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Analysis of pavement structure sensitivity to passage of oversized heavy duty vehicle in terms of bearing capacity

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Analysis of pavement structure sensitivity to passage of oversized heavy duty vehicle in terms of bearing capacity

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Abstract. Oversized heavy duty vehicles occur in traffic very rarely but they reach extremely high weights, even up to 800 tonne. The detrimental impact of these vehicles on pavement structure is much higher than in case of commercial vehicles that comprise typical traffic, thus it is necessary to assess the sensitivity of pavement structure to passage of oversized vehicles. The paper presents results of sample calculations of load equivalency factor of a heavy duty oversized vehicle with usage of mechanistic-empirical approach. The effects of pavement thickness, type of distress (cracking or rutting) and pavement condition (new or old with structural damage) were considered in the paper. Analysis revealed that a single pass of an 800 tonne oversized vehicle is equivalent to pass of up to 377 standard 100 kN axles. Load equivalency factor calculated for thin structures is almost 3 times lower than for thick structures, however, the damage effect caused by one pass of an oversized vehicle is higher in the case of thin structure. Bearing capacity of a pavement structure may be qualified as sufficient for passage of an oversized heavy duty vehicle when the measured deflection, for example in an FWD test, does not exceed the maximum deflections derived from mechanistic-empirical analysis. The paper presents sample calculation of maximum deflections which allow to consider passage of an oversized vehicle as safe over different pavement structures. The paper provides road administration with a practical tool which helps to decide whether to issue a permit of passage for a given oversized vehicle.

Keywords
Oversized vehicles, heavy duty vehicles, bearing capacity of pavement structure, flexible pavements, load equivalency factors, standard axle, equivalent axle.

1. Introduction
Oversized heavy duty vehicles are used to carry untypical freights which cannot be divided into smaller parts. Most commonly the oversized freights include turbines of power plants, transformers, parts of ships or industrial machines. Oversized heavy duty vehicles occur in traffic very rarely but they reach extremely high weights, even up to 800 tonnes, while the weight of a typical commercial vehicle does not exceed 40 tonnes, except for overloaded vehicles. The definitions of an oversized heavy duty vehicle and an overloaded vehicle should be clearly separated. An overloaded vehicle is one that exceeds legal axle load or gross weight, while an oversized heavy duty vehicle is an untypical vehicle constructed specially for carrying freights heavier and with a larger volume than typical freights. The problem of vehicle overloading has been widely described in other publications [1, 2, 11-18] and it does not lie within the scope of this paper. In the case of oversized heavy duty vehicles, the basic problem is the issuing of permission for passage. Officers of road authorities most often have to make a decision without any specific data to assess if the passage of a given oversized vehicle is safe or if it may cause pavement damage.

2. Objectives and scope
The main objective of this paper is to present the methodology of calculations of fatigue damage and load equivalency factor of heavy duty oversized vehicles. The methodology is supported by calculations performed for a sample oversized vehicle. Calculations include both thin and thick pavements as well as two variants of pavement technical condition: good and poor. Further part of the paper presents the determination of the maximum pavement structure deflection which allows to permit safe passage of an oversized vehicle without pavement failure.

3. Load of the chosen oversized vehicle
The load of freight in the oversized heavy duty vehicle chosen for calculations (OSV) is distributed onto a group of wheels in a multi-axle trailer. A group of ballast tractors pulls or pushes the trailer with the freight, as shown in Figure 1. Loads of particular axles usually do not exceed 80 kN, so the level of axle load is comparable to loads of typical heavy traffic. On the other hand, the distances between particular axles and wheels are much smaller than in typical vehicles. Moreover, in the case of oversized vehicles the number of axles and wheels is much higher.

In the calculation example considered in this paper the vehicle consists of two trailers and two ballast tractors. Each trailer is equipped with 16 rows of axles, 2 axles per row, and each axle consists of 4 wheels. The distance between neighboring axle rows equals 1.65 m. The wheelbase across the vehicle is 3.60 m. The tare weight is 215 tonnes, the maximum weight of the transported cargo is 500 tonnes, so the maximum total weight of the trailer is 715 tonnes. The load is evenly distributed on each axle and may reach 112 kN per axle. The suspension of each axle is hydraulically adjusted in such a way that the load of each axle remains constant during transport. The ballast tractors are equipped with two steering axles with single wheels and two drive axles with twin wheels. The total weight of one ballast tractor is 48 tonnes. The load of ballast tractor is distributed on each axle and equals 120 kN per axle. The tire-pavement contact pressure equals 850 kPa. The speed of the oversized vehicle is much lower than the speed of typical traffic and does not exceed 20 km/h, which has an impact on elastic modulus of asphalt layers and in consequence on increase of fatigue damage.

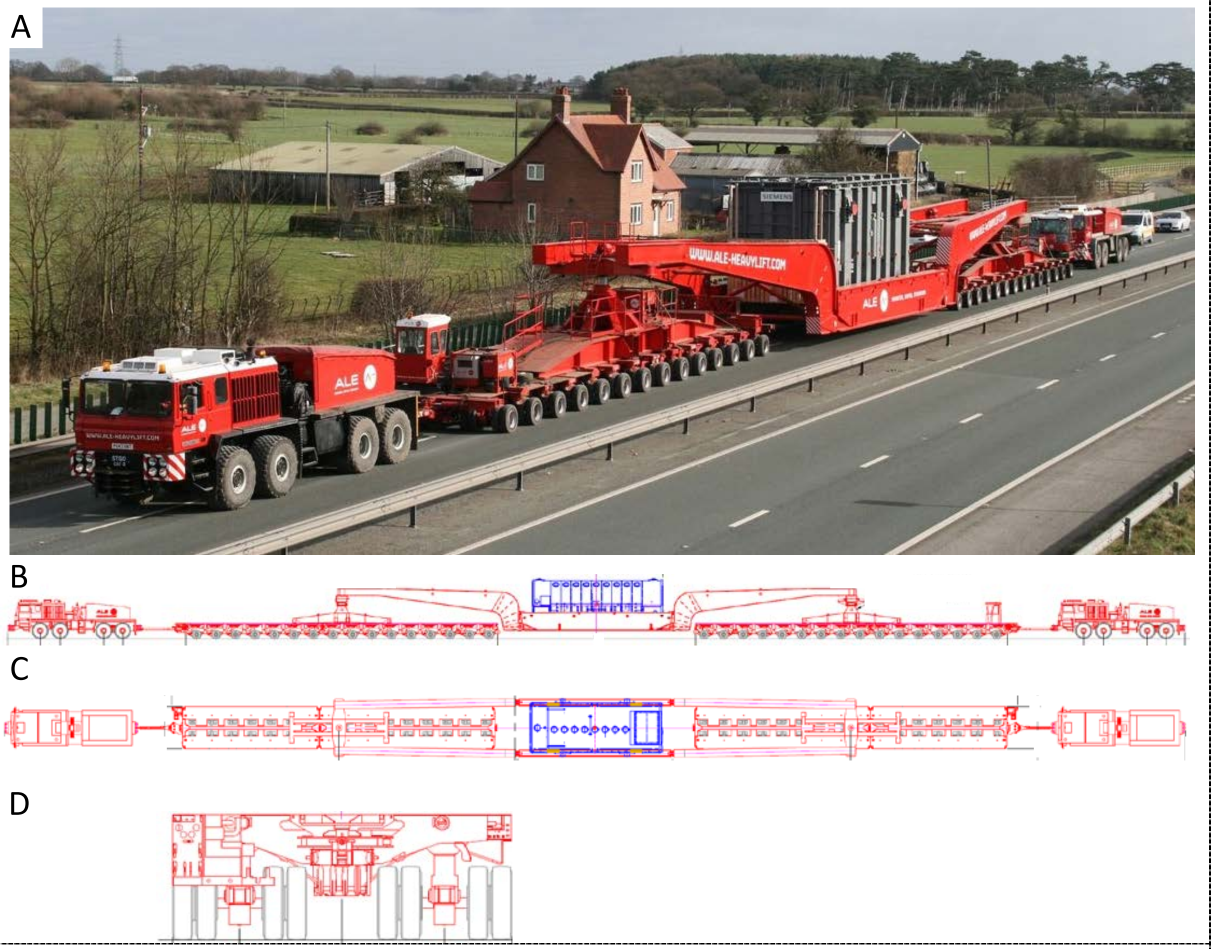

Figure 1. An example of oversized heavy duty vehicle – a group of two trailers and two ballast tractors A) general photograph [19], B) side view scheme C) top view scheme D) trailer front view scheme.

4. Pavement structure assumed for analysis

Calculations were performed for flexible pavement structures assumed on the basis of the Polish catalogue of typical flexible and semi-rigid pavements. Structures similar to those assumed for analysis are commonly used on the Polish road network. Thicknesses and mechanical parameters of structure layers are presented in Table 1. Calculations were performed for two pavements: thick (30 cm of asphalt layers) for very heavy traffic and thin (12 cm of asphalt layers) for light traffic.

Typical values of stiffness modulus of asphalt layers were assumed for calculation of fatigue damage caused by a standard axle load (variant 0). Typical values were assumed on the base of research project described in brief in [9]. However, for calculation of fatigue damage caused by the axles of the oversized vehicle, reduced values of stiffness modulus were assumed. The reduction of stiffness modulus values results from lower speed of the oversized vehicle. Two variants of pavement structure condition were considered: good condition without damage (variant 1) and bad condition near the level of terminal serviceability of pavement structure (variant 2). In the variant 2 stiffness modulus of asphalt layers was reduced to 50% and stiffness modulus of subbase and subgrade was reduced like for bad drainage conditions. All values of stiffness modulus used in the analysis are presented in Table 1.

Table 1. Thicknesses and mechanical properties of pavement structure layers.

No.	Pavement layers	Layer thickness [cm]	Volumetric properties of asphalt layers [% v/v]		Stiffness modulus [MPa]		
			Binder content	Air voids	**Variant 0** Standard load, good pavement condition v=60 km/h	**Variant 1** Oversized vehicle good pavement condition, v=20 km/h	**Variant 2** Oversized vehicle bad pavement condition v=20 km/h
				Thick structure (traffic category KR7)			
1.	Wearing course, SMA11 50/70	4	16	3	7300	5300	2650
2.	Binder course, AC16W 35/50	8	10.5	6	10300	8500	4250
3.	Asphalt base, AC22P 35/50	18	10	7	9800	8100	4050
4.	Subbase, crushed stone	20	-	-	400	400	250
5.	Subgrade	-	-	-	120	120	60
				Thin structure (traffic category KR2)			
1.	Wearing course, AC11S 50/70	4	14	2.5	9300	6800	3400
2.	Asphalt base, AC22P 35/50	8	10	8	8100	6100	3050
3.	Subbase, gravel	25	-	-	250	250	150
4.	Subgrade	-	-	-	80	80	35

5. Analysis of pavement structure response under loads of the oversized vehicle

The program BISAR from Shell company was used to perform calculations of deflections and strains in pavements caused by load of oversized vehicle. Firstly, the critical locations were determined. Critical locations are defined as points where tensile or vertical strains reach maximum values. When the criterion of fatigue cracking of asphalt layers is considered, the critical locations occur at the bottom of asphalt layers (horizontal strains ε_{xx} and ε_{yy}). When the permanent deformation of subgrade is considered, the critical locations occur at the level of subgrade surface (vertical strains ε_{zz}). The procedure of determination of critical locations and strain values is as follows:

1) Calculation of strains in the direction transverse to vehicle movement (along the X-axis) and identification of critical sections at which strains reach their extremes.
2) Calculation of strains along the direction of travel (along the Y-axis) at critical sections, from the load of one row of wheels.
3) Calculation of strains taking into account the influence of neighboring axles, in accordance with the superposition principle.
4) Calculations are performed separately for ballast tractor and for trailers.

The results of strain calculations for trailer on thick new pavement (variant 1) at a critical section is shown in Figure 2. The critical point at the bottom of asphalt layers occurred for x = 1000 mm, and at this point $\varepsilon_{yy,\ max}$ = 73.0 μstrain. Similarly, the critical point for vertical strain at the top of subgrade surface occurred for x = 1000 mm and equaled $\varepsilon_{zz,\,min}$ = - 214.0 µstrain. For the example considered the dimension x of the maximum strains at the bottom of asphalt layers and at the top of subgrade surface is the same (x = 1000 mm), however for other examples of calculations it can be different. Figure 3 presents strains along the Y-axis at the critical strain location (x = 1000 mm). In the case of horizontal strain at the bottom of asphalt layers, the difference between minimum and maximum values of ε_{yy} is higher than for ε_{xx}, thus strain ε_{yy} is assumed as critical strain for calculations of fatigue damage. The values of vertical strains at the top of subgrade surface are negative and for calculations of fatigue damage the extreme values are assumed. This approach is the same as in damage calculations in fatigue tests and it has been described in more detail in the work [16].

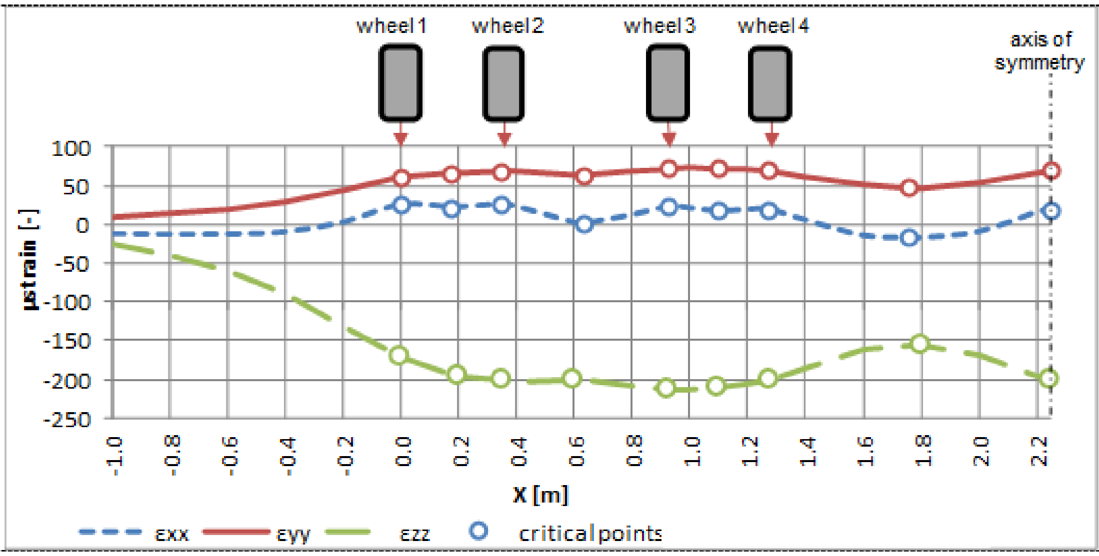

Figure 2. Strains caused along the X-axis by a row of wheels at a critical section perpendicular to the direction of vehicle movement, thin pavement, variant 1.

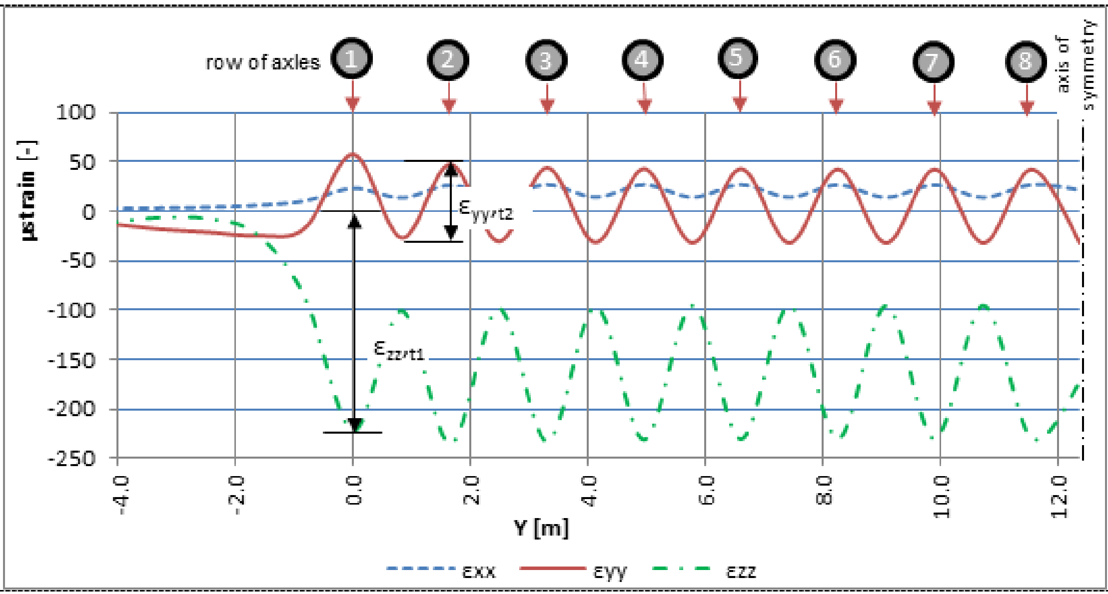

Figure 3. Strains caused by consecutive axles of the oversized vehicle trailer along the direction of vehicle movement (Y-axis), thin pavement, variant 1.

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6. Analysis of the fatigue damage and load equivalency factors caused by oversized vehicles

The analysis of fatigue damage caused by oversized vehicles is based on mechanistic-empirical approach. Two variants of pavement distress were considered: bottom-up fatigue cracking of asphalt layers and permanent deformation of the subgrade. For asphalt layers the bottom-up fatigue cracking AASHTO 2004 criterion was used. It is given in equation (1). The criterion was developed in the USA and it is described in detail in the Mechanistic-Empirical Pavement Design Guide [3]. The AASHTO 2004 criterion was adapted to Polish conditions by Judycki [8].

$$N_f = D_{FC} \cdot 7.3557 \cdot 10^{-6} \cdot C \cdot k'_1 \left(\frac{1}{\varepsilon_t}\right)^{3.9492} \left(\frac{1}{E}\right)^{1.281} \quad (1)$$

where:

N_f – number of load repetitions to fatigue cracking of asphalt layers on the area FC of the lane.
D_{FC} – fatigue damage parameter,
k'_1 – correction parameter, introduced to provide a correction for different asphalt layers thicknesses,
ε_t – horizontal tensile strain at the critical location at the bottom of asphalt layers,
E – stiffness modulus of the asphalt layers [MPa],
C – laboratory-to-field adjustment factor which includes the effect of binder and air content in asphalt mixture.

Fatigue life of pavement structure due to permanent deformation of the subgrade was calculated according to the Asphalt Institute criterion:

$$N_f = k_1 \left(\frac{1}{\varepsilon_t}\right)^{n_1} \quad (2)$$

where:

N_f – number of load repetitions to occurrence of permanent structural deformation of 12.5 mm depth at the pavement surface,
ε_t – vertical compressive strain at the critical location at the subgrade surface,
$k_1 = 0.0105$ – empirical parameter,
$n_1 = 0.223$ – empirical parameter.

The result delivered from equations (1) or (2) of fatigue criteria is the number N_f of load repetitions to pavement distress. The number N_f depends on strain at critical location ε_t and, in turn, the strain ε_t depends on axle load and distance to neighboring axle, as shown in Figure 3. In the case of criterion of fatigue cracking of asphalt layers, the value of ε_t in equation (1) should be assumed as the difference between minimum and maximum strain ε_{yy}. In the case of permanent deformation, the value ε_t in equation (2) should be assumed as the absolute vale of the minimum ε_{zz}. A more detailed explanation of this approach is available in [16].

According to Miner's law, each transition of vehicle axle causes accumulation of fatigue damage. In the case of a single axle transition, the fatigue damage is equal to:

$$d_j = \frac{1}{N_{fj}} \quad (3)$$

where:

d_j – fatigue damage caused by axle with load Q_j,
N_{fj} – number of repetitions of load Q_j to occurrence of pavement distress,
j – axle number.

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In the case of transition of a multiple axle, the fatigue damage is delivered from the formula:

$$d_j = \sum_{i=1}^{n} \frac{1}{N_{f\,i,j}} \tag{4}$$

where:

$N_{fi,j}$ – number of repetitions of load causing strain ε_{tj} at the critical point of pavement structure to occurrence of pavement distress,

j – axle number,

i – critical point number,

n – total number of critical points along the direction of vehicle movement (Y-axis).

The load equivalency factor of one axle in the vehicle can be calculated based on of fatigue damage according to equation (5), delivered from the work of Judycki [5, 6].

$$F_j = \frac{d_j}{d_s} \tag{5}$$

where:

F_j – load equivalency factor for axle Q_j,

d_s – fatigue damage caused by a standard axle with load Q_s = 100 kN,

d_j – fatigue damage caused by axle j, according to equations (3) or (4).

The load equivalency factor for the whole vehicle is delivered from the following formula:

$$F_v = \sum_{j=1}^{n_O} F_j \tag{6}$$

where:

F_v – load equivalency factor of the vehicle,

F_j – load equivalency factor of a given axle j (single or multiple) in the vehicle,

j – axle number,

n_o – total number of axles in the vehicle.

Calculations of fatigue damage and load equivalency factors were performed for an example of oversized vehicle OSV in accordance with equations (1-6). The results are presented in Table 2. As shown in Table 2, the load equivalency factor depends on the pavement distress criterion as well as pavement structure thickness and condition. Oversized vehicles have greater load equivalency factor for thick pavements and better pavement technical condition. Nevertheless, higher fatigue damage from the OSV is observed for thinner pavements and worse pavement technical condition. The values of fatigue damage are relatively low, even for thin pavements in poor condition, which means that one pass of the OSV should not cause serious damage to pavement structures. It may be assumed that the level of fatigue damage lower than 1% can be acceptable to permit the passage of the OSV.

According to studies of commercial vehicle loads in Poland [15, 18], an average articulated heavy vehicle with trailer or semi-trailer reaches load equivalency factor in the range from 1.60 to 1.95 100 kN ESALs. One passage of the OSV may cause the same fatigue as passage of 200 typical commercial heavy vehicles.

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Table 2. Bearing capacity of pavement structures, fatigue damage and load equivalency factors of the oversized vehicle (OSV)

Pavement structure thickness	Variant of pavement conditions	Fatigue cracking of asphalt layers			Structural deformation		
		Bearing capacity [100 kN ESALs]	OSV fatigue damage d_{FC}	OSV load equivalency factor F_{FC}	Bearing capacity [100 kN ESALs]	OSV Fatigue damage d_{DEF}	OSV Load equivalency factor F_{DEF}
Thick (30 cm HMA)	Good (1)	$66 \cdot 10^6$	**0.0006%***	184	$251 \cdot 10^6$	0.0001%	321
	Poor (2)	$2 \cdot 10^6$	**0.0073%***	171	$13 \cdot 10^6$	0.0028%	377
Thin (12 cm HMA)	Good (1)	$368 \cdot 10^3$	**0.02%***	80	$405 \cdot 10^3$	0.01%	58
	Poor (2)	$31 \cdot 10^3$	0.07%	75	$17 \cdot 10^3$	**0.38%***	64

* critical value of fatigue damage

7. Determination of the required bearing capacity of pavement structure

The bearing capacity calculated from the pavement model for the assumed mechanical parameters and presented in Table 2 is theoretical. In the field the pavement thickness as well as stiffness modulus of subgrade and pavement layers may be varied. The differences can be especially high in the case of thin pavements in poor technical condition, and this variation may result in underestimation of fatigue damage caused by the OSV. In consequence, the pass of the OSV may cause local appearance of serious pavement damage. At weak points, both permanent deformation and cracks of asphalt layers can be expected. In order to avoid overestimation of bearing capacity of pavement structure it is recommended to perform a Falling Weigh Deflectometer (FWD) test, which allows to localize weak areas in the road pavement. The judgment of bearing capacity of pavement can be performed in two ways: by determining critical maximum deflections under an FWD plate or by determining stiffness modulus of pavement layers using back-calculations. The back-calculations deliver real values of stiffness modulus, which can be further used in mechanistic-empirical analysis according to the approach described above.

Critical deflections were calculated based on the mechanistic model of pavement structure and mechanical parameters of layers assumed for pavement in bad condition. The critical deflections were determined in the following steps:

1. Calculation of the maximum deflection at pavement surface under flexible plate (standard axle wheel) using the BISAR software,
2. Deflections calculated for flexible plate were multiplied by factor of 0.785 to account for differences in deflections under flexible and rigid plate [5], as well as the dynamic factor f_d=0.83 [3] and the temperature factor f_t=1.14ºC [10] to standardize temperature of deflection measurement from 13ºC to 20ºC.

The values of critical deflections are given in Table 3.

Table 3. Critical deflections under FWD plate

Pavement structure thickness	Critical deflection calculated for standard axle [mm]	Critical deflection calculated for FWD [mm]
Thick (30 cm of HMA)	0.39	0.3
Thin (12 cm of HMA)	1.20	0.9

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8. Summary

1) The methodology of calculation of fatigue damage and load equivalency factor of heavy duty oversized vehicles is based on mechanistic-empirical approach. The methodology was used to perform calculation for one example of an oversized vehicle, however, it is universal and can be adopted for any type of vehicle. The paper provides road administration with a practical tool, which helps to decide whether to issue a permit of passage of an oversized vehicle.
2) Two variants of pavement structure condition (good and poor) as well as two types of pavements structure thickness (thick and thin) were considered in the analysis. Analysis revealed that new pavements in good technical condition have enough bearing capacity to bear an oversized vehicle without any pavement failure, even if their thickness is low (12 cm). The fatigue damage caused by an 800 tonne oversized vehicle on new pavement in good condition varies from 0.0006% to 0.02%.
3) Load equivalency factor can reach a level of up to 321 ESALs (100 kN). One pass of an oversized vehicle is equivalent to pass of approximately 200 commercial heavy vehicles, occurring in typical road traffic flow. Load equivalency factor of an oversized vehicle is lower for thinner pavements and for pavements in worse condition, in contrast to fatigue damage caused by the oversized vehicle.
4) In the case of pavements in poor technical condition, fatigue damage caused by oversized vehicle is much higher. Moreover, bearing capacity of old pavements may be locally underestimated, thus it is advisable to perform an FWD test to identify and localize weak areas in pavements. The paper presents methodology for determination of critical deflections under an FWD plate. Critical deflections can be used to assess sensitivity of pavement to passage of oversized vehicles.

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