disapproval to the user.
- The combination vehicle model in the package is "vectorized", which allows arbitrary many vehicle units to be combined.
- The tool is implemented in Modelica and can generate executable assessment code on FMU format. The model package is available at https://research.chalmers.se/en/publication/532168, but it can be better to handle the continued development at https://github.com/ or similar.

The model package covers, so far, only conventional vehicle technologies, see 4.1. However, due to the physical way of modelling, it can be developed to include novel vehicle engineering innovations, such as propulsion on trailing units, actively steered axles and dynamically liftable axles. For this reason, it is also important to mention that the model package is fully open (understandable and free of charge) so that also vehicle unit manufacturers can use it to foresee how a novel design will be assessed.

Visions for future digital services using the tool, such as Lastbilskalkylatorn LBK, is to extend the application to more and more parts of the road network, including across country borders. Different road networks could use different requirement values on the PBS measures. To enable such a future, it is important that assessments have a base which is strictly defined (mathematical and executable models) and open (publicly available, free of charge, and understandable for vehicle engineers).

While visioning, we can as well point out that a digital service could be extended in future, to refine the approval/disapproval to be very specific, such as for a certain route and during a certain time. Certain routes might have limitations due to some weak bridge and others due to a narrow roundabout. Certain times there can be bad weather, such as heavy snow or wind and waves for bridges.

4.1 Future development

The version of the OpenPBS presented in present paper has limitations which also can be future work:

- The numerical requirement levels on each PBS measure are **not** proposed.
- It is **not** discussed whether approval in a digital service should be sufficient or necessary to allow a certain combination vehicle. However, also if the digital service is neither sufficient nor necessary, but only a recommendation, it can have a value since it can be made very easily available.
- The selection of PBS measures is **only** from project (Vinnova, Performance Based Standards for High Capacity Transports in Sweden, 2013-2017) which aimed at Swedish road and traffic conditions and vehicle parameters presently available in the Swedish vehicle register.
- The influence of actively controlled systems is **not** included.
    - The tool is **not** developed for propulsion on trailing units.
    - Regarding steering on other than first unit's first axle: The tool is **not** developed for such steering, except low-speed friction steered axles.
    - The tool is **not** developed for dynamically lifted axles.
- Only yaw moment free couplings are included. For instance, this means that B-dollies with dual drawbar is **not** possible to represent.

The most difficult limitation to overcome would probably be how to include actively controlled systems; it could lead to that algorithms from vehicle and trailer manufacturers must be runnable as black-box models in the models.

5 Acknowledgements

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