PERFORMANCE OF ARTICULATED VEHICLES AND ROAD TRAINS REGARDING ROAD DAMAGE AND LOAD CAPACITY

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Abstract

In the framework of the OECD study "Moving Freight with Better Trucks" - which will be published at this conference as well - several vehicle combinations which are worldwide in operation were examined regarding different performance criteria. One criterion was the road wear performance of these articulated vehicles. With given tyre and vehicle data (mainly weights and axle loads) the road wear performance was calculated for each vehicle combination. The method according COST 334 is presented and the vehicle combinations are compared.

Dans le cadre de l‘ étude OECD "Moving Freight with Better Trucks", des combinaisons différentes de poids lourds étaient examinées par des critères différents. L'usure de chaussée par des poids lourds était un des critères examinés. En se fondant sur des dates des pneus et des véhicules, l'usure de chaussée étaient calculé par les résultats de COST334. Par la contribution présente, la méthode et les résultats seront présentés ainsi que les véhicules comparés.

Keywords

Road wear performance, vehicle combinations, load capacity

1. Introduction

Besides safety performance, economic performance and environmental performance the road wear performance of trucks and truck combination plays a major role for road authorities and administrators. The society has to pay for the rutting damage caused by truck traffic. Road wear performance can be calculated and can be brought in relation to the payload moved. This is the topic of this paper. Different worldwide used truck combinations were compared.

2. Methode

The most comprehensive study in recent years concerning the influence of tyres and axle loads in relation to pavement damage (rutting of asphalt roads in the primary road network) was the so called COST 334 Study "Effects of Wide Single Tyres and Dual Tyres" published in 2001. From extensive rutting tests performed in different European countries with different tyres, tyre configurations, axle loads, inflation pressures, etc. a so called tyre configuration factor (TCF) was defined. The TCF value relates the pavement wear of a given tyre to the pavement wear of a reference tyre. Within different axle categories (steered, driven or towed axle) there is a wide range of TCF values which reflects the fact that there are more and less pavement damaging tyres and tyre configurations as options possible.
Tyre assembly (single/dual), tyre width and tyre diameter are the most important factors which influences the TCF.

The damage contribution of a single passage of an axle is expressed by the so called axle wear factor (AWF). This AWF is a dimensionless factor relating the damage contribution of a specific tyre at a given axle load to the damage contribution of a single passage of the reference tyre(s) with a reference axle load. Reference for the AWF means a passage of a 10 t axle equipped with 295/80R22,5 tyres mounted as twin assembly. To adjust the axle load effect on pavement damage a load equivalency factor (LEF) was introduced by COST 334, too. If only primary asphalt roads are considered and only primary rutting as damage cause is taken into account the pavement damage increases with the power of 2 by axle load.

The sum of all axle wear factors are called vehicle wear factor (VWF). For equal TCF and LEF the higher the number of axles the higher is the vehicle wear factor, but on the other hand the higher the payload can be.
For the same gross vehicle weight the higher the number of axles the lower is the axle wear factor for each axle and also the vehicle wear factor as sum of all axles.

The performance of a vehicle regarding pavement wear can be calculated by relating the payload to the vehicle wear factor. This performance indicator: VWF / Payload is abbreviated in the following as PER (vehicle road wear performance).

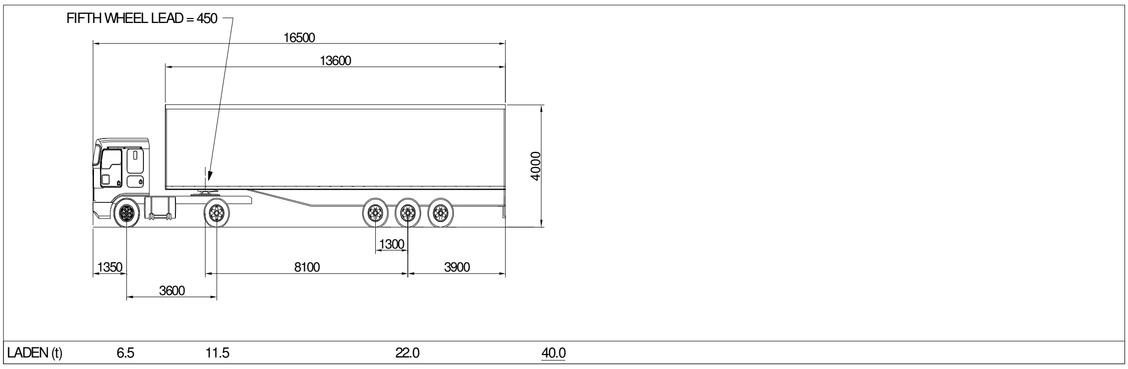
The following formulas have been used:

- Load Equivalence Factor: LEF= $(\text{axle load} / 10)^2$
- Tyre Configuration Factor: $(\text{tyre width}/470)^{-1,65} \times (\text{tyre diameter} /1059)^{-1,12}$
- Calculated Tyre Configuration Factors: TCF: see Table 4.67 in the COST 334 Report
- Axle Wear Factor: AWF=TCF x LEF
- Vehicle Wear Factor: VWF=SUM (AWF)
- Vehicle Road Wear Performance: PER: VWF / Payload

From the members of the OECD working group the vehicle data as gross vehicle weight (GVW), payload, axle loads for 39 articulated vehicles were provided and the data on tyre size and tyre assembly (single/dual) as well.
The truck combinations were divides in “workhorse vehicles”, vehicles mostly in operation today, “high capacity vehicles” up to 50 t GVW and 25 m length and very high capacity vehicles as road trains in operation in America or Australia with a length over 30 m. Table 1 shows for calculation explanation a selected workhorse vehicle (Europe 2), which has a share of > 50% on European roads.

Table 1: Selected Workhorse Vehicle: Europe 2, Calculation Principle

Country of origin and vehicle number:	Europe 2
Vehicle classification:	Workhorse vehicle
Payload (t):	26.0
Deck space (m^2):	33.1
Total cargo volume (m^3):	87.6



Tyres	295/80R22,5	295/80R22,5	385/65R22,5	385/65R22,5	385/65R22,5
D / S	S	D	S	S	S
axle load (t)	6,5	11,5	7,33	7,33	7,33
AWF	1,33	1,32	1,21	1,21	1,21
VWF	6,28				
PER	: 26 = 0,24				

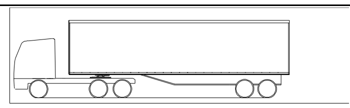
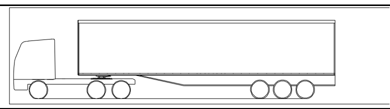
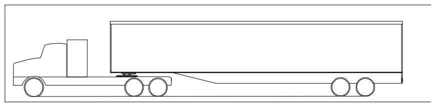
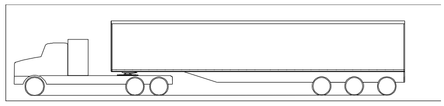
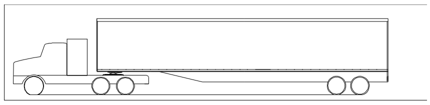
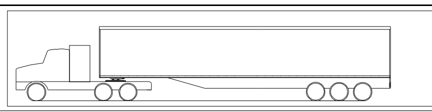
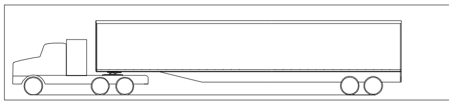
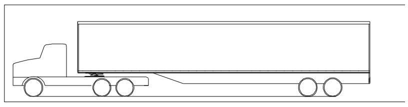
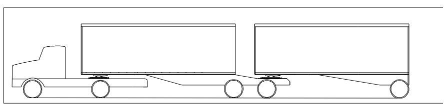
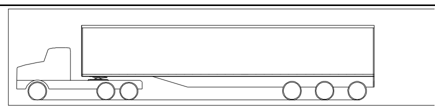
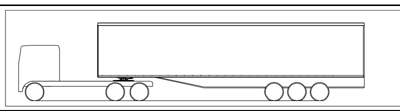
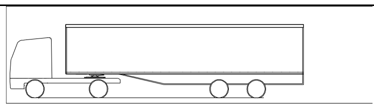
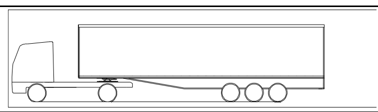
As one can see, the steering axle is the most aggressive axle for the road surface (AWF), having in mind that the steering axle is loaded every time with the engine’s weight but the other axles have less axle loads when the truck combination is operated in empty condition.

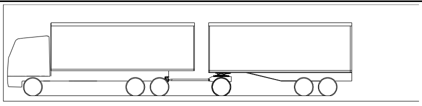
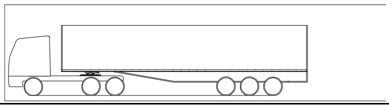
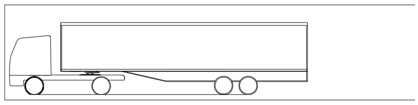
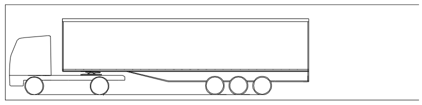
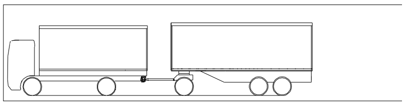
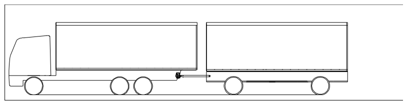
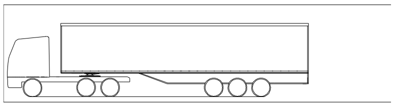
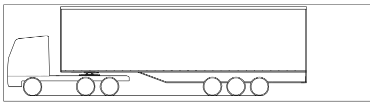
3. Results of Pavement Wear Performance Calculation

Table 2 shows the examined “workhorse vehicles” for this study. They are divided by continents: For 2 South African, 8 American, 1 Australian and 10 European trucks the road wear performance was calculated with the formulas above (all with max. payload and given curb weight). The calculation results for VWF and PER can be found in the Appendix. The tyre data are based on the ARRB tables for the calculation of the Australian PBS.[1] The PER values are shown in Fig.1.

[1] Some minor corrections were made, e.g. instead 295/75R22.5 tyres 295/80R22.5 tyres were used for calculation (US trucks), no data on 295/75R22.5 tyres available in the COST 334 report.

Table 2: HGV-type: Workhorse Vehicles

Vehicle origin & identification number	GCM (t) / Payload (t)	Length (m)	Vehicle Classification	Schematic	Vehicle description & vehicle code
AFRICA					
South Africa 1 ZA1-w	43.500 28.140	15.313	Workhorse		Tractor semi-trailer T12b3
South Africa 2 ZA2-w	49.300 31.900	17.745	Workhorse		Tractor semi-trailer T12b3
AMERICA					
Canada 1 CA1-w	39.500 25.300	21.550	Workhorse		Tractor semi-trailer T12b2
Canada 2 CA2-w	46.500 31.300	21.550	Workhorse		Tractor semi-trailer T12b3
Mexico 1 MX1-w	44.000 28.649	20.800	Workhorse		Tractor semi-trailer T12b2
Mexico 2 MX2-w	48.500 32.349	20.800	Workhorse		Tractor semi-trailer T12b3
Mexico 3 MX3-w	44.000 28.649	21.565	Workhorse		Tractor semi-trailer T12b2
United States 1 US1-w	36.350 21.150	19.770	Workhorse		Tractor semi-trailer T12b2
United States 2 US2-w	36.360 23.460)	21.980	Workhorse		B-double T11b2b1
United States 3 US3-w	41.900 26.700	19.770	Workhorse		Tractor semi-trailer T12b3
AUSTRALIA					
Australia1 AU1-w	45.500 29.000	19.000	Workhorse		Tractor semi-trailer T12b3
EUROPE					
Belgium 1 BE1-w	39.000 25.000	16.200	Workhorse		Tractor semi-trailer T11b2
Denmark 1 DK1-w	44.000 30.000	16.480	Workhorse		Tractor semi-trailer T11b3

Denmark 2 DK2-w	48.000 32.000	18.750	Workhorse		Rigid truck trailer R12a1b2
Denmark 3 DK3-w	48.000 32.300	16.500	Workhorse		Tractor semi-trailer T12b3
Europe 1 EU1-w	38.000 24.000	16.500	Workhorse		Tractor semi-trailer T11b2
Europe 2 EU2-w	40.000 26.000	16.480	Workhorse		Tractor semi-trailer T11b3
Europe 3 EU3-w	40.000 27.000	16.895	Workhorse		Truck trailer R11a1b2
Europe 4 EU4-w	40.000 25.000	18.750	Workhorse		Rigid truck with rigid drawbar trailer R12a2
United King-dom 1 UK1-w	44.000 29.109	16.500	Workhorse		Tractor semi-trailer T12b3
United King-dom 2 UK1-w	44.000 28.000	16.500	Workhorse		Tractor semi-trailer T12b3

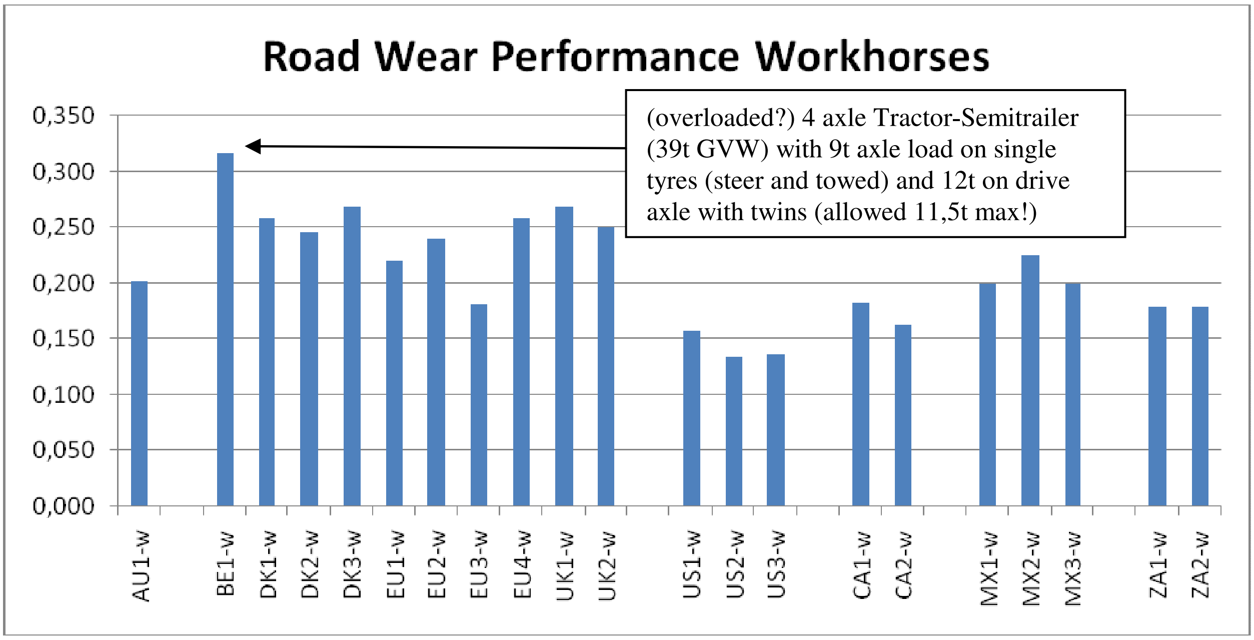
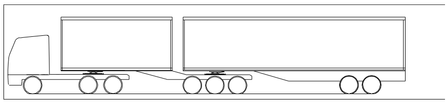
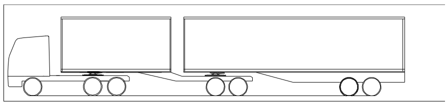
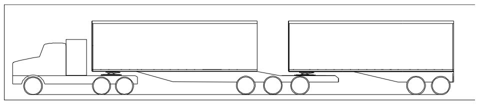
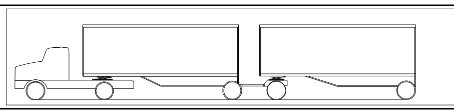
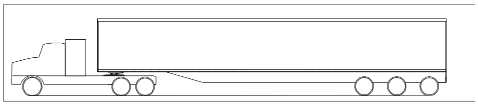
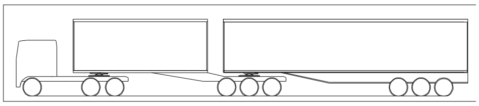
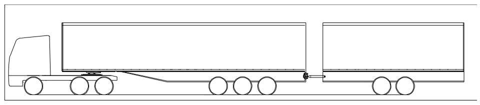
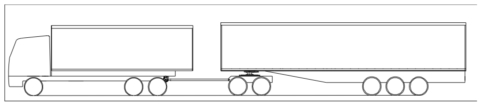
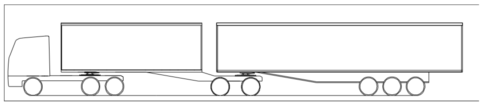
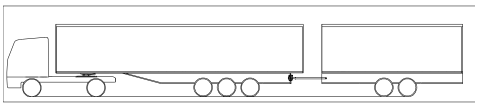
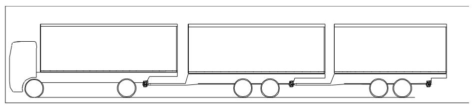
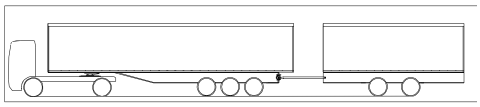
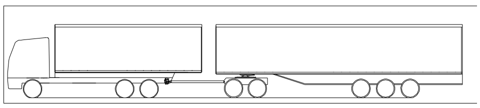


Figure 1: Road Wear Performance Workhorses

European workhorse trucks have significant higher road wear compared to the vehicles of other regions of the world. This is mainly because the have single tyres on the towed axles of trailers and semi-trailers. In other countries towed axles on truck units are equipped with twin tyres. The worst truck unit is the 39 t GVW vehicle on 4 axles (Belgium 1)

The twelve “higher capacity vehicles” are described in Table 3 and the results are in Figure 2.

Table 3: HGV-type: Higher Capacity Vehicles

Vehicle origin & identification number	GCM (t) / Payload (t)	Length (m)	Vehicle Classification	Schematic	Vehicle description & vehicle code
AFRICA					
South Africa 3 ZA3-h	56.000 33.800	21.972	Higher capacity		B-double T12b3b2
South Africa 4 ZA4-h	56.000 34.240	21.983	Higher capacity		B-double T12b2b2
AMERICA					
Canada 3 CA3-h	62.500 42.300	20.430	Higher capacity		B-double T12b3b2
United States 4 US4-h	36.360 23.586	22.060	Higher capacity		‘A’ train double T11b1a1b1
United States 5 US5-h	44.100 28.900)	25.120	Higher capacity		Tractor semi-trailer T12b3
AUSTRALIA					
Australia 2 AU2-h	68.000 44.500	25.010	Higher capacity		B-double T12b3b3
EUROPE					
Belgium 2 BE2-h	60.000 39.300	25.250	Higher capacity European modular vehicle		Tractor semi-trailer with rigid drawbar trailer T12b3a2
Denmark 4 DK4-h	60.000 40.700	25.250	Higher capacity European modular vehicle		Truck trailer R12a2b3
Denmark 5 DK5-h	60.000 38.000	25.100	Higher capacity European modular vehicle		B-double T12b2b3
Germany 1 D1-h	40.000 25.000	25.235	Higher capacity European modular vehicle		Tractor semi-trailer with rigid drawbar trailer T11b3a2
Netherlands 1 NL1-h	50.000 33.410	24.200	Higher capacity		Rigid truck with two rigid drawbar trailers R11a2a2
Netherlands 2 NL2-h	60.000 37.702	25.250	Higher capacity European modular vehicle		Tractor semi-trailer with rigid drawbar trailer T11b3a2
Netherlands 3 NL3-h	60.000 39.720	25.240	Higher capacity		Rigid truck trailer R12a2b3

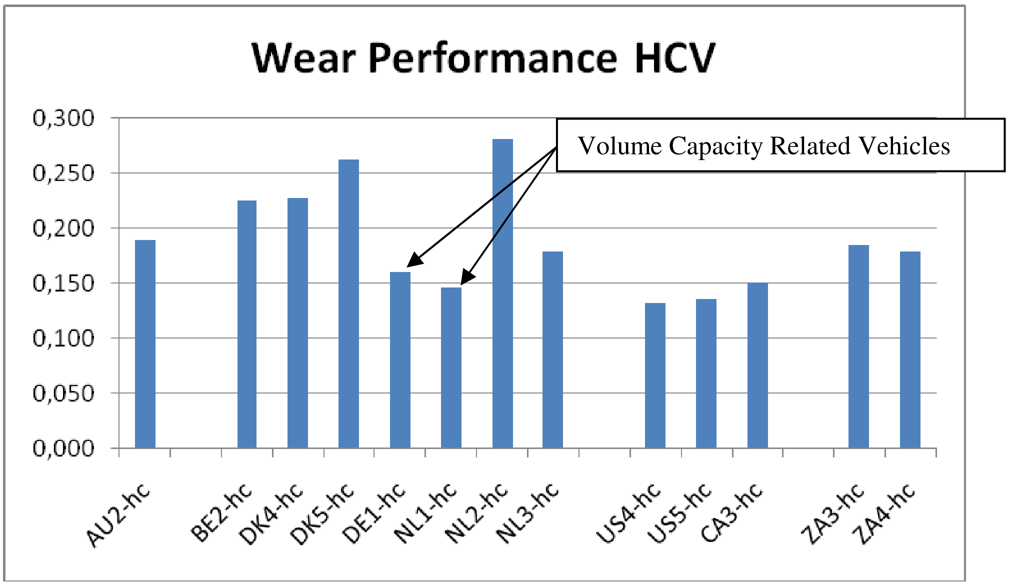
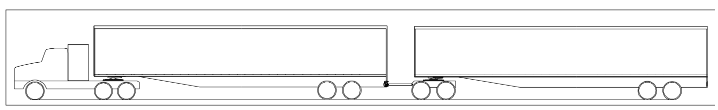
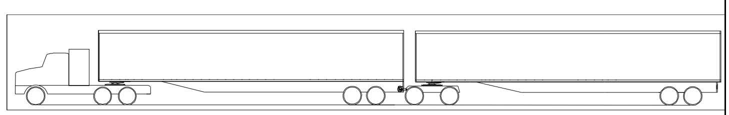
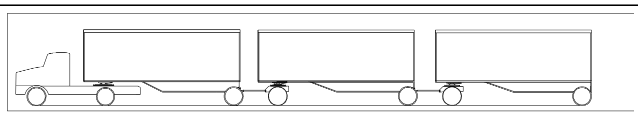
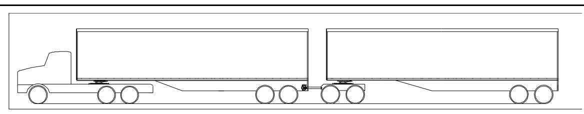
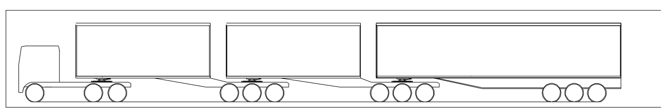


Figure 2: Road Wear Performance of High Capacity Vehicles

The comparison shows e.g. for the same 7 axle truck unit with 40t GVW (Germany 1) or 60 t GVW (Netherland 2) an increase from 0,160 to 0,281 (+75%) or the comparison of truck units with the same GVW of 60 t on 8 axles (Belgium 2) or on 7 axles (Netherland 2): 0,226 vs. 0,281 (+ 25%). Except the volume oriented vehicles (DE 1 and NL 1) the European units have a worse performance than the vehicles of the other states.

The fife "very high capacity vehicles" (GVW 53 t - 90 t), coming only from America and Australia, are described in Table 4 and the results are shown in Figure 3.

Table 4: Very High Capacity Vehicles

Vehicle origin & identify-cation number	GCM (t) / Payload (t)	Length (m)	Vehicle Classi-fication	Schematic	Vehicle descript-tion & vehicle code
AMERICA					
Canada 4 CA4-v	62.500 37.300	38.330	Very high capacity		A' train double T12b2a2b 2
Mexico 4 MX4-v	66.500 42.849	39.080	Very high capacity		'A' train double T12b2a2b 2
United States 6 US6-v	53.752 37.287	31.570	Very high capacity		'A' train triple T11b1a1b 1a1b1
United States 7 US7-v	57.040 32.840	30.960	Very high capacity		'A' train double T12b2a2b 2
AUSTRALIA					
Australia 3 AU3-v	90.500 60.000	33.310	Very high capacity		B-triple T12b3b3b 3

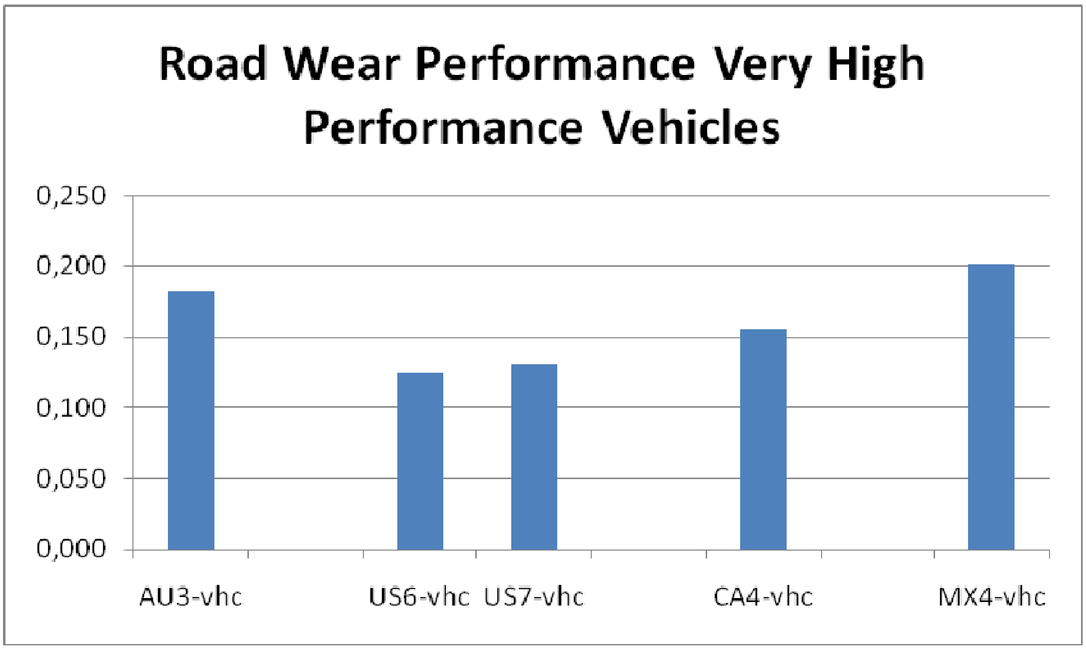


Figure 3: Road Wear Performance of Very High Capacity Vehicles

The very high capacity vehicles perform relatively well regarding pavement damage. The wear performance values are very low compared to the other vehicle classes. The reason for this is that only the steering axle is equipped with single tyres, all other tyres (drive and towed) are twins. On the other hand this means higher rolling resistance values and worse economic (fuel consumption) and environmental (CO_2) performance.

Figure 4 shows the results of road wear performance for all kind of truck units at a glance.

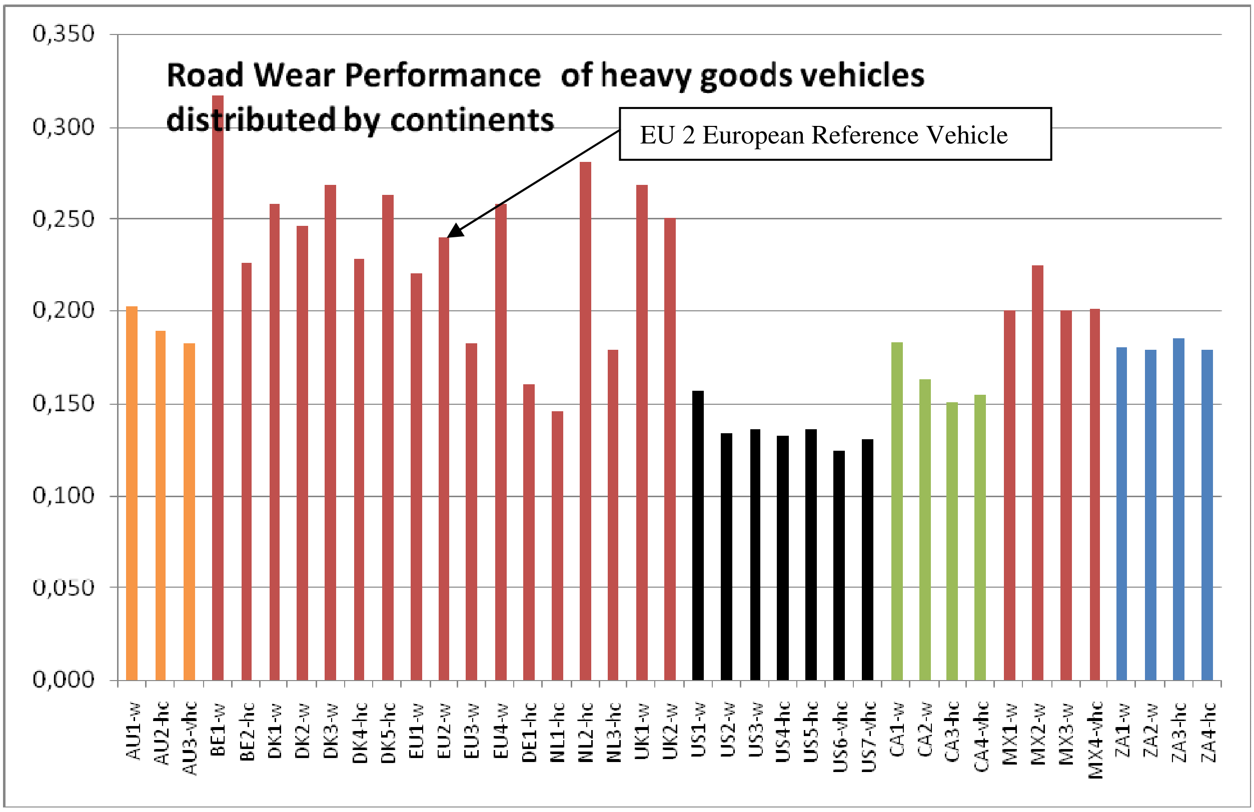


Figure 4: Road Wear Performance of HGV by States and Continents

The volume related truck units have of course better road wear performance than the weight related units.

In the distinction of payload capacity and volume capacity the determinant factor is the specific weight or the so called "density" of the load to be transported. Table 5 shows examples of the specific gravity for different goods.

The example truck Europe 2, see table 1 above, has 26 t payload capacity and 87.6 m³ volume capacity. This means the cargo may have a density 0.3 kg/dm³ or less to avoid overloading. As one can see from table 5, empty beer bottles in boxes have just the density of 0.3 kg/m³.

Table 5: Specific gravity of several goods (kg/dm³ = t/m³)

Water, Milk, Beer, etc.	1 kg / dm³
Fuel, Oil, Ethanol, etc.	0,6 - 0,8 kg /dm³
Earth and Soil	1,3 - 2,0 Kg / dm³
Concrete	2,2 kg / dm³
Bricks	1,9 kg / dm³
Alloy	2,7 kg / dm³
Steel	7,9 kg / dm³
Wood (dry)	0,5 - 0,9 kg / dm³
Rubber	1,2 kg / dm³
Beer boxes with 20 empty bottles (0,3mx0,3mx0,4m) weigh 10 kg	0,3 kg / dm³
Beer boxes with 20 filled bottles (same size, but 20 kg)	0,6 kg / dm³
Refrigerators (white goods)	0,14 kg / dm³
Nine passenger cars,1,5 t each, on a 100m³ transporter	0,135 kg / dm³
Single dispatched items (parcels)	0,15 kg/ dm³
Styropor	0,04 kg / dm³

Fluid and bulk transporters tend to be overloaded because of the high specific weight of the cargo. The more cargo space is available the more the danger of overloading is given. WIM measurements from Germany (3 measuring sites on highways) show that nearly one third of the heavy vehicles are overloaded. That is a strong argument for mandatory on board weigh (and axle load) measurements, see Figure 5.

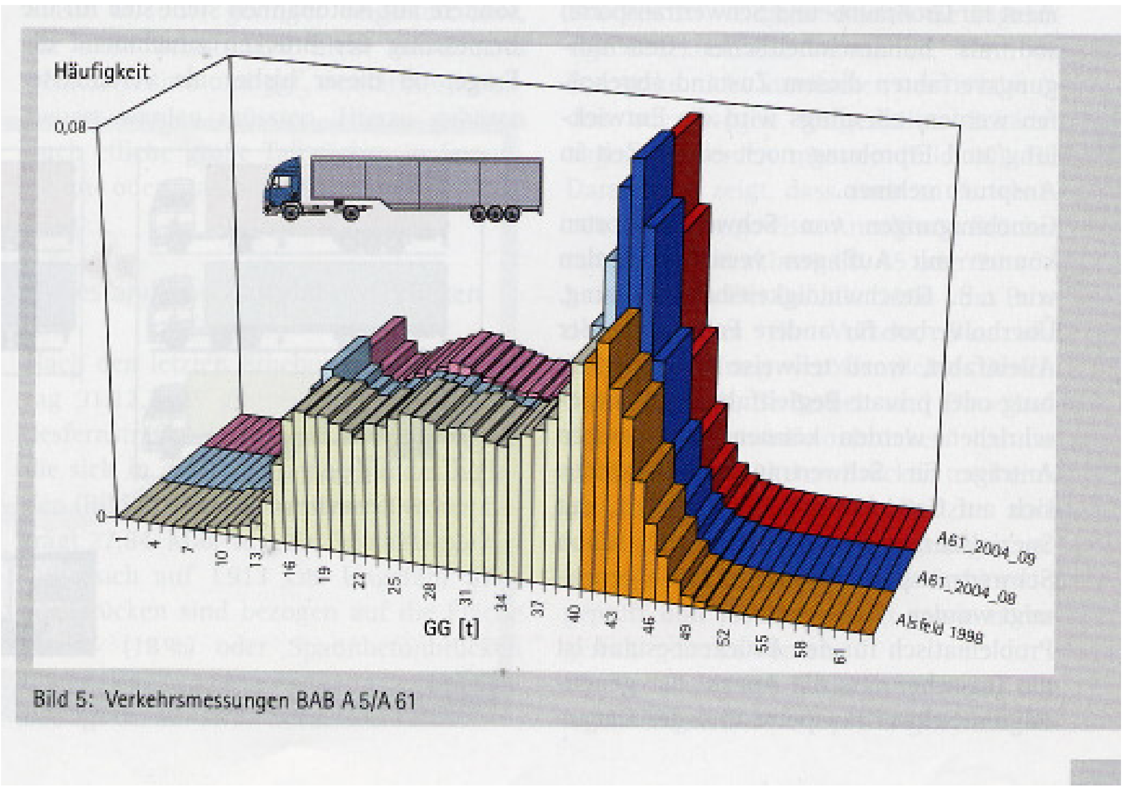


Figure 5: GVW measurement results for Europe 2 truck combination in Germany at 3 sites

Figure 6 shows the relation between payload and gross vehicle weight. The differences between workhorse and high or very high capacity vehicles are small. The payload share on the GVW is in almost all cases between 60% and 70%. An analogue performance could be evaluated for cargo volume.

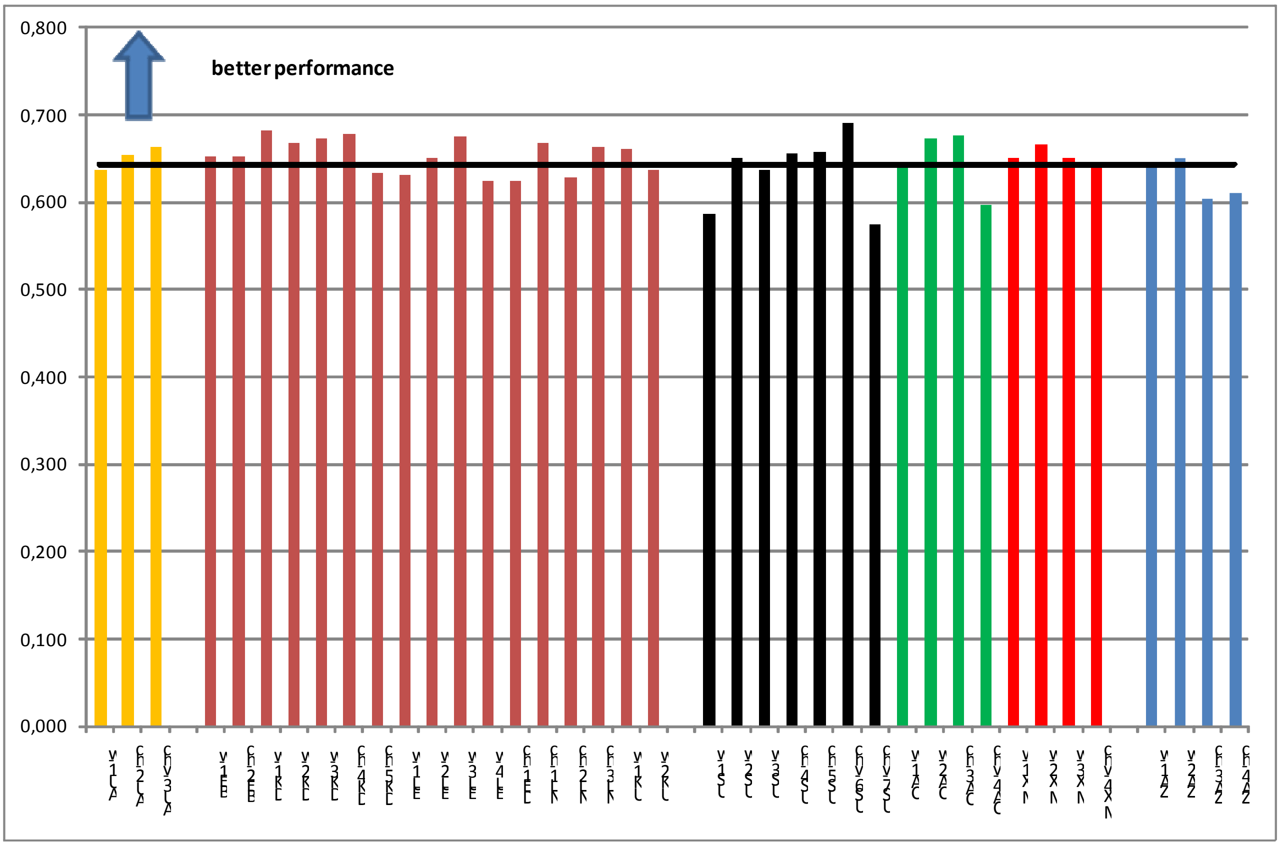


Figure 6: Load Efficiency (Payload/ GVW) of HGV by Continents

This paper describes only the performance of different truck units on pavement wear. The performance concerning bridge loads or turning ability and other impacts on infrastructure are not examined. The topography and the existing road network in different countries and regions in the world plays a major role in defining maximum weights or dimensions for articulated vehicles.

4 References

- COST 334 Report, 2001, www.rws.nl/rws/dww/home/cost334tyres
- OECD/JTRC Report: “Moving Freight with Better Trucks”, 2010
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Appendix

Vehicle	Vehicle ID	Veh.Wear Factor VWF	Payload [t]	Wear Performance	Payload/GWW	Payload/GVW
Australia 1	AU1-w	5,86	29,0	0,202	29,0/46=0,637	0,637
Australia 2	AU2-hc	8,41	44,5	0,189	44,5/68=0,654	0,654
Australia 3	AU3-vhc	10,96	60,0	0,182	60,0/91=0,663	0,663
Belgium 1	BE1-w	7,23	22,8	0,317	25,0/39=0,585	0,585
Belgium 2	BE2-hc	8,88	39,3	0,226	39,3/60=0,653	0,653
Canada 1	CA1-w	4,62	25,3	0,183	25,3/40=0,640	0,640
Canada 2	CA2-w	5,09	31,3	0,163	31,3/47=0,673	0,673
Canada 3	CA3-hc	6,38	42,3	0,151	42,3/63=0,677	0,677
Canada 4	CA4-vhc	5,79	37,3	0,155	37,3/63=0,597	0,597
Denmark 1	DK1-w	7,75	30,0	0,258	30,0/44=0,682	0,682
Denmark 2	DK2-w	7,88	32,0	0,246	32,0/48=0,667	0,667
Denmark 3	DK3-w	8,67	32,3	0,268	32,3/48=0,673	0,673
Denmark 4	DK4-hc	9,26	40,7	0,228	40,7/60=0,678	0,678
Denmark 5	DK5-hc	10,01	38,0	0,263	38,0/60=0,633	0,633
Europe 1	EU1-w	5,32	24,0	0,221	24,0/38=0,632	0,632
Europe 2 **Ref**.	EU2-w	6,28	26,0	0,240	26,0/40=0,65	0,650
Europe 3	EU3-w	4,94	27,0	0,182	27,0/40=0,675	0,675
Europe 4	EU4-w	6,44	25,0	0,258	25,0/40=0,625	0,625
Germany 1	DE1-hc	4,18	25,0	0,160	25,0/40=0,625	0,625
Mexico 1	MX1-w	5,76	28,6	0,200	28,6/44=0,650	0,650
Mexico 2	MX2-w	7,28	32,3	0,225	32,3/49=0,666	0,666
Mexico 3	MX3-w	5,76	28,6	0,200	28,6/44=0,650	0,650
Mexico 4	MX4-vhc	8,60	42,8	0,201	42,8/67=0,644	0,644
Netherlands 1	NL1-hc	4,87	33,4	0,146	33,4/50=0,668	0,668
Netherlands 2	NL2-hc	10,61	37,7	0,281	37,7/60=0,628	0,628
Netherlands 3	NL3-hc	7,11	39,7	0,179	39,7/60=0,662	0,662
South Africa 1	ZA1-w	5,08	28,1	0,180	28,1/43,5=0,646	0,646
South Africa 2	ZA2-w	5,70	31,9	0,179	31,9/49=0,651	0,651
South Africa 3	ZA3-hc	6,24	33,8	0,185	33,8/56=0,604	0,604
South Africa 4	ZA4-hc	6,11	34,2	0,179	34,2/56=0,611	0,611
UK 1	UK1-w	6,99	26,1	0,268	29,1/44=0,593	0,593
UK 2	UK2-w	6,99	28,0	0,250	28,0/44=0,636	0,636
United States 1	US1-w	3,32	21,1	0,157	21,1/36=0,586	0,586
United States 2	US2-w	3,13	23,4	0,134	23,4/36=0,650	0,650
United States 3	US3-w	3,63	26,7	0,136	26,7/42=0,636	0,636
United States 4	US4-hc	3,14	23,6	0,133	23,6/36=0,655	0,655
United States 5	US5-hc	3,92	28,9	0,136	28,9/44=0,657	0,657
United States 6	US6-vhc	4,64	37,3	0,124	37,3/54=0,691	0,691
United States 7	US7-vhc	4,30	32,8	0,131	32,8/57=0,575	0,575
					average	0,643