FALCON III: Defining a Performance-Based Standards Framework for High Capacity Vehicles in Europe

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Abstract

The FALCON project ("Freight and Logistics in a Multimodal Context") is a collaborative effort funded by the Conference of European Directors of Roads (CEDR), and has set out to address ambitious carbon emission reduction targets set by the European Commission. A primary goal of the project is to define a potential Performance-Based Standards (PBS) framework for cross-border road freight transport in Europe. First, a representative fleet of heavy vehicle combinations carrying modular loading units was formulated in collaboration with industry. The fleet was then simulated against a wide range of potential performance standards sourced from various countries. These findings together with expert opinion were then used to draft recommendations for a PBS framework for Europe.

Keywords: Performance-Based Standards, High Capacity Vehicles, Commercial Vehicle Technology, Smart Infrastructure Access Policy

1. Introduction

The European Commission has set ambitious carbon emission reduction targets of 20% by 2020 and 80% by 2050, relative to 1990 levels (Committee on Climate Change, 2016). The European transport sector contributes approximately 20% of current carbon emissions, and of this trucks and buses account for around a quarter (European Commission, 2014). Improving the efficiency of road freight transport is hence pivotal in recent carbon reduction efforts. The use of High Capacity Vehicles (HCVs) is a proven highly effective means of reducing the carbon emissions of road freight transport, which has been demonstrated in numerous countries including Australia (National Transport Commission, 2008) and South Africa (Nordengen, Kienhöfer and de Saxe, 2014). In Europe, Directive 96/53EC (European Council, 1996) describes the European Modular System (EMS), which permits individual EU members to allow defined HCV combinations up to 25.25 m in length to operate internally. So far this has been adopted by Sweden, Finland, Netherlands, Germany and Spain (Aurell and Wadman, 2007; Kraaijenhagen *et al.*, 2014; *European Modular System: News*, 2017). However, there is a need for a uniform cross-border framework which permits HCVs on designated routes, and which permits HCVs that are more productive than those permitted by EMS in order to make more substantial headway in the reduction of carbon emissions.

The FALCON project ("Freight and Logistics in a Multimodal Context") is a collaborative effort funded by the Conference of European Directors of Roads (CEDR). Its objective is to assess the feasibility of a suitable framework for cross-border HCV transport in Europe. The consortium members consist predominantly of research entities and industry organisations in Europe. As part of this effort, a framework based on Performance-Based Standards (PBS), coupled with a suitable 'Smart Infrastructure Access Programme' (SIAP) is being conceptualized and evaluated. This paper focusses on two aspects of the project: (i) the definition of a representative fleet of potential HCVs for Europe, and (ii) the definition of the PBS and SIAP frameworks under which they should operate. Detailed results have been excluded for brevity, but will be presented in the final project report.

2. Methodology

The methodology used in the study can be summarised as follows:

1. Define a representative fleet of current heavy vehicle combinations and proposed high capacity vehicles in Europe.
    a. Vehicle units and loading units should be modular in line with EMS.
2. Gather all potentially relevant performance standards from various countries.
3. Simulate the representative fleet against all performance standards. Assess:
    a. a representative loading case (based on available EU statistics), and
    b. a critical loading case (with high mass and centre of gravity).
4. Observe the performance of the representative fleet, and assess the following:
    a. Which standards are appropriate for a European PBS framework?
    b. Which standards are not, or need to be redefined?
    c. Which combinations perform poorly, and require active intervention systems?
    d. Do any of the pass/fail criteria need refining for European conditions?
5. Give recommendations on:
    a. a proposed European PBS framework,
    b. a proposed road access classification system for European PBS, and
    c. a supporting framework including intelligent access, self-regulation, etc.

3. Representative fleet

The representative fleet was defined from a number of sources, and importantly had to present multimodal potential in line with Directive 96/53EC. The representative fleet included existing EU combinations complying with Directive 96/53EC, current EMS combinations operating in some EU member states, and longer combinations being tested in isolated pilot programmes in certain countries (potential "EMS 2" vehicles). All vehicle combinations were simulated carrying standardized multimodal loading units, all of which were considered uniformly loaded with a cargo of uniform density. The loading units considered were: 20' / 40' / 45' / 13.6 m / 14.92 m containers, and the C782 swap body.

The configurations and dimensions of the combinations were defined in consultation with operators and tractor and trailer manufacturers. Minor modifications were made to ensure modularity between combinations. Vehicle parameters such as suspension characteristics, centres of gravity, roll centre height *etc.* were agreed by members of the consortium to be representative of current European vehicles and were sourced from OEMs and published data. It was assumed that no active control systems were present, such as roll stability control, or electronic stability control, as passive performance was to be measured (with the exception of simulating an ABS braking manoeuvre). Tyre data were sourced from experimental measurements captured previously, and were corroborated by Michelin for representativeness. Separate winter tyre data were used for low friction simulations. A selection of powertrains were matched to combinations according to combination mass and number of drive axles.

3.1 Loading conditions

To determine suitable representative EU loading conditions, the relevant literature was reviewed (Lumsden, 1998; European Environment Agency, 2010; European Commission, 2011; Davydenko, 2014; Kharrazi, 2017; TML, 2017). It was concluded that the mass utilization for a typical tractor semi-trailer in the EU is 50-60%, whereas volume utilization is typically 80-90%. Loading deck surface utilization for a tractor-semitrailer is typically 85-95%. For long-haul transport (> 150 km), volume utilisation increases with trip length (Davydenko, 2014). Therefore, payload was assumed to be volume-based. To find a representative payload density, average tractor-semitrailer payload masses ("load factors") in a number of EU countries were reviewed, as shown in Figure 1 (EU average in the centre).

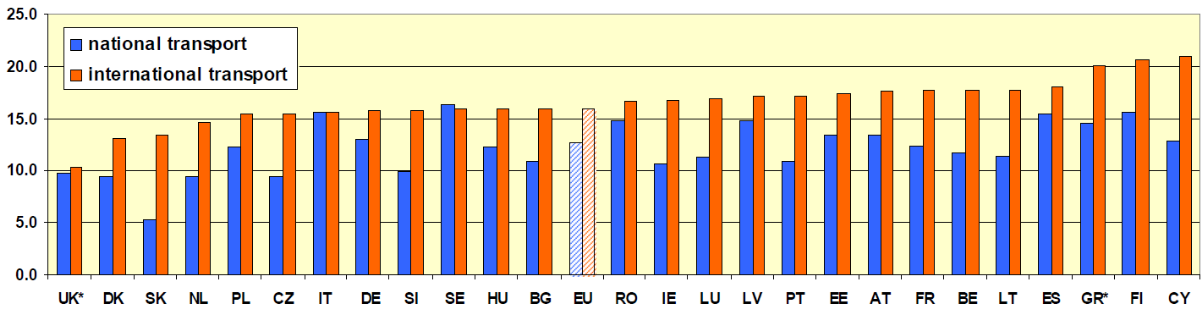


Figure 1 – Average load factor per country, 2010 (European Commission, 2011)

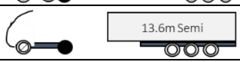
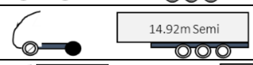
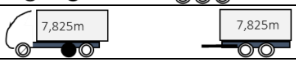
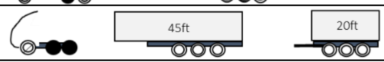
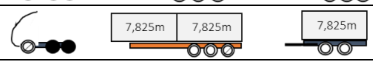
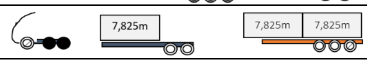
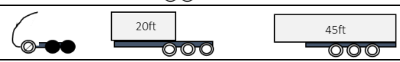
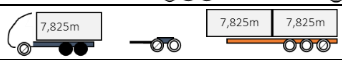
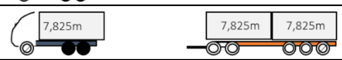
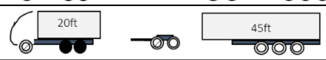
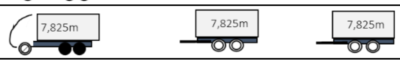
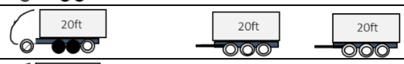
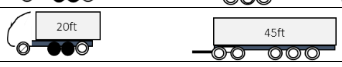
Given that a typical 13.6 m EU semitrailer carries approximately 28 tonnes of loaded cargo, and has an internal volume of 87 m^3, the average density was calculated to be 156.3 kg/m^3. A 20% safety factor was added to this to yield a payload density of 187kg/m^3. A second "critical" loading case was defined by increasing the density uniformly for all vehicle units until allowable axle loads were approached while maintaining acceptable combination mass. This critical loading density was found to be 280 kg/m^3.

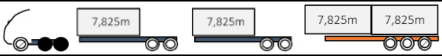
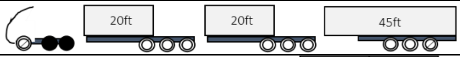
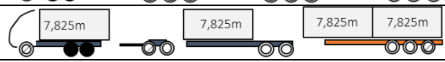
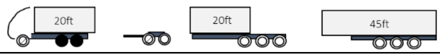
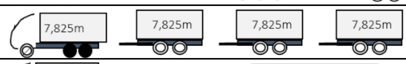
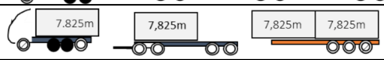
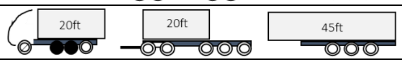
The volume utilization determines the height of the centres of gravity, which is critical in influencing lateral and roll dynamics of the vehicles. The average volume utilization in Europe is 82% (Lumsden, 1998). Assuming homogenous cargo, the centre of gravity of the loaded cargo is at 41% of the internal height of each loading unit. This correlates well with a common assumptoin regarding mixed freight: that the load is distributed with 70% of the mass in the lower half of the load space and 30% in the top half, giving a centre of gravity height of 40% of the internal loading space (Fancher *et al.*, 1986).

3.2 Representative vehicle combinations

The representative fleet is summarised in Table 1. The fleet was categorised into six groups. Groups 1 and 2 represent vehicle combinations that comply with 96/53/EC and represent vehicles that are legal to operate for EU cross border transport (combinations 1.2 and 1.4 are exceptions). Groups 3 and 4 represent EMS-type vehicles that are currently operating in number of EU member states on a national level. Finally, Groups 5 and 6 are combinations with lengths typically above 30 m that are being tested in isolated national pilot programmes. The UK "longer semi-trailer" has been included in the fleet (2x7.825 m).

Table 1 – Representative vehicle fleet

Vehicle group and code †		**Vehicle description**
1.1	TR6x2-ST3 (45ft)	
1.2	TR6x2-ST3 (2x7.8m)	
1.3	TR4x2-ST3 (13.6m)	
1.4	TR4x2-ST3 (14.9m)	
2.1	TK6x2-CT2 (2x7.8m)	
2.2	TK6x2-FT1+1 (2x7.8m)	
2.3	TK6x2-CT3(2x20ft)	
3.1	TR6x4-ST3-CT3(45ft+20ft)	
3.2	TR6x4-ST3-CT2(3x7.8m)	
3.3	TR6x4-LT2-ST3(3x7.8m)	
3.4	TR6x4-LT3-ST3(20ft+45ft)	
4.1	TK6x4-DY2-ST3 (3x7.8m)	
4.2	TK6x4-FT2+3 (3x7.8m)	
4.3	TK6x4-DY2-ST3 (20ft+45ft)	
4.4	TK6x4-FT2+3 (20ft+45ft)	
4.5	TK6x4-CT2-CT2 (3x7.8m)	
4.6	TK8x4-CT3-CT3(3x20ft)	
4.7	TK8x4-FT2+3(20ft+45ft)	

5.1	TR6x4-ST3-DY2-ST3 (2x45ft)	
5.2	TR6x4-ST3-FT2+3 (2x45ft)	
5.3	TR6x4-LT2-LT2-ST3 (4x7.8m)	
5.4	TR6x4-LT3-LT3-ST3 (2x20ft+45ft)	
6.1	TK6x4-DY2-LT2-ST3 (4x7.8m)	
6.2	TK6x4-DY2-LT2-ST3 (2x7.8m+45ft)	
6.3	TK6x4-CT2-CT2-CT2 (4x7.8m)	
6.4	TK8x4-LT2+2-ST3 (4x7.8m)	
6.5	TK8x4-LT2+3-ST3 (2x20ft+45ft)	

† ***TR***axb = Tractor (a = # of wheels, b = # of driven wheels), ***TK***axb = Rigid truck (a = # of wheels, b = # of driven wheels), ***ST***a = Semi-trailer (a = # of axles), ***CT***a = Centre-axle trailer (a = # of axles), ***FT***a+b = Full trailer (a = # of front axles, b = # of rear axles), ***LT***a = Link trailer (a = # of axles), ***DY***a = Dolly (a = # of axles)

4. Performance standards considered

Potential performance standards were sourced from: the Australian PBS framework (National Transport Commission, 2008), Directive 97/27/EC (European Council, 1997), Netherlands Directive JBZ 2013/ 9832 (Netherlands Vehicle Authority (RDW), 2013), Canadian PBS (Ervin and Guy, 1986), and UNECE regulations (UNECE, 2014). It was important to explore performance standards beyond the extensive Australian framework as the operating and regulatory conditions are clearly different between Australia and Europe. Factors that shaped the Australian scheme initially and over time, such as existing legislation and the performance of the existing Australian fleet, will not in general be the same in Europe. Table 2 summarises the performance standards considered, categorised into: driveability, manoeuvrability, high-speed stability, winter conditions, and infrastructure. Summer and winter coefficients of friction were taken to be 0.8 and 0.3 respectively.

Table 2 – Performance standards evaluated

Standard	Manoeuvre	Source
Driveability		
Startability	Start on incline	Australian PBS
Gradeability A (Maintain motion)	Maintain motion on incline	Australian PBS
Gradeability B (Maintain speed)	Maintain speed on 1% incline	Australian PBS
Acceleration Capability	Accelerate from rest	Australian PBS
Manoeuvrability		
Low Speed Swept Path	90° turn, radius 12.5 m	Australian PBS
Frontal Swing	90° turn, radius 12.5 m	Australian PBS
Difference of Maxima	90° turn, radius 12.5 m	Australian PBS
Maximum of Difference	90° turn, radius 12.5 m	Australian PBS
Tail Swing	90° turn, radius 12.5 m	Australian PBS
Steer-Tyre Friction Demand	90° turn, radius 12.5 m	Australian PBS
Turning circle	Roundabout	Directive 97/27/EC
NL multi turning circle	Roundabout (various, modified)	Netherlands JBZ 2013/ 9832
High-speed stability		
Static Rollover Threshold	Tilt-table / Constant radius turn	Australian PBS

Rearward Amplification	Single lane change (SAE)	Australian PBS (modified)
High-Speed Transient Off-tracking	Single lane change (SAE)	Australian PBS
High-Speed Steady-State Off-tracking	Constant radius turn	Canada
Dynamic Load Transfer Ratio	Single lane change (SAE)	Canada
Yaw Damping Coefficient	Pulse steer input @ 80 km/h	Australian PBS
Tracking Ability on a Straight Path	Rough road & cross slope at speed	Australian PBS
Winter conditions		
Low friction braking	Straight line ABS stop (low mu)	ECE Reg. 16
Steer tyre friction demand	90° turn, radius 12.5 m (low mu)	Australian PBS, low mu
Drive tyre friction demand	90° turn, radius 12.5 m (low mu)	Canada, but Aus. manoeuvre
Low friction startability	Start on incline (low mu)	Australian PBS, low mu
Infrastructure		
Bridge loading	N/A	Custom approach
Road wear	N/A	Custom approach

In addition to the Australian manoeuvrability standards, two variations of a “roundabout” manoeuvre were added. This includes the standard UK/EU roundabout test from Directive 97/27/EC, which is important in order to incorporate for the UK as a potential participant in a European PBS-type scheme, as this is a non-negotiable element of heavy vehicle regulation in the country. However this roundabout test was designed for standard tractor semi-trailer combinations; combinations longer than this are unlikely to pass, and even longer combinations are unlikely to be able to complete the manoeuvre at all. It will therefore only be a requirement for a limited road access class of vehicles. An alternative test from the Dutch Directive JBZ 2013/ 9832 that accommodates both the standard roundabout manoeuvre and long vehicle combination was also considered. The test is divided into four levels, where level 1 is the standard roundabout test for combinations less than 17 m in length, and the vehicle must perform the full 12.5 m 270° turn. Longer vehicle combinations are accommodated in Levels 2–4, which only require a 120° turn to be performed at increasing outer radii. The minimum inner radius is also adjusted accordingly.

The Australian rearward amplification standard was assessed in a modified form closer to an earlier RTAC (Roads and Transport Association of Canada) definition: the amplification was measured at the rearmost trailer (not roll-coupled unit), and the pass/fail criterion was simply a ratio, i.e. not linked to the rollover threshold of the rear trailer/s.

Regarding winter conditions, it was decided that instead of a full assessment of all low and high speed standards under low friction conditions, only braking and low-speed standards would be assessed. This assumes that the worst realistic scenario is that a driver would have to decelerate quickly in sudden unexpected icy conditions, and must then navigate safely at low speed. This is a simpler approach, and avoids parameter-sensitive simulations of high speed low friction dynamics. This is supported by the fact that existing PBS schemes in Australia and South Africa impose additional requirements to ensure that drivers are of a standard of at least above legal minimums, and that speeding is strictly monitored and managed. The drive tyre friction demand is a modification of the Canadian friction demand in a tight turn standard, adjusted to be assessed using the same 90° turn as the Australian standards.

5. Summary and discussion of simulation results

This section outlines the important findings from the simulation results, and discusses their implications for the proposed PBS framework. The vehicle models used by HAN, VTI and CSIR were cross-validated to ensure consistency. Detailed simulation reults and discussions will be published in the full project report.

5.1 Vehicle dynamics

Simulation methodology

Vehicle dynamics simulations were carried out by the CSIR South Africa using a combination of commercial vehicle dynamics software and first principle calculations using TruckSIM and MATLAB. Vehicles were assessed for both representative and critical loading conditions.

Results and discussion

High-Speed Steady Off-tracking was shown to be highly correlated with combination length and so was deemed to add no additional value. Suitable length limits per road access level should be imposed instead. Tracking Ability on a Straight Path was shown to be very highly correlated with High-Speed Transient Off-tracking, and the existing pass/fail criteria for HSTO were consistently shown to be the limiting case for all vehicles. Additionally, the TASP standard was noted by South African PBS assessors to be problematic in terms of complexity and the consistency of simulations between assessors, and it requires the simulation of a unique manoeuvre to obtain a single performance result. Given the above, it was decided that the TASP standard added no additional value.

Performance based on the Netherlands turning circle manoeuvre was shown to correlate well with that of the Australian Low-Speed Swept Path standard. However, the Netherlands test is more complex (multiple different manoeuvres depending on vehicle length), requires more road space during testing, and has unreasonably high allowances for tail swing. The Australian 90° turn is a standardised manoeuvre, and includes a reasonable assessment of tail swing, frontal swing, and friction demand within the same manoeuvre. The Netherlands standard was therefore considered to add little value.

All vehicles meet the important Static Rollover Threshold requirement of $\geq 0.35 \cdot g$, except for combinations 1.2 & 1.4 in the critical loading case. However, over half the combinations exceed the recommended limits for Load Transfer Ratio (≤ 0.6) and Rearward Amplification (≤ 2). Given that LTR and RA are highly sensitive to dimensional parameters such as wheelbases and hitch offsets, it was deduced that this was likely a shortcoming of the given vehicle designs. It was shown that this could be addressed with relatively minor modifications to the vehicle designs. In particular, the A-double combination 5.1 performed less well than expected from experience in Australia and South Africa, but was shown to perform well with minor and representative modifications to wheelbases, hitch locations and drawbar length.

The centre-axle trailer combinations 4.5, 4.6, and 6.3 all exhibited a Load Transfer Ratio of 1, meaning that they experienced wheel-lift during the lane-change manoeuvre. These vehicles were consistently poor performers in other safety-critical standards, including Rearward Amplification. Combination 2.2 (the only combination with the FT1+1 trailer) also performed poorly relative to its peers in Group 2. Thus, to be able to include these combinations in a future European HCV framework, their performance should be improved by tuning design parameters such as coupling location or wheelbase, or through active control systems.

Strong correlation was exhibited between Load Transfer Ratio and Rearward Amplification. This might suggest that LTR can be excluded (as in the Australians PBS scheme), on the grounds that the standard is difficult to measure in the field, and so RA was preferable while capturing most of the same effects. However, the need to experimentally test LTR is no longer a primary concern as it was in the early days of PBS, and it has value in giving a very direct measure of the rollover risk of the rearmost trailer. It was decided to retain the "raw" method of assessing RA to directly assess the "whiplash" phenomenon, and to include LTR as a direct measure of rollover risk. Both standards are assessed in the same manoeuvre and so there is negligible added simulation effort in assessing both.

5.2 Winter conditions

Simulation methodology
Standards addressing winter conditions were assessed by VTI Sweden and HAN University of Applied Sciences in the Netherlands. Simulations were carried out using MATLAB SimMechanics models. Winter tyre data were provided by VTI, sourced from gathered data on ice at the VTI tyre testing facility. For the ABS braking manoeuvre, custom ABS models were developed at the University of Cambridge. Each ABS model was designed to be representative of existing systems in consultation with industry experts. Results of the ABS simulations were still pending at the time of writing.

Results and discussion
In the analysis of low friction startability performance, it was found that none of the vehicle fleet achieved a startability result of more than 3% in low friction, far from the 15% (Level 1) or 12% (Level 2) requirements in the Australian scheme. One potential solution to overcome this is to permit a temporary increase in the drive axle load during start up, through the use of lift axles or other means of load transfer.

Both the friction demand of steer tyres and drive tyres were assessed in low friction conditions, using the Australian 90° low-speed turn manoeuvre. It should be noted that the friction demand is calculated as the ratio of horizontal and normal forces at the tyre contact point, and it is not normalized by the friction coefficient. Both steer tyre and drive tyre friction demand were found to decrease from high to low friction. This can be explained by the fact that the friction demand is not only dependent on the friction level, but also on other tyre properties such as cornering stiffness (Kharrazi, Bruzelius and Sandberg, 2017). Therefore it is important to assess friction demand at both high and low friction.

5.3 Bridge loading

Simulation methodology
The impact of the representative fleet on bridges was assessed by IFSTTAR France using the ST1 software. Axle loads calculated from the vehicle models were provided by CSIR. The impact of the fleet was assessed on a catalogue of bridges, including simply-supported single span bridges, two-span continuous bridges, and spans of 10, 20, 35, 50 and 100 m. The metrics considered were the bending moment at the mid-span, shear force at the supports, and fatigue loading. Dynamic effects were not considered at this stage. Combination 2.1 was considered to be the reference case. Traffic load models from Eurocode 1 were used.

Results and discussion

The simulation showed that, in general, the high capacity vehicles were not more aggressive than the reference combination 2.1. A need for some level of normalization by volume/length or mass/cargo mass was also shown.

5.4 Road wear impact

Simulation methodology

The impact of the representative fleet on roads was assessed by BRRC in Belgium. Axle loads were provided by CSIR from the vehicle models. Seven pavement structures were evaluated:

- a flexible pavement (designed for low traffic loading),
- two thick bituminous pavements (designed for medium and high traffic respectively),
- two semi-rigid pavements (designed for medium and high traffic respectively), and
- two concrete pavements (designed for medium and high traffic respectively).

Stresses and strains were computed using the software Alizé-LCPC, modelling the road structures with a linear elastic multi-layer model. Material properties were obtained from the Alizé-LCPC database. A standard axle of 10kN was modelled and used as a reference. From the stresses and strains, the number of repetitions of the loads applied by the axle groups before failure of the pavement were calculated. The vehicle combinations were then ranked according to aggressiveness. Additional rankings were carried out according to aggressiveness normalised by payload volume, payload mass, and combination mass. Combinations 1.3 and 2.1 were used as the reference vehicles.

Results and discussion

On a vehicle level, none of the high capacity vehicles was excessively aggressive when compared to reference combination 2.1. For individual axle groups, combinations 4.5 and 6.1 were generally speaking more aggressive than 3.1 and 5.1 (only selected fleet vehicles were assessed). One of the axle groups of combination 6.1 was found to be more aggressive than the axle groups of reference trucks 1.3 and 2.1. The axle groups of the other combinations were comparable to the axle groups of reference combinations 1.3 and 2.1. For the flexible pavement designed for low traffic volumes, high capacity vehicles (as characterised by combinations 4.5, 5.1 and 6.1) imposed severe loading on the road. However these vehicles are not expected to operate on routes which include such pavement structures.

6. PBS framework recommendations

Given the findings of the simulation work, and inputs from expert PBS opinion, the following recommendations are made for the European PBS framework.

6.1 Vehicle safety standards

The following recommendations are made (with reference to Table 2):

1. The Australian driveability standards should be retained. The pass/fail criteria should be reviewed in the context of existing European infrastructure and geography.
2. The Australian manoeuvrability standards should be retained as these are well suited to regular and long vehicle combinations. The UK/EU roundabout test should be an added requirement for vehicles accessing large portions of the road network. Pass/fail

criteria should be reviewed in the context of European road geometries such as lane widths and intersection layouts.

3. The Australian high-speed dynamic standards should be kept, with some exceptions:
    a. It is recommended that Tracking Ability on a Straight Path be removed.
    b. The Load Transfer Ratio standard should be added.
    c. The Rearward Amplification standard should be decoupled from rollover risk (now addressed with LTR), and should only assess the amplification of acceleration at the rearmost trailer.
4. All standards assessed for low friction conditions add value and should be retained. Some additional work is required to determine adequate pass/fail criteria.

6.2 Bridge loading effects

The proposed method for the assessment of bridge loading effects focusses on the development of a deterministic "bridge formula" (a probabilistic bridge formula would need to consider the uncertainties of structure/materials and of actions/loads through for example reliability calculations). In this case, the permitted vehicle, axle and axle group loads should have the shape $W = f(L, N)$, where L is the length between the first and last axles in the group being considered, and N is the number of axles. The proposed method for determining a suitable bridge formula is then as follows:

1. Create a representative set of vehicles (as done), structures and structural effects that represent that which currently exists in Europe.
2. Calculate the effects of all vehicles on all structures against all structural effects. From this, define a suitable limit for each effect, taking into account, for example, the fractions of the effects of the load model, a fractile of the effects of the vehicles or depending on the acceptability (or not) of given vehicles.
3. For each structural effect, the outcome would be a limit that should not be exceeded. A bridge formula can be fitted as follows:

A first solution may be a linear fit for equation $W = f(L, N)$ as follows: $W = a_0 L \times N + a_1 L + a_2 N + a_3$, where a_0, a_1, a_2, a_3 are constant numerical values. This equation must fit the envelope of effects for each vehicle, axle and group of axles. Another option would be to fit higher order equations to the envelope of the most aggressive effect. To do that, the degree of the fitted curve can be fixed *a priori* as the highest degree of the influence lines, given that the effect is linked to the influence line which is a polynomial function of given order. For example, for a single span structure, the polynomial is linear with respect to shear force, and of degree two for bending moments.

6.3 Road wear impact

The following procedure is proposed for assessing a given vehicle combination for inclusion in a European PBS framework:

1. Use combination 2.1 loaded to 40 tonnes (the legal limit in EU) as the reference case.
2. For each individual country, select representative road structures (~three) from those present in the country (as the road structures differ significantly between countries).
3. Compute the aggressiveness of combination 2.1 on each of these road structures, and consider this to be the upper limit of permitted aggressiveness for new vehicles.
4. Assess the aggressiveness of the proposed vehicle relative to the reference case.

5. For each of the representative pavements, calculate the maximum load that can be carried by the proposed vehicle while ensuring the maximum permitted aggressiveness is not exceeded. In this way, new vehicle combinations can be permitted subject to a maximum load specific to each vehicle. The approach takes national differences into account but can be used throughout Europe.

The computations can be done by the local road regulator, which will be best placed for selecting the most representative road structures. The computations can also be done with the design tools and software that are currently in use on a local (national or regional) level. The definition of *aggressiveness* must be fixed, *i.e.* whether it is based on a vehicle or axle group level, or whether the aggressiveness is scaled by payload volume etc. A measure scaled by volume will be the most representative of the net impact of the overall freight task.

6.4 Road access classification

Table 3 outlines the existing Australian road access classification system. It ranges from Level 1 vehicles which are permitted access to all of the Australian road network and for which the required performance criteria are set accordingly strictly. Levels 2–4 accommodate longer vehicle combinations that are restricted to increasingly smaller subsets of the road network, with accordingly less strict criteria on some standards. At the extreme end is Level 4, which caters for the longest vehicles operating in remote regions of the country. This is the category into which new Australian “road train”-type combinations are categorised.

Table 3 – Australian road access level classification

Road access level	Permitted vehicle length	Permitted routes	Performance criteria
Level 1	≤ 20 m	Unrestricted road access	Most stringent
Level 2	≤ 30 m	Significant freight routes	
Level 3	≤ 42 m	Major freight routes	
Level 4	≤ 60 m	Remote areas	Least stringent

Using the Australian framework as a baseline, the proposed road access classification system for Europe is shown in Table 4. Consideration was given to the existing road network characteristics, existing regulations, and geography. The concept of “unrestricted road access” was deemed inappropriate for equivalent Level 1 European vehicles, and was replaced with “existing truck routes”, to avoid the possibility of long articulated heavy vehicles travelling through medieval European city centres for example. The UK/EU roundabout test would be enforced for this level. A new “Level 0” was added, to account for city-level freight activities such as garbage collection and home grocery delivery. Here, it is envisaged that additional stricter manoeuvrability tests (as yet undefined) representative of small city intersections be imposed. This also allows for the possibility of higher capacity vehicles serving these industries in the future, provided that they can be shown to meet the strict manoeuvrability criteria (using advanced steering control systems for example) as well as other city-level requirements for noise and air pollution (by using electric drive for example). Levels 2 and 3 were deemed approximately equivalent to the Australian system, with the observation that Level 1 would typically serve EMS-type vehicle combinations, and Level 2 would serve “EMS 2”-type combinations. Level 4 was deemed non-applicable to European conditions.

Table 4 – Proposed European road access level classification

Road access level	Permitted routes	Notes
Level 0	Unrestricted road access	Stricter manoeuvrability criteria for city access for garbage trucks, home delivery *etc.*
Level 1	Existing truck routes	Includes EU/UK roundabout manoeuvre
Level 2	Significant freight routes	Approximately equivalent to EMS vehicles
Level 3	Major freight routes	Approximately equivalent to EMS 2 vehicles

6.5 Supporting framework

It is proposed that a European PBS framework should adopt a set of supporting frameworks such as those that have been put in place in Australia and South Africa. These include systems that ensure adequate driver training, speed monitoring, vehicle maintenance, loading control, and vehicle tracking (to ensure compliance with approved routes). Such systems are crucial for the long term sustainability and impact of a PBS framework. Reference should be made to the Australian Intelligent Access Programme (IAP) and National Heavy Vehicle Accreditation Scheme (NHVAS) (NTC, 2011), and the South African Road Transport Management System (RTMS) (SABS Standards Division, 2014). Any existing equivalent systems in Europe should be used where possible.

7. Conclusions and future work

1. The FALCON project has set out to contribute to the reduction of carbon emissions in European road freight transport, through a Performance-Based Standards framework. This paper describes the methodology that could be used to achieve this, and gves recommendations for the proposed framework.
2. A representative fleet of European vehicle combinations was defined and simulated against a wide range of potential performance standards. Findings from these results were used to guide the choice of applicable European performance standards.
3. The proposed framework is based largely around the Australian PBS scheme, with modifications and additions addressing inner-city manoeuvrability, existing European regulations, regional icy conditions, and European-specific approaches to infrastructure protection.
4. The project is currently ongoing, and remaining tasks include the refinement of various pass/fail criteria for European conditions, and making final conclusions on the inclusion of certain standards in the proposal.

8. References

- Aurell, J. and Wadman, T. (2007) *Vehicle combinations based on the modular concept*. 1/2007. Available at: http://www.nvfnorden.org/lisalib/getfile.aspx?itemid=260.
- Committee on Climate Change (2016) *Carbon budgets: how we monitor emissions targets*. Committee on Climate Change. Available at: https://www.theccc.org.uk/tackling-climate-change/reducing-carbon-emissions/carbon-budgets-and-targets/ (Accessed: 6 June 2017).
- Davydenko, I. (2014) *Vrachtauto's zijn toch beter benut? Een eerste kijk naar gewicht, volume en oppervlakte benutting in Nederlands wegvervoert*. The Hague.
- Ervin, R. D. and Guy, Y. (1986) *The influence of weights and dimensions on the stability and control of heavy duty trucks in Canada (UMTRI-86-35/I)*. Ann Arbor, Michigan: University of Michigan Transportation Research Institute.
- European Commission (2011) *Road freight transport vademecum: Market trends and structure of the road heaulage sector in the EU in 2010*. Brussels.

- European Commission (2014) *Strategy for reducing heavy-duty vehicles' fuel consumption and CO2 emissions*. Brussels.
- European Council (1996) 'Council Directive 96/53/EC of 25 July 1996 laying down for certain road vehicles circulating within the community the maximum authorized dimensions in national and international traffic and the maximum authorized weights in international traffic'. Brussels, European Union: Council of the European Union, pp. 59–75.
- European Council (1997) *Directive 97/27/EC of 22 July 1997 on the masses and dimensions of certain categories of motor vehicles and their trailers*. European Parliament, Council of the European Union.
- European Environment Agency (2010) *Loading factors for freight transport*. Available at: https://www.eea.europa.eu/data-and-maps/indicators/load-factors-for-freight-transport/load-factors-for-freight-transport-1.
- *European Modular System: News* (2017). Available at: http://www.modularsystem.eu/en/news/ (Accessed: 4 July 2017).
- Fancher, P. S. *et al.* (1986) *A factbook of the mechanical properties of the components for single-unit and articulated heavy trucks (UMTRI-86-12)*. UMTRI-86-12. Ann Arbor, Michigan: University of Michigan Transportation Research Institute.
- Kharrazi, S. (2017) *Loading Conditions of Commercial vehicles in Sweden data provided by L. Larsson*.
- Kharrazi, S., Bruzelius, F. and Sandberg, U. (2017) *Performance based standards for high capacity transports in Sweden - FIFFI project 2013-03881 - Final report*. Linköping.
- Kraaijenhagen, B. *et al.* (2014) *Greening and safety assurance of future modular road vehicles: book of requirements*. NL Innovatie, HTAS I 10103.
- Lumsden, K. (1998) *Truck Masses and Dimensions: Impact on Transport Efficiency*. Brussels.
- National Transport Commission (2008) *Performance based standards scheme – The standards and vehicle assessment rules*. Melbourne.
- Netherlands Vehicle Authority (RDW) (2013) 'Beleidsregel ontheffing gerelateerde voertuigdocumenten (JBZ 2013/ 9832)'.
- Nordengen, P. A., Kienhöfer, F. W. and de Saxe, C. C. (2014) 'Vehicle safety performance improvements using a performance-based standards approach: four case studies', in *13th International Symposium on Heavy Vehicle Transport Technology (HVTT)*. San Louis: IFRTT.
- NTC (2011) *Performance based standards: Regulatory impact statement*. Melbourne.
- SABS Standards Division (2014) 'SANS 1395-1:2014, South African National Standard, Road transport management systems'. Pretoria.
- TML (2017) *Commercial vehicle of the Future: a roadmap towards fully sustainable truck operations*. Leuven.
- UNECE (2014) 'E/ECE/324/Rev.1/Add.12/Rev.8: Regulation No. 13: Uniform provisions concerning the approval of vehicles of categories M, N and O with regard to braking'. United Nations Economic Commission for Europe.