MODEL AND ROAD SURFACE SENSITIVITY OF LONGITUDINAL PERFORMANCE BASED STANDARDS

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Abstract

Performance-based standards (PBS) is a regulation policy to address the complexity of variations in vehicle combinations. It enables a direct way of addressing certain requirements associated with the safety, environment and road network and their implications to the vehicle specific quantities without stipulating vehicle properties.

Computer-based simulations may be an efficient tool to assess the performance measures. However, using simulations through models in a legislation raise questions of model accuracy and model complexity. What is a required level of modelling details to be used to assess a PBS measure?

In this paper, we investigate three level of complexity of models and the impact this have on three longitudinal performance measures; Startability, Gradeablity and Acceleration Capability. Simulations for 10 vehicle combinations are compared with two different engine alternatives. For Nordic countries, slippery road conditions are common during winter conditions. Hence, low friction is included in the comparison.

The comparison suggested that the complexity could potentially be kept really low, without major loss of accuracy. However, for slippery conditions, a higher levels of complexity might be required.

Keywords: Longitudinal performance based standards, Models complexity, Road surface sensitivity

1. Introduction

Transport efficiency is a major drive to introduce longer and heavier vehicle combinations to the road network. These vehicles sort into a category of so-called high capacity transport (HCT) vehicles which offer increased transport efficiency and the possibility to reduce fuel consumption, fewer drivers per transported tonnage, alignment with container standards etc. Introducing HCT vehicles on the road network will have an impact on road wear, traffic safety and environment. Studies in Sandin et. al. (2014) and Andersson et. al. (2011) suggest that the accident risk would decrease by the introduction of HCT vehicles even though the amount of statistical data to establish the relationship between e.g. combination length and crash risk is limited. Road wear might also have positive effects with the introduction of longer and heavier vehicle combinations, see e.g. Nordengen et al. (2012).

From a legislator point of view, there are a number of aspects that needs to be balanced and taken into account when introducing longer and heavier vehicle combinations. Aspects such as traffic safety, traffic efficiency, environment (pollutions), road network cost need to be considered. Various legislation principals could be applied to address these aspects, such as principal-based regulations or prescriptive regulations. One regulatory policy that has attained much focus recently is performance based standards (PBSs). A number of countries have implemented or considering implementing such policies to address the aspects of HCT vehicles, see Kharrazi et al. (2015). Australia can be considered to have the most comprehensive system in use. Sweden is a country currently investigating the possibilities to introduce a PBS based legislation framework for HCT vehicles.

Using a PBS policy enable the legislator to connect and address specific requirements connected to for example properties of the road network or traffic safety to properties of the vehicle combinations without being prescriptive in dimensions or weight. A strictly defined performance measure is used to measure the compliance of the legislation. These measures can be assessed for a particular vehicle combination through full-scale tests on a test track, or through simulations. Assessment through simulations obviously offers advantages in terms of cost efficiency. It also makes it possible to assess a vehicle performance before it is built.

Simulation models are used in many contexts and with many purposes in industry and academia. In general, there is a trade-off between accuracy and simplicity of deductive simulation models. A similar relationship can also be found between complexity and transparency and readability. Simulation models in a legislation context is a relatively new phenomenon and implications of model robustness and accuracy need to be thoroughly investigated. In this paper, we investigate the possibility to reduce model complexity to incorporate only the vehicle characteristics with the strongest influence on the PBS measures.

The potential benefit of reducing the complexity of the models used to assess the vehicles performance w.r.t PBS, is ease of use, transparency, robustness towards modeling errors and inconsistencies in the model. These properties can be of importance for both legislators and applicants and make the introduction and acceptance of a PBS framework easier. The cost of reducing the model complexity is the potential risk of reducing the accuracy of the assessment. It should be noted that this study is focused on the assessment accuracy with simple models and does not discuss the "required" accuracy for a PBS framework.

In this study, we compare three levels of complexity of models and their impact on the result of three selected PBS measures taken from Australian scheme for the longitudinal direction, see National Transport Commission (2008). The most comprehensive model is an OEM developed model, which is internally widely accepted and used for longitudinal dynamics simulations. The second level is a model taken from Kati et. al. (2014) which makes use of an engine map, considering effects of rotating parts, but neglects time delays in gear shifting. The third and simplest model is derived here and is based on first principal modelling. The derived models are not simulation models, but simple expressions dependent on the most influencing components such as the maximum torque that the engine can produce.

The three levels of complexity of the models are compared for a range of truck combinations and load cases. Of particular interest to Swedish conditions is slippery winter roads with ice and snow. Sweden recently introduced a legislation on winter tires for heavy vehicles on the driven axle. This was mainly motivated by transport efficiency, see Hjort (2012). The traction requirement of the winter tires is strongly connected to a PBS framework. Hence, a special focus is given to the influence of the tractive friction on the investigated PBS measures.

2. Longitudinal Performance Based Standards

We will focus on the traction and longitudinally related measures; Startability, Gradeablity and Acceleration capability. These are presented in the following sub-sections below with a short recapitulation of their definitions according to National Transport Commission (2008). All these PBS measures can be assessed trough computer-based simulations. This implies that the outcome the assessment will be determined by the accuracy of the simulation model, i.e. the ability to predict a real vehicles behavior. In National Transport Commission (2008) the accuracy is not stated explicitly as a requirement. However, the accuracy of the model is stated implicitly in terms of components and phenomena that needs to be considered and taken into account for. These are listed here,

- gross combination mass,
- engine power vs speed characteristics,
- clutch and transmission (engagement of the clutch, torque converters etc.),
- the influence of rotating components (engine inertias etc.)
- general losses in the road- and air- interaction and transmission
- time delays due to gear shifting
- the tire friction limitations (including the normal force and its

This raise the question of model complexity and the required level of accuracy to meet the initial objectives of a PBS legislation principal to quantify a road or traffic safety related property.

The following subsection will present a simple expression for each of the three investigated PBS measures. The aim of these is to incorporate as few parameters and vehicle dependencies as possible to keep readability and transparency, and yet some accuracy. These expressions will, later on, be used in a comparison with two more models with higher degrees of complexity.

2.1 Startability

Startability is a measure of the ability to commence forward motion on specified road grade from a stand still. The test procedure states that the vehicle needs to maintain a steady forward (upward) motion in the slope with a constant or increasing speed for at least 5 meters. The performance is measured in the maximum road grade that the vehicle is able to start from. From a policy perspective, a certain minimum level of road grade is specified that a vehicle combination needs to commence. This makes it possible to test on a test track, given that this slope is present at the track. For the PBS measure itself, it is for obvious reasons hard to find the maximum road grade for a specific vehicle combination on a test track. This makes it harder to validate model accuracy using this PBS measure.

The most contributing components for the Startability PBS is the powertrain and the tire. In the powertrain, it is the ability to produce a high level of torque and to distribute this through the clutches/torque converters to the wheels. The maximum torque that the engine, T_{eng} , as a function of engine rotational speed ω can produce can be considered known from the supplier. The transmission ratio of the first gear$R_{tm,1}$ and the final drive ration R_{fd} can also be considered known as well as the tire radius R_{whl}. A maximum propelling force that can be achieved by the powertrain, given ideal clutch conditions without torque amplification, is then given by,

$$F_{PTmax} = \max_{\omega} \frac{T_{eng}(\omega) R_{tm,1} R_{fg}}{R_{whl}} \quad (1)$$

The tires will, in some conditions, limit this propelling force by the friction μ. Further on, it will be assumed that the change of the load transfer due to the slope is neglected for both total load Mg and the load on the driven wheels N_D. A simple expression for the maximum slope that the vehicle combination can commence is then given by the fraction of the maximum propelling force and the normal load according to,

$$S_{\%} = \left[100 \frac{\min(N_D \mu, F_{PTmax})_D}{Mg} \eta \right]_{INTEGER} \quad (2)$$

where the hard brackets indicate the integer part of the term and η is an efficiency factor for the powertrain.

2.2 Gradeability

Gradeability is very similar to Startability but with the difference that the speed needs to be maintained. The test procedure states that the vehicle combination needs to maintain a steady or increasing speed for at least 5 meters. The performance is either measured in road grade for a specific speed or speed at a specific road grade. Typical speeds are between 60 to 80 km/h.

For Gradeability with the maintained specific speed,v_{ref}, a similar expression to (2) can be found. Here the speed is higher than for the Startability measure. The consequence is that an optimal gear needs to be found for this particular speed and that air drag and rolling resistance of the tires needs to be considered. An optimal gear can be found by maximizing the propelling torque for the given set speed, v_{ref} according to

$$i = \operatorname*{argmin}_{i} T_{eng}(\omega_i) R_{tm}(i) \quad (4)$$

where the engine speeds ω_i for the gears, i, is given by,

$$\omega_i = \frac{v_{ref} R_{fg} R_{tm}(i)}{R_{whl}} \quad (5)$$

The fraction of the maximum propelling force and the normal load, including the rolling resistance, through the rolling resistance coefficient C_{rr}, and the air drag, is given by,

$$G_{\%} = \left[\left(\frac{\min(N_d\,\mu, F_{PTmax})}{Mg}\eta - C_{rr} - \frac{0.5\rho_{air}C_d A_{front}v_{ref}^2}{Mg}\right) * 100\right]_{INTEGER} \quad (6)$$

Where η is the same powertrain efficiency term as in (2), and ρ_{air}, A_{front} and C_d are the density of air, effective frontal area and the air drag coefficient.

2.3 Acceleration capability

Acceleration capability is a measure of how fast a vehicle combination is able to clear for example a rail crossing from a stand still. The associated test procedure prescribes acceleration from rest until a 100 meters' distance is travelled on a flat road without a grade. The performance measure is the required time to complete the 100 meters. The traveled distance is measured anywhere on the truck, e.g. the front axle needs to travel the 100 meters. This implies that longer vehicle combinations will not be penalized due to their length as if they would have if the 100 meters would have excluded the length of the vehicle combination.

The measure depends heavily on how the powertrains maximal capabilities, and not only at a certain speed as for the Startability and Gradeability measures. Here, a range of speeds from zero up to the speed that the vehicle combination reaches at the travelled 100 meters needs to be considered for the powertrain. This is largely due to the strong rotational speed dependence of the engine torque as well as the quantization effects of the transmission. A speed dependent maximum torque at the wheels can be obtained from,

$$F_{PTmax}(v) = \max_i T_{eng}\left(\frac{vR_{fg}R_{tm}(i)}{R_{whl}}\right)\frac{R_{tm}(i)R_{fg}}{R_{whl}} \quad (7)$$

The travelled distance from this force is now given by integrating the produced acceleration twice according to,

$$\dot{s} = v$$
$$\dot{v} = \frac{\min(F_{PTmax}(v), \mu N_d)\eta}{M} \quad (8)$$

and the measure is obtained from the implicit equation,

$$s(t_{AccCap}) = 100 \quad (9)$$

2.4 Comments on the assumptions

The above expressions use the powertrain force produced at the tires, neglecting all dynamic losses and efficiencies. It is unrealistic to use the theoretical upper limit of the propelling torque (and the maximum friction). Hence, one efficiency term has been added, η, to reflect that the forces are not utilized fully. Neither have any consideration have been taken to torque limiting functionality to save the powertrain.

The expressions also make use of the static load distribution, that can be measured easily using scales on a real vehicle. However, the transfer of this load distribution due to the road slope is neglected. This will make the expressions independent of geometries and center of gravity heights that might be hard to measure on a real vehicle. The assumption will gradually become increasingly more inaccurate with increased road slop. However, the road slopes relevant to these measures will not affect the measures substantially.

The coefficient of friction might, however, be non-trivial to measure in a real vehicle. With the connected legislations on tires, the coefficient of friction μ might be seen as a PBS index by itself.

Used parameters for all three measures are,

- Total mass of combination plus mass over driven axle(s), M
- The transmissions gear ratios (final drive plus gearbox gears), $R_{tm}(i), R_{fd}$
- The coefficient of friction between the tires and the road, μ
- The maximum engine torque versus engine rotational speed, $T\_eng(\omega)$
- The average rolling resistance of the tires, C_{rr}
- The aerodynamic drag and the frontal area, C_d, A_{front}
- The radius of the tires, R_{whl}

All these quantities can readily be found at the suppliers or typical values with common acceptance.

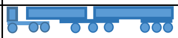
3. Experimental setup

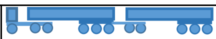
The comparison between different levels of model complexity will be done in the following section. Here we present the conditions for this comparison. The comparison will be performed on a set of different vehicle combinations, taken from Kati et. al. (2014). The other two models will briefly be presented here as well as the different test cases.

3.1 The test vehicles

10 different vehicle combinations will be used in the comparison. which are listed in Table 1 below. The selected combinations include conventional European combinations (No 1,2), 25.25 m Scandinavian combinations (No 3-5), as well as prospective HCT vehicles based on the European modular system (No 6-10).

Table 1 – Table of tested vehicle combinations and their basic dimensions

No	Description	Figure	Length [m]	Total Weight [tonnes]	Weight on driven axles [tonnes]
1	Tractor with semitrailer		16.50	40	12.12
2	Truck with full trailer		18.75	40	16.05
3	Tractor, semitrailer, center. -axle trailer		25.25	60	12.12
4	Truck, dolly and semitrailer		25.25	60	18.71
5	B-double (7.82m + 13.6m)		25.25	60	13.40

6	A-double		31.50	80	19.00
7	Truck and double center-axle trailers		27.30	66	18.70
8	B-double (13.6 *2)		30.9	80	19.00
9	Truck and B-double		33.8	90	19.00
10	B-triple		33.8	90	19.00

3.2 Test cases

Two different friction levels are considered for the comparison, which is characterized by the normalized peak friction in the tire models as well as the coefficient of friction in the expressions (2), (6) and (9). A value of $\mu = 0.9$ is used to representing dry asphalt conditions and a low value of $\mu = 0.25$ is used for winter condition roads. The lower value originates from the Swedish road administration, and a grip guarantees for minor roads during winter time on the Swedish road network. This is included as a worst case scenario in the comparison.

Furthermore, two engine alternatives are included in the comparison; a strong engine with 750hp and a weaker alternative with only 330hp. The characteristics are taken as generic for the two simpler models. The weaker engine option is not tested together with the lower friction has it is anticipated that the lower friction level will still be the limiting factor.

3.3 The reference models

The two models used in the comparison against the simple expressions represent 2 complexity levels. The simpler of the two consider rotational components of the powertrain as well as tire characteristics and load transfer due to road slope, see Kati et. al. (2014). The most complex model includes these effects in a more detailed fashion, and the powertrain is more carefully described. This model is widely used and accepted across the OEM.

It should be stressed that the exact performance and the level of details in the model are not the focus of this study. The study aims at illustrating differences and similarities between models with different complexity that are parameterized to describe the same vehicle combinations.

4. Results

The result of the comparison between the three models in the three test cases for the 10 vehicle combinations is presented here for the three PBS measures. The result is presented in bar plots for all three models, test cases and combinations. A bar plot is also given for the relative error between the OEM model and the other two. The relative error is defined as, e.g. for the Startability measure:

$$\frac{S_{\%} - S_{\%,OEM}}{S_{\%,OEM}}$$

4.1 Startability

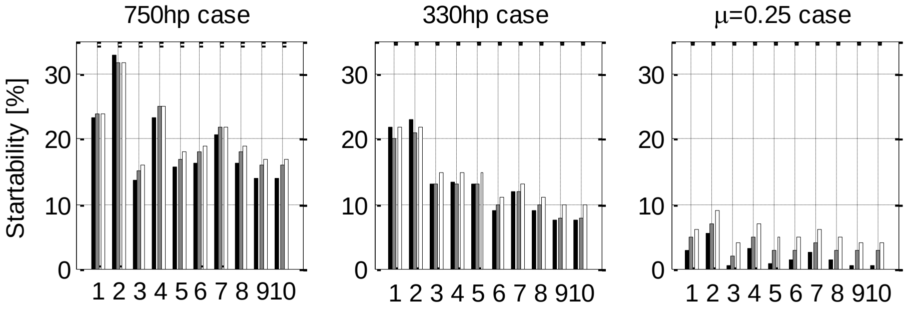


Figure 1 – The Startability PBS measure. Black is the OEM model result, grey the intermediate model and white the expression (2).

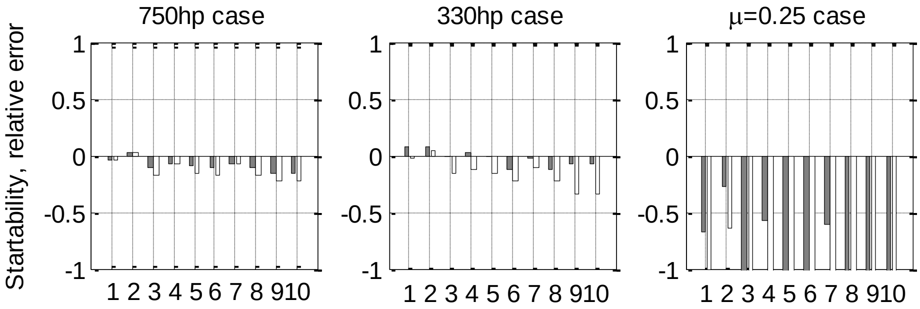


Figure 2 – The relative error of the Startability to the OEM model. Grey bar is the intermediate and white the expression (2).

4.2 Gradeablity

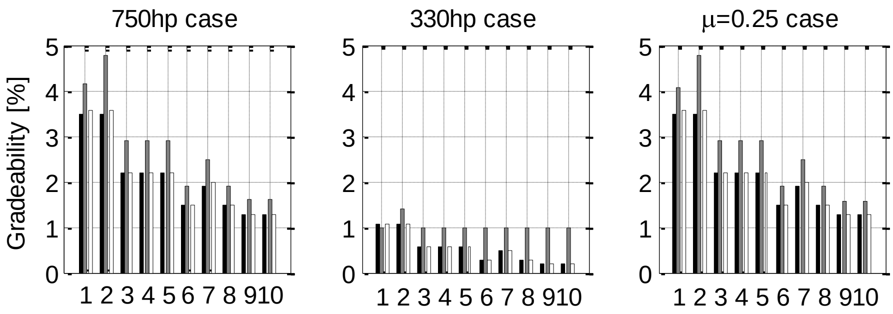


Figure 3 – The relative error of the Startability to the OEM model. Grey bar is the intermediate and white the expression (2).

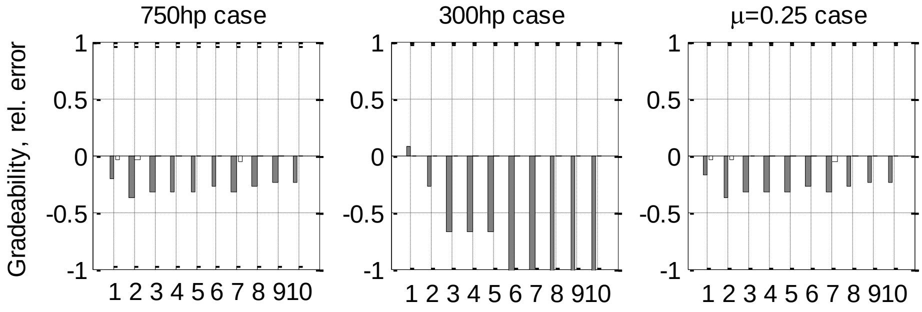


Figure 4 – The relative error of the Gradeability measure to the OEM model. Grey bar is the intermediate and white the expression (6).

4.3 Acceleration capability

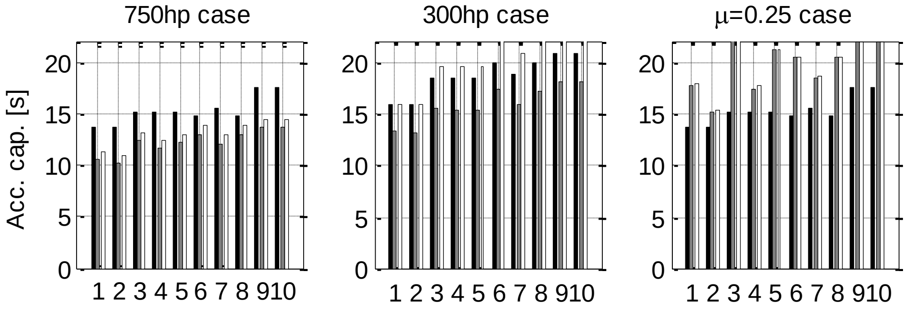


Figure 5 – The Acceleration Capability PBS measure. Black is the OEM model result, grey the intermediate model and white the expression (9).

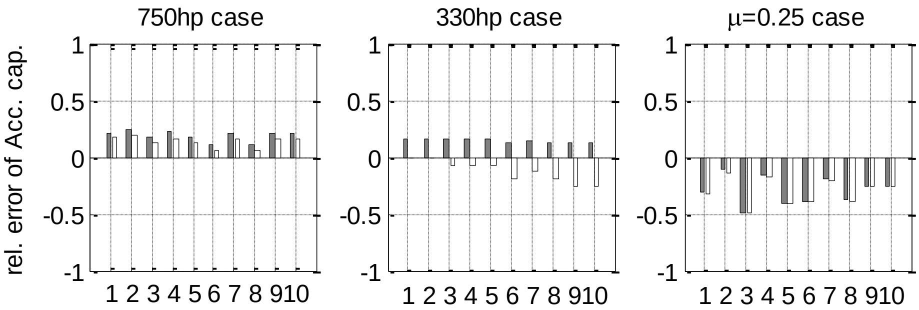


Figure 6 – The relative error of the Acceleration Capability measure to the OEM model. Grey bar is the intermediate model and white the result form (6).

5. Discussion

It can be noticed that the general match between all three models is quite good. For the Startability measure, this is particularly true for the two engine cases and all the vehicle combinations. The relative error is about 10-15 % for most of the vehicle combinations with a higher relative error for the heavier combinations peaking at 30%. For cases when the measure has a low absolute value, the sensitivity and impact of the simplifications and assumptions becomes gradually more prominent. For the slippery condition, this become even more emphasized with large relative errors for both the intermediate model and the simple expression. Both of them are overestimating the measure indicating that the propelling force that can be extracted for that friction is exaggerated in these two models and that the real force that can be used is limited by a portion of the maximum friction.

For the Gradeability measure, the match between the simple expressions and OEM model is very good This implies that the simplifications made are justified and the accuracy of the simple expression is within the rounding error of the measure. With the intermediate model, the measure is overestimated for almost all the cases with both large absolute and relative errors. This speaks against intuition that the accuracy increases with the model complexity. The intermediate and simple models' parameters have been changed to match the OEM models, but only the basic parameters are used by the simpler one. An explanation of the large discrepancy between the OEM and the intermediate models could be that parameters not used in the simple model may have a large impact if they are improperly tuned. This would then illustrate the importance of transparency and simplicity of the models used in a legislation.

The Acceleration Capability measure shows an approximately 20% relative error for the two least complex models compared to the OEM model for both engine cases. The simpler ones show a very similar behavior for the stronger engine case, while they differ to some extent for the weaker engine case. For the slippery case, the two simpler models perform very similarly for all the vehicle combinations. They both overestimate the measure, indicating that they underestimate the traction force that can be utilized compared to the OEM model. The errors are substantial.

6. Conclusions

Performance-based standards may be a well-suited policy to address the complexity of variations in vehicle combinations. It also enables a direct way of addressing certain requirements associated with the safety, environment and road network and their implications to vehicle specific quantities without being prescriptive on these. A key point in succeeding in introducing such policy is the ease of verifying compliance with the measures. An appealing approach is through computer based simulations.

This paper raises the question of how complex models used to verify compliance with the PBS measures needs to be. This is done by comparing three models with very different complexity for a range of vehicle combinations. The simplest ones, derived here, only make use of the most basic phenomena and are simple enough to be used and understood by any non-expert in the field. The comparison shows a good match between the three models for three longitudinal performance based standard measures, despite their large difference. However, slippery conditions in low speeds seem to require a high level of model complexity.

The simplicity of the models used to assess the performance measures would decrease the risk of inaccurate and erroneous results due to incorrect parameters and other mistakes in the model. It would also increase the understanding and potentially make the processes and routines in the legislations simpler. It is of importance that the accuracy of the model output is high enough to claim that it can assess the effect of the vehicle on the safety or infrastructure issue the PBS measure is supposed to address. The question of accuracy and its connection to model complexity should be further investigated in a larger context. The accuracy of the models should also be further investigated with respect to model validation.

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