



ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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# Safety, Productivity, Infrastructure Wear, Fuel Use and Emissions Assessment of the International Truck Fleet

# **A Comparative Analysis**

By

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#### Abstract

This report completes the ITF/OECD report *Moving Freight with Better Trucks* by providing full information on the performance benchmarking study undertaken for 39 trucks across OECD/ITF countries. All of the vehicles examined are intended for longer distance transport. The three vehicle categories are workhorse vehicles, higher capacity vehicles and very high capacity vehicles.

This report describes the methodology and presents the detailed results of the benchmarking exercise. The performance measures examined include vehicle dynamic safety performance, energy efficiency, CO<sub>2</sub> efficiency, Infrastructure impact, and freight transport productivity measures.

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#### 1. INTRODUCTION

The Joint OECD/ITF Transport Research Centre (JTRC) Research Working Group have conducted an investigation of the safety, environmental and productivity performance of current and future heavy vehicle configurations from 10 countries, with a view to defining the societal value of road transport. This stand alone report focuses on vehicle safety and productivity measures and represents the comprehensive analysis that supports chapter 4 of the JTRC OECD report "Moving Freight with Better Trucks". The study focused on vehicles used primarily for medium to long distance higher speed highway travel. This transport vehicle class rapidly increased during the industrialization era as manufacturing and globalized trade resulted in an increase in demand for timely and flexible transport. Ships, barges and trains naturally have played a major role for such transport but during the past 50 years the demand for freight transport to be undertaken by road has increased enormously.

The transportation of goods is a prerequisite for almost all local, regional and global trade and production. The transportation of these goods by road is an indispensable element of the freight task except in the limited circumstances where freight that can be transported from door-to-door by rail or water alone. Transportation sustainability will depend on system optimization involving all modes of transport. This particular analysis focuses on the safety and productivity of commercial vehicles influenced by various regulatory regimes with a view to understanding how truck transport can be optimized to deliver improved societal value.

### 2. HEAVY VEHICLE CONTEXT

As evident in Figure 1, heavy vehicles have come a long way in the last century. From their early beginnings as two axle horseless carriages they have evolved into complex vehicle configurations specifically designed for particular freight tasks. Heavy vehicles are regionally unique because their design, axle loading, mass and volume are directly influenced by the regulations (which can differ significantly among most nations). Truck design is also influenced by factors associated with operations, and manufacturing. The three main factors that influence truck design are described below.



Figure 1 Comparing the first Daimler truck 1896, 1,2 t curb weight, 1,5 t payload, engine: 2 cylinders, 1.000 cm<sup>3</sup>, 4 HP, max. velocity 16 km/h with a highly efficient two floor semitrailer.

#### 2.1 **Operational Factors**

Large trucks exist to do work and to do it efficiently. Their worth and function are tied directly to work performance in exchange for money. This mode of operation is very different from passenger cars. The tasks that commercial vehicles perform are highly varied, and vehicles are purposefully designed to reflect task-specific requirements. For example, vehicles designed to transport goods between cities are very different from those designed for deliveries within urban areas. They can perform special purpose tasks such as collecting garbage or performing maintenance such as repairing the electrical network.

Generally, competitive forces within the transport industry provide strong incentives to encourage the efficient use of fuel. However there are segments of the industry that are less sensitive to fuel use optimization given the priorities of the operator or the nature of the freight task or work function.

Freight tasks vary, as do the weight and shape of cargo transported, therefore vehicle duty cycles and fuel consumption varies for a given cargo and vehicle task. For long haul transport in particular, the nature of goods transport can be volume limited, mass limited or, for low density goods that cannot be stacked to full vehicle height, limited by the available deck area. Fuel efficiency for volume limited freight tasks requires a different evaluation metric than that of a mass limited freight task.

A vehicle having low fuel consumption is not necessarily a vehicle having good fuel efficiency. Fuel consumption references fuel used to move a vehicle. Fuel efficiency refers

to the fuel used to accomplish a specific freight or work task. For road freight transport, fuel efficiency is the preferred performance metric.

#### 2.2 Regulatory Factors

Basic aspects of truck design such as the length, wheelbase, width, height, axle loads, axle spacing and GVW, are influenced and limited by size and weight regulations. Since many of these factors directly influence fuel consumption it can be concluded that fuel consumption and fuel efficiency are directly related to size and weight regulation. Size and weight regulations can exist at both the state, provincial, regional, national or international level. In general each country has its own unique set of regulations governing vehicles using their highway network. Some aspects of these regulations such as vehicle width and height are largely harmonized within international regions; however vehicle weight (a first order factor affecting vehicle fuel consumption) is highly variable.

#### 2.3 Manufacturing Factors

For a given heavy truck purchase, the customer exercises choice (particularly in North America) for major components used in the assembly of the vehicle such as engine, transmission, drive axles and suspensions. The customer also specifies the vehicle GVW, suspension and axle load rating, the vehicle wheelbases, and drive axle spread. In some cases components such as engine, transmission, drive axles and suspensions are supplied by a third party to the manufacturer as plug in components which are fully compatible within the truck manufacturing industry. The customer may have a choice of three or four different engine manufactures and corresponding model subsets as well as different transmissions and drive axle assemblies sourced from separate manufactures. In addition, final drive gear ratio choices are specified to match the intended operating drive cycle in light of the engine characteristics, transmission, wheel and tire sizes. In effect a significant portion of the heavy truck industry produces custom built vehicles. Viewed externally, the trucks from a given manufacturer may appear to be identical, but the systems contained within the skin of the vehicle can be substantially different. The performances of these third party components are beyond the control of the truck manufacturer yet they influence the overall fuel efficiency of the vehicle.

In most cases, vehicle manufacturers do have control over the shape and aerodynamic treatments of the power unit (truck tractor or cab and chassis). However, the manufacturer does not necessarily have control over the aerodynamics of the final vehicle. Tractors are coupled to trailers and depending on the whole vehicle configuration, the drag coefficient of the vehicle can vary by as much as 20% depending on the vehicle shape and spacing of the trailer(s).

#### 3. BENCHMARKING CONCEPT

Member countries were invited to submit representative vehicles for evaluation and to provide their technical information. Each vehicle was classified in the following three general categories:

- Workhorse vehicle the vehicle most commonly used for long haul transport. This vehicle is generally at the upper end of the weights and dimensions that is permitted general or widespread access. Workhorse vehicles were defined in this study as having a gross combination mass (GCM) of less than 50 tonnes and a length of less than 22 metres. Of the 39 vehicles in the study, 21 of the vehicles were classified as workhorse vehicles.
- Higher capacity vehicle This vehicle is typically operated under restricted access conditions dependant on the suitability of the road network. This vehicle will be heavier and/or longer than the workhorse vehicle. Higher capacity vehicles were defined in this study as having a GCM of up to 70 tonnes and a maximum length of 30 metres. Thirteen vehicles were classified as higher capacity vehicles..
- Very high capacity vehicle This vehicle typically operates under permit conditions and often in rural or remote areas. It is heavier and/or longer than the high capacity vehicle. Very high capacity vehicles were defined in this study as having a GCM of at least 52 tonnes and a length of at least 30 metres. Five vehicles were classified as very high capacity vehicles..

#### 3.1 Vehicle benchmarking method

Each vehicle was examined against vehicle safety performance measures based largely on the Australian National Transport Commission's (NTC) Performance Based Standards (PBS) scheme. The subset of measures used provides an understanding of general vehicle performance in the broader international context. Some of the Australian measures were not used in this analysis because they did not provide distinguishing value for the vehicles examined. The load transfer ratio measure which is widely used internationally but not included in the Australian system was added to the performance measure subset because of its usefulness and value.

The University of Michigan Transport Research Institute (UMTRI) and JTRC conducted a survey of member countries and compiled the vehicle data. ARRB Group was contracted to conduct the simulations for the PBS analysis, while UMTRI conducted the productivity analysis. For the PBS simulations, a computer model was created for each of the 39 vehicles. Each vehicle model was based on the characteristics supplied by the member organisations. The computer model was used to simulate the performance of the vehicle for each of the manoeuvres selected for evaluation. Independent replication was conducted using another model developed by LCPC/CETE (France).

#### 3.2 Computer modeling and simulation

A computer model was created for each of the 39 vehicles. Each vehicle model was based upon the characteristics supplied by the member organisations. The computer model was used to simulate the performance of the vehicle for each of the manoeuvres selected for evaluation. ARRB completed this assessment using modelling techniques developed in-house and validated in numerous field tests and comparative studies over the last 12 years.

An example of validation of the computer model against test data can be seen in Figure 2, where there is a close relationship between the yaw rates measured during the field test and those determined in the simulations.



Figure 2 Example simulation validation

#### 3.3 Assumptions

During the course of the modelling process, a number of assumptions were made. This was done in order to ensure that the performance result achieved by each vehicle was based on the individual characteristics of each vehicle, such as the payload, the trailer configuration

and the dimensions of the vehicle units. Including specific vehicle characteristics such as suspension details or tyre characteristics would have reduced the potential for a comparison between the vehicles. Some of the assumptions made were as follows:

- The loading condition assumes van units (body design similar to a pantechnicon suitable for carrying palletised loads) with 70% of the load mass located in the lower 50% of the load space.
- The payload centre-of-gravity height was located at 40% of the load space height.
- The same generic suspension parameters were used for all vehicles as follows:
  - parabolic leaf springs used for the steer axle
  - standard air suspension for drive axles and towed axles of trailers.
- The same tyre type was used on each axle, though whether dual-tyre or (super-) single tyre axles were used were as specified by each member country. No steerable or liftable towed axles were considered.
- The centre-of-gravity height for prime mover/tractor units was taken to be 1.1 metres above the ground.
- The centre-of-gravity height for all converter dollies was taken to be 1.0 metre above the ground.

The maximum allowable mass and heights were specified by each country.

#### 3.4 Vehicles

During the course of this investigation, a total of 39 vehicle configurations from 10 countries were modelled and the performance assessed. A brief description of each of the vehicles assessed can be found in Table 1.

The European modular vehicle or European Modular System (EMS) vehicle, was also examined during this study. The European modular vehicle comprises vehicle units that are coupled together to have the commonly available load space lengths of 7.82 metres and 13.6 metres. Examples of this modular concept are shown in Figure 3. The vehicles also have a gross combination mass (GCM) of up to 60 tonnes.

From the vehicles identified by the OECD member countries, four vehicles were identified as being European Union international traffic vehicles as no member can prohibit the use of these vehicles in international traffic within its territory. These vehicles have been referred to as European vehicles (Europe 1, Europe 2, Europe 3 and Europe 4) in **Error! Reference source not found.** Of those European vehicles which were not European international vehicles, four were then identified as EMS vehicles. Those vehicles have been identified in Table 1, as vehicle classification type 'European modular vehicle'.



Figure 3: European modular vehicle concept (Berndtsson and Lundqvist 2007)

Table 1. Vehicles as modelled during benchmarking study<sup>1</sup>

<sup>&</sup>lt;sup>1</sup> These vehicles represent real vehicles. Their lengths do not necessarily correspond exactly to the maximum authorised length.

Vehicle origin & identification number	GCM (t) / Payload (t)	Length (m)	Vehicle Classification	Schematic	Vehicle description & vehicle code
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
Canada 3 CA3-h	62.500 42.300	20.430	Higher capacity		B-double T12b3b2
Canada 4 CA4-v	62.500 37.300	38.330	Very high capacity		A' train double T12b2a2b2
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

Vehicle origin & identification number	GCM (t) / Payload (t)	Length (m)	Vehicle Classification	Schematic	Vehicle description & vehicle code
Denmark 3 DK3-w	48.000 32.300	16.500	Workhorse		Tractor semi-trailer T12b3
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		B-double T12b2b3
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

Vehicle origin & identification number	GCM (t) / Payload (t)	Length (m)	Vehicle Classification	Schematic	Vehicle description & vehicle code
Europe 4 EU4-w	40.000 21.900	18.750	Workhorse		Rigid truck with rigid drawbar trailer R12a2
Germany 1 DE1-h	40.000 20.800	25.235	Higher capacity European modular vehicle		Tractor semi-trailer with rigid drawbar trailer T11b3a2
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-v	66.500 42.849	39.080	Very high capacity		'A' train double T12b2a2b2

Vehicle origin & identification number	GCM (t) / Payload (t)	Length (m)	Vehicle Classification	Schematic	Vehicle description & vehicle code
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	25.200	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
South Africa 1 ZA1-w	43.500 28.140	15.313	Workhorse		Tractor semi-trailer T12b2
South Africa 2 ZA2-w	49.300 31.900	17.745	Workhorse		Tractor semi-trailer T12b3
South Africa 3 ZA3-h	56.000 33.800	21.972	Higher capacity		B-double T12b3b2
Vehicle origin &	GCM(t)/	Length (m)	Vehicle	Schematic	Vehicle description &

identification number	Payload (t)		Classification	vehicle code
South Africa 4 ZA4-h	56.000 34.240	21.983	Higher capacity	B-double T12b2b2
United Kingdom 1 UK1-w	44.000 29.109	16.500 height = 4.0 m	Workhorse	Tractor semi-trailer T12b3
United Kingdom 2 UK2-w	44.000 26.130	16.500 height = 4.90 m	Workhorse	Tractor semi-trailer T12b3
United Kingdom 3 UK3-w	44.000 28.000	18.750	Workhorse	Rigid truck with rigid drawbar trailer R12a3
United States 1 US1-w	36.350 (80,138 lbs) 21.150 (46,628 lbs)	19.770	Workhorse	Tractor semi-trailer T12b2
United States 2 US2-w	36.360 (80,160 lbs) 23.460 (51,720 lbs)	21.980	Workhorse	B-double T11b2b1

#### 3.5 Performance measures

#### 3.5.1 About Performance Based Standards

Performance based standards for heavy vehicle safety were first introduced by the Canadian Heavy Vehicle Weights and Dimensions Study in 1986. Australia has further refined PBS and is acknowledged as the leader in the implementation of PBS. The PBS scheme examines the actual performance of the vehicle on the road, rather than the approximation of a vehicle's behaviour through the enforcement of prescriptive standards. PBS allows for vehicles to be physically tested or simulated, with the performance of the vehicle compared to the performance levels for each standard to determine the hierarchy of the road that the vehicle may safely travel upon.

In Australia, the Performance Based Standards scheme uses 16 safety standards and 4 infrastructure standards to assess non-standard vehicles. Five safety measures were selected as well as the load transfer ratio (LTR), which is a well established international PBS measure that was not adopted in Australia.

#### Low speed swept path (LSSP)

The low speed swept path is the maximum width of the swept path of a vehicle simulated driving through a 90° turn of 12.5 m radius at a speed of 5 km/h. Figure 4 Example output of LSSP manoeuvre shows an example output of a LSSP simulation for a tractor semi-trailer. The outer path of the vehicle is shown by the solid bold line. The maximum swept width is indicated. Note – This manoeuvre is not intended to apply universally and represents a less severe test than the EU directive (BO Kraftkreis turning circle). However it does allow a relative comparison of vehicle performance in the context of this study.



Figure 4 Example output of LSSP manoeuvre

#### Static rollover threshold (SRT)

Rollover stability is a significant safety issue and arguably the most important performance measure for heavy vehicles because it has been strongly linked to rollover crashes.

The measure of rollover stability is static rollover threshold (SRT) which is the level of lateral acceleration that a vehicle can sustain without rolling over during a steady state turn. The SRT is expressed as a fraction of the acceleration due to gravity in units of 'g', where 1 g is an acceleration of 9.807 m/s<sup>2</sup> corresponding to the force exerted by the earth's gravitational field. High values of SRT imply better resistance to rollover.

To determine the SRT the vehicle must be driven along a specified circular path at an initial speed that is at least 10 km/h slower than the speed at which the rollover instability will occur. From the initial speed, the driver must increase the speed of the vehicle at a slow, steady rate until the point rollover is reached. The vehicle must reach a level of not less than 0.35 g during this manoeuvre.

Figure 5 shows a semi-trailer negotiating a tight radius turn and encountering wheel lift-off leading to rollover.



Figure 5: Vehicle performing static rollover threshold test

The required performance level to pass PBS is shown in **Error! Reference source not found.**2. The performance level required to meet the SRT measure is independent of the specific road levels i.e. the same level of SRT is required regardless of the road access granted to the vehicle.

#### Table 1: SRT performance levels

Road class	Performance level required
All lavals	Road tankers hauling dangerous goods in bulk and buses and coaches
All levels	not less than 0.40 g. All other vehicles not less than 0.35 g.

#### Yaw damping coefficient (YDC)

An important consideration in the stability and handling of heavy vehicles is the time taken for yaw or sway oscillations take to 'settle down' or decay after a severe manoeuvre has been performed. Vehicles that take a long time to settle increase the driver's workload and represent a higher safety risk both to other road users and the driver. The yaw damping coefficient (YDC) performance measure quantifies the rate at which yaw oscillations decay after a short duration steer input (pulse input) at the hauling unit. The intention of the yaw damping response test is to provide a steering input that will excite the rear unit of the combination into a yawing motion. The YDC of the vehicle combination is determined from the time history of the yaw motion. A higher YDC means better performance. This manoeuvre is more relevant to the safety of multi-combination vehicles with more than one articulation point. The YDC performance level required by PBS is shown in Table 2.

 Table 2: YDC performance levels

Road class	Performance level required
All levels	Not less than 0.15 at the certified vehicle speed

#### 3.5.2 Rearward amplification (RA)

A lane change manoeuvre is the method used to measure the rearward amplification (RA), highspeed transient offtracking (HSTO) and load transfer ratio (LTR) of a vehicle combination. The intention of the lane change manoeuvre is to produce a known lateral acceleration at the steer axle, at a given frequency, and to record the lateral acceleration experienced at the rear unit. The ratio of peak lateral acceleration at the rear unit to that at the steer axle is the RA of the vehicle.

RA generally pertains to heavy vehicles with more than one articulation point, such as rigid trucktrailers and road train combinations. RA describes the tendency for the trailing unit(s) to experience higher levels of lateral acceleration than the hauling unit during a dynamic manoeuvre. It is a serious safety issue in rapid path-change manoeuvres as it can lead to rear-trailer rollover. Each unit in the combination amplifies the lateral acceleration of the unit immediately ahead of it, and thus amplification of lateral acceleration increases toward the rear of the vehicle. Lower values of rearward amplification indicate better performance. Higher values of rearward amplification imply higher probabilities of rear-trailer rollover. The RA performance level required by PBS is shown in Table 3.

Road class	Performance level required
All levels	Not greater than 5.7 times the static rollover threshold of the rearmost
	unit or roll-coupled set of units taking account of the stabilising influence
	of the roll coupling.

 Table 3: RA performance levels

#### 3.5.3 High speed transient offtracking (HSTO)

High speed transient offtracking (HSTO) is measured during the same lane change manoeuvre as described above. During the manoeuvre, the lateral displacement of the rear end of the last trailer of an articulated vehicle may overshoot the final path of the front axle of the hauling unit. The lateral overshoot may interfere with overtaking or passing vehicles and thus represents a safety risk. HSTO measures this lateral overshoot. The performance levels required to meet each PBS level are shown in Table 4

Road class	Performance level required
Level 1	Not greater than 0.6 m
Level 2	Not greater than 0.8 m
Level 3	Not greater than 1.0 m
Level 4	Not greater than 1.2 m

**Table 4: HSTO performance levels** 

#### 3.5.4 Load transfer ratio (LTR)

Also measured during the lane change manoeuvre, the load transfer ratio is the proportion of load on one side of a vehicle unit transferred to the other side of the vehicle in a transient manner when undergoing the manoeuvre. The LTR value returned is the maximum LTR achieved during the manoeuvre. A value of 0 means that the vehicle is evenly balanced on both sides of the vehicle, while a value of 1 means that all the vehicle load is on one side of the vehicle, wheel lift-off has occurred, and rollover is imminent. Therefore, the LTR measure provides a clear indication of the proximity of rollover for any vehicle unit during the lane change manoeuvre. Although not used in Australian PBS system, the LTR measure was included in this study as it gives an easily conceptualised measure of vehicle performance during the lane change manoeuvre. Based on international experience a ratio of 0.6 is the maximum level of load transfer considered safe during the lane change manoeuvre.

#### 3.6 Influences on performance measures

A further investigation of the simulation results was performed in order to determine the major influences on each of eight performance measures examined.

Nine factors were examined, and an analysis between each performance measure and each factor examined in order to determine which of the factors had the greatest influence upon the performance measure. The most influential factors were those with a high correlation, as well as having a steeper gradient in a linear line of best fit plotted between the factor and performance result. All of the factors were normalised to a value between 0 and 1 prior to applying a line of best fit in order to rule out any bias from the factors with larger values (e.g. the internal cargo volume varies between 77 m<sup>3</sup> and 233 m<sup>3</sup>, while the values for the coupling ratio varies between 0 and 1). The performance of all 39 vehicles were used in the study.

The following nine factors were used in the analysis:

- Standard axle repetitions (SARs) per axle group: to determine the number of equivalent standard axle repetitions from the vehicle, each axle group is normalised by comparing the equivalent damage by one pass of the axle group to the same damage of a number of passes of a 'measure' axle. This factor gives an idea of whether axles are typically overloaded on the vehicle.
- Ratio of 'B' type couplings to total couplings: gives a ratio of the different coupling types present on the vehicle. 'B' type couplings include turntables and fifth wheels, while other couplings include drawbar type trailers.
- Gross combination mass: the total mass of the entire vehicle.
- Payload: the gross combination mass less the tare weight of the vehicle.
- Payload per axle: the total payload of the vehicle divided by the total number of axles.
- Internal cargo volume: the total volume available to transport cargo.

- Total vehicle length: the length from the front to the rear of the vehicle.
- Number of axles: the total number of axles on the vehicle.
- Product density: the density of the payload needed to totally fill the available cargo volume at maximum axle loads.

A tenth factor was identified only for the steer tyre friction demand, with the ratio of the load on the steer axle to the load on the drive axle group calculated.

Graphs of the factors plotted for each of the performance measures, as well as box-and-whisker plots of the data can be seen in Appendix A: Further results.

# 3.6.1 Influences on TASP results

The highest correlations between the Tracking Ability on a Straight Path (TASP) results and the examined factors were for the coupling ratio variable (Figure 6) as well as length (Figure 7) and volume.

The relationship between coupling ratio and TASP, was that as the coupling ratio increased (ie. the relative prevalence of 'B' couplings increased) the TASP value decreased, resulting in improved performance. Figure 6 is a scatter plot showing the individual TASP results for each of the 39 vehicles. The x-axis displays the coupling ratio for each vehicle. A coupling ratio of 0 equates to no 'B' couplings present in the combination such as a truck with rigid drawbar. A coupling ratio of 1 equates to all couplings present in the combination being of the 'B' type, such as a tractor semi-trailer, a B-double or a B-triple. Figure 6 shows the best TASP results were achieved by vehicles with a coupling ratio of 1.



Figure 6: Coupling ratio factor against TASP results

Length and volume are closely related, as the vehicles simulated had similar widths and heights. **Error! Reference source not found.** indicates that longer vehicles tended to achieve worse TASP results. This result is expected as variations in the TASP road and in particular crossfall cause the rear units of longer

vehicle to shift laterally across the road width, resulting in a larger lateral displacement for longer vehicles.



Figure 7: Vehicle length against TASP results

#### 3.7 Influences on LSSP results

As would be expected, the major influence on the low speed swept path (LSSP) results was vehicle length and consequently volume. Figure 8 shows that an increased length (volume) corresponds to an increased low speed swept path (worse performance), with the longest vehicle (39 m) achieving the worst LSSP of 13 m.



Figure 8: Vehicle length against LSSP results

An increased number of axles was also found to correspond with an increase in low speed swept path (worse performance). Figure 9 shows that more axles results in a greater LSSP.





#### 3.7.1 Influences on STFD results

The major influence on the steer tyre friction demand measure was found to be a ratio of the load on the steer axle to the load on the drive axle group. Figure 10 shows the relationship between STFD results and steer/drive load ratio, indicating that as the load on the steer axle increases with respect to the load on the drive axle group, the steer-tyre friction demand decreases. This is as expected, as a comparatively high load on the steer axle causes a greater available tyre/road friction limit, resulting in the used proportion of that friction limit being lower.





#### 3.7.2 Influences on SRT results

A factor found to influence the SRT results is the payload divided by the number of axles. Figure 11 shows that as this ratio increases, the SRT value decreases (poorer performance). Increased payload per axle results in increased vertical force acting on the suspension and tyres on that axle, increasing the amount of roll experienced by the vehicle during the turning manoeuvre. It is also expected that as the ratio of payload to number of axles increases, the greater the ratio of sprung mass to unsprung mass, thus

increasing the centre of gravity height of the vehicle. It is well accepted that the SRT of a vehicle is highly dependant on the centre of gravity height of the vehicle. However, this study was performed with the assumption that the entire load space was filled and the payload centre of gravity was located at 40% of the load height. Therefore the centre of gravity height of the vehicle is only influenced by the ratio of sprung mass to unsprung mass, the influence of this ratio is captured by the payload per axle factor shown in Figure 11.





#### 3.7.3 Influences on YDC results

The greatest influence on the yaw damping coefficient (YDC) measure was the coupling ratio factor. Figure 12 shows that as the ratio of B-couplings to A-couplings increases this results in better YDC performance. There is a large grouping of vehicles with a coupling ratio of 1, with results ranging from 0.37 for a B-double and 0.82 for a semi-trailer (semi-trailers achieved the top seven results). As discussed in Section 3.5.1, YDC pertains to vehicles with more than one articulation point, therefore it is more pertinent to draw conclusions for the results achieved by these vehicles. Figure 12 clearly shows, that the worst YDC results were achieved by vehicles with either no B-type couplings or a coupling ratio of 0.5. This was a common trait of all vehicles that failed the YDC PBS requirement.





#### 3.7.4 Influences on RA results

As is the case with the YDC measure, the largest influence on the RA measure is also the coupling ratio (Figure 13). Vehicles with a coupling ratio of 0.6 or less achieved results ranging from 0.91 (very good performance) to 3 (worst performance - rolling over during the manoeuvre). This wide range of results prevents strong conclusions being drawn for these vehicles. However, it is clear that the vehicles with a coupling ratio of 1 all achieved RA results that comfortably satisfy the PBS requirements.





#### 3.7.5 Influences on HSTO results

The greatest influence on the HSTO performance measure is also the coupling ratio. Figure 14 shows a clear distinction in the HSTO results achieved by vehicles based on coupling ratio. All vehicles with a coupling ratio of 0.6 or less achieved a HSTO result greater than 0.6 m, and those vehicles with a coupling ratio greater than 0.6 achieved a HSTO result less than 0.6 m (better performance). The HSTO value of 0.6 m is significant in Australia as that is equal to the maximum HSTO value permitted by vehicles granted general access to the road network. These results allow for the interpretation that vehicles with a coupling ratio of less than 0.6 do not satisfy the general access requirements.



Figure 14: Coupling ratio against HSTO results

#### 3.7.6 Influences on LTR results

The greatest influence on the LTR measure is again the coupling ratio. Figure 15 shows LTR to be generally lower for the vehicles with a higher proportion of B-couplings.



Figure 15: Coupling ratio against LTR results

#### 3.7.7 Summary of influences on performance measures

Table 5 summarises the truck characteristics which influence performance measures.

#### **Table 5 Influences on performances measures**

Tracking ability on a straight path	The greatest influence on the TASP results was coupling ratio and vehicle length. As the coupling ratio decreased and the vehicle length increased, the TASP result increased (poorer performance).
Low speed swept path	The greatest influence on the LSSP results was vehicle length. As the vehicle length increased, so did the LSSP value (poorer performance).
Steer-tire friction demand	The greatest influence on the STFD result was the ratio of the load on the steer axle to the load on the drive axle group. As this ratio increased, the STFD value decreased.
Static rollover threshold	A factor found to influence the SRT results was the payload divided by the number of axles. The analysis showed that as this ratio increases, the SRT value decreases (poorer performance).
<ul> <li>Yaw damping coefficient</li> <li>Rearward amplification</li> <li>High speed transient offtracking</li> <li>Load transfer ratio</li> </ul>	The greatest influence on these three measures was the coupling ratio factor. A higher ratio of B-couplings to A-couplings results in better high speed dynamic performance in each of YDC, RA, HSTO and LTR measures.
	All the vehicles with a coupling ratio of 1 achieved RA results that comfortably satisfy the PBS requirements.

# 4. **RESULTS**

The simulation of the 39 vehicle configurations generated a large volume of results. This section of the report presents the results of each vehicle for each performance measure as well as the performance of each vehicle classification (workhorse, higher capacity and very high capacity).

# 4.1 **Presentation of results**

# 4.1.1 Box and whisker plots

As box and whisker plots have been commonly used in order to display the range of data, a short explanation of box and whisker plots is presented in Figure 16.



Figure 16: Explanation of box and whisker plots

#### 4.2 Tracking ability on a straight path

The performance of the vehicles for the TASP measure is given in Figure 17, Figure 18 and Figure 19. Figure 17 shows the performance results of the vehicles grouped by classification, while the horizontal lines show the PBS level that the vehicle would have met for this measure. All graphs in Section 4 when showing these coloured lines represent the same performance levels. If only one horizontal line is shown, this is the performance level required to pass PBS. There is not a large amount of variation between the three defined world regions (Australia & South Africa, Europe & North America) in terms of TASP performance, while workhorse vehicles tend to perform better than high or very high capacity vehicles. The lower the TASP value, the better the performance of the vehicle.



Figure 17: Tracking ability on a straight path performance by classification

Figure 18 shows the performance level of the vehicles in order of performance from best to worst. A large range of performances are seen in the vehicle pool, with all of the vehicles passing the modified PBS Level 3. 31 of the total 39 vehicles passed PBS Level 1. Of the best performing vehicles (15 in total), 14 were tractor semi-trailers. This is expected as these vehicles are shorter and comprise fewer articulation points. However, 8 high capacity vehicles and 2 very high capacity vehicles were also able to satisfy the Level 1 (general access) requirement.



Figure 18: Tracking ability on a straight path performance in order of performance

*Best performers – the best performing vehicles comprise shorter vehicles with few articulation points, thus resulting in a smaller tracked width* 

*Worst performers – the worst performing vehicles comprise longer vehicles with numerous units, resulting in a greater tracked width.* 

Figure 19 shows the TASP performance of the vehicles split into the predefined vehicle classifications. The box-and-whisker plot shows a higher TASP value (worse performance) with increasing capacity. This indicates that as the vehicles become longer and have more vehicle units, the tracking ability is worse, which is to be expected. Figure 19 shows that the results achieved by very high capacity vehicles and workhorse vehicles overlap, i.e. the best performing very high capacity vehicles achieve the same or better results than the worst performing workhorse vehicles.



Figure 19: Tracking ability on a straight path performance by classification

#### 4.3 Low speed swept path

Figure 20 shows the LSSP performance results for each vehicle separated into their classification. The workhorse vehicles tended to perform the best of the three classifications, followed by high capacity then very high capacity vehicles, which corresponds to an increase in length of the vehicles. The European vehicles generally achieved a better LSSP result which corresponds with the higher prevalence of 'A'-type couplings which tend to give better low-speed manoeuvrability, though poorer high-speed dynamic performance. All of the vehicles pass PBS Level 4, while all but two of the European vehicles pass PBS Level 1 for LSSP.



Figure 20: Low speed swept path performance by classification

Figure 21 shows the LSSP performance of the vehicles in order of performance from best to worst. A total of 20 of the 39 vehicles pass PBS Level 1 for LSSP, of which 16 are from the European vehicle pool of 18 vehicles. All European workhorse vehicles are well below level 1. They fulfil the turning circle of BO Kraftkreis and that is necessary for passing roundabouts and slopes in mountain areas. None of very high capacity vehicles satisfied the Level 1 (general access) requirement for low speed swept path.



Figure 21: Low speed swept path performance in order of performance

Best performers – the best performing vehicles comprise vehicles with short vehicle units with 'A' type couplings to help in the low speed manoeuvres.

Worst performers – the worst performing vehicles comprise longer vehicles with long vehicle units making it difficult to negotiate tight corners.

Figure 22 shows a worsening in performance (an increase in low speed swept path) with increasing capacity. Though there is little difference between the LSSP of the workhorse and high capacity vehicles, the very high capacity vehicles are noticeably poorer performing with four of the five worst performing vehicles coming from the very high capacity category.





The result of this analysis showed that the very high capacity vehicles achieve the worst low speed swept path result. This result is expected as these vehicles are typically long vehicles (greater than 30 m) comprising long trailers. It is expected that the low speed swept path of these vehicles would improve considerably if fitted with steerable axles or active steering systems. These systems enable the axles and or wheels on trailer to rotate as the vehicle turns, which reduces tire scrubbing and increases manoeuvrability.

#### 4.4 Steer-tyre friction demand

The steer-tyre friction demand for each vehicle was determined during the low speed turning manoeuvre. All of the vehicles satisfied the performance level that the steer-tire friction demand needs to be less than 80% of the maximum available tire/road friction limit as required by PBS. This performance level is required for all levels of road access, and although the results varied between vehicles, a low friction demand does not necessarily indicate a proportional increase in active safety. As such, for this benchmarking study, a simple Pass/Fail has been returned for this safety measure, with all vehicles achieving the pass result.

#### 4.5 Static rollover threshold

The SRT performance values are presented in Figure 23, Figure 24 and Figure 25. Figure 23 shows the performance of the vehicles grouped by classification. The SRT performance increases slightly with

increasing capacity. All seven Australian and South African vehicles pass the PBS requirement. The majority of the 15 North American vehicles pass the PBS performance level of 0.35, with the two workhorse vehicles from Mexico just failing the requirement, each achieving a SRT of 0.34. Of the 18 European vehicles only 10 of the vehicles pass the SRT requirement.



Figure 23: Static rollover threshold performance by classification

Figure 24 shows the distribution of the SRT results for the benchmarking study, in order from highest SRT (best) to lowest SRT (worst). A total of 29 of the 39 vehicles pass the performance level required to pass PBS, with a range of results from an SRT of 0.28 g through to 0.43 g.



Figure 24: Static rollover threshold performance in order of performance

Best performers – the vehicle dimensions and layout did not affect the SRT measures as much as the loading of each axle. These good performing vehicles had low axle loads and low standard axle repetitions.

*Worst performers – conversely, these poorly performing vehicles had high axle loads and high standard axle repetition counts.* 

Figure 25 shows the distribution of the SRT performance results for each classification of vehicle. The median value of SRT increases slightly (better performance) as the capacity increases. This indicates that the vehicles in this study have increased rollover stability as the capacity increases from 'workhorse' to 'high capacity' to 'very high capacity' vehicle classification.



Figure 25: Static rollover threshold performance by classification

At first these results may appear counter intuitive – as the 'very high capacity' vehicles are shown to have the best roll stability. However, this is a 'static' low speed measure of rollover, hence the total number of vehicle units does not influence roll stability i.e. the SRT of any combination vehicle is equal to the SRT of the least stable vehicle unit in the combination. Typically the 'very high capacity' vehicles comprise more axles for the increase in capacity and coupling types, which improve roll stability. Therefore, in isolation, the units that comprise the 'very high capacity' vehicles were shown to have a higher rollover threshold than the units of the other vehicle categories.

The distinction between 'static rollover threshold' and 'dynamic roll stability' should be clarified. Static rollover threshold is the amount of the lateral acceleration required to produce total rollover of a vehicle or roll coupled unit. Rollover occurs when the lateral acceleration exceeds the vehicle's rollover limit. When a vehicle undergoes a dynamic manoeuvre, such as lane change manoeuvre, the effect at the rear trailer is amplified, and this results in increased lateral acceleration acting on the rear trailer. This in turn
increases the likelihood of the rear trailer rolling over under some circumstance. For example, a semitrailer such as UK 2, with a poor SRT of 0.33 is unlikely to rollover during a lane change manoeuvre. However, the US 6 triple road train, with a superior SRT of 0.41, may rollover during the same lane change manoeuvre, as the lateral acceleration experienced by the road train's rear trailer is greater (amplified).

The rearward amplification (RA) and load transfer ratio (LTR) measures address this safety issue. The RA measure considers the SRT of the vehicle; the vehicle is deemed to pass if the RA is no more than 5.7 times the SRT unique to that vehicle. The results from the RA and LTR measures are presented in Sections 4.7 and 4.9 respectively.

Vehicles shown to have a high rollover threshold are not necessarily less prone to rollover during a dynamic manoeuvre

# 4.6 Yaw damping coefficient

The YDC performance values are presented in Figure 26, Figure 27 and Figure 28. Figure 26 shows the YDC measure results grouped by classification. Only three vehicles, all of which are from Europe, do not meet the PBS performance level required to pass this measure. The three vehicles that fail YDC were Germany 1 (a tractor semi-trailer and rigid drawbar trailer), Netherlands 1 (a truck and two rigid drawbar trailers) and Netherlands 2 (a tractor semi-trailer and rigid drawbar trailer).

These three vehicles along with the poorly performing Belgium 2 (tractor semi-trailer and rigid drawbar trailer) and United Kingdom 3 (truck and rigid drawbar trailer) are the vehicles that have 'A'-coupled rigid drawbar trailers. These vehicles, which while performing reasonably well on the LSSP measure, do not perform as well on the high speed dynamic performance measures.



Figure 26: Yaw damping coefficient performance by classification

Figure 27 shows the YDC results in order of performance from highest damping (best) to lowest damping (worst). The results presented in Figure 27 have been separated into two categories: 'semi-trailers' shown in dark red and 'other vehicles' shown in light blue. The yaw damping performance measure generally pertains to heavy vehicles with more than one articulation point, such as truck-trailers and road train combinations, hence the YDC results for these vehicles are more relevant than for those obtained for the semi-trailers included in this benchmarking study. Of the three vehicles that fail the YDC requirements all were classified as 'high capacity' vehicles.



Figure 27: Yaw damping coefficient performance in order of performance

Best performers – the six best performing vehicle are the semi-trailers, which are completely roll-coupled throughout the vehicle. Australia 2 (B-double) is the next best performing vehicle after the semi-trailers and is also completely roll-coupled.

Worst performers – the four worst performing vehicles all have rigid drawbar trailers, while the worst has two rigid drawbar trailers. Rigid drawbar trailers perform poorly in terms of yaw damping oscillations.

Figure 28 shows a non-linear relationship between YDC performance and capacity. While the performance worsens when increasing capacity from workhorse to high capacity vehicle (as expected), the performance then improves when increasing capacity from high capacity to very high capacity. This result is due to the majority of the vehicles with rigid drawbar trailers (shown to perform worse in this measure) being present in the high capacity category. All very high capacity vehicles pass the YDC measure.



Figure 28: Yaw damping coefficient performance by classification

# 4.7 Rearward amplification

Rearward amplification, high speed transient offtracking and load transfer ratio are all calculated from the lane change manoeuvre. The RA performance values are presented in Figure 29, Figure 30 and Figure 31. During the lane change manoeuvre, three vehicles displayed critical instability (i.e. experiencing wheel lift or rolling over completely). These vehicles were a European truck trailer (EU3), the Dutch truck and two rigid drawbar trailers (NL1) and the United States 'A' train triple (US6). These three vehicles are shown in Figure 29 as having a value of 3, though no true value was able to be obtained due to the instability of the vehicle during the manoeuvre.



Figure 29: Rearward amplification performance by classification

Figure 30 shows RA results for each of the vehicles. As the performance level required to pass PBS for the RA measure is dependent upon the SRT of the vehicle, the requirement for RA is unique to each vehicle, hence there is no single definable value for all vehicles. Therefore, in Figure 30, vehicles that pass the RA requirement are shown in light blue, vehicles that fail are shown in red, vehicles that fail and experienced 'wheel lift off' during the manoeuvre are in shown in dark red and vehicles that rolled over during this manoeuvre are shown in black. The five vehicles that failed the RA measure, were the two Danish truck trailers (DK2 and DK4), as well the aforementioned Europe 3, United States 6 and Netherlands 1.



Figure 30: Rearward amplification performance in order of performance

Best performers – All of the top six performing vehicles in the RA manoeuvre had only 'B' type couplings.

Worst performers – the poorer performing vehicles all had at least one 'A' type coupling, which does not provide roll coupling through the connection. While the United States 6 vehicle did have a number of 'B' type couplings, it also had the largest amount of vehicle units in the simulation study (six in total) which amplified the oscillation affect. The Europe 3 truck trailer was also found to be unstable and performed poorly in this manoeuvre, similar to all the truck trailers in this performance measure.

As seen in Figure 31, the RA levels do not change a great deal between the three vehicle classification levels. Of the five vehicles that fail the rearward amplification measure, two vehicles are in the workhorse category, two are in the higher capacity category and one is in the very high capacity category, showing a spread of failures. The three vehicles that reached critical instability during this manoeuvre were not shown in Figure 31.



Figure 31: Rearward amplification performance by classification

# 4.8 High speed transient offtracking

The HSTO performance values are presented in Figure 32, Figure 33 and Figure 34. The majority of vehicles pass PBS Level 1, with all Australian and South African vehicles as well as all but one North American vehicle passing HSTO PBS Level 1 (general access to the entire road network). Of the 18 European vehicles, eight pass PBS Level 1, five pass PBS Level 2, three pass PBS Level 3 and two do not pass HSTO for any level.



Figure 32: High speed transient offtracking performance by classification

The three vehicles (EU3, US6 and NL1) that reached a high level of instability during the lane change manoeuvre are shown in Figure 33 as having a value of 1.2, though no true value was able to be obtained due to the instability of these vehicles during the manoeuvre.



Figure 33: High speed transient offtracking performance in order of performance

Best performers – All of the top seven performing vehicles in the HSTO manoeuvre had only 'B' type couplings.

Worst performers – the poorer performing vehicles both had a number of 'A' type couplings, which do not provide roll coupling through the connection. While the United States 6 vehicle did have a number of 'B' type couplings, it also had the largest amount of vehicle units in the simulation study (six in total) which amplified the oscillation affect. The Europe 3 truck trailer was also found to be unstable and performed poorly in this manoeuvre, similar to all the truck trailers in this study.

Similar to the values shown for the YDC manoeuvre, the results shown in Figure 34 indicate that there is not a linear relationship between HSTO performance and capacity. While the performance worsens when increasing capacity from workhorse to high capacity vehicle, the performance then improves when increasing capacity from high capacity to very high capacity. This is again likely due to the greater occurrence of rigid drawbar trailers present in the high capacity vehicle category, and the correlation between rigid drawbar trailers and poor HSTO performance.

The three vehicles for which an accurate value of HSTO was not able to be obtained are not shown in Figure 34.



Figure 34: High speed transient offtracking performance by classification

# 4.9 Load transfer ratio

The load transfer ratio performance values are presented in Figure 35 **Error! Reference source not found.**, and Figure 37. Figure 35 shows that the majority of the vehicles passed the safe LTR of 0.6, with one South African, two American and seven vehicles from Europe reaching an unsafe level of load transfer during the manoeuvre.



Figure 35: Load transfer ratio performance by classification

Figure 36 shows the LTR results in order of performance from best to worst, and shows a range of values from 0.27 to a value of 1.0 experienced by the three vehicles. Again, the vehicles with more 'A'-type couplings performed worse for this measure, with the 8 worst performing vehicles having at least one 'A'-type coupling.



Figure 36: Load transfer ratio performance in order of performance

Best performers – The three best performing vehicles comprised purely of 'B' type, roll-coupled units, showing that the 'B' type couplings provided a greater level of stability than the 'A' type couplings.

Worst performers – the poorer performing vehicles both had a number of 'A' type couplings, which do not provide roll coupling through the connection. While the United States 6 vehicle did have a number of 'B' type couplings, it also had the largest amount of vehicle units in the simulation study (six in total) which amplified the oscillation affect. The Europe 3 truck trailer was also found to be unstable and performed poorly in this manoeuvre, similarly to all the truck trailers in this study.

Figure 37 shows similar median values of LTR with increasing capacity. Additionally, of the three vehicles that reached an LTR of 1.0, there was one vehicle from each classification, while of the 10 vehicles that didn't meet the safe level of 0.6, there were five vehicles from the workhorse category, four from the high capacity category and one from the very high capacity category.



Figure 37: Load transfer ratio performance by classification

# 4.10 Results summary

**Tracking ability on a straight path** – Results show that the high capacity vehicles (typically longer with more articulation points) experienced more lateral movement (swept width) during this manoeuvre. However, there were examples when the best performing very high capacity vehicles achieved results equal to or better than workhorse vehicles.

Low speed swept path – Results showed the highest correlation between vehicle category and the LSSP measure. All workhorse vehicles from Europe, Australia and South Africa passed the Level 1 (most demanding) requirement. The workhorse vehicles from Canada and Mexico did not meet these requirements. Vehicles from the North American region typically required more road space to perform these low speed turning manoeuvres. None of the very high capacity vehicles passed the Level 1 requirements, this was the only performance measure in which no very high capacity vehicles were able to meet Level 1 requirements. This implies that low speed manoeuvrability would prevent these vehicles from accessing the entire road network including inner urban and city areas. However, it is expected that the low speed swept path of these vehicles would improve considerably if fitted with steerable axles or active steering systems.

**Steer tire friction demand** – All vehicles were able to satisfy the requirement of this performance measure.

**Static rollover threshold** – Results showed that very high capacity and high capacity vehicles were able to achieve better performance than workhorse vehicles in most instances. Typically higher capacity vehicles comprise more axles for the increase in capacity and coupling types that improve roll stability.

**Yaw damping coefficient** – Results showed a non-linear relationship between YDC and capacity. This measure relates to the high speed dynamic behaviour of the vehicle in a straight path, on this basis it is similar to TASP. However, the results differ from TASP as there is no positive linear correlation with YDC and capacity, hence length. The worst performing vehicles were typically European vehicles in the high capacity category comprising A-type couplings. This implies that unlike TASP, YDC is sensitive to the configuration of the vehicle units, rather than just length.

**High speed dynamic performance during a lane change** - Rearward amplification (RA), high-speed transient offtracking (HSTO) and load transfer ratio (LTR) are assessed via the lane change manoeuvre and relate to the dynamic stability of the vehicle. The results were similar for all vehicle categories, indicating that very high capacity vehicles can perform equally or better than some common workhorse vehicles. There was one vehicle from each of the categories (workhorse, high capacity and very high capacity) that reached critical instability (experiencing wheel lift off) during this manoeuvre.

# 4.11 Summary of PBS Level reached

The benchmarking study used eight performance measures to examine the on-road safety of each vehicle. The results from each performance measure were examined in isolation.

Table 6 shows the summary of the PBS levels reached by each vehicle. A total of 23 of the 39 vehicles meet the PBS requirements.

Vehicle	LSSP PBS level reached	SRT PBS Pass/Fail	YDC PBS Pass / Fail	RA PBS Pass/Fail	HSTO PBS Level reached	LTR* Safe/Unsafe	PBS level reached
AU1-w	1	Pass	Pass	Pass	1	Pass	1
AU2-hc	2	Pass	Pass	Pass	1	Pass	2
AU3-vhc	3	Pass	Pass	Pass	1	Pass	3
BE1-w	1	Fail	Pass	Pass	1	Fail	Fail
BE2-hc	1	Fail	Pass	Pass	2	Safe	Fail
CA1-w	3	Pass	Pass	Pass	1	Pass	3
CA2-w	3	Pass	Pass	Pass	1	Pass	3
CA3-hc	2	Pass	Pass	Pass	1	Pass	2
CA4-vhc	4	Pass	Pass	Pass	1	Pass	4
DK1-w	1	Pass	Pass	Pass	1	Pass	1
DK2-w	1	Fail	Pass	Fail	3	Fail	Fail
DK3-w	1	Pass	Pass	Pass	1	Pass	1
DK4-hc	2	Fail	Pass	Fail	3	Fail	Fail
DK5-hc	2	Pass	Pass	Pass	1	Pass	2
EU1-w	1	Pass	Pass	Pass	1	Pass	1
EU2-w	1	Pass	Pass	Pass	1	Pass	1
EU3-w	1	Fail	Pass	Fail	Fail	Fail	Fail
EU4-w	1	Pass	Pass	Pass	3	Pass	3
DE1-hc	1	Pass	Fail	Pass	2	Pass	Fail
MX1-w	3	Fail	Pass	Pass	1	Pass	Fail
MX2-w	2	Fail	Pass	Pass	1	Pass	Fail
MX3-w	3	Fail	Pass	Pass	1	Pass	Fail
MX4-vhc	4	Pass	Pass	Pass	1	Pass	4
NL1-hc	1	Fail	Fail	Fail	Fail	Fail	Fail
NL2-hc	1	Pass	Fail	Pass	2	Pass	Fail
NL3-hc	1	Pass	Pass	Pass	2	Fail	Fail
ZA1-w	1	Pass	Pass	Pass	1	Fail	Fail
ZA2-w	1	Pass	Pass	Pass	1	Pass	1
ZA3-hc	2	Pass	Pass	Pass	1	Pass	2
ZA4-hc	2	Pass	Pass	Pass	1	Pass	2
UK1-w	1	Pass	Pass	Pass	1	Pass	1
UK2-hc	1	Fail	Pass	Pass	1	Fail	Fail
UK3-hc	1	Fail	Pass	Pass	2	Pass	Fail
US1-w	2	Pass	Pass	Pass	1	Pass	2
US2-w	2	Pass	Pass	Pass	1	Pass	2
US3-w	2	Pass	Pass	Pass	1	Pass	2
US4-hc	1	Pass	Pass	Pass	1	Fail	Fail
US5-hc	4	Pass	Pass	Pass	1	Pass	4
US6-vhc	3	Pass	Pass	Fail	Fail	Fail	Fail
US7-vhc	3	Pass	Pass	Pass	1	Pass	3

Table 6: PBS level reached by each vehicle

# 5. PRODUCTIVITY AND EFFICIENCY BENCHMARKING

<u>Road freight efficiency (productivity</u>) can be reasonably measured by the quotient:

Loading capacity [which can either be payload capacity or volume capacity] (x utilization rate) divided by fuel (or energy) consumption x time needed for the transport. Time is distance divided by speed. Therefore the efficiency is:

# Payload x average speed / fuel (or energy) consumption x distance

The higher the payload and the higher the transport speed and the lesser the fuel consumption and the lesser the transport distance the higher is the efficiency of the (road) transport system.

The following section derives simplified measures of productivity and efficiency that allows a comparative analysis of the diverse candidate vehicles evaluated by this study. The analysis does not consider driving cycles given that a single cycle cannot be applied uniformly across the international fleet because of topography, operational and speed limit variations. The primary variables influencing energy consumption for large trucks are vehicle mass, aerodynamic drag and tire rolling resistance. These variables are highly influenced by size and weight regulations (axle load and tire fitment [dual/single]) while other components such as the engine and driveline are more universally similar. Therefore this study only examines the energy consumed to overcome rolling resistance and aerodynamics by the vehicles at a steady state speed of 90 km/hr on level ground with no wind effects. Other universally consistent energy losses such as drive line, the engine and auxiliary loads were applied equally to all vehicles using a constant of 225 kWh (although higher powered engines would have higher thermal losses), thus providing approximate values of total energy use. As discussed in Section 2, there are operational, regulatory and manufacturing factors that influence the vehicle and the amount of energy consumption.

# 5.1 Cargo Mass and Volume Performance

Given that the task of a commercial vehicle is to transport freight, limited either by mass or volume, the value of the vehicle and the regulatory system that governs it can be initially assessed by determining the amount of freight that the vehicle can accommodate. To assess volumetric capacity, the inner dimensions of the freight compartment were used to calculate the available freight volume assuming maximum GVM condition. For mass capacity, the tare (curb) weight of the vehicle was subtracted from the allowable gross vehicle mass (GVM) yielding the freight mass capacity of the vehicle. The results for the 39 vehicles are shown in Figure 38 and Figure 39.





Figure 38 Cargo mass capacity of the vehicles

### Figure 39 Cargo volume capacity of the vehicles

From Figure 38 it can be seen that cargo mass varies significantly within each vehicle category. In almost all cases the workhorse vehicles have less cargo mass capacity than the high and very high capacity vehicles. Overall, the larger vehicles show greater variation in the cargo mass capacity. It is worth noting that the poorest cargo mass capacity vehicle was found in the high capacity category rather than the workhorse as would be expected.

Figure 39 shows that the cargo volume capacity increases consistently from the workhorse to the high capacity and to the very high capacity vehicles as would be expected. The findings in Figure 38 and Figure 39 suggest that most regulatory systems promote volumetric capacity over mass capacity so that on balance, the data suggest that cubic capacity is valued more highly than improvements in cargo mass.

### 5.2 Payload Efficiency

Payload efficiency is a measure of the proportion of GVW that is utilized for freight transport based on either mass or volume.



Figure 40 Payload mass efficiency (payload/GVW)

Figure 40 shows that payload mass efficiency is reasonably uniform for all vehicles with a few exceptions. The worst performing vehicles are designed for volume transport. While variations do occur within each vehicle category there is little difference among the three vehicle categories. Indeed it can be concluded that the variation in payload mass efficiency is similar in magnitude for all three vehicle categories, that is, no vehicle category shows significantly superior payload mass efficiency. Given the uniformity among the vehicle classes, and the presence of outliers within the group of vehicles assessed, this measure may be a suitable candidate for a productivity performance measure for size and weight regulation. For example it may be desirable to require that all general freight vehicles have a payload mass efficiency greater than 0.6. As with all measures, there are limitations to its use. This measure would only be suitable for freight that can be loaded such that allowable gross vehicle mass is achieved.



Figure 41 Payload volume efficiency (m<sup>3</sup>/GVW)

Figure 41 shows that there are large variations in payload volume efficiency within each vehicle class but only the very high capacity vehicles exhibit consistently better payload volume efficiency. This supports the earlier observation that higher productivity vehicles are more likely to have increased volume efficiency than cargo mass efficiency.



### 5.3 Optimum Freight Density

Figure 42 Optimum cargo density

Optimum freight density is defined as the density of freight that would occupy the total available cubic capacity of a vehicle while simultaneously reaching the maximum allowable cargo mass of the vehicle. The optimized vehicle density per vehicle presented in Figure 42 clearly shows that the very high capacity vehicles are better suited to lower density freight. On balance, the workhorse vehicles appear to be better suited to carry higher density freight. This finding is of particular interest to the rail vs. road debate given that rail is traditionally strong in dense bulk freight markets while increased truck size appears better suited for freight of lower density.

### 5.4 Calculating Power and Energy

The primary variables influencing energy consumption for large trucks are the driving cycle, the efficiency of the engine and power train, vehicle mass, aerodynamic drag and tire rolling resistance. However, many of these variables can be considered the same for all trucks or are variables that depend on the specific region. This means that they are either unnecessary or unsuitable for use in an international vehicle benchmarking study. For this reason, all energy and emission analyses for this study assume the vehicle is travelling at a constant speed of 90 km/h in calm wind conditions as shown in Figure 43. Only three variables are considered: vehicle mass, tire rolling resistance and overall vehicle aerodynamic drag. While this analysis does not consider the energy required for acceleration, the study focuses on vehicles for higher speed longer haul applications where acceleration is less frequent.



Source: Adapted from Woodrooffe & Associates - DOE

### Figure 43 Typical Energy Distribution for a North American Tractor Semi Trailer

### 5.4.1 Energy Consumption

The power required to overcome aerodynamic drag and tire rolling resistance at constant cruising speed on a level road with no wind can be expressed as follows:.

$$P = \P_{R} + F_{A} \ge v = \left(C_{R} * m * g + \frac{1}{2} * \rho * C_{D} * A * v_{x}^{2}\right) * v$$

P is the power required to overcome the resistive forces – (expressed as Watts)  $F_R$  is the tire rolling resistive force  $F_A$  is the aerodynamic resistive force  $C_R$  is the tire rolling resistance coefficient  $C_D$  is the aerodynamic drag coefficient A is the frontal area of the vehicle v is the velocity of the vehicle  $\rho$  is the air density *m is mass* 

### g is gravity

This equation excludes all internal losses such as engine losses, power train losses and power take off. These losses are represented in the final calculations by a constant of 225 kWh applied equally to all vehicles in this analysis.

### Rolling resistance

A typical  $C_R$  value for a traditional tire dual tire axle is approximately 0.006 (1). Super single tires decrease rolling resistance by up to 20 %, therefore for single tires a  $C_R$  value of 0.005 was used for the axles equipped with these tires.

### Air resistance

The projected frontal area of a heavy truck varies depending on the design of the truck tractor and the height and width of the trailer. The frontal area for each vehicle was determined from the vehicle data submitted by each member country. The drag coefficient  $C_D$  varies depending on the vehicle type and shape. For the purpose of this study all vehicles were assumed to have the same drag coefficient ( $C_D$ ), that of a typical European box type tractor semi trailer combination:  $C_D$  of 0.55 with no side wind effects. This single value was considered representative for the vehicles assessed in this analysis. For all calculations, air density  $\rho$  was assumed to be 1.23 kg/m<sup>3</sup>. (Only GB1 was calculated with 5 m height and a greater frontal area.)

## 5.5 Calculation of CO<sub>2</sub> Emissions

The amount of CO<sub>2</sub> produced per kWh is estimated as follows:

The amount of diesel fuel consumed for truck applications is approximately 200 grams/ kWh (assuming 50% efficiency). The mass of diesel fuel is approximately 850 grams/litre. The amount of  $CO_2$  emissions produced by diesel fuel is 2.668 kg/litre. Therefore the amount of  $CO_2$  produced per kWh is 0.627 kg (2).

### 5.5.1 Productivity Metrics related to energy consumption and CO<sub>2</sub> emissions

As with the previous measures, energy-related productivity performance is based on the transport task in terms of cargo mass and or volume. The most obvious metrics are cargo mass energy vs. emissions efficiency and volumetric energy vs. emissions efficiency.

Cargo mass energy efficiency by energy consumed and cargo volume capacity by energy consumed are defined as follows and the results are shown in Figure 44 and Figure 46.

 $e_{mass}$  = (cargo mass capacity)/ E [cargo tonne km/kWh]





Converting these terms to  $CO_2$  emissions produced is determined by applying the constant 0.627 kg  $CO_2$  per kg of fuel. These results are shown in Figure 45 and Figure 47.

Figure 44 Payload mass efficiency by energy consumed (ton km/kWh)

Payload mass efficiency by energy consumed and  $CO_2$  emissions produced shown in Figure 44 and Figure 45, show good variation between vehicles within each group but the metric does not adequately differentiate the relative performance of the workhorse, high capacity and very high capacity vehicles. Payload volume efficiency by energy consumed and  $CO_2$  emissions in Figure 46 and Figure 47, produced improved differentiation among the vehicle classes as well as within each vehicle class.



60 50 Cargo m<sup>3</sup> km / kWh 40 30 20 10 0 UK1-w UK2-w UK3-w CA1-w MX1-w US2-w US2-w US2-w ZA3-hc NL2-hc NL3-hc CA3-hc US4-hc DK1-w DK2-w DK3-w EU1-w EU2-w EU3-w EU4-w BE2-hc DK4-hc DK5-hc DE1-hc NL1-hc US6-vhc US7-vhc AU1-w ZA1-w ZA2-w BE1-w ZA4-hc US5-hc AU3-vhc CA4-vhc **MX3-vhc** Better performance Workhorse High Capacity Very High Capacity

Figure 45 Payload mass efficiency by CO<sub>2</sub> emissions (ton km/kg CO<sub>2</sub>)

Figure 46 Payload volume efficiency by energy (m<sup>3</sup> km/kWh)



Figure 47 Payload volume efficiency by CO<sub>2</sub> emissions (m<sup>3</sup> km/kg CO<sub>2</sub>)

It appears that volumetric performance metrics are better suited to heavy trucks that are mass based metrics. However, the mass capacity of the vehicle is an important and valuable characteristic as illustrated in the following example.

Consider Figure 48, two vehicles of equal cargo volume capacity but with different cargo mass capacities due to differences in regulated GVW.



Figure 48 Two vehicle units of identical volume but of different mass capacities

If evaluated on the basis of mass efficiency (tonne-km/kWh), vehicle A will clearly have superior performance compared with vehicle B (if both vehicles have the same engine power and fuel consumption). On the other hand, if the vehicles are evaluated on the basis of volumetric capacity (m<sup>3</sup> km/kWh), then vehicle B is the clear winner given that the lower vehicle mass would require less work to transport the volume and therefore less energy would be consumed. This presents a problem because in practical terms, vehicle A is considered more valuable because it can transport more product of

higher density than vehicle B. In fact the value of the volume capacity of the vehicle is directly related to its mass capacity – they are inseparable. Clearly the maximum volumetric efficiency would occur when the density of the cargo is such that it reaches volumetric and mass limits of the vehicle simultaneously. For this reason, it becomes necessary to co-relate volumetric and mass capacities. Considering these conditions the potential measures that were selected to express mass and volumetric efficiency for this study are as follows, assuming constant travel speed of 90 km/h:

It is proposed to account for volumetric efficiency by combining the cargo volumetric capacity with the cargo mass capacity as follows:

 $e_{volume-mass}$ = ((cargo volume capacity) x (allowable cargo mass)) / E



[cargo tonne-m<sup>3</sup> km /kWh]

Figure 49 Cargo mass x volume by energy consumption



Figure 50 Cargo mass x volume by CO<sub>2</sub> emissions produced

The cargo mass volume results shown in Figure 49, very effectively differentiate the productivity performance of the three vehicle classes. Within each vehicle class the variations are significant and the performance measure results show improvement with each increasing vehicle capacity category. This measure appears to be the most sensitive and revealing of all of the productivity measures examined. Since  $CO_2$  production is directly proportional to diesel fuel use, the emissions characteristics relative to each vehicle will be the same as those shown in Figure 49. Both the cargo mass volume by energy consumption and cargo mass volume by  $CO_2$  production are potential candidates for energy and emissions related productivity measures.

### 5.6 Lane Footprint

This measure is intended to provide some estimate of how well a vehicle utilizes available road space as a function of cargo volume or mass transported. This measure does not include any factor to account for the space between vehicles.

#### Cargo Mass Road Footprint = Available Cargo Mass / Overall Vehicle Length





Figure 51 indicates that for the most part, the very high capacity vehicles have a superior cargo mass road footprint, meaning that the amount of roadway real estate required for a given cargo mass is less than that of the workhorse and high capacity vehicles.



Figure 52 Cargo Volume Road Footprint

Figure 52 shows the cargo volume per metre length of roadway occupied. For most vehicles the results are fairly uniform across different classes and regions. This is largely because vehicle width and height are fairly standard in most regions meaning that to increase volume capacity requires increased length. However, one UK vehicle stands out because the UK does not impose a regulatory height limit, meaning that some vehicles can be as high as 4.9 m, the nominal maximum that can safely fit underneath motorway bridges. This offers substantial volume increases without increasing length but, as shown by the safety benchmarking, can reduce performance in measures related to rollover.

# 6. INFRASTRUCTURE CHALLENGES

### 6.1 Introduction

To assess the mechanical impacts of trucks and longer/heavier vehicle combinations on the infrastructure as a whole, it is necessary to consider, in the following order:

- The actions applied to the structure, *i.e.* traffic loads, which include wheel loads, axle loads, group of axles (bogie) loads, gross vehicle weights and the sum of all vehicle loads applied simultaneously on a bridge span, or a set of bridge spans that are not independent.
- The load effects that traffic loads induce in a structure are a function of the traffic loads and the mechanical behaviour of the structure (generally assumed to remain elastic). This involves knowledge of

the stresses and strains induced in the structure as well as material properties such as modulus, Poisson and Young's coefficient. [Ryall et al., 2000].

• The impact on turnability (e.g. passing roundabouts) is not checked in this chapter

Most bridge and pavement infrastructures are designed according to codes and standards on the basis of conventional load models [Dorton and Bakht, 1984], [CEN, 2002], [TRB-AASHTO, 2005]. These are calibrated once, when a code is designed, and are rarely re-calibrated (*e.g.* every 10 or more years) when a code is revised. Such load models are designed to be as simple as possible in order to avoid gross errors by infrastructure designers and consultants and to remain understandable and easy to use with available tools and computer software. Load models are also general enough to cover almost all load cases. Some cases are explicitly excluded from certain codes, *e.g.* long span bridges (over 200 m for one span) in the Eurocode EN1991-2, Traffic Loads on Road Bridges [CEN, 2002]. For such exceptional structures, detailed and particular specifications must be drawn up by the owner prior to design and construction.

The conventional load models are, therefore, often conservative because they must remain simple and usable while allowing for many different existing traffic cases, potentially unknown future traffic developments and all the potential extremes of load and load effects that could occur over the lifetime of the structure (*i.e.* 10 to 40 years for a pavement, and 50 to 100+ years for a bridge). As a result, they tend to be based on extrapolations of the loads and load effects that can be measured over short- (hours to months) or medium- (several years) term periods.

When exposed to repeated traffic (or other) loads of variable intensity, some structures are affected by fatigue damage (mainly cracking), which may modify their properties and strengths. In addition to traffic loads, road infrastructure is also exposed to other stresses; for example weather (temperature, wind, rain, snow and ice), natural events (ground movements, earthquakes...), and chemical actions (de-icing salts used in cold or temperate climates). Similarly, many structures are subject to material behaviour which induces strains and, consequently, load effects and stresses – such as concrete shrinkage and creep. Thus, materials and structures – as well as truck weights and dimensions – evolve over time and as a consequence standards need to be periodically reassessed.

Allowing higher capacity vehicles access to roads that were not designed for them would require an assessment of whether the infrastructure is able to accommodate them, at what cost, and what, if any, specific actions would need to be taken in order to accommodate them safely. Technical standards and guidelines are usually based on so-called standardized design vehicle concepts and on the legally permitted maximum size and load. Many higher capacity vehicles fall outside the limits specified for these design vehicles, which could potentially have serious consequences for both the infrastructure and the vehicle.

### 6.2 The effect of truck traffic on pavements

In order to maintain the road in a serviceable condition, truck (and other heavy vehicle) traffic needs to be suited to the pavement on which it travels. This can be achieved in a number of different ways:

- pavement design (e.g. stronger, more durable),
- pavement maintenance (e.g. increased frequency or higher standard),
- truck regulation (e.g. limiting load, wheel and suspension configurations)
- truck traffic management (e.g. limiting access).

Limiting the configuration or access of trucks can have negative effects on productivity and consequently external costs such as congestion and emission costs. However, modifying an existing road asset is a very complex and expensive undertaking that can require large quantities of natural resources and involve a significant decrease in road capacity for a long period. This means that in most, but not all, cases it is more cost-effective to limit the truck configuration (weights and dimensions) and/or limit the access rather than improve the pavement or accept the maintenance consequences.

### 6.2.1 Risks for road owners and users

Truck (and other heavy vehicle) traffic can result in severe pavement wear if the vehicles are not well suited to the pavement. When this traffic becomes more aggressive than the pavement can bear, large scale deterioration will occur such as rutting, potholes, peeling (or scabbing), punching or stepping. This deterioration can have an effect on the safety of road users and may even prevent the use of the road. When this occurs road owners have to carry out repairs as rapidly as possible, using expensive and often less efficient techniques. As a consequence, their resources are wasted, their pavement asset is not improved and the evenness of pavement will have deteriorated. This reduction in evenness in turn increases the impact of truck traffic and the situation thus degenerates inexorably. The DIVINE project [OECD, 1999] demonstrated and quantified this phenomenon.

Building pavements to carry very heavy traffic requires materials of high quality in thick layers. As well as being expensive, this may also involve the use of scarce resources (aggregates, binders etc.). Despite this investment, truck traffic always generates some form of pavement deterioration and the road owner must therefore undertake regular maintenance. This maintenance, under heavy traffic, has a significant price in terms of the consumption of high quality, expensive (and sometimes scarce) materials. As these road works will also disrupt traffic, all stakeholders have an interest in well-spaced and timely maintenance. Adopting less aggressive trucks can contribute to a reduced maintenance requirement.

# 6.2.2 The influence of truck configuration

# Axle load

Since the 60s, it has been known that axle weight has a considerable influence on pavement wear related to the failure mode cracking. Figure 53 is a representation of the fourth power law, which states that adding 2 tonnes to a 10 tonne axle doubles the aggressiveness of the axle and thus reduces the service life of the road by half.



**Figure 53 Aggressiveness against a 10 t reference axle according with the fourth power law** Failure mode "cracking"



Source: SETRA, internal

### Figure 54 Aggressiveness of tridem axles

#### Groups of axles

When axles are close, the effect they have on the road depends on their spacing and each of them will be more aggressive than if it was isolated. In Figure 54, the impact of tridem axle spacing and wheel types has been calculated using the French software *Alize* [CFTR, 2003].

#### Wheels and tires

The load transmission from the wheel to the road is also very important. The parameters to consider are:

- Single or dual wheel,
- Tire specification (e.g. dimension, pressure).

This question was extensively studied by the project COST 334 [COST 334, 1998], which showed for example that dual wheels are substantially less aggressive than singles (see Figure 54).

### Load distribution

As seen above, for a given load the type of axle (e.g. spacing, wheel, tires) has a major effect on how aggressive it is for the pavement. Typically, each truck will have several different types of axle. For example the steer axle might be a standard width single, the drive axle might be a standard width dual, a tag axle might be a reduced diameter single and the tridem trailer bogie might use wide singles. How the load is distributed between these different axles can greatly affect the aggressiveness of the vehicle.

In 2008, a study for the European Commission [De Ceuster et al., 2008] quantified the impact of load distribution. It was found that even where vehicles that were within the gross weight limits imposed by European directive 96/53EC, the most aggressive load distribution was four times more aggressive than the least aggressive. It is very important that weight limits are expressed for each axle type in order to limit the occurrence of poor load distributions.

Even where regulation offers strict control of axle weights it is possible to reduce the aggressiveness of the vehicle by encouraging carriers to optimize the distribution of axle loads in favour of lower road damage. The modern instrumentation of trucks, in particular on-board axle weighing systems, is expected to improve the ability to implement such policies.

#### Suspensions and steerable Axles

The type and performance of suspensions have an important impact on dynamic load repetition in some cases (see section below). In the DIVINE project [OECD, 1999], it was shown that some suspension designs could cause a reduction in road service life of around 15%.

Although steerable axles are likely to be beneficial to pavement protection by reducing the lateral forces applied to the road surface during cornering, knowledge of pavement surface behaviour is not yet sufficient to quantify the extent of their impact.

### 6.2.3 Pavement characteristics to take into account

#### Materials

Different materials will have a different fatigue response to cumulative loads. Therefore, different road surfaces will behave differently with respect to a change in axle load. An exponential power,  $\alpha$ , represents this behaviour for each type of pavement:

- Non granular pavement:  $\alpha$  around 4,
- Bituminous pavement: α around 5,
- Hydraulic bounded or concrete pavement:  $\alpha$  between 10 and 12.

The high exponential power applied to hydraulically bound pavement layers shows that they behave well with high levels of traffic but are highly sensitive to overload. For the failure mode rutting a power of 2 can be considered for thick bituminous roads in the primary network. [COST 334]

# Design

The main objective of pavement design is to distribute loads spatially in order to reduce pressure on the subgrade. Pavements which are designed for heavy traffic have a spatial distribution, which introduces a large interaction between the axles of a truck.

Other areas of road design, such as traffic lane width and number of lanes, must also be considered, because:

- The number of lanes influences the number of trucks to take into account.
- Small width of lanes channels all of the trucks into a common position, thereby augmenting their cumulative aggressiveness.
- In the case of concrete pavements, the edge of the pavement is its weakest part; therefore if the truck is near this edge, its aggressiveness increases.

### Maintenance and evenness

The DIVINE project [OECD, 1999] showed that an uneven road surface can result in a dynamic axle load that is 20% greater than the static axle load. Furthermore, poorly sealed surfaces or bad drainage will cause water to penetrate into the pavement layers. This water will have different effects, depending on the layer concerned:

- In the case of a wet surface layer, heavy traffic generates the poorly understood phenomenon of ravelling, which leads to pot-holes and peeling,
- In the case of a wet bound layer, the pavement is less efficient and fatigues quickly,
- In the case of a wet subgrade, the pavement is more stressed and fatigues quickly.

When a road is in such a condition, the axle load must be lowered to maintain the same level of aggressiveness to the pavement.

### Climate

At very low temperatures the modulus of road materials increases and the strains are reduced underneath the passing truck. However, during or after the winter, in thaw periods, trucks become very aggressive on pavements because of water in the subgrade. Depending on the importance of this phenomenon, temporary measures to restrict axle loads (or axle group loads) can be taken to protect pavements.

Wet periods (rain, high humidity) have the same type of effect as thaw periods, but with lower magnitudes.

Bitumen bound materials are sensitive to hot conditions caused by the ambient temperature and solar radiation. In such conditions, they are sensitive to creep and their rigidity decreases. Creep leads to rutting under truck traffic. A decrease in stiffness, in conjunction with low bearing strength of the subgrade (if, for example, the subgrade was wet) causes a substantial increase in pavement stress.

# 6.2.4 Methods for evaluating truck aggressiveness on pavement structure

#### Equivalent Standard Axle Load (ESAL) and Vehicle Wear Factor (VWF)

The aggressiveness of a truck on pavements may be assessed through the "equivalent standard axle load" measure (ESAL). This methodology consists of determining the number of standard axles that would have the same impact on a stretch of pavement as the passing of the group of real axles with real loads that is to be assessed. Once the aggressiveness of each group of axles has been calculated, the overall aggressiveness of a truck can obtained by adding the number of standard axles represented by each individual group of axles fitted to the vehicle under consideration.

To enable clear and easy comparisons between vehicles, the aggressiveness of any particular truck can be compared with a reference vehicle to produce a "relative wear factor". The relative wear factor of a truck is obtained by dividing the truck wear factor (VWF) by the wear factor of a reference truck (VWF<sub>ref</sub>) using the following formula:

**Relative Vehicle Wear Factor:** 
$$VWF_{rel}(truck_x) = \frac{VWF(truck_x)}{VWF(truck_{ref})}$$
 (1)

In this study, a 40 t / 16.50 m long, 5 axle truck with a 2-axle tractor and a 3-axle semi-trailer was defined as the reference vehicle. Thus, the relative aggressiveness of the reference vehicle equals 1.



**Reference truck:** 

The ESAL methodology only allows the wear factor to be calculated individually for each axle. The method can be improved by taking the interaction between closely spaced axles into account (see section 7.2.2). Additional improvements can be achieved by considering the type of tire and the assembly configuration (single/dual). Data on the footprint of the tire (contact area between tire and pavement) are needed to calculate the stresses in the pavement structure. For the purposes of this study, COST333 and  $334^2$  results have been used with the assumption that the drive axle and any other axles equipped with twin tires use 315/80 tires while single non-driving axles use 385/65 wide tires.

The aggressiveness of a group of axles may be assessed through the "wear factor" which is relative: it is the ratio between the damage created by the load and the damage created by the equivalent reference group of axles.

Wear factor of a group of axles:  $WF_{\text{group of axles } i} = k_i \left(\frac{W_i}{W_{ref}}\right)^{\alpha_i}$ 

(2)

where:

 $k_i$  and  $\alpha_i$  are two parameters which depend, for each group of axles i, on the type of pavement and the expected traffic volume;

W<sub>i</sub> is the total weight carried by the group of axle i ;

 $W_{ref}$  is the total weight carried by the equivalent reference group of axles.

<sup>&</sup>lt;sup>2</sup> COST – European Cooperation in the field of Scientific and Technical Research – is a European programme supporting cooperation between scientists and researchers across Europe; it is the first and widest European intergovernmental network for coordination of nationally funded research activities. COST 323 was aimed at defining pan-European requirements for heavy vehicle weigh-in-motion (WIM), and for the development of associated systems. COST 333 aimed at developing a coherent, harmonised and cost-effective European road pavement design method, which was to open new possibilities for industry to collaborate in the field of pavement design and construction. COST 334 studied the effects of Single Wide Tyres and Dual Tyres.
While the exponent used in the ESAL calculation does vary among countries and for each type of pavement, the commonly used value 4 is generally accepted (the empirically developed "fourth power" law). However, more accurate results may be obtained by using a more precise formula or model of the impact of a group of axles on the pavement, such as the ALIZÉ software [CFTR, 2003].

Pavement behaviour is also highly dependent on the materials used and the traffic volume it is designed for. In according with the results of the COST333 and COST 323 actions [Jacob *et al.*, 2002], four road structures, representative of the European roads, have been selected to perform aggressiveness calculations in this study, based on the typical pavement design parameters shown in Table 7:

- bituminous pavement, designed for low traffic volume (5 million 8 t standard axles) ;
- bituminous pavement, designed for moderate traffic volume (10 million 8 t standard axles);
- bituminous pavement, designed for heavy traffic (100 million 8 t standard axles);
- cement pavement, designed for heavy traffic (100 million of 8 t standard axles).

Traffic intensity	Weak	Moderate	Heavy	Heavy
Asphalt thickness (mm)	100	200	330	280
Asphalt Young's modulus (MPa)	7 500			
Asphalt Poisson's ratio	0.4			
Granular layer thickness (mm)	300	250	200	
Young's modulus of granular material (MPa)	200		-	
Granular layer Poisson's ratio	0.3			
Cement bound base layer thickness (mm)			200	
Cement bound base Young's modulus (MPa)	- 1		10 000	
Cement bound base Poisson's ratio				0.2
Subbase Young's modulus (MPa)	70			
Subbase Poisson's ratio	0.3			

Table 7- Pavement design parameters with respect to the traffic intensity

Several countries have software which calculates the constraints within pavement. These allow the aggressiveness of different configurations (axle load, type of axle...) to be evaluated for each type of pavement. Direct measurements can be also taken from instrumented pavements or on pavement fatigue carrousels.

#### Application of the aggressiveness assessment for typical trucks

Using Equation 1 above, the relative VWF has been calculated for each vehicle configuration described earlier in this report.



In this study, wheel configurations (single, dual) have been taken into account. The results are presented in Figures 55 to 58 for the four road structures defined above.

Figure 55- Relative VWF for typical trucks on a bituminous pavement designed for a low traffic volume



Figure 56– Relative VWF for typical trucks on a bituminous pavement designed for a medium traffic volume



Figure 57 Relative VWF for typical trucks on a bituminous pavement designed for a high traffic volume



Figure 58 Relative VWF for typical trucks on a cement pavement designed for a high traffic volume

In general, it can be seen that most of the vehicles assessed are less aggressive than the reference truck (whose VWF is represented by the solid red line). For a bituminous pavement designed for a low volume traffic 10 vehicles were found to be more 'aggressive' than the reference vehicle, while for a cement pavement designed for a high volume of traffic, only 4 of the 39 vehicles were more aggressive.

However, there is a large variation in the wear factor with respect to the vehicles' shape and the type of pavement on which they are driving.

This is illustrated in Table 8, below:

		Bituminous	Bituminous	Bituminous	Cement
		pavement, low	pavement, medium	pavement, high	pavement, high
		volume traffic	volume traffic	volume traffic	volume traffic
	Min	0,335	0,116	0,098	0,010
Relative VWF	Max	1,631	1,917	1,818	5,032
	Ratio max/min	4,872	16,570	18,529	513,264
	Nb of trucks whose VWF > 1	10	6	4	4
	Average	0,798	0,518	0,466	0,582
	Standard deviation	0,327	0,469	0,439	0,999

Table 8 - Basic statistics for VWF

It can be seen that the ratio between the less aggressive and the most aggressive trucks varies from about 5 on bituminous pavement for low volume traffic to more than 500 for a cement pavement with a high volume of traffic. This means that for the harder type of pavement (cement pavement), the most aggressive vehicles are responsible for most of the pavement wear.

There is also no direct link between the category the vehicles belong to (workhorse/high capacity/very high capacity) and the corresponding impact on pavements.

Whatever the type of pavement, the vehicles that are most aggressive toward the pavement do not change. Likewise, some vehicle shapes are amongst the less aggressive shapes, whatever the type of pavement.

The absolute value of the VWF is highly dependent on the type of pavement considered. The VWFs are quite similar for all vehicle configurations travelling on a bituminous pavement designed for a low volume of traffic, but they vary much more on a cement pavement designed for a high volume of traffic. The higher the  $\alpha$  value, the more sensitive a pavement is to the heaviest axle loads, while the lowest axle loads do not affect the pavement at all.

The analysis so far has been confined only to the effect that a single vehicle has on the pavement. However, trucks perform a vital economic role so it is also essential to consider the induced pavement wear with respect to the quantity of freight that each vehicle is moving. To achieve this, the relative VWF per unit of payload is calculated by dividing the VWF(HGV<sub>x</sub>) and the VFW(HGV<sub>ref</sub>) respectively by the payload of the considered vehicle x and that of the reference vehicle. The relative VWF per unit of payload for each vehicle type is shown in Figure 59 to Figure 62:



Figure 59 Comparison of relative VWF per unit of payload for a bituminous pavement with a low volume traffic





Figure 60 Comparison of relative VWF per unit of payload for a bituminous pavement with a medium volume traffic

# Figure 61 Comparison of relative VWF per unit of payload for a bituminous pavement with a high volume traffic



Figure 62 Comparison of relative VWF per unit of payload for a cement pavement with a high volume traffic

The same basic statistics show that, in relation to the changes on different pavement types, the same conclusions may be drawn when relating the various VWFs to the payload. A strengthening of the threshold effect could be observed because fewer vehicles have a VWF greater than 1 but at the same time the ratios of the maximum VWF to the minimum VWF were significantly greater when the VWF was related to the payload.

			1	1 0	
		Bituminous pavement, low volume traffic	Bituminous pavement, medium volume traffic	Bituminous pavement, high volume traffic	Cement pavement, high volume traffic
	Min	0,265	0,092	0,080	0,008
Relative VWF	Max	1,860	1,811	1,576	4,361
	Ratio max/min	7,018	19,775	19,577	561,853
	Nb of trucks whose VWF > 1	4	3	3	5
	Average	0,677	0,446	0,400	0,493
	Standard deviation	0,316	0,417	0,384	0,826

#### Table 9 Basic statistics for VWF per unit of payload

However, the conclusions are different when the different categories of vehicle are compared using the VWF per unit of payload, as shown in Table 10.

		Workhorse	High capacity	Very high capacity
Ψ	Min	0,028	0,027	0,008
Ş	Max	4,361	2,705	0,447
Relative	Ratio max/min	156,465	100,051	57,648
	Average	0,607	0,455	0,178
	Standard deviation	0,603	0,433	0,141

It can be seen that this analysis suggests that the high and very high capacity vehicles tend to cause less pavement wear per unit of goods transported, than the workhorse vehicles. This is particularly true for the very high capacity vehicles where the relative VWF per unit of payload is always less than 1 (i.e. less than a standard EU articulated vehicle of 40 tonnes on 5 axles), unlike several other workhorse trucks. Conversely, most of the workhorse trucks have rather high VWFs and the reference truck is amongst the most aggressive per tonne of goods transported.

#### The importance of differentiating the types of pavement

By using the fourth power law, the relative VWF has been obtained for the 39 vehicle shapes. The average relative aggressiveness is 0.978 and 18 vehicles were found to be more 'aggressive' than the reference truck. The basic statistics are shown in Table 11.

		Bituminous pavement
	Min	0,536
Relative VWF	Max	1,598
	Ratio max/min	2,981
	Nb of trucks whose VWF > 1	18
	Average	0,978
	Standard deviation	0,276

Table 11 Basic statistics for relative VWF obtained by fourth power law



#### Figure 63 Comparison of truck's aggressiveness for a pavement obtained by the fourth power law3

The relative VWFs values obtained by the fourth power law provides an answer that is considerably different to the relative VWFs calculated specifically for a cement pavement designed for a high traffic volume. For example, for Denmark 1, the specific value for the cement pavement is about 3.8 times

<sup>&</sup>lt;sup>3</sup> It can be noticed that the "Belgium 1" Truck (4 axle articulated truck) is less aggressive than the "European 1" truck, despite having the same silhouette and weighing 1 more ton.. This is due to a more uniform load split among the axles: 9+12+9+9 (BE1) instead of 6+12+10+10. (EU1) However, the BE1 load configuration is not very common in practice; it was included in the study for informative purposes.

greater than that predicted by the fourth power law. If the fourth power law does not take into account the type of pavement then the predicted value of aggressiveness may not be relevant to that type of pavement.

#### Limits of the benchmarking method

The aggressiveness of the trucks assessed in this study, was obtained for a fixed load distribution. Variations in the load distribution will affect the vehicle wear factor value but this has not been studied. It should also be noted that, although the sample of the vehicles studied is large, it does not take into account all the special cases.

It has been shown that high capacity and very high capacity truck combinations seem to cause less wear and tear to the road per tonne of goods transported. Conversely, most of the workhorse trucks have rather high VWFs and the reference truck is amongst the most aggressive per tonne of goods transported.

#### 6.2.5 Observation

The fourth power law is too simple to evaluate truck aggressiveness on various pavement types. Using a more general power law requires first a calibration of two parameters to the pavement structure and material. If this calibration is not possible, it is necessary to document these parameters from the literature. If policy makers are considering a change to the permitted configurations of trucks then an assessment of how aggressive each load distribution permitted by the existing and proposed regulations should be undertaken.

For a pavement designed to bear heavy traffic most of the maintenance cost is associated with maintenance of the surface layers rather than the structure. However, the mechanisms which lead to the failure of the surface layers of these pavements are very complex and are not yet well understood. So, in most cases, analysis of the maintenance cost is based on empirical approaches that are unable to differentiate the impact of different truck configurations.

To contain pavement wear, weight limits of trucks must be specified in terms of load by type of axles. The most advanced truck technologies shall be used to ensure a well balanced load distribution among axles to reduce the pavement wear and the maintenance cost as well as to increase the road serviceability.

Pavement wear assessment highly depends on the material and structure concerned. It is essential to improve the knowledge on surface layers behaviour under traffic loads, above all those designed for heavy and dense traffic. That would provide a background to optimize truck configurations.

Figure 64 illustrates the truck configuration performances (rutting failure mode) derived from the COST 334 approach, which reflects the tyre size (width and diameter) and configuration (S/D) and which is based on the second power law to axle load.



Figure 64 - Road wear performance (rutting failure mode) of the 39 trucks based on the COST 334 approach Source: Glaeser K P (2010)

#### 6.3 The effects of trucks on bridges

#### 6.3.1 . Background and methodology

The effects of traffic loads on bridges are more difficult to assess than on pavements, because a load case usually involves more than one truck. The number of trucks involved depends on the bridge length, width (*i.e.* number of traffic lanes) and traffic density. Yet the more cars on the bridge, the less trucks, and that reduces the load effects. In addition, one load case generates an almost infinite number of load effects, *i.e.* shear forces and bending moments in each section of the bridge, pier reactions, torsion, etc. All these load effects induce strains in the structure and stresses in the materials.

The main tool used to calculate load effects, stresses or strains in bridges under traffic loads is the transfer function known as the "influence line" or "influence surface". For any given bridge section and load effect, for example a bending moment at mid-span, the influence line is equivalent to the load effect induced by a unit load applied at a point x along the bridge structure (Figure 65).

Then, assuming a linear behaviour of the bridge, for a set of axle loads  $F_i$  applied at the abscissa  $x_i$ , the total load effect is:  $S = \Sigma_i F_i f(x_i)$ .

For a number of reasons, the theoretical influence lines usually differ from the real influence lines of the bridge. Bridge weigh-in-motion systems, *i.e.* WIM systems that use instrumented bridges as the weighing scales, can be used to evaluate the real influence lines and thus optimise the evaluation of traffic loading on bridges<sup>4</sup>.



Figure 65 Bending moments at mid-span (spans 1 and 2) and on pier of a continuous 3 span (30 – 40 - 30 m) girder bridge, in kN.m/kN

The use of influence lines to assess strains and stresses is based on the assumption that the behaviour of the bridge remains elastic, *i.e.* the strains and stresses are proportional to the applied loads. However, in some cases such as a cracked concrete bridge where a temperature gradient exists, non linear behaviour may occur. Influence lines are expressed in kN/kN or kN.m/kN (shear forces or moments), or in µdef/kN or MPa/kN (strains or stresses). If the load effect depends on the transverse location of the load, the influence line is replaced by an influence surface (2-D function of x,y).

Once the influence lines or surfaces of the main load effects to be checked, are known, the induced load effects (or stresses/strains) can be easily calculated for any single load case. However, in conditions of typical free flowing traffic (which could be measured by a set of WIM data), more complex analyses using software such as CASTOR-LCPC or POLLUX [Eymard & Jacob, 1989] is required to calculate the

<sup>&</sup>lt;sup>4</sup> ref. ARCHES report no D16, in finalisation

time history of the load effects so that the extreme values (local maxima and minima) and the so-called "level-crossing" values<sup>5</sup> can be identified.

To assess the lifetime of a bridge feature under repeated traffic loads (see 7.3.3 for more details on fatigue), it is necessary to know the time history of the stress cycles, or at least the "rain-flow<sup>6</sup>" – the distribution of the stress variations. The same software can be used to provide this for free traffic conditions.

The extreme load effects calculated or measured on a bridge under traffic loads, need to be extrapolated all along the bridge lifetime. These extrapolated values are known as nominal values and can be expressed as values which are exceeded over a lifetime D with a probability  $\alpha$ . Then, such a value is said to have a return period T $\approx$ -D/ln(1- $\alpha$ ) $\approx$ D/ $\alpha$  if  $\alpha$  is small enough (*e.g.* 0.05). In the Eurocodes, the recommended return period for the nominal loads on road bridges is 2 000 years, which corresponds to a 5% probability of being exceeded in 100 years.

Conventional load models (design loads) for bridges increase the nominal loads by safety factors ( $\gamma_s$ ) to allow for uncertainties that are not explicitly contained in the models. In addition, some dynamic amplification factors (DAF) are applied to the static design loads. The extent to which DAF are applied depends on the span length and, sometimes, on the bridge type.

Bridges are routinely designed for loads considerably larger than those imposed by vehicles currently in use. The use of longer and heavier vehicles would, however, mean significant differences in applied loading, dynamic effects, overloading etc. Even if the vehicle is composed of current trailer units, it cannot be assumed that its loading is automatically catered for by the current loading specifications.

The ability of a bridge to carry longer and heavier vehicles would not only depend on the axle loads and spacing, and the gross weight, but also on the length of the bridge span and the effects considered (shape of the influence lines). In addition to the vertical loads considered so far, the specifications of a bridge will also allow for the horizontal forces transmitted through the deck as a result of vehicle braking and cornering.

Therefore, to assess bridges under traffic loads, it is necessary to have detailed data on the traffic loads, *e.g.* WIM data [Jacob et al., 2002], the relevant transfer functions (e.g. influence lines and

<sup>&</sup>lt;sup>5</sup> In a "peak crossing" counting method, the turning points in a load-time trace are classified according to their load level. A "level crossing" counting method counts the number of time a load-time trace crosses a certain level either in a positive or negative direction.

<sup>&</sup>lt;sup>6</sup> A range-pair counting method counts load variations directly for fatigue issues. Ranges are counted as range pairs. It searches for full-load cycles that are contained within main load variations. The "rain-flow" counting method is a particular "range-pair" counting method which takes into account some "memory" as a scanning window, adapted for fatigue problems.

surfaces), and additional information about the expected lifetime of the bridge, the traffic trend, and a fatigue model.

#### 6.3.2 Extreme traffic loads and load effects on road bridges

The first issue to be considered in a bridge design, or verification, is to check that none of the structural components will fail or be damaged under the maximum load effect encountered during the bridge lifetime. Most of the design codes distinguish the ultimate limit states (ULS), which correspond to failure or permanent damages, and the serviceability limit states (SLS), which correspond to strains which may affect the bridge operation (*e.g.* traffic safety) but not the stability of the structure, and are reversible. The SLS are reached under the nominal values of the loads while the ULS are reached under the design values of the load, *i.e.* the nominal values multiplied by the safety factors.

The number of elements of a bridge that are sensitive to the live (traffic) loads is unlimited so it is common to identify 3 scales:

- the local effects, with influence lines or surfaces of between around 1 to 3 meters in length and width, and which are only related to axle loads or bogie loads;
- the semi-local effects, with an influence area of a few meters (approximately 2 to 10 m), which are related to bogie loads or the gross weights of short vehicles;
- the global effects, with an influence area of more than 5 to 10 m, generally a whole span or even the whole bridge (if multi span). These are related to the gross weights of the trucks, and generally by the number of trucks on the bridge at the same time.

Local effects can include punching forces, some shear forces, and the bending moments of local details (e.g. steel plate of an orthotropic deck), etc. Semi-local effects include the shear forces of short spans, the bending moment of very short spans (less than 10 m), and the effects in cross beams, etc. The mid-span and on-pier bending moments of medium and long spans (main girders, concrete boxes), and the tension in cables (cable stayed and suspended bridges) are considered to be global effects.

The extreme values of local and semi-local effects are governed by the heaviest axle loads or bogie loads that are likely to occur within the lifetime of the bridge [Flint & Jacob, 1996]. The maximum permitted loads are important, but not directly linked to these extreme values, because of:

- the variable number of axles on trucks;
- overloading (illegally loaded vehicles);
- abnormal load vehicles, i.e. vehicles carrying indivisible loads of exceptional mass or length, which operate either with a permanent authorization or under special permits.

In some countries there are some frequent exceptional loads, for example the large cranes in the Netherlands. In some countries (e.g. France), log trucks are authorized at higher gross weights than those normally permitted (48 t on 5 axles and 57 t on 6 axles instead of 40 or 44 t).

For global effects and some semi-global effects, particularly on multi-lane bridges, the loads imposed by individual vehicles are no longer the factor that determines the extreme loads on the bridge. In these situations it is the combination of the loads imposed by two or more trucks travelling on the bridge at the same time. The gross mass, length, spacing and respective location of each truck in each traffic lane all influence the induced load effects. It is still possible to assess the "aggressiveness" of a single truck, which is of interest for span length or influence length up to approximately twice the truck length, but not for very long spans. It was found in the background studies of the Eurocode EN1991-2 [Flint & Jacob, 1996] that for span lengths up to 30 or 40 m, the free traffic case was governing the extreme load effects, i.e. the heaviest single truck, or crossing case of two very heavy trucks. Above this length, the congested case was dominant, with a queue of stationary heavy trucks being the worst case.

The equivalent uniformly distributed load (EUDL), which is the total truck mass divided by its total length, is an important parameter used to assess the global, and some semi-local, load effects. That is the origin of the US bridge formula which is used to limit the total mass carried by any series of consecutive axles in a truck or combination by:

$W = 500^{*}(L^{*}N/(N-1) + 12N + 36)$ W in pound, L in feet		
or $W \approx 250^{*}(3L^{*}N/(N-1) + 12N + 36)$ W in tonne, L in meter	(3')	

W = maximum allowable vehicle weight that can be carried on a group of two or more axles (permissible bridge formula mass),

L = distance between the outer axles of any two or more consecutive axles,

N = the number of axles being considered.

Figure 66 shows the relative aggressiveness of each of the 39 international trucks assessed in the performance benchmarking (see chapter 4), in comparison with the 40 tonne European reference truck, composed of a 2-axle tractor and a semi-trailer with a tridem axle. For each truck (the categories on the x-axis), the coefficient plotted on the y-axis is the ratio of the maximum load effect (here bending moment) under the considered truck to the maximum load effect (here bending moment) under the European reference truck. For span lengths of 50 to 100m, the longer and heavier trucks are much more aggressive than the reference truck, but it should be noted that for such span lengths, more than one reference truck may be together on the same span.

All vehicles examined in this study comply with regional bridge loading but these vary between different countries. In the absence of an accepted international bridge load factor measure suitable for this analysis, a simplified method of evaluation was investigated based on the U.S. bridge formula.

The coefficient of relative aggressiveness  $C_n$ , , corresponding the Bridge formula (green bars in the chart) are defined as:

$$c_n = W_n/W_{n,bf}$$
  $C_{ref} = W_{ref}/W_{ref,bf}$   $C_n = c_n/c_{ref}$ 

where:  $W_n$  and  $W_{ref}$  are the gross weights of a given truck n, and of the reference 40 tonne truck,  $W_{n,bf}$  and  $W_{ref,bf}$  are the maximum gross weights of these two trucks according to the US bridge formula given in Eq. 3'. In our case,  $c_{ref} = 40/33.5 = 1.194$ .

 $C_n$  gives an account of the relative excess of weight of the truck n with respect to the reference truck, both related to the bridge formula load limit.



# Figure 66 Comparison of impacts of trucks on bridges as shown by the relative coefficients of aggressiveness with respect to a reference truck (5 axle articulated tractor with semi-trailer, 2S3, 40 t, 16.5 ù) regarding the maximum bending moment at mid span of simple supported and 2 or 3 span continuous beams.

The bridge formula (green bars in Figure 66) almost fits the 20m span length bending moment. This means that if a truck conforms to the US bridge formula, the maximum bending moment induced by the vehicle on a 20m span will remain almost constant whatever the truck design. However, for span lengths above 30 or 40 m, the bridge formula substantially under-estimates the extreme load effects of long and heavy vehicles, particularly the Australian 12 axle combination of 33.3 m and 90.5 t (AU3-v), two

Canadian 8 or 9 axle combinations of 20.4 and 38.33 m and 62.5 t (CA3-h and CA4-v), and the European Modular System with 8 axles, 25.25 m and 60 t (NL2-h).

On very short spans (10 m), the bridge formula is also inaccurate for some trucks, such as a Canadian or an US 3-axle tractor with 3-axle semi-trailer of 46.5 or 44.1 t and 21.55 or 25.1 m (CA2-w or US5-h), as well as a Mexican combination (3-axle tractor with 3-axle semi-trailer + dolly 2 axle + tandem), with 66.5 t and 39 m (MX4-v).

These results show that the bridge formula was calibrated against the bending moment of a 20m span, i.e. of an average US truck length. For shorter spans (i.e. 10m), this formula would apply on a subset of consecutive axles of a truck. For longer spans, the formula does not apply while more than one truck may be on the span in the same traffic lane.

Figure 67 suggests that the bridge formula for the on-pier bending moment was calibrated for a 2 span continuous beam of 10 + 10 m, which also corresponds with a total loaded length close to the average US truck length. For any longer spans, the formula under-estimates the load effects of most of truck combinations.



Figure 67 Coefficients of aggressiveness of a series of 39 international trucks (OECD) with respect to a reference truck (5-axle articulated, tractor with semi-trailer, 2S3, 40 t, 16.5 m), regarding the span length for several load effects (mid span and over an intermediate pier bending moment for simple supported, 2 and 3 span continuous beams, and shear forces).

As the productivity of the vehicle increases the impact on the bridges tend to increases. Figure 66 and Figure 67 show that much more bars exceed the reference truck aggressiveness (red line,  $C_n=1$ ) among the high and very high capacity vehicles than among the workhorses. (However the lowest aggressiveness was from the high capacity vehicle group, which proves that some of these vehicles perform very well. That is the case for long or very long vehicles with a low ratio gross weight/length (EUDL). The worst performing vehicle was also found in the very high capacity vehicle category: the Australian 12 axle combination of 33.3 m and 90.5 t (AU3-v), with an EUDL of 2.72 instead of 2.42 for the reference truck.

Figure 68 illustrates the relationship between the coefficients of aggressiveness  $C_n$  and the EUDL of each of the vehicles, for each load effect and the bridge formula. It shows that the effects of the vehicles which comply to the bridge formula are directly proportional to their EUDL (this comes directly from the construction of the formula). It also shows that there is a linear trend between the EUDL and the coefficient of aggressiveness, in particular for the short and medium spans. For the longer span lengths, the points are more scattered, because of the lower impact of a single vehicle on a longer span. In other words, increasing the maximum mass of a truck, without increasing its length, significantly increases its aggressiveness to bridges.



Figure 68 Coefficients of aggressiveness as a function of the EUDL (ratio of gross vehicle weight divided by the total vehicle length).

The bridge structural indicators were developed specifically for this study in order to compare the relative bridge impact of vehicles from several countries. Given that bridge formulae differ from country

to country, and that the strength of the bridge stock varies from country to country, it would be appropriate that each country use their own bridge formula as opposed to the US formula used for this generalized analysis.

Several European studies, for example De Ceuster et al. (2008), investigated the effect of longer and heavier vehicles on the load effects induced in bridge structures compared to those of standard trucks. It was shown that to match the effects of the reference truck the total mass must not be increased by a greater proportion than its length, thus maintaining a constant EUDL. Even when the length and mass were increased by the same proportion the aggressiveness of the truck combination tends to increase, particularly for medium and long spans, and it was shown that the European Modular System (EMS) truck of 60 t and 25.25 m was approximately 50% more aggressive on most bridges than the standard 5 axle articulated vehicle of 40 t and 16.5 m. In order for the 8-axle EMS combination to be equally aggressive as the 5 axle, 40 tonne reference vehicle, the gross weight would need to be limited to about 50 to 52 tonnes.

A report by TNO [Vrouwenvelder, 2008] is less pessimistic and tends to suggest that EMS combinations would not have too many unfavourable effects on Dutch bridges, provided that the greater weight is uniformly distributed over the greater vehicle length. However, it was suggested that in future, combinations restricted to a maximum weight of less than 60 t would help to avoid any unfavourable effects on bridges.

Glaeser et al. (2006) studied the likely effect of the introduction of 60-tonne, 25.25m LHVs on German bridges and concluded that they would reduce the load reserve of current bridges but would not harm their wearing capacity. The bridges constructed from pre-stressed concrete before the 1980's were particularly at risk because they were designed for a different temperature range, and thus the combination of a temperature gradient and the maximum traffic loads could become critical.

Knight et al. (2008) investigated the likely effect of different LHV combinations and concluded that most of the combinations assessed would not have negative effects on current UK trunk road bridges. In fact, for some combinations (intended for increased volume capacity not increased mass capacity)\_the bending moment and sheer forces could actually be lower. According to the British road authorities, only some 3% of UK trunk road bridges would not be suitable for existing 44 tonne vehicles or 60 tonne LHVs. If 82 tonne vehicles were to be permitted then up to about 25% of road bridges on the main network and a greater proportion of bridges on the local network would be at risk.

Finally it should be noted that most of the studies based on the EUDL, the bridge formula, or even the maximum load effects induced by one truck, ignore the cumulative effects of:

- a platoon of heavy trucks, on one lane,
- heavy trucks side by side, either crossing each other or overtaking each other on a peak of the influence line.

For bridges with more than 2 lanes, these effects could be greater. The probability of occurrence of multiple trucks on a bridge deck, with respect to the span/bridge length, the truck lengths and the traffic density, are not very well known or well modelled. Therefore, the best approach to assess the extreme load effects is to use medium or long term WIM data (e.g. recorded over at least a week, preferably a month or more) recorded on all the traffic lanes (used by trucks), and then to carry out the appropriate extrapolations, which are based on some stationary assumptions. However, most design standards including the Eurocode on "Traffic Loads on Road Bridges", EN1991-2 [CEN, 2002], make some very conservative judgements about the number of vehicles on the bridge, the dynamic amplification, overloading etc., and bridges have to be designed to withstand these conservative loads for the life of the structure. These loads are much greater than anything likely to be actually observed by WIM data even over a couple of months.

In addition to the vertical loads, horizontal forces (braking and cornering forces) and shock loading (e.g. collisions with piers, safety barriers, etc.) need to be considered.

# 6.3.3 Fatigue of bridges

Steel bridges and steel parts of composite bridges have some details (welds) that are sensitive to fatigue. Repeated traffic loads induce stress variations (cycles) which may propagate cracks, generally initiated during the construction of the bridge. Not all trucks contribute to fatigue damage but the heaviest trucks do. For a common assessment of the fatigue resistance of new bridges, the simple Miner's law<sup>7</sup> is used, combined with traffic load data from WIM sites [Jacob, 1998].

Roughly speaking, the damage (and therefore the aggressiveness in fatigue) of an axle or a truck is proportional to the 3<sup>rd</sup> or the 5<sup>th</sup> power of the load (assuming that the stress is proportional to the load, and that a single axle or truck induces one cycle), and the damage increases proportionally to the traffic density.

<sup>&</sup>lt;sup>7</sup> Palmgreen-Miner's rule is based on a linear damage hypothesis, and states that where there are k different stress magnitudes in a spectrum,  $S_i$  ( $1 \le i \le k$ ), each contributing  $n_i(S_i)$  cycles, then if  $N_i(S_i)$  is the number of cycles to failure of a constant stress reversal  $S_i$ , failure occurs when:  $\Sigma_i n_i/N_i = C$  (C is experimentally found between 0.7 and 2.2, usually for design purposes, C is assumed to be 1). This can be thought of as assessing what proportion of life is consumed by stress reversal at each magnitude then forming a linear combination of their aggregate. Though Miner's rule is a useful approximation in many circumstances, it has two major limitations:

it fails to recognize the probabilistic nature of fatigue and there is no simple way to relate life predicted by the rule with the characteristics of a probability distribution;

<sup>-</sup> there is sometimes an effect in the order in which the reversals occur. In some circumstances, cycles of low stress followed by high stress cause more damage than would be predicted by the rule. It does not consider the effect of overload or high stress which may result in a compressive residual stress. High stress followed by low stress may have less damage due to the presence of compressive residual stress.

A bridge verification for fatigue starts by checking if, under a rather heavy load, for example the daily maximum load, the fatigue limit  $S_e$  is exceeded for the design detail under consideration. If not, there is no damage and no further checks are required. If the limit is exceeded, a lifetime calculation is necessary, and all the stress cycles with an amplitude larger than  $S_t$  must be taken into account.

As in section 7.3.2, the local effects are sensitive to the repeated axle or bogie loads. That is mainly the case in orthotropic decks. For such a structure, the lateral wheel location (wheel path) is of great importance. For local or semi-local effects, the damage increases approximately proportionally to the number of axles or trucks, and with the 5<sup>th</sup> power of the mean axle loads or gross weight. One truck mostly induces one stress cycle.

Global effects are more complex because a large proportion of cycles, particularly the cycles with the largest magnitude, are induced by the presence of more than one truck. It then becomes necessary to calculate (or measure) the real stress cycle distribution under a given traffic pattern. Main girder details (of composite bridges or steel bridges) such as vertical stiffeners welded on girder flanges are sensitive to fatigue due to the global bending moment (at mid span or on pier). Span lengths between 30 and 90 m are common for these bridges. For the shortest spans, one truck (or two trucks side by side) induces a stress cycle. For the longest spans, a small number of closely spaced trucks may induce larger stress cycles. Because of the 5<sup>th</sup> power dependence, if two heavy trucks are passing side by side on a bridge of e.g. 40 to 60 m in length, instead of two cycles of amplitude S, the fatigue sensitive detail may get one cycle of let say 1.5 S, which induces  $0.5 (1.5)^5 = 3.7$  times more damage.

Figure 69and Figure 70 show the relative aggressiveness in fatigue of a single truck with respect to the reference truck, for stresses induced at mid span by bending moments, and for several load effect induced stresses, for span lengths from 10 up to 100 m. The bar charts are similar to those of Figure 67 and Figure 68 with more difference because of the 3 or 5<sup>th</sup> powers. As for the maximum load effects, the bridge formula fits very well the results for span lengths of 20 m (at mid-span) and of 10 m (on-pier).

Compared to the reference truck (5 axle, 40 t and 16.5 m), on short simple supported spans (10 m) most of the longer (and heavier) trucks are less aggressive, particularly if the axle or bogie loads are decreased (Figure 69). Short and heavy trucks or those with higher bogie loads are more aggressive. But for span lengths above 40 m (mid span effects) or even 20 m (bending moment on pier), longer (and heavier) trucks become 3 to 4 times more aggressive, and up to 10 times for the 90.5 t and 33.3 m Australian AU3-v combination (Figure 70).

The relationship between fatigue damage and the load or stress amplitude is not linear. This means that if the total vehicle weight is increased by the same proportion (e.g. 10%) as the number of vehicles is decreased, then the net result is increased bridge damage and reduced lifetime. If the truck gross weights are increased, the vehicle length is increased proportionally (to maintain the same load per metre of bridge) and more axles are added (to maintain the same axle loads) then the fatigue damage on medium

and long spans could still be increased. This is also the case for shorter spans where there are structural elements that are sensitive to the bending moment on pier effects (i.e. load effects of multiple span bridges which have influence lines of the same sign).

The three European Modular System trucks loaded at 60 t (BE2-h, DK4-h and DK5-h) are almost 3 times more aggressive than the reference truck for pier moment effects, and 2.5 times for the mid span moment effect on medium and long span bridges.



Figure 69 Aggressiveness in fatigue of a series of 39 international trucks (OECD) with respect to a reference truck (5-axle articulated, tractor with semi-trailer, 2S3, 40 t, 16.5 m), regarding the bending moment induced stresses at mid span of simple supported and 2 or 3 span continuous beams



Figure 70 Aggressiveness in fatigue of a series of 39 international trucks (OECD) with respect to a reference truck (5-axle articulated, tractor with semi-trailer, 2S3, 40 t, 16.5 m), regarding the span length for several load effect induced stresses (at mid span and on pier bending moment for simple supported, 2 and 3 span continuous beams, and shear forces).

#### 6.3.4 Dynamic truck/bridge interaction

The European ARCHES project (Assessment and Rehabilitation of Central European Highway Structures)<sup>8</sup>, includes a task on the assessment of realistic dynamic loading of bridges. Some stresses are thought to be induced in bridges due to dynamic interaction between traffic and the bridge. In Western countries the mean allowance for dynamic amplification is up to about 30% (Cooper in the UK recommends 27% [Cooper, 1997] and the United States AASHTO code specifies 30%). If road surfaces are poorly maintained, dynamic loading is thought to be considerably higher. However, the dynamic values specified in bridge design codes are generally based on measurements of the bridge response during the passage of typical vehicles, usually when they are alone on the bridge. This does not correspond to the maximum loading situations found on bridges under normal traffic conditions (i.e. on bridges without load limits). There is increasing analytical and experimental evidence to suggest that the dynamics of the critical multiple vehicle events are much less – as low as 6%. Figure 71 shows two rather different examples of measured dynamic amplification factors (DAF). The upper graph shows DAF values of 148 000 loading events measured on a simply supported pre-stressed concrete beam bridge deck

<sup>&</sup>lt;sup>8</sup> See http://arches.fehrl.org

with a 24-m span. The lower graph shows DAF values for 56 000 loading events measured on a 7.2-m integral slab bridge. While DAF values of lighter individual vehicles are much higher, reaching values over 2 on the simply supported bridge with a bump over the expansion joint, DAF values of the heaviest loading events in both cases approach 1.



Figure 71 Measured DAF factors of loading events on a 24-m long simply supported span with a relatively smooth pavement (top) and on a 7.2-m long integral bridge with a very smooth pavement (bottom) – MP = multiple truck event, BD = Bridge Design, RBBA = Reliability Based Bridge Assessment.

The diagrams in Figure 71 demonstrate another important difference between two sites. The first measurements were done on the 10<sup>th</sup> Trans European Road corridor in Slovenia with an average daily traffic of around 25 000 vehicles of which around 3 000 were trucks (motorway in 1 direction). There are

very few exceptionally heavy vehicles on Slovenian (and other Central European) roads, so the maximum loading events were caused by two heavy vehicles meeting around the midspan. The second measurements were done in the Netherlands on a motorway carrying nearly 60 000 vehicles per day, of which there were around 5 000 trucks per direction. In contrast to the Slovenian site, trucks in the Netherlands could not overtake each other. The extreme loading events in this case were caused by the exceptional vehicles, such as cranes and low-loaders, the most aggressive one being a 107-tonne low loader with 6-axles. Its 57-tonne twin axle induced strains that were almost 30% higher (the 226 µs dot in the chart above) than any other vehicle.

The ARCHES project will publish new recommendations regarding the DAF values to apply for assessment of existing bridges.

### 7. CONCLUSIONS

The benchmarking process used in this study confirms that performance measures applied to vehicles complying with a variety of size and weight regimes can differentiate safety and productivity performance providing an objective means of measuring and ranking vehicle in terms of safety and efficiency. The measures used and data obtained from this research effort provide evidence that regulatory systems could reliably promote safer and more efficient vehicles by using performance measures to guide policy decisions. The study has also shown that significant safety and productivity improvements are possible within the existing worldwide fleet.

#### 7.1 Operational

Trucks exist to do work and to do it efficiently. Their worth and function are tied directly to work performance in exchange for money, which is very different from the personal use passenger car. Freight tasks vary, as do the weight and shape of cargo transported, so vehicle use and fuel consumption vary for a given cargo and duty cycle, which is also very different from passenger cars where the weight and fuel consumption vary comparatively little between empty and full load.

For all truck transport, the nature of goods movement can be volume limited or mass limited. Productivity measures based on the product of cargo mass and volume have proven to be a particularly effective means of capturing vehicle efficiency in the context of mass and volume capacity. Overloading is an important issue in most countries in the world and increasing volume capacity can easily be used to overload the vehicle by mass. Onboard weigh measuring systems on each axle or axle unit should therefore be a requirement for future vehicles.

#### 7.2 Energy and Emissions

From the vehicles examined in this study, it is apparent that the higher productivity vehicles in use around the world are delivering greater increases in cargo volume than cargo mass.

Payload mass efficiency may be a suitable candidate for a productivity performance measure for size and weight regulation. It may be desirable to require that all general freight vehicles have a payload mass efficiency greater than 0.6. However this measure would only be suitable for conditions where freight can be loaded such that allowable gross vehicle mass is achieved.

Cargo mass volume by energy consumption and cargo mass volume by CO<sub>2</sub> production may be potential candidates for energy and emissions related productivity measures.

A vehicle rated as having low fuel consumption on standard tests will not necessarily show good fuel or emissions efficiency in use. Fuel and emissions efficiency depend on the amount of fuel used to accomplish a specific freight task. For road transport, fuel efficiency measured with respect to the quantity of cargo transported (by mass and volume separately) are preferred performance metrics.

#### 7.3 Vehicle Design

Basic aspects of truck design such as the length, wheelbase, width, height, axle loads, axle spacing and GVW, are influenced and limited by size and weight regulations. Since these factors directly influence fuel consumption it can be concluded that fuel consumption and fuel efficiency are strongly related to size and weight regulation.

The benchmarking process has shown that in many instances higher capacity vehicles performed equally if not better than workhorse vehicles. Despite workhorse vehicles being used to transport the majority of the freight around the world, the workhorse vehicle is not necessarily any safer or better performing than the high capacity or very high capacity vehicles simulated in this study.

Vehicles with 'A'-type couplings (non-roll coupled connections such as drawbars between vehicle units) performed well in low speed turning manoeuvres. However, they performed poorly in high speed dynamic manoeuvres in comparison to vehicles with 'B'-type couplings (roll coupled connections between vehicle units such as fifth-wheel connections). Such couplings provide increased stability to the vehicles and tend to perform better during the dynamic manoeuvres.

The study brought out the different focus that different regions have in the composition of their representative vehicles. The European countries tend to design their vehicle combinations in order to have a lower swept path, while sacrificing higher speed dynamic performance, while the Australian, South African and North American vehicles performed better at the dynamic measures but less well on the low speed swept path measures.

Commercial vehicle size and weight regulations were initially introduced to protect roads and bridges from excessive deterioration caused by larger heavier vehicles. The regulations also mitigate other concerns such as safety risks and compatibility with other road users. The prescriptive nature of the regulations influence key aspects of truck design such as the length, width, height, wheelbase, number of axles, axle loads, axle spacing and GCM. These vehicle characteristics influence vehicle stability, manoeuvrability, productivity, fuel use and emission output. Therefore size and weight regulation represents a tool that can not only protect the infrastructure but also create vehicles that provide significant societal benefits. In order to realise these benefits the regulatory community should keep the size and weight regulations under review to ensure, with the support of full cost benefit analyses, that the freight transport task can be optimised to deliver these broader societal benefits.

Truck traffic must be adapted to the road design, geometry, traffic, capacity, and particularly to the pavement and bridge assets. In turn, these assets should be developed to facilitate the optimal use of road capacity by trucks, funded by financial mechanisms that support such use. Regulatory systems should encourage the use of trucks that are less aggressive to the infrastructure and the models used to assess the aggressiveness should be improved so that pavement characteristics are more accurately considered than is the case with traditional "fourth power law" methods.

For pavement fatigue and wear assessment, axle loads and configurations are much more important than the gross vehicle mass (GVM). It is therefore essential that this is reflected in the regulation of vehicle weights and dimensions. If gross vehicle masses were to be increase then it would be necessary to increase the number of axles to ensure the axle loads remained the same or reduced. Distributing the load more evenly amongst all the axles can also substantially reduce the truck aggressiveness and thus the pavement damage and maintenance cost.

Load effects, strains or stresses of traffic loads on bridges must be analysed on several scales which involve axle loads, single vehicle gross vehicle mass and a series of consecutive or adjacent vehicles' gross vehicle masses. Moreover, these effects depend on the bridge type, span length, and bridge section or detail considered. The extreme (maximum) loads govern the brittle failure (ultimate limit state) while the repeated heavy loads have the most influence on fatigue damage assessment.

Bridge and road wear both vary significantly with changes to the maximum GVM of the vehicle. However within this correlation, it is also possible for vehicles with a lower GVM limit to have a higher infrastructure impact than vehicles with a higher GVM limit. This suggests that by optimising the vehicle configuration it is possible to both improve the productivity and simultaneously reduce the impact on the infrastructure. The aggressiveness of a single truck increases approximately linearly with its gross vehicle mass for (extreme) load effects, and with a 3<sup>rd</sup> to 5<sup>th</sup> power of its gross vehicle mass for fatigue damage, but decreases with its length for a constant mass. Thus to contain bridge damage, increases in gross mass should be accompanied by proportional increases in length and the number of axles. The use of a bridge formula, as in North America, provides a useful means of ensuring an appropriate relationship between gross mass, length and number of axles for short and medium span bridges, or for local and semi-local load effects. However, such formulae must be adapted to the bridge conditions and designs in the region to which it is applied.

For medium and long span bridges (above 50 m), enforcing a minimum gap between trucks that exceed certain gross mass limits would reduce bridge damage and the risk of deterioration or failure. For short and medium span bridges, it would be beneficial to avoid two very heavy vehicles crossing or overtaking at critical positions. ITS systems, including WIM and GPS, and variable message signs could provide the mechanism required to achieve such positional control.

When increasing the GVM of trucks, containment is an issue. Barriers currently in use which just comply with minimum standards are not designed to cater for the worst case that might occur with trucks even today. Lane departure warning may help to reduce the risk breaking through guardrails. The risks of trucks colliding with the pier of a bridge will also grow and is an issue because it may lead to a bridge collapsing on a trafficked road underneath. The development of collision mitigating braking systems for trucks offers the potential for the speed of a truck to be reduced before impact, which could substantially reduce the risk.

Overtaking bans for trucks and other speed-limited vehicles on specified road sections can be permanent, limited to certain time periods or dynamic. Studies and accumulating experience have shown that such bans can improve the coexistence of heavy trucks and light vehicles on heavily trafficked roads and improve the utilisation of the road capacity. Dynamic truck traffic management, e.g. overtaking ban depending on traffic density, speed and road condition, or dynamic lane allocation, has the potential to reduce congestion and improve safety. It will require advanced infrastructure-to-vehicle communication and strict compliance. The Intelligent Access Programme now being deployed in Australia is a first practical example of such a supervisory system.

The availability of enough parking facilities is a high priority for safe, legal and efficient truck operations and the demand grows with the volume of truck traffic as well as the size of the trucks. It is necessary to identify the proper need of parking areas/space by main itinerary routes on public as well as concessionary networks, Where undersupply is identified it is necessary to build more parking lots in the most critical zones.

Intermodal terminals serve a balance of modes and need to be designed according to the current and future truck and train characteristics, e.g. weights and dimensions, performances, etc. They must be

located in the right place for the logistic chain, and above all well connected to the various transport networks (road, rail and waterborne). Access rights and operating hours are very important issues. Land use planning needs careful consideration, especially in urban and peri-urban areas in order to avoid dying city centres on the one hand and encouraging mega stores at highway exits on the other.

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# **APPENDIX A: FURTHER RESULTS**

During the examination of the results, a number of productivity measures in addition to those shown above were examined to observe whether a relationship exists between the performance of the vehicle and the productivity measure. The extra productivity measures examined are as follows:

- Standard axle repetitions per axle group
- Ratio of 'B' type couplings to total couplings
- Gross combination mass
- Payload
- Payload per axle
- Internal cargo volume
- Total vehicle length
- Number of axles
- Product density

#### Standard axle repetitions per axle group







#### Ratio of 'B' type couplings to total couplings



#### **Gross combination mass**





# Payload




# Payload per axle





### Internal cargo volume





## **Total vehicle length**





#### Number of axles





# **Product density**



