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INFRASTRUCTURE CATALOGUE AND CRITERIA FOR A PBS APPROACH OF EUROPEAN HEAVY COMMERCIAL VEHICLES REGULATION AND SMART ACCESS PROGRAMME

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ABSTRACT

In Europe, regulation on weights and dimensions of trucks are prescriptive, rather than performance based, as it is introduced in some other countries (Australia, Canada, South Africa). The performance based standards (PBS) allow more flexibility in the vehicle design and optimize their performances with respect to the infrastructure constraints. Thus, PBS facilitate innovation and industrial progresses, while mitigating adverse effects on infrastructure and road safety. Therefore, the European project FALCON (2016–2018), supported by CEDR proposed a methodology for the development of performance-based criteria and future PBS in Europe. This paper presents the approach developed for bridges and pavements criteria assessment and implementation.

For bridges, an exhaustive catalogue of structures has been developed, made of a pool of influence lines representative of the European bridge stock. Then, several design traffic load models used in the EU Member States, including the load models proposed in the Eurocode EN1991-2 *Traffic loads on road bridges* have been applied and compared on these structures. The governing load models and structures for the current traffic loads have been determined. This enabled proposing a performance-based standard approach, using either a bridge formula or a well-chosen upper limit of the load effects induced by the authorized heavy vehicles.

For pavements, a catalogue representing the standard, bituminous and rigid, European pavement structures was developed. The various wears have been reviewed, and design criteria have been listed. The individual impacts of the vehicles of a reference fleet have been calculated, making possible to rank them in terms of aggressiveness for the pavement.

That paves the way for a future PBS approach of heavy vehicle type approval, or a revision of the European Directive 2015/719 on commercial vehicles weights and dimensions. It also opens new perspectives to develop a SIAP (Smart Infrastructure Access Programme) to be implemented on the Trans-European road Network, as a tool to enhance the durability of the existing infrastructure with the lowest restrictions on the road freight movements.

1. PROBLEM STATEMENT

The slogan of the conference HVTT15 (IFRTT, 2018) stated: “*Economy on the wheels: fast changes, slow infrastructures*”. European road infrastructure was designed and built over the last several decades: pavements have a design period of 20 to 40 years. Bridges are designed for 100 years in average. However, traffic is changing rapidly, such as truck configurations which have fast changed, with a current trend towards longer and heavier combinations, with truck loadings of long freight transport optimized for a maximization of loaded trips.

This fact is reflected in the standards: regulations on traffic may change quite fast, whereas the traffic load models of infrastructure design standards are carefully calibrated by integrating safety factors in order to cater for future evolutions of traffic. For example, in Europe, traffic loads and dimensions are regulated according to Directive (EU) 2015/719 (which amends Directive 96/53/EC) whereas traffic load models for road bridge design are given by Eurocode 1-2 (CEN, 1991).




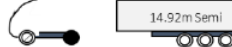

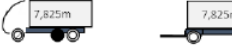



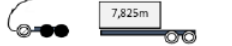
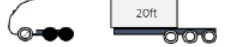









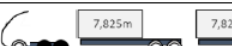
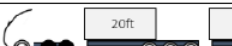

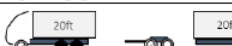



Nowadays, traffic load regulations are country specific, whereas freight transport is international. Harmonization between these regulations would facilitate freight, even if road design procedures remain national. Moreover, this regulation could also take better into account the damage induced by the various truck configurations and loadings, by introducing performance based standards (PBS). Those standards are already implemented in some countries, for example through bridge formula (Australia, Canada, South Africa...).

This article presents work performed within the European CEDR project FALCON, for PBS development for trucks weights and dimensions and design loads for bridges and pavements, using a truck fleet proposed as representative of the European heavy traffic. It first presents briefly the proposed vehicle fleet, and then details the considered methodologies for PBS development for bridges and pavements.

2. DEVELOPMENT OF A REPRESENTATIVE VEHICLE FLEET

A representative fleet of 27 heavy vehicle combinations, was identified as representative of the European truck silhouettes and loads as described in (de Saxe C. et al., 2018) and in Figure 1. This fleet is divided into 6 groups. Groups 1 and 2 gather vehicles fitting with the Directive 2015/719 limits, i.e. 18.75 m in length and 40 t gross vehicle mass, and currently in use for International transport in the European Union (EU). Groups 3 to 6 contain modular high capacity vehicles (HCV or EMS), which are longer and mostly heavier than the vehicles allowed by the European Directive 2015/719, but composed of standard units. These HCVs are in use in some European countries (e.g. DE, DK, FI, NL, SE...), sometime with some road use limitation.

The impact of all these vehicles has been assessed, on both bridges and pavements. The chosen road infrastructure and the corresponding methodologies are detailed in the following sections.

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)	

Silhouettes 1.1 to 2.3 comply with the European Directive 2015/719 and are allowed for International transport in the EU. Silhouettes 3.1 to 4.7 are called EMS (European Modular System) among the HCVs and do not exceed 25.25 m in length. They have a gross mass limit of 60 t (and less in some countries such as Germany). Silhouettes 5.1 to 6.5 are often named VHCVs (Very High Capacity Vehicles) and currently experimented in Sweden and Finland.

Figure 1 - Representative FALCON vehicle fleet

3. PERFORMANCE BASED STANDARDS FOR IMPACT OF TRAFFIC LOADS ON BRIDGES

3.1. Objectives and methodology

The objective is to find a rational criterion, which would make it possible to discriminate the vehicles configurations and loadings with acceptable induced damage on existing European bridges. To achieve that, several steps have been followed:

1. A representative pool of bridge structures, and the corresponding load effects to be assessed, have been proposed.
2. Then, the impacts of the vehicles of the representative vehicle fleet on these bridge structures have been assessed, for two types of limit states: extreme load effects (Flint & Jacob, 1996) and lifetime in fatigue (Jacob & Kretz, 1996). A classification of these vehicles by damage levels has been proposed. This could be the basis for the development of a bridge formula.
3. In parallel, European traffic load models for bridges have been reviewed. While a common European framework exists for those traffic load models, namely Eurocode 1-2, national specificities exist, for example through the national annexes. This leads to quite different design values. A methodology for derivation of a threshold of admissible load effects has been proposed.

3.2. Types of bridges

The representative pool of bridge structures to be assessed has been defined by choosing a given number of influence lines. This is a procedure which has already been used during the background works of the Eurocodes (Jacob, 1989) (Croce, 2001) and the studies evaluating the impact of new types of traffic (EU, 2008) (OECD, 2011).

In this study, two types of bridges (single span, two-span bridges), with several types of load effects, and 5 span lengths are studied (Table 1). The impacts of the vehicles of the FALCON fleet have been assessed on 25 influence lines.

Table 1 - Catalogue of influence lines for FALCON study of impact on bridges.

No	Bridge structure	Load effects	Span/total length	Limit state
1	Simply supported, single span	Bending moment at midspan 1, shear at support 0	10 - 20 - 35 - 50 - 100 m	Extreme effects & Fatigue
2	Two-span, continuous bridge	Bending at midspan 1 and support 1, shear at support 0	10 - 20 - 35 - 50 - 100 m	Extreme effects & Fatigue

3.3. Results

3.3.1. Importance of the catalogue of influence lines

Table 2 shows that the vehicle inducing the maximum load effect for a sample of influence lines, even within a given group of vehicles, is not always the same among the whole FALCON fleet. This point highlights the need for a representative catalogue of influence lines, which well represents the stock of the bridges within a country/group of countries.

Table 2 - Vehicle inducing the maximum load effect on a sample of influence lines.

Load Effect	Vehicle
Bending moment at midspan, single-span structure, span of 10 meters	4.6
Bending moment at midspan, single-span structure, span of 20 meters	1.4
Bending moment at midspan, single-span structure, span of 35 meters	1.3
Bending moment at midspan, single-span structure, span of 50 meters	1.3
Bending moment at midspan, single-span structure, span of 100 meters	1.3
Shear on support, single-span structure, span of 10 meters	3.3
Shear on support, single-span structure, span of 20 meters	6.4

3.3.2. Need for standardisation

Comparing the load effect induced by a given vehicle with the maximum load effect induced by all the vehicles of the fleet (Figure 2), shows that HCV's do have in general higher impact than standard vehicles. However, they carry more goods, in mass or volume. Reported to a constant freight demand (in ton.km or m³.km) and correct truck loading, there would be less vehicles on the road and not more damage.

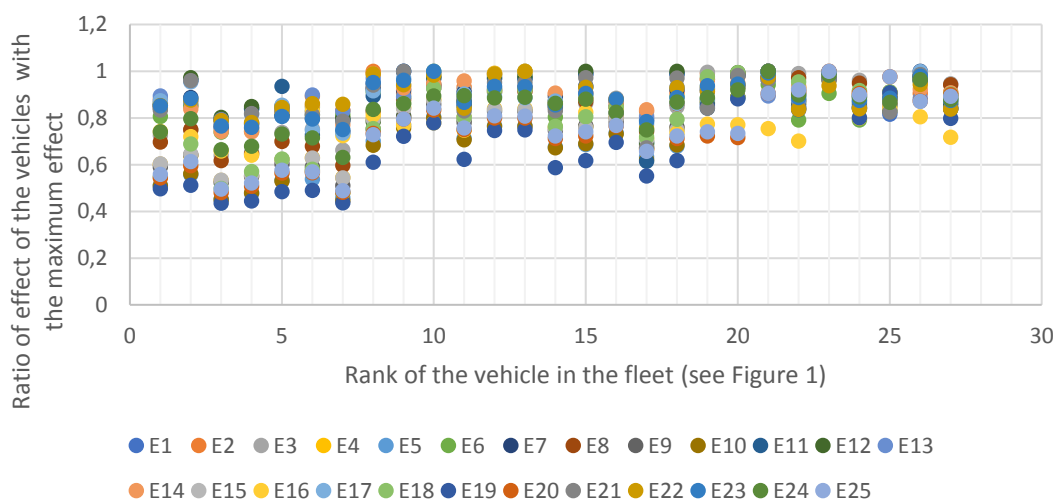


Figure 2 - Ratio of load effect (bending moments) to maximum load effect within the fleet (E1 – E25 are the various bending moments that have been investigated, see Table1).

3.3.3. Parameters to take into account in PBS for bridges

Figure 3 shows the ratios of bending moments induced by the vehicles of the fleet to those induced by the reference vehicle 2.1. The ratio is quite small for the first two groups of standard vehicles, but increases for other vehicles groups (HCVs), approaching a ratio of 2 in groups 5 and 6. Vehicles 5.3, 5.5 and 6.3 have the highest values in both cases.

The main differences between groups 1-2 and groups 5-6, which can explain the observed differences in bending moments, are:

1. gross vehicle masses and axle loads,
2. vehicle lengths,
3. numbers of axles.

Generally the number of axles is increasing with the gross vehicle mass and length (volume). A performance based standard for vehicles should take into account these parameters. All current bridge formulas specify a maximum allowed gross vehicle mass depending on the vehicle length, the spacing between axles or series of consecutive axles, and the number of axles.

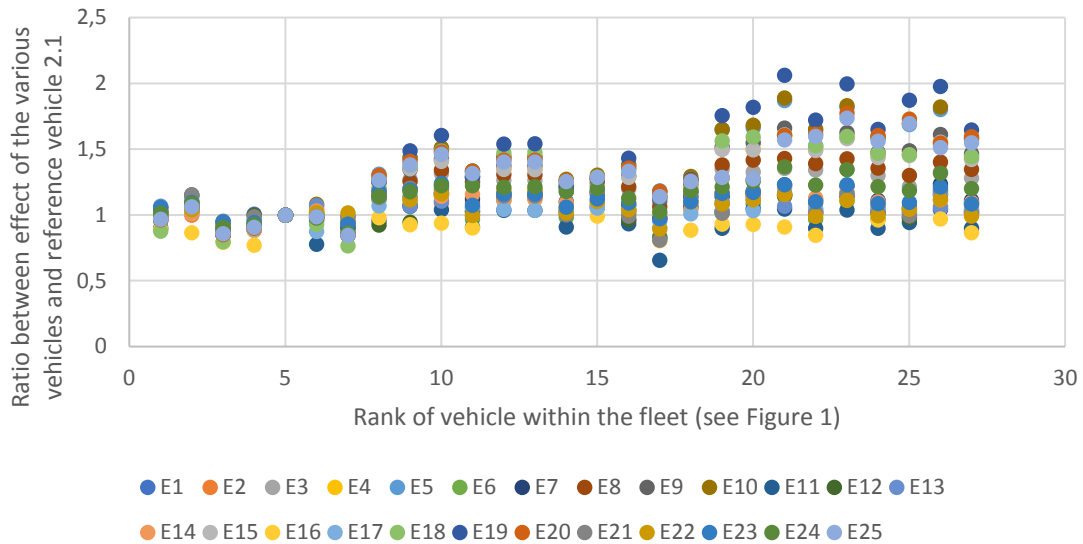


Figure 3: Ratio of bending moments by the various vehicle configurations with the bending moment of reference vehicle (2.1), where E1 – E25 are the various bending moments that have been investigated, see Table 1.

3.3.4. Upper limits of load effects induced by the vehicles

In the South African PBS criteria, the load effect of any vehicle is limited to a given proportion of the same load effect due to the standard traffic load model of the bridge code. In FALCON (Schmidt et al., 2017) reviewed the European design criteria. The design of bridges is mainly regulated by Eurocode 1-2, providing the traffic load models to be used (e.g. load model 1 in Figure 4).

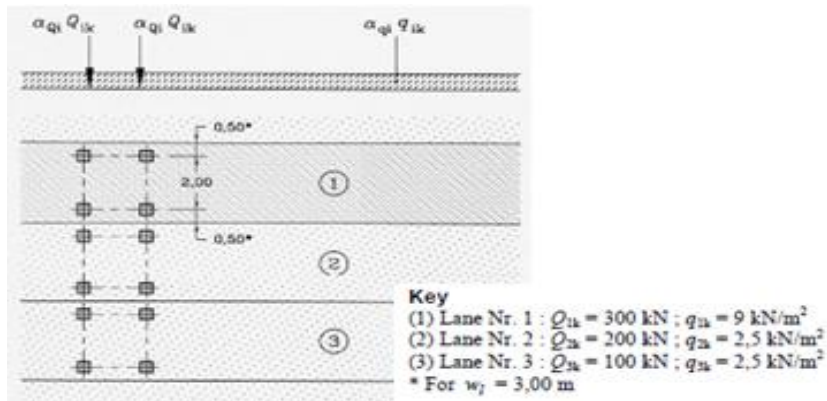


Figure 4 - Load model 1 of Eurocode 1-2.

Table 3 - National α -factors in The Netherlands and Germany, for an annual traffic volume higher than 2 million vehicles and a span length of 20 m.

	The Netherlands	Germany
α -factors	$\alpha_{Q1} = 1.0$ for $N > 2\,000\,000$ and $L = 20 \text{ m}$ (as in the Netherlands, this coefficient depends on the volume of traffic and the span length) $\alpha_{q1} = 1.15 \forall i > 1, \alpha_{qi} = 1.40$	$\alpha_{Q1} = 0.8$ $\alpha_{Q2} = 0.8$ $\forall i > 2, \alpha_{qi} = 0$ $\forall i, \alpha_{qi} = 1.00$

But these load models integrate some country specific coefficients depending on the expected traffic volume or on the span length, as shown in Table 3 for The Netherlands and Germany. This means that a complete review of the European situation has to be done, and

the critical load model(s), allowing the lowest load effects, must be determined. Within project FALCON, only the Dutch and German situation have been considered on a single 20 m span bridge.

3.4. Future works

Methodologies have been proposed for the development of PBS for bridges, and first results have been given. The future work should generalize this work by:

- Extending the catalogue of influence lines, and agreeing it at European level. A transverse section of the bridge structures should also be proposed to determine the critical traffic situations (single trucks, following trucks, truck jam...).
- Applying European design criteria on these influence lines, to determine the deterministic thresholds of load effects within the structure.
- Taking into account uncertainties both on the loading (overloading, uneven loading distribution on the bridge surface...) and on the structure (materials, design, etc.). Reliability analyses and calibration of reliability indices should be done (FIB, 2016).

4. PERFORMANCE BASED STANDARDS FOR PAVEMENTS

New road pavements are designed for lifetimes limited to a few decades, usually 20 to 40 years. During this period the pavement is exposed to various weather conditions and to a whole spectrum of traffic loads. These are the main factors influencing pavement wear. In the current design procedure, the road structure is represented by a linear-elastic multi-layer model and the expected traffic loads are expressed in a number of standard axle loads. The effect of an axle load on the multi-layer model is expressed in strains or stresses at different depths. The expected lifetime is determined using fatigue laws for the materials in the road structure.

A maximal allowed axle load for vehicles limits the strains and stresses imposed to the pavement. Existing roads were designed for vehicle combinations in operation or expected when the design was done. Therefore, any new vehicle combination must respect the existing axle load limitation. Therefore, higher and longer combinations are equipped with more axles so that the heavier load is distributed over more axles, without increasing the axle loads. However, road managers need assessing the impact of newly developed vehicle combinations on existing pavements.

4.1. Methodology

Materials and layer thicknesses in pavements are very different throughout Europe. In the FALCON project 4 road structures were considered: a concrete, a semi-rigid and a thick bituminous structure for main roads, and a fully flexible road structure designed for lower traffic volume roads. Such a limited number of road structures was sufficient to illustrate a method of verification of the impact of new vehicle combinations on existing pavements. It also proves that such a method can become part of a PBS approach and that new vehicle combinations can be accepted on the selected road sections.

One vehicle combination was chosen in each vehicle group for a detailed assessment of its impact on pavements. Vehicles are considered as a sequence of consecutive axle groups. An axle group consist either of one single axle, or a tandem or tridem axle. The load effects induced by axle groups were used to define equivalent standard axle loads as described in (Cocu & Pilate, 2007) and (Stet et al., 2006). This method uses the concept of aggressiveness of an axle group - and hence of the vehicle combination - for each pavement. Then, the vehicle combinations were compared on 4 different road structures.

The software ALIZE-LCPC for pavement structures analysis and design (Balay, 2013) was used to compute strains and stresses. The road structures and their behaviour were represented by a linear elastic multi-layer model. The vehicle combinations were completely modelled in the software. A single standard axle of 100 kN was used as reference load. Theoretical strains and stresses generated by the truck loads at different depths in the road structure were computed with this software. The use of a linear elastic multi-layer model is quite common for the design of new pavements and for the assessment of existing pavements. It does not take into account the viscosity of some pavements. However, in most countries the use of software that can model the viscosity is not common practice.

Variations in temperature between different seasons are not taken into account. The computations are based upon elasticity moduli of the materials at 15°C, assumed here as the average temperature over the year. The climate conditions throughout Europe are very different and this variations are not taken into account in these computations. The particular case of frost actions including thaw cycles would need additional computations.

These simplifications are acceptable to compare the impacts of different axle loads and trucks under the same conditions, but not their overall performance all over Europe and under all conditions.

The trucks on European roads are often not fully loaded or at least not up to the maximum allowed gross weight. Mostly, the transported goods fill the volume capacity of the trucks before the mass capacity. In order to perform the comparison between vehicle combinations, the carried goods were considered having the same density rather than filling the weight capacity. It was checked on some examples that the ratio between the aggressiveness of two different combinations does not depend on the gross mass, as long as the load density remains the same.






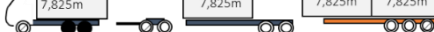
The comparison of aggressiveness of different vehicle combinations is more relevant per unit of carried goods, in volume. Each vehicle combination is assumed to comply with the maximal allowed axle load, and thus the hypothesis for road structure design. Finally, the optimal choice of vehicle combinations to carry a given volume of freight can be determined with respect to the aggressiveness per unit of freight, on each type of pavement.

4.2. Selected vehicle combinations

Table 4 reports the selected vehicle combinations. Silhouette 1.3 complies with the European Directive 2015/719 and is considered here as the main reference. Silhouette 2.1 partly complies but its length (19.3 m instead of 18.75 m) and its second mass (44.3 t instead of 40 t, or 44 t in combined transport). It is taken as a second reference. Silhouettes 3.1, 4.5, 5.1 and 6.1 are HCVs, the 3 last ones exceeding the 25.25 m of an EMS.

Two series of computations have been made: (1) with 6 vehicle combinations on 4 pavement structures, and (2) with 3 vehicle combinations carrying more load on the “thick bituminous” pavement only. The second-last column of Table 4 gives the gross vehicle mass taken into account for the series (1) and the last column the mass for the series (2). The parameters of these computations are given in (de Saxe et al., 2018).

Table 4 – Vehicle combinations used for pavement assessment

Vehicle group and code †		Vehicle description	Length (m)	Mass (r/c) (tonnes)	
1.3	TR4x2-ST3 (13.6m)		16.4	29.7	37.7
2.1	TK6x2-CT2 (2x7.8m)		19.3	35.4	44.3
3.1	TR6x4-ST3-CT3(45ft+20ft)		23.7	47.3	58.1
4.5	TK6x4-CT2-CT2 (3x7.8m)		27.9	51.4	64.7
5.1	TR6x4-ST3-DY2-ST3 (2x45ft)		31.1	62.6	78.2
6.1	TK6x4-DY2-LT2-ST3 (4x7.8m)		35.4	71.0	88.7

† **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), **LT**_a = Link trailer (a = # of axles), **DY**_a = Dolly (a = # of axles)

4.3. Types of pavements

A concrete, a semi-rigid and a thick bituminous structure designed for French traffic class T1, and a fully flexible road structure designed for the lower French traffic class T5 were used, fully described in Tables 5 and 6.

Table 5 – Types of pavement used

Traffic	Pavement structures		
	Thick Bituminous	Semi-rigid	Concrete
T1 500 HV/day during 20 years	8.5 cm BB (bituminous concrete) 10 cm GB3 (base course asphalt material) 11 cm GB3 Subgrade E = 50 MPa	8.5 BB (bituminous concrete) 22 cm GC3 (cement treated gravel) 20 cm GC3 Subgrade E = 50 MPa	20 cm BC5 concrete 18 cm BC2 concrete Subgrade E = 50 MPa
	Flexible		
T5 25 HV/day during 20 years	5 cm BBSG (bituminous concrete) 25 cm UGM (unbound granular material) Subgrade E = 40 MPa		

Table 6 – Pavement characteristics (*E* = elastic modulus, *v* = Poisson ratio)

Traffic Pavement	Material	E (MPa) at 15°C, 10 Hz	v
T1 Concrete	BC5 (concrete)	35000	0,25
	BC2 (concrete)	20000	0,25
	PF2 (subgrade)	50	0,35
T1 Semi-rigid	BBSG (bituminous concrete)	5400	0,35
	GC3 (cement treated gravel)	23000	0,25
	GC3 (cement treated gravel)	23000	0,25
	PF2 (subgrade)	50	0,35
T1 Thick bituminous	BBSG (bituminous concrete)	5400	0,35
	GB3 (base course asphalt material)	9300	0,35
	GB3 (base course asphalt material)	9300	0,35
	PF2 (subgrade)	50	0,35
T5 Flexible	BBSG (bituminous concrete)	5400	0,35
	GNT3 (untreated granular material)	200	0,35
	PF2 (subgrade)	50	0,35

4.4. Definitions of aggressiveness

Fatigue laws of materials describe the relationship between strains ε_i or stresses σ_i , and the number of applications of axle loads at pavement failure. The only failure criterion is the stress or strain at a given depth of the road structure. For the concrete and semi-rigid pavements, the fatigue law for hydraulically bound materials is used; for the thick bituminous and flexible pavements the fatigue law for bituminous materials is used.

The following criteria have been taken for the four road structures:

- Concrete pavement: tensile stress σ_i at a depth of 0,200 m at the bottom of the concrete layer.
- Semi-rigid pavement: tensile stress σ_i at a depth of 0.305 m under the first layer of "GC3".
- Thick bituminous pavement: strain ε_i in the direction of the vehicle motion at a depth of 0.185 m at the bottom of the first layer of "GB3".
- Flexible pavement: strain ε_i in the direction of the vehicle motion at a depth of 0.050 m at the bottom of the bituminous layer.

The ALIZE-LCPC software determines, from the strains ε_i or stresses σ_i , the number of repetitions $N_{gr,i}$ of the loads applied by the axle groups at the pavement failure. The number of repetitions is N_{ref} under the reference axle (a 100 kN single axle with two 50 kN single wheels) at pavement failure. For single axles the fatigue laws can be applied directly. However, tandem and tridem axle groups consist of two or three consecutive axles close to each other, so that the strains and stresses imposed by the load of the first axle are not relaxed before the next axle applies its load. Therefore, for tandem and tridem axle groups, stresses or strains are taken into consideration under each axle of the group and in the middle between two consecutive axles of the group. Thus, for a tridem axle group, the stresses or strains lead to three accepted numbers of repetitions N_d , N_b and N_f for each of the individual axles in the group, which are combined in Equation (1) to get the accepted number of repetition of the whole axle group, as briefly presented by (Stet et al., 2006) and in detail in (Cocu & Pilate, 2007):

$$3 N_{TR} = \frac{1}{\frac{1}{3} \frac{1}{N_b} + \frac{1}{3} \frac{1}{N_d} + \frac{1}{3} \frac{1}{N_f}} \quad (1)$$

4.4.1. Aggressiveness of an axle group

The aggressiveness $A_{gr,i}$ of the i -th axle group is the ratio between N_{ref} and $N_{gr,i}$:

$$A_{gr,i} = \frac{N_{ref}}{N_{gr,i}} \quad (2)$$

$N_{gr,i}$ (and N_{ref}) are computed as mentioned above and use only the strain ε_i or stress σ_i at one particular depth in the pavement structure computed with the ALIZE-LCPC software.

4.4.2. Aggressiveness of a vehicle

The aggressiveness A of a whole vehicle is the sum of the aggressiveness's $A_{gr,i}$ of all m axle groups of the vehicle:

$$A = \sum_{i=1}^m A_{gr,i} \quad (3)$$

4.4.3. Aggressiveness of a vehicle per freight volume or mass unit

The ratio A/V takes the cargo (payload) volume V of each vehicles into account. The ratio between cargo mass (CM) and the gross vehicle mass (GVM) depends on the vehicle type. This ratio differentiates the cargo volume and the cargo mass at constant density. Therefore $(A/V)/(CM/GVM)$ is computed for each vehicle combination and for each road structure.

Both A and A/V depend on the vehicle and on the pavement. For each pavement, a comparison is made between A and A/V , both for the HCVs and the standard vehicles. E.g. the silhouette 2.1 is more aggressive than the silhouette 1.3, while both comply with the European Directive 2015/719. It is recommended that any vehicle combination be less aggressive (per cargo unit) than the silhouette 2.1. Therefore, it is recommended to compute the ratios of aggressiveness A and of aggressiveness per cargo unit A/V between a HCV and the silhouette 2.1.

4.4.4. Evaluating the aggressiveness of axle groups

The impact of any axle group of a given vehicle is characterized by its aggressiveness. The number of repetitions N_i of the axles group at failure is compared to N_{ref} .

A criterion of performance of the HCVs with respect to its axle group consists of:

- determining the minimum N_{pav} of the N_i for each of the 4 road structures and for the axle groups of silhouettes 1.3 and 2.1, N_{pav} being a reference value,
- then for any HCV 3.1, 4.5, 5.1 and 6.1, the ratios N_{pav}/N_i are computed for the 4 road structure.

If $N_{pav}/N_i > 1$ the i^{th} axle group of the HCV is more aggressive than the most aggressive axle group of silhouettes 1.3 and 2.1, which is a bad performance.

4.5. Results on pavements

With respect to the aggressiveness A , and if comparing no fully loaded vehicles at constant load density on the four road structures (series 1 of computations), almost all HCV combinations are more aggressive than the reference vehicle 1.3 but not than the reference vehicle 2.1. However, the ratio A/V is always the highest for the vehicle 2.1 (as shown in Table 7), which also has on all the road structure the highest value of $(A/V)/(CM/GVM)$. It means that the HCVs are more efficient for pavements than the standard vehicle 2.1.

Table 7 – Aggressiveness A and ratio A/V for each vehicle on the different pavements (tb: thick bituminous, sr: semi rigid, c: concrete, ff: fully flexible, tb (2): series 2 of computations)

Vehicle	A				A	A/V			
	tb	sr	c	ff	tb (2)	tb	sr	c	ff
1.3	0.68	0.09	0.39	2.45	-	0.007857	0.001042	0.004494	0.028207
2.1	1.93	0.55	1.00	3.20	3.85	0.020171	0.005719	0.010433	0.033391
3.1	1.12	0.10	0.37	3.44	1.99	0.009523	0.000871	0.003115	0.029273
4.5	2.31	0.09	1.00	4.34	-	0.016076	0.000622	0.006960	0.030221
5.1	1.60	0.12	0.67	4.94	-	0.009488	0.000686	0.003952	0.029297
6.1	3.03	0.83	1.65	5.85	5.76	0.015819	0.004357	0.008616	0.030530

If considering the axle groups separately (as shown in Table 8), one axle group of HCV 6.1 is more aggressive than the worst axle group of vehicles 1.3 and 2.1 on all pavements. The axle groups of the other HCVs are comparable to the axle groups of the reference vehicles. On the flexible pavement, some of the axle groups of HCV 4.5, 5.1 and 6.1, are quite aggressive. However, this type of pavement is not used on motorways and main highways,

but on secondary roads. Some caution is needed for such road sections if used as access to the main network.

In the series 2 of computations, with vehicles loaded at the maximum weight capacity on the thick bituminous pavement, we also noticed that the ratio between the aggressiveness A of two different vehicle combinations is almost independent on the gross vehicle mass, as long as the load density remains the same. This is because the gross vehicle mass increases more or less proportionally to the vehicle length (and volume), and the number of axles increases as well.

Table 8 – Number N_i of allowed axle group passages and aggressiveness $A_i = N_{ref}/N_i$ (N_{ref} for standard single axle) for each axle group (A to E) of the vehicles on the pavements (tb: thick bituminous, sr: semi rigid, c: concrete, ff: fully flexible, tb (2): series 2 of computations)

Vehicle			tb		sr		c		ff	
	axle	type	N_i	A_i	N_i	A_i	N_i	A_i	N_i	A_i
reference	A	Single	1.50E+09	1.00	4.43E+07	1.00	1.16E+09	1.00	5.99E+02	1.00
T1.3	A	Single	5.65E+09	0.27	1.39E+09	0.03	9.51E+09	0.12	8.99E+02	0.67
	B	Single	8.27E+09	0.18	1.41E+09	0.03	1.02E+10	0.11	1.45E+03	0.41
	C	Tridem	6.32E+09	0.24	1.62E+09	0.03	7.47E+09	0.16	4.35E+02	1.38
T2.1	A	Single	6.25E+09	0.24	1.94E+09	0.02	1.18E+10	0.10	9.12E+02	0.66
	B	Tandem	1.73E+09	0.87	1.07E+08	0.41	2.01E+09	0.58	5.40E+02	1.11
	C	Tandem	1.81E+09	0.83	3.99E+08	0.11	3.58E+09	0.32	4.18E+02	1.43
T3.1	A	Single	6.25E+09	0.24	1.84E+09	0.02	1.33E+10	0.09	9.31E+02	0.64
	B	Tandem	2.43E+10	0.06	8.35E+09	0.01	3.85E+10	0.03	1.68E+03	0.36
	C	Tridem	2.18E+09	0.69	6.53E+08	0.07	5.69E+09	0.20	3.73E+02	1.61
	D	Tridem	1.15E+10	0.13	8.59E+09	0.01	2.59E+10	0.04	7.19E+02	0.83
T4.5	A	Single	4.50E+09	0.33	3.48E+09	0.01	7.65E+09	0.15	7.95E+02	0.75
	B	Tandem	5.89E+09	0.25	2.81E+09	0.02	6.97E+09	0.17	8.53E+02	0.70
	C	Tandem	1.63E+09	0.92	1.28E+09	0.03	3.04E+09	0.38	4.10E+02	1.46
	D	Tandem	1.87E+09	0.80	1.69E+09	0.03	3.86E+09	0.30	4.20E+02	1.43
T5.1	A	Single	6.04E+09	0.25	1.81E+09	0.02	1.04E+10	0.11	9.13E+02	0.66
	B	Tandem	2.03E+10	0.07	6.72E+09	0.01	2.91E+10	0.04	1.50E+03	0.40
	C	Tridem	2.97E+09	0.50	1.38E+09	0.03	5.58E+09	0.21	4.16E+02	1.44
	D	Tandem	5.66E+09	0.26	3.23E+09	0.01	1.14E+10	0.10	6.20E+02	0.97
	E	Tridem	2.94E+09	0.51	1.14E+09	0.04	5.65E+09	0.21	4.05E+02	1.48
T6.1	A	Single	4.23E+09	0.35	8.13E+08	0.05	6.98E+09	0.17	8.17E+02	0.73
	B	Tandem	6.64E+09	0.23	1.17E+09	0.04	8.91E+09	0.13	9.12E+02	0.66
	C	Tandem	4.05E+09	0.37	1.90E+09	0.02	7.58E+09	0.15	5.08E+02	1.18
	D	Tandem	9.79E+08	1.53	7.15E+07	0.62	1.21E+09	0.96	3.62E+02	1.65
	E	Tridem	2.72E+09	0.55	4.45E+08	0.10	4.78E+09	0.24	3.68E+02	1.63

4.6. Future works

The computations on pavement presented in this document are limited in scope and some simplifying assumptions were made. Climate aspects and the viscoelastic behaviour of bituminous materials were neglected. The analysis is based on fatigue performance whereas for flexible road structures rutting criteria should also be considered. The only criterion of failure considered is the stress or strain at a particular depth in the road structure.

A limited number of trucks was considered and of the silhouette 2.1, complying with the European Directive 2015/719 and in operation throughout the EU, is the most aggressive under the assumptions made. Computations should be extended to a larger variety of vehicle combinations, with other road structures, other assumptions, and other models (e.g. including climate effects or viscoelastic behaviour), to check if other vehicle combination may turn out to be the most aggressive. Future work should include more elaborated models, and more pavement types existing in the EU. However, the developed methodology will remain valid.

5. CONCLUSION

This paper summarizes results of the CEDR project FALCON on the development of PBS (performance based standards) for heavy commercial vehicles approval and assessment, with respect to their impact on road infrastructure, mainly bridges and pavements. It is shown that whereas for pavements vehicles can be classified by aggressiveness level, for bridges it is more complex: some vehicles can be more aggressive than others on some types of structures, but less on other structures. Therefore the framework methodology differs for both types of infrastructure.

The main advantage of HCVs is the reduction of the number of vehicles and axles used for transporting the same freight, and lower axle loads in average. Since the aggressiveness of the HCVs under consideration does not exceed the aggressiveness of allowed standard trucks on the road network, it is not necessary to introduce new criteria of acceptance for these HCVs with respect to road structure.

Two vehicle combinations with the same CM (cargo mass or payload) or GVM (gross vehicle mass) may have different aggressiveness due to different load distributions, i.e. different number of axles, different consecutive axles or axle groups spacing, more axles with dual tyres, different distribution of the weight on the axles. The aggressiveness per unit of cargo gives an indication of the efficiency of the load distribution in the vehicle. Hence, this may be of interest for vehicle manufacturers and carriers. The manufacturers may also limit the aggressiveness of individual axle groups by the vehicle design.

Throughout Europe the method for pavement design is not standardised, the materials used for road construction and the climate conditions are different. Therefore, it is recommended that for each new HCV configuration to be operated on a given road network, aggressiveness computations are made on a set of pavement structures that are representative of the road network. Then a threshold of aggressiveness per cubic meter or tonne can be applied to that HCV on each category of road. This is the background of a SIAP (Smart Infrastructure Access Programme). If a HCV complies with the threshold for the weakest road section of a given road network, it may be allowed on all this network or networks of the same access level.

Although the set of pavement structures considered in this document is not sufficient and the computations of aggressiveness are simplified and do not take climatic conditions into account, the results presented show the feasibility of the recommended approach.

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