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Performance based standards for high capacity transports in Sweden

FIFFI project 2013-03881 – Report 1
Review of existing regulations and literature

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Abstract

Project “Performance Based Standards for High Capacity Transports in Sweden” started at the end of 2013 to investigate applicability of PBS in Sweden. The purpose of the project is to propose a performance based regulation of HCT vehicles and their access to the road network; under a PBS approach to regulation, standards would specify the performance required from vehicle, rather than mandating how this level of performance should be achieved by putting limits on the vehicle length or weight. In this project, all the three domains of safety, infrastructure and environment will be addressed, but the focus is on safety for which extensive testing, simulations and analysis are planned. This report gathers the outcome of work packages 1 and 2 of the project, which is a review of the existing regulation in Sweden, PBS approaches in other countries and relevant literature and regulations.

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Referat

Projektet "Performance Based Standards for High Capacity Transports in Sweden" startade i slutet av 2013 för att undersöka möjligheterna att applicera prestandabaserade kriterier, eller Performance Based Standards (PBS), i Sverige. Vid prestandabaserade föreskrifter så specificeras kriterier eller standarder för en prestandanivå som ett fordon måste uppfylla, istället för att bestämma hur samma prestandanivå skulle uppnås genom att sätta gränser för fordonets längd eller vikt. Projektet kommer att beakta de tre domänerna säkerhet, infrastruktur och miljö, men fokus kommer att ligga på säkerhet och det planeras därför omfattande testning, simulering och analys. Denna rapport beskriver resultatet från projektets arbetspaket ett och två som omfattat en genomgång av nuvarande regelverk i Sverige, PBS-koncept i andra länder samt relevant litteratur och övriga regelverk.

Titel:	Prestandabaserade kriterier för högkapacitetstransporter i Sverige FIFFI projekt 2013-03881 – Rapport 1, genomgång av befintliga regelverk och litteratur
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Preface

This report includes the gathered information within the work packages 1 and 2 of the project: “Performance Based Standards for High Capacity Transports in Sweden”, supported by Vinnova with the reference number: 2013-03881. The project is led by the Swedish National Road and Transport Research Institute (VTI); other parties involved in the project are Chalmers University of Technology, Volvo Group Trucks Technology, Scania, Parator Industri AB, Swedish Transport Administration (Trafikverket) and Swedish Transport Agency (Transportstyrelsen).

The authors would like to acknowledge certain individuals from the project partners who were of great help during the process of preparing this report:

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Linköping, March 2015

Sogol Kharrazi
Project leader

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Quality review

Review seminar was carried out on 25 February where Inge Vierth reviewed and commented on the report. Sogol Kharrazi has made alterations to the final manuscript of the report. The research director Jonas Jansson examined and approved the report for publication on 16 April 2015. The conclusions and recommendations expressed are the author's/authors' and do not necessarily reflect VTI's opinion as an authority.

Kvalitetsgranskning

Granskningsseminarium genomfört 25 februari 2015 där Inge Vierth var lektör. Sogol Kharrazi har genomfört justeringar av slutligt rapportmanus. Forskningschef Jonas Jansson har därefter granskat och godkänt publikationen för publicering 16 april 2015. De slutsatser och rekommendationer som uttrycks är författarens/författarnas egna och speglar inte nödvändigtvis myndigheten VTI:s uppfattning.

Contents

Summary

Performance based standards for high capacity transports in Sweden. FIFFI project 2013-03881 Report 1, Review of existing regulations and literature

by Sogol Kharrazi (VTI), Robert Karlsson (VTI), Jesper Sandin (VTI) and John Aurell (John Aurell Consulting)

The transport sector is facing a major challenge to reduce energy consumption and limit environmental impact; therefore, there is a great interest in increasing the efficiency of the transport system in Sweden, which makes the High Capacity Transports (HCT) an attractive solution. The existing legislation in Sweden, allows heavy vehicle combinations with maximum length of 25.25 metre and maximum weight of 60 ton on the road network. In order to introduce HCT vehicles in Sweden, the existing regulations should be modified and a proper way of regulating HCT vehicles and their access to the road network should be developed to ensure that a certified HCT vehicle would not have negative effects on traffic safety, infrastructure and environment.

One approach is to use performance based standards (PBS) for regulation of heavy vehicles access to the road network; under a PBS approach to regulation, standards would specify the performance required from vehicle, rather than mandating how this level of performance should be achieved by putting limits on the vehicle length or weight. A PBS approach for regulation of heavy vehicles on roads will enable development of cost effective HCT vehicles without negative effects on traffic safety, infrastructure and environment. Furthermore, the inherent flexibility in the PBS approach allows industry to develop innovative vehicles optimized for a specific application. PBS has been implemented in Australia, Canada, and New Zealand.

In this scope, the project “Performance Based Standards for High Capacity Transports in Sweden” started at the end of 2013 to investigate applicability of PBS in Sweden. The purpose of the project is to propose a performance based regulation of HCT vehicles and their access to the road network. The core of the proposed regulatory framework will be a set of performance based standards. In this project all the three domains of safety, infrastructure and environment will be addressed, but the focus is on safety for which extensive testing, simulations and analysis are planned. This report gathers the outcome of work packages 1 and 2 of the project, which is a review of the existing regulation in Sweden, PBS approaches in other countries and relevant literature and regulations.

In the discussion chapter at the end of the report, a set of candidate performance measures with respect to safety and manoeuvrability are proposed for further investigation within the project. It is anticipated that some of the listed measures are highly correlated; however, this should be verified by the investigation results, before a measure can be eliminated. An important aspect is to investigate these measures with respect to both high and low friction surfaces and possible correlation between them.

The reviewed regulations on performance of heavy vehicles with respect to environment, namely exhaust emissions, fuel consumption and noise, are all performance based. Thus, the main issue with respect to HCT vehicles is whether the existing environmental regulations are suitable for them or not.

The pavement function and design along with the main deterioration mechanisms and their relationship to heavy loads are described in this report. One of the main concerns with the HCT vehicles is the effects of passes of multiple heavy axles on the pavement, an area in which the current knowledge is not sufficient. Another important issue is the loading on bridges, which are the primary part of the infrastructure that put restrictions on the allowed axle load and gross weight of heavy vehicles, to avoid excessive loading. In Sweden, the bearing capacity of a bridge is determined by calculating the load effects and resulting stresses using reference vehicles. One possible approach to address the HCT vehicles effects on bridges is to consider more reference vehicles.

Sammanfattning

Prestandabaserade kriterier för högkapacitetstransporter i Sverige. FIFFI projekt 2013-03881 – Rapport 1, genomgång av befintliga regelverk och litteratur

av Sogol Kharrazi (VTI), Robert Karlsson (VTI), Jesper Sandin (VTI) och John Aurell (John Aurell Consulting)

Transportsektorn står inför stora utmaningar när det gäller att minska energiförbrukning och miljöpåverkan. Därför är det av största intresse att effektivisera transportsystemet i Sverige, vilket gör High Capacity Transport (HCT) till ett attraktivt alternativ. Den nuvarande lagstiftningen i Sverige tillåter tunga fordonskombinationer med en maximal längd av 25,25 meter och en maximal vikt på 60 ton. För att kunna introducera HCT-fordon i Sverige så behöver regelverk och föreskrifter utvecklas på ett sätt som säkerställer att ett certifierat HCT-fordon inte får negativa effekter på trafiksäkerhet, infrastruktur och miljö.

Ett sätt att reglera tunga fordons tillträde till vägnätet är att använda prestandabaserade kriterier, eller Performance Based Standards (PBS). Vid prestandabaserade föreskrifter så specificeras kriterier eller standarder för en prestandanivå som ett fordon måste uppfylla, istället för att bestämma hur samma prestandanivå skulle uppnås genom att sätta gränser för fordonets längd eller vikt. Ett PBS-baserat regelverk för tunga vägfordon skulle möjliggöra en utveckling av kostnadseffektiva HCT-fordon utan negativa effekter på säkerhet, infrastruktur och miljö. Den större flexibiliteten inom PBS konceptet gör det också möjligt för industrin att utveckla innovativa fordon som är optimerade för specifika ändamål. PBS används i Australien, Canada och Nya Zeeland.

Med detta som bakgrund så startade projektet "Performance Based Standards for High Capacity Transports in Sweden" i slutet av 2013 för att undersöka möjligheterna att applicera PBS i Sverige. Syftet med projektet är att föreslå ett prestandabaserat regelverk för HCT-fordon och deras tillträde till vägnätet. En central del i det föreslagna regelverket kommer att vara en uppsättning prestandabaserade kriterier. Projektet kommer att beakta de tre domänerna säkerhet, infrastruktur och miljö, men fokus kommer att ligga på säkerhet och det planeras därför omfattande testning, simulering och analys. Denna rapport beskriver resultatet från projektets arbetspaket ett och två som omfattat en genomgång av nuvarande regelverk i Sverige, PBS-koncept i andra länder samt relevant litteratur och övriga regelverk.

I diskussionen i slutet av rapporten så föreslås en uppsättning av möjliga prestandamått som är kopplade till säkerhet och manövrerbarhet, och som ska utredas närmare i fortsättningen av projektet. Några av prestandamåtten är sannolikt starkt korrelerade, men detta behöver verifieras genom djupare utredning innan några mått kan elimineras. En viktig aspekt är att undersöka de här måtten med hänsyn tagen till både hög och låg friktion och möjliga korrelationer mellan dem.

De genomgångna regelverken för miljökrav och tunga fordon, det vill säga utsläpp, bränsleförbrukning och buller, är samtliga prestandabaserade. Den huvudsakliga frågan är därför huruvida nuvarande miljökrav kan omfatta även HCT-fordon eller inte.

Vägöverbyggnadens funktion och konstruktion beskrivs i rapporten tillsammans med tunga lasters koppling till nedbrytningsmekanismer. En väsentlig fråga för HCT-fordon är effekterna av när fler axlar passerar ett vägavsnitt omedelbart efter varandra. Detta är ett område där det saknas tillräckligt med kunskap. En annan viktig fråga gäller belastningen på broar, vilket är huvudskälet till de begränsningar på axelvikter och totalvikter som sätts för att undvika överbelastning. I Sverige bestäms bärigheten hos en bro genom att beräkna belastningseffekter och resulterande påfrestning med hjälp av referensfordon. Ett sätt att uppskatta effekterna av HCT-fordon är att använda fler referensfordon.

1. Introduction

The large increase in the goods transport demands, the growing congestion problem and the environmental concerns over transportation emissions and fuel consumption, make High Capacity Transport (HCT) vehicles an attractive alternative to the conventional heavy vehicle combinations on the road; an alternative which is also expected to result in significant economic benefits. HCT refers to introduction of heavy vehicle combinations with higher capacity (longer and/or heavier vehicles) than the existing vehicles on the roads. With HCT vehicles, the existing capacity in the road infrastructure can be utilized efficiently without requiring too high investments, and the goods can be transported with fewer vehicles. It is expected that this will result in a reduction in the transport cost, fuel consumption, emissions and the traffic congestion.

The existing legislation in Sweden, allows heavy vehicle combinations with maximum length of 25.25 m and maximum weight of 60 t on the road network. However, dispensations of longer and heavier HCT vehicles for trial periods have been granted which have shown considerable CO_2-reduction, fuel saving and improved transport economy (Cider & Ranäng 2013, Skogforsk 2013, Adell et al. 2014).

The great transport efficiency concern in Sweden has led to development of a roadmap for realization of HCT on Swedish road network (Berger et al. 2013). The assumed target for the roadmap is that by the year 2030, 5% of all domestic goods transport on the road is operated by HCT vehicles. To achieve the HCT target by 2030, several actions and measures are proposed in the roadmap within the areas of: infrastructure adaptation, information system, HCT logistics, HCT vehicle combinations and legislations. One of the key issues discussed in the roadmap is Performance Based Standards (PBS), which is a way of regulating HCT vehicles and their access to the road network. Under a performance based approach to regulation, standards would specify the performance required from vehicle operations rather than mandating how this level of performance should be achieved by putting limits on the vehicle length or weight. The PBS concept versus other regulatory principles is further discussed in next section.

1.1. PBS versus other regulatory principles

There is a wide spectrum of regulatory principles which differ significantly in terms of how specific and well quantified they are, from "principle-based regulations" at one end to prescriptive regulations at the other. Principle-based regulations do not include quantified limits and are specified very broadly in terms of objectives (OECD 2005). For instance a principle-based regulation for heavy vehicles can be that the vehicle operators need to minimize the risk of involvement of their vehicles in accidents, without specifying any policies for achieving the objective.

On the other hand, prescriptive regulations outline specifically how an objective should be achieved with explicitly defined and quantified mandates. Prescriptive regulations are currently the predominant regulatory principle used for regulation of heavy vehicles, worldwide. The common approach is setting limits on the vehicle weight and length to ensure safety and to protect infrastructure.

Performance based standards is a regulatory principle between the two abovementioned extreme approaches, which includes specific performance criteria/measures with quantified required level of performance. It is more precise than principle-based regulation, but provides more flexibility, which encourages innovative novel products, than prescriptive regulations. PBS for regulation of heavy vehicles access to the road network has been implemented in Australia, Canada, and New Zealand. The country which has made the most progress in PBS is Australia; the Australian PBS scheme is divided in two parts: 4 infrastructure standards and 16 safety standards. For each standard, four performance levels are defined that correspond to different access level to the road network (NTC 2008).

There are different approaches for implementing PBS in a regulatory framework, such as using PBS as an underlying basis for developing prescriptive regulations like the Canadian approach where "vehicle-envelopes", defining the general vehicle layout, were developed using PBS. Another example is the Australian approach in which PBS is used to determine access requirement for different parts of the road network and is complementary to the general prescriptive regulations. Considering the different implementation approaches, the degree of flexibility in a performance based regulation can vary considerably; greater flexibility might increase the risk of non-compliance if not complemented with a comprehensive enforcement strategy.

1.2. PBS project

With a PBS approach for regulation of heavy vehicles on roads, development of cost effective HCT vehicles without negative effects on traffic safety, infrastructure and environment will be possible. Furthermore, the inherent flexibility in the PBS approach allows industry to develop innovative vehicles optimized for a specific application. Therefore, the project "Performance Based Standards for High Capacity Transports in Sweden" started at the end of 2013 to investigate applicability of PBS in Sweden. In this project all the three domains of safety, infrastructure and environment will be addressed, but the focus will be on safety for which extensive testing, simulations and analysis are planned.

The project objective is to propose a performance based regulation of HCT vehicles and their access to the road network; the core of the proposed regulatory framework will be a set of performance based standards. The project goals are:

1. Formulation of a set of performance based standards, suitable for Sweden with attention to snowy and icy road conditions. The purpose of the standards is to ensure that a certified HCT vehicle does not have negative effects on traffic safety, infrastructure and environment. Each performance based standard consists of three parts: a performance measure, the acceptable performance level and, if applicable, a test manoeuvre during which the performance of the vehicle should be measured.
2. Proposal of an assessment and approval procedure; in other words, a description of how a HCT vehicle should be assessed in accordance to the developed PBS. The assessment procedure can be formula-based calculations, simulations or full scale testing with instrumented vehicles. However, the ambition is to avoid full scale testing. It is not within the project goals to implement an assessment tool, but only to establish the base for a future such.
3. Proposal of an implementation method which includes how the regulations should be changed, who is responsible for assessment and approval of the vehicles, compliance monitoring and enforcement.
4. Identification of a number of HCT vehicles with high efficiency, low impact on infrastructure and safe performance as potential future HCTs. The proposed HCT vehicles should include combinations that are suitable for all the three application areas of HCT, namely bulky goods, medium-heavy goods and heavy goods transport.

In this report the outcomes of work packages 1 and 2 of the project are gathered; in these work packages the existing regulation in Sweden, PBS approaches in other countries and relevant literature were reviewed and discussed, the result of which is presented in the following chapters. In Chapter 2, the Swedish regulations on dimensions and weights of heavy vehicles are presented which is followed by the review of existing PBS approaches in other countries in Chapter 3. Descriptions of common safety and manoeuvrability related performance measures for heavy vehicles are provided in Chapter 4, followed by a short summary of the results of the existing studies on heavy vehicle accident in Chapter 5. In Chapters 6 and 7, the existing regulations with respect to impact of heavy vehicles on the environment and infrastructure are described and finally in Chapter 8 some discussions on preliminary selection of performance measures for further study within the project are presented.

2. Swedish Legislations for Heavy Vehicles Dimensions and Weights

The existing legislation in Sweden allows heavy vehicle combinations with maximum length of 25.25 m and maximum weight of 60 t on the road network. However, dispensations of longer and heavier HCT vehicles for trial periods have been granted. A short summary of the regulations of heavy vehicle dimensions and weights in Sweden and the requirements for granting dispensations are provided in this chapter.

Swedish regulations on other aspects of heavy vehicles, such as braking performance, exhaust emissions and noise, which are mostly based on European regulations, are described in Chapters 3-4. It should be noted that many of the European regulations on motor vehicles, applied in Sweden, are adopted from United Nations Economic Commission for Europe (UNECE) regulations or Global Technical Regulations (GTR) which are global systems attempting to harmonize motor vehicle regulations worldwide.

2.1. Requirements on “double-combinations”

Long vehicle combinations have a long history in Sweden, and there was no limit on the total length of vehicle combinations before 1968. Quite a few were 30 m and longer. The most common length for long haul vehicles was however 24 m, and the most common combination type was truck and full trailer. In 1968, with a transition period to 1972, the maximum authorized total length was set to 24 m. Swedish regulations allowed the use of two trailers in a vehicle combination, so called double combinations, but only with reduced speed, 40 km/h. However, the Swedish transport authority granted exemptions which allowed the same speed for the so called double-combinations as for a truck and full trailer combination, if certain requirements were fulfilled. These requirements were partly prescriptive and partly performance based, which are described in the following paragraphs. The permitted total length remained 24 m.

The requirement on the brake system were prescriptive. It stipulated that all vehicle units in the combination shall be equipped with ABS according to the demands in UNECE regulation no 13. There was performance based requirements on course stability, which were tested in a double lane change manoeuvre where the maximum lateral acceleration of the towing vehicle, following the ideal path, is 1.75 m/s^2. The test had to be performed with a fully laden vehicle with evenly distributed load at the allowed speed, and the following demands had to be fulfilled (Nordström & Nordmark 1981):

- The rearward amplification of yaw velocity may not exceed 2.
- All wheels shall stay within a prescribed area.
- The dynamic load transfer must be less than 100 % on all wheels, i.e. no wheel is allowed to lift from the ground.

The requirement on the steady-state rollover stability was also performance based. The vehicle had to be tested according to the method described in (Nordström & Nordmark 1981) and the steady-state rollover threshold had to be at least 4 m/s^2 for a fully laden vehicle with evenly distributed load.

2.2. The modular system

In 1983 a European directive, 85/3/EEC, was published. This directive harmonized lengths and weights for international traffic. The length was set to 15.5 m respectively 18.0 m for tractor-semitrailer combinations and truck-trailer combinations. The gross combination weight was set to 40 t. A new European directive on weights and dimensions, 96/53/EC, was issued in 1996 (EC 1996). This directive also harmonized the lengths of heavy vehicle combinations in 85/3/EEC for national traffic, which was increased to 16.50 m and 18.75 m for tractor-semitrailer and truck combinations, respectively. However, article 4 of the directive gives each member country the possibility to use longer vehicle combinations in its territory, as long as they are based on the modular system; it reads:

“the Member State which permits transport operations to be carried out in its territory by vehicles or vehicle combinations with dimensions deviating from those laid down in Annex I also permits motor vehicles, trailers and semitrailers which comply with the dimensions laid down in Annex I to be used in such combinations as to achieve at least the loading length authorized in that Member State, so that every operator may benefit from equal condition of competition (modular concept)”. A modular combination is with other words a vehicle combination that principally consists of vehicle units defined in Annex I of the directive. An additional unit, converter dolly that converts a semitrailer to a full trailer is also necessary. These vehicle units are coupled together in combinations in order to achieve a total loading length that is a multiple of the module lengths 7.82 m and 13.6 m. These modules are implicitly defined in the directive. The lengths are the envelopes of the lengths of the loading modules. The short module 7.82 m, which is a CEN standard for swap bodies, also includes other standardized load units as 7.45 m, 7.15 m and 20 ft (6.10 m). The long module 13.6 m, which is the European semitrailer length, includes the 40 ft (12.19 m) ISO container. The commission declared in December 2006 that also the 45 ft (13.72 m) ISO container may be used nationally and in modular combinations if national legislation gives the permission, although its length exceeds 13.6 m with roughly 11 cm.

In 1998, Sweden introduced a new traffic ordinance, SFS 1998:1276, and adopted the modular system and increased the total allowed length to 25.25 m for modular vehicle combinations, while 24 m was valid for other vehicles (SFS 1998). The modular combinations are based on the two load modules with 7.82 m and 13.6 m length. These modules can be combined to three different vehicle combinations with a combination of one long and one short module:

- Truck with 7.82 m platform – converter dolly – 13.6 m long semitrailer
- Tractor – link trailer with 7.82 m platform – 13.6 m long semitrailer
- Tractor – 13.6 m long semitrailer – centre axle trailer with 7.82 m platform

There are special requirements for these vehicle combinations. A large amount of stability analyses and tests were carried out beforehand which resulted in a few prescriptive requirements with respect to stability (VV 2005):

- The distance between king-pin and the centre of the bogie of the last semitrailer shall not be less than 7.5 m.
- No axles except the front axles are allowed to steer above 40 km/h.

There are also performance based requirements on the swept path width of the vehicle combinations (VV 1997):

- The maximum allowed swept path width for each vehicle unit of a modular combination is 7.2 m in a 360 degree turn with 12.5 m radius.
- The maximum allowed swept path width for the modular combination is 10.5 m in a 360 degree turn with 12.5 m radius.

However, if the wheelbase of the last semitrailer of a combination does not exceed 8.115 m or the distance between the front point and the last axle of the combination does not exceed 22.5 m, the turning performances are deemed to comply with the requirements.

2.3. Dispensations

Ten years after successful use of the modular system in Sweden, efforts were made to develop the modular system and introduce vehicle combinations longer than 25.25 m (Aurell & Wadman 2007). As mentioned, the Swedish regulations allow currently a maximum gross combination weight of 60 t and a maximum length of 25.25 m. However, the possibility of granting dispensations for longer/heavier vehicles is addressed in the traffic ordinance (SFS 1998). Accordingly, HCT vehicles have been driven on specific routes in Sweden for trial periods. So far the following HCT vehicles have been tested on Swedish roads (Skogforsk 2014):

- ST (Större Traver) vehicle which is 24 m long with a maximum weight of 74 t. Two combinations were tested: truck-dolly-semitrailer and tractor-link trailer-semitrailer combination.
- ETT (En Trave Till) vehicle which is 30 m long with a maximum weight of 90 t. It is a truck-dolly-link trailer-semitrailer combination, see Figure 2.1.
- DUO2 vehicle which is 32 m long A-double with a maximum weight of 80 t. It is a tractor-semitrailer-converter dolly-semitrailer combination.
- ECT (En Coil Till) vehicle which is 21.5 m long with a maximum weight of 74 t. It is a tractor-link trailer-semitrailer combination.
- Wood chips transporter which is 25.25 m long with a maximum weight of 74 t. It is a truck-dolly-semitrailer.
- Clifton – Järnmalmexpress which is 24 m long with a maximum weight of 90 t. It is a truck-dolly-link trailer-semitrailer combination.

The analyses of the results show considerable CO_2-reduction, fuel saving and improved transport economy. There have been no accidents related to vehicle length or weight (Cider & Ranäng 2013, Skogforsk 2013, Adell et al. 2014).

The success of the granted dispensations has resulted in more application submissions from various operators in Sweden. Currently tens of HCT vehicle applications are being assessed by Swedish Transport Agency and Swedish Transport Administration. More than half of them only exceed the weight limit. In the following sections the procedures for granting dispensation are summarized. More information can be found in the Swedish Transport Administration handbook on dispensations (Trafikverket 2011).

Figure 2.1. An example of a vehicle driving under dispensation: ETT vehicle, 30 m and 90 t. (Foto: Erik Viklund, Skogforsk).

2.3.1. Dispensation procedure for heavier vehicles

If anyone wish to perform transports with vehicles which are within the legal length but are heavier than the permitted weight, a dispensation is required from the Swedish Transport Administration. The details of the dispensation management is currently under discussion between the Swedish Transport Administration and the Swedish Transport Agency.

2.3.2. Dispensation procedure for longer vehicles

Dispensations for vehicle combinations that are longer than 25.25 m can be granted by the Swedish Transport Agency through a regulation under the support of the Road Traffic Ordinance, chapter 4 § 12, 13 and 17b (SFS 1998). Before issuing the regulation, the Swedish Transport Agency consults primarily with the Swedish Transport Administration and the involved municipality about theirs views on the suitability of the roads that are considered for the vehicle. Furthermore, the vehicle combination will be assessed with respect to carrying capacity, swept path, dynamic stability, rollover propensity and coupling strength. For vehicle combinations which are also heavier than the permitted weight, additional assessment with respect to the ability to start and maintain motion on graded roads and the parking brake performance on a slope will be carried out. Applicants may submit calculations or results from full-scale testing to support the vehicle assessment. The vehicle performance will be checked by the Transport Agency.

The regulation includes details of the vehicle configuration, the permitted route and the demands placed on the vehicle combination, as well as, an impact assessment according to The Swedish Transport Agency template for regulation work. The regulation proposal is sent for comments to:

- Affected municipalities
- Affected county boards
- National police (Rikspolisstyrelsen)
- Regional police authority (Polismyndighet)
- Swedish Transport Agency central
- Concerned regional office within the Swedish Transport Administration
- Trade associations

Responses are compiled and evaluated. Depending on the comments, regulation may be amended. If the changes are principal, the regulation will be reviewed again by the parties. After the final assessment, the Swedish Transport Agency decides to issue the regulation. The provision is limited to 3 years.

2.4. PBS in Sweden

As described in previous sections, PBS has been partially used in Sweden for regulation of double combinations in the past, and as a basis for the modular combinations and for granting dispensations in recent years. Additionally, following the increased interest in HCT vehicles, the project of “PBS for HCT in Sweden” started at the end of 2013 to investigate the applicability of PBS in Sweden and to propose a regulatory framework based on PBS by identifying a set of performance based standards suitable for Sweden, with attention to winter road conditions. This report includes the gathered information within the work packages 1 and 2 of this project.

It should also be noted that following the increase in the maximum permitted weight of heavy vehicles in Finland from 60 t to 76 t, which has been in effect since October 2013, a maximum weight limit of 74 t has been discussed in Sweden. The Swedish Transport Agency and Swedish Transport Administration were instructed by the government to prepare a proposal on the required actions and changes in the regulations for introducing vehicle combinations with maximum weight of 74 t on the Swedish road network. The proposals were published in two reports in August 2014, see (Transportstyrelsen 2014, Trafikverket 2014), which also include some discussions on a PBS based approach for regulation of heavier and longer vehicle combinations.

3. Existing PBS Approaches

Performance based standard has been implemented in New Zealand, Canada and Australia. South Africa is also investigating the possibility of introducing PBS. In this chapter a review of the PBS approaches in these countries are provided.

3.1. New Zealand

New Zealand was probably the first country to use performance based standards for regulating heavy vehicles. PBS has been used in New Zealand within a generally prescriptive regulatory framework since about 1989 (OECD 2005). In 2002 the regulations were reviewed and a new rule came into force which required that all heavy vehicles, i.e. above 12 t for motor vehicles and 10 t for trailers, shall have a minimum steady-state rollover threshold (SRT) of 0.35 g (LTSA 2002). The reason for this was that heavy vehicles were frequently involved in rollover accidents; there is research showing that low SRT correlates with high rates of rollover accident (Winkler et al. 2000, Muller et al. 1999).

In New Zealand, the maximum legal length for vehicle combinations is 20 m and the maximum legal gross combination weight is 44 t. In 2010 the Rule was amended to allow HCT vehicles to operate on routes that can accommodate them (LTSA 2010). The requirements for route-specific permitting of HCT vehicles are not formally specified in regulations; however, in practice the regulators have used performance based standards to determine whether or not the route can accommodate these vehicles. The New Zealand transport agency has a draft document on the policies for permitting vehicles that are over 23 m but no more than 25 m in length (NZTA 2013).

The primary standard deals with low speed turning in a 120°, 12.5 m radius wall-to-wall turn with the requirement that the vehicle does not cross a 4.9 m radius inner circle. This requirement is based on the performance of the worst case standard legal vehicle which is a 19 m four axle semitrailer (de Pont 2010). Vehicles that meet this requirement are then assessed using the Australian PBS with a few variations and additions. The added performance measures are dynamic load transfer measured in a single lane change manoeuvre and high speed steady-state offtracking at a lateral acceleration of 0.2g. The regulator has discretion to decide whether or not to issue the permits and the results of the PBS based assessment is used for decision making.

3.2. Canada

In 1987, the result of the Vehicle Weights and Dimension Study, a major research study to identify HCT vehicles with minimal impact on infrastructure and satisfactory dynamic performance, was presented. It included regulatory principles for interprovincial heavy vehicle weights and dimensions in Canada, based on the seven performance based standards below (VWDS 1987):

- Static rollover threshold
- Dynamic load transfer ratio
- Friction demand in a tight turn
- Braking efficiency
- Low-speed offtracking
- High-speed offtracking
- Transient high-speed offtracking

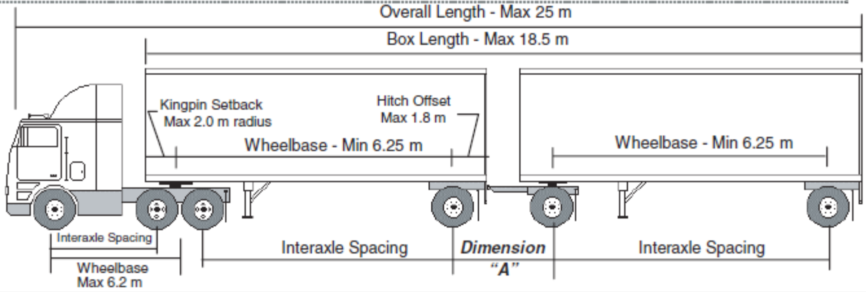
A national implementation committee developed detailed specifications for the most common vehicles based on the regulatory principles. In this work they used a prescriptive approach based on performance standards (VWDS 1987). These specifications were used to develop a national Memorandum of Understanding (MoU) on Vehicle Weights and Dimensions. All Canadian provinces implemented the MoU in 1989. The MoU was subsequently amended. The MoU defines the following vehicle categories (NCHRP 2010):

- Category 1: Tractor Semitrailer: from 3 to 6 axles, may be 23 m long
- Category 2: A Train Double: from 5 to 8 axles, may be 25 m long
- Category 3: B Train Double: from 5 to 8 axles, may be 25 m long
- Category 3: C Train Double: from 5 to 8 axles, may be 25 m long
- Category 5: Straight Truck: with 2 or 3 axles, may be 12.5 m long
- Category 6: Truck - Pony Trailer: from 3 to 6 axles, may be 23 m long
- Category 7: Truck - Full Trailer: from 4 to 7 axles, may be 23 m long
- Category 8: Intercity Bus: with 2 or 3 axles, may be 14 m long

Conclusively, PBS has been used in Canada as a basis for developing a prescriptive limits regulatory framework. Using the PBS and the results of a sensitivity analysis a set of size and weight limits, "vehicle envelopes", defining the general vehicle layout were developed. This PBS/Prescriptive approach provides flexibility in design for various vehicle categories (Woodrooffe 2012). Examples of weight and length limits for one vehicle category are shown in Figure 3.1 and Figure 3.2.

CATEGORY 2: A TRAIN DOUBLE

Part 1 - Dimension Limits

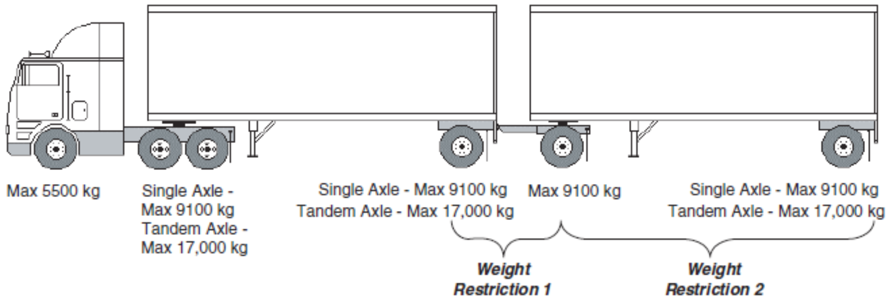


DIMENSION	LIMIT
Overall Length	Maximum 25 m
Overall Width	Maximum 2.6 m
Overall Height	Maximum 4.15 m
Box Length	Maximum 18.5 m
Tractor:	
Wheelbase	Maximum 6.2 m
Tandem Axle Spread	Minimum 1.2 m/Maximum 1.85 m
Lead Semitrailer	
Wheelbase	Minimum 6.25 m
Kingpin Setback	Maximum 2.0 m radius
Tandem Axle Spread	Minimum 1.2 m/Maximum 1.85 m
Hitch Offset	Maximum 1.8 m
Track Width	Minimum 2.5 m/Maximum 2.6 m
Second Semitrailer or Full Trailer	
Wheelbase	Minimum 6.25 m
Tandem Axle Spread	Minimum 1.2 m/Maximum 1.85 m
Track Width	Minimum 2.5 m/Maximum 2.6 m
Interaxle Spacings	
Single Axle to Single or Tandem Axle	Minimum 3.0 m
Tandem Axle to Tandem Axle	Minimum 5.0 m
Dimension "A" (from the centre of last axle on the lead semitrailer to the centre of the first axle on the converter dolly or second trailer)	Not controlled

Figure 3.1. Length envelopes for a train double in Canada, a PBS/Prescriptive approach (NCHRP 2010).

Category 2: A Train Double

Part 2 - Weight Limits



WEIGHT	LIMIT
Axle Weight Limits:	
Steering Axle	Maximum 5500 kg
Single Axle (dual tires)	Maximum 9100 kg
Tandem Axle:	
Axle Spread 1.2 m - 1.85 m	Maximum 17 000 kg
Weight Restriction 1: Sum of Axle Weights of Lead Semitrailer Plus Weight of Converter Dolly Axle	If Dimension "A" is less than 3 metres, the weight of the axle(s) on the lead semitrailer plus the weight of the converter dolly axle(s) is limited to a maximum of 17,000 kg for a two axle group or a maximum of 23,000 kg for a three axle group.
Weight Restriction 2: Sum of Axle Weights of Full Trailer or Second Semitrailer	The weight of the second trailer must not exceed the weight of the tractor drive axle(s) plus the weight of the axle(s) on the first semitrailer.
Gross Vehicle Weight Limits:	
Five Axles	Maximum 41 900 kg
Six Axles	Maximum 49 800 kg
Seven Axles	Maximum 53 500 kg
Eight Axles	Maximum 53 500 kg

Figure 3.2. Weight envelopes for a train double in Canada, a PBS/Prescriptive approach (NCHRP 2010) Australia.

3.3. Australia

Australia has the most comprehensive existing PBS approach to regulation of HCT vehicles, development of which took almost 10 years. The National Transport Commission (NTC) in Australia initiated the process around 1999 and the scheme went into operation in October 2007. The PBS scheme in Australia is a voluntary process and operates as an alternative to the prescriptive regulations; it allows operators to use vehicles which do not conform to the prescriptive limits on mass and dimension, as long as their performance comply to a set of standards, covering safety, manoeuvrability and infrastructure. The Australian Design Rules (ADRs) including brakes, couplings, suspensions and tyres remain a requirement for all heavy vehicles (Arredondo 2012, ARTSA 2003).

One of the major phases of the PBS schemed development in Australia was identification of the essential performance measures, for which the following criteria were considered (NRTC 1999):

- Relevance to replacing and augmenting prescriptive limits
- Relevance to the entire vehicle, the load carried and the vehicle-road interaction

- Perceptions of importance to the identified outcomes in all zones of vehicle operation and regulation (urban, rural and remote zones)
- Inter-relationships between measures, which make one key measure representative of a group of similar measures
- Comprehension by all stakeholders
- Ability to be enforced with confidence.

During the process of establishing the performance standards, relevant information on heavy vehicle investigation where performance based approach has been used was gathered, including information on links between the crash rates of heavy vehicles and performance measures. Furthermore, the performance of the existing Australian fleet was assessed with respect to the candidate standards, using simulation and models of 139 representative heavy vehicles. The selected vehicles covered a diverse range of vehicle configurations, freight transport tasks and operating situations. As part of the existing fleet study, results from a number of field studies with various heavy vehicles in Australia were also reviewed (NRTC 1999, NRTC 2002).

Additionally, workshops with interested parties and stakeholders were organized in all Australian states, where the candidate performance standards were discussed and adjusted accordingly. The intention was to evaluate the potential costs and benefits of the eventual PBS scheme for all stakeholders and to enhance the credibility of the scheme (NRTC 2001-2).

The current set of Australian performance measures are listed in Table 3.1. For each performance measure, four level of required performance are decided that correspond to different access to the road network. Accordingly, the Australian road network is classified into four groups (NTC 2008).Another important aspect of a PBS scheme development is the assessment and implementation procedure. Figure 3.3, depicts the application and decision making procedure for the Australian PBS scheme. The decision is made by the PBS review panel, based on the recommendation by the panel's Secretariat and assessment results. The PBS review panel is made up from a representative from each Australia state and territory, the commonwealth and an independent chairperson and deputy person, in total 11 people. The assessor is a person who has applied to carry out assessment of vehicles by numerical modelling or testing and has been authorized by the PBS review panel (Arredondo 2012).

Table 3.1 Performance measures in the Australian PBS scheme.

	Safety - Longitudinal Performance		**Safety - Directional Performance**	**Infrastructure**
Low speed	Startability Gradeability Acceleration capability	**Low speed**	Low-speed swept path Frontal swing Tail swing Steer-tyre friction demand	Pavement vertical loading Pavement horizontal loading Tyre contact pressure distribution Bridge loading
High speed	Overtaking provision Tracking ability on a straight path Ride quality (driver comfort)	**High speed**	Static rollover threshold Rearward amplification High-speed transient offtracking Yaw damping coefficient Handling quality Directional stability under braking	

The assigned permit by the PBS review panel might include some operating conditions relevant to the usage of the vehicle; examples of such operating conditions are: fitting an underrun protection device, displaying a long vehicle sign at the front and rear of the vehicle, road friendly suspension for the tandem axles, etc. In some circumstances Australian road authorities may also require the vehicle to operate under the Intelligent Access Program (IAP) and/or to fit the vehicle with on board mass monitoring. The IAP is a national program for remote monitoring of the vehicles and is capable of monitoring vehicles' route, time and speed (Arredondo 2012).

The Australian PBS scheme is under continuous assessment and review. Some of the operational improvements under considerations are: allowing the manufacturers to certify their own vehicles and allowing for the modular assessment, i.e. independently assessing the prime mover and the towed units (Arredondo 2012).

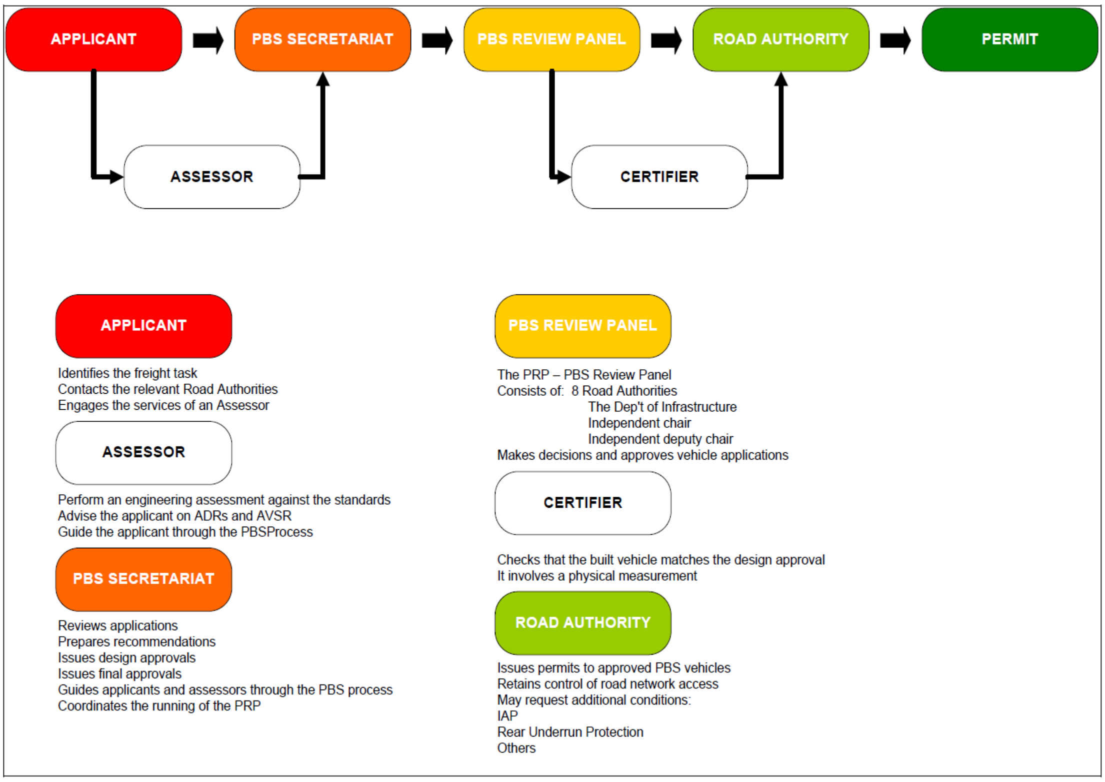


Figure 3.3. Application and decision making procedure of the Australian PBS scheme (Arredondo 2012), South Africa.

3.4. South Africa

The existing legislation in South Africa, allows heavy vehicles with maximum overall length of 22 m and maximum weight of 56 t. However, in August 2004 a PBS committee was established to investigate the PBS approach and evaluate its potential in South Africa. For this purpose, demonstration projects of concept heavy vehicles are being carried out under the Road Transport Management System (RTMS) scheme. RTMS is an industry-led, voluntary self-regulation scheme in South Africa that encourages transport companies and cargo owners to implement a vehicle management system that promotes safety, productivity and preservation of the road infrastructure (Dessin et al. 2008, Nordengen 2012).

In the RTMS scheme, the Australian PBS and suggested level of performance are used to certify heavy vehicles for the demonstration projects. However, the infrastructure standards, such as the limits for axle loads and bridge formulas, are adapted to South African road traffic regulations and design codes of practice (Nordengen 2012).

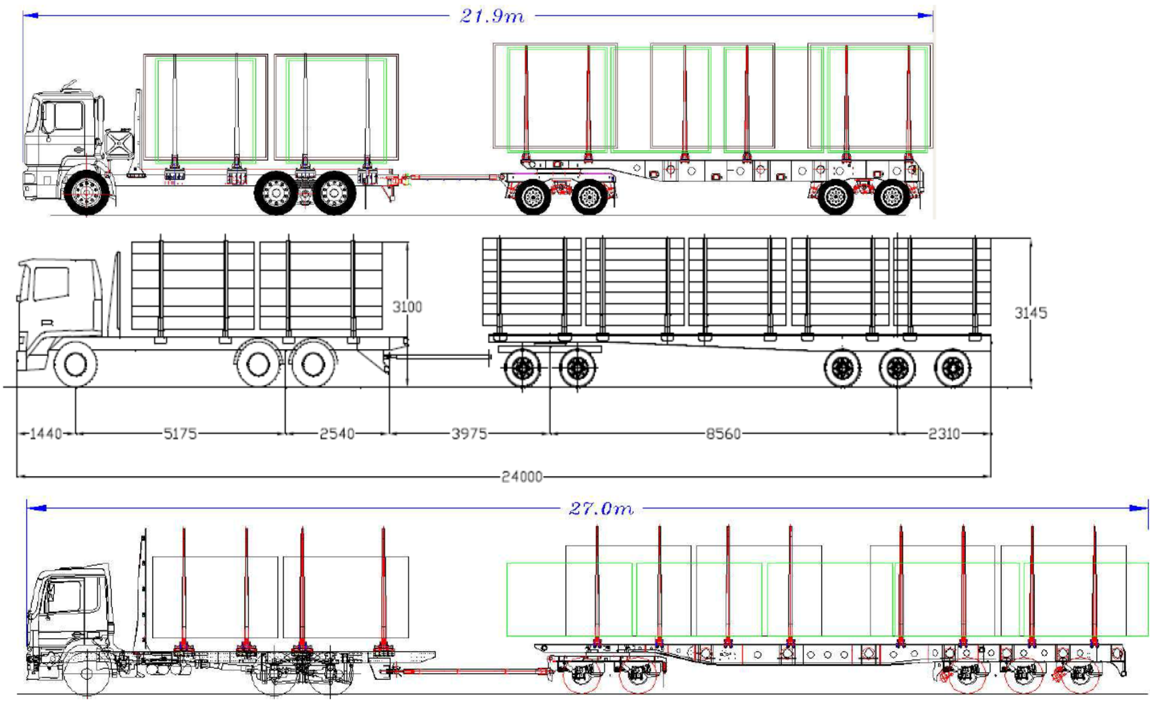


Figure 3.4. Layout of the 22 m baseline (legal), Mondi (24 m) and Sappi (27 m) demonstration vehicles (Nordengen 2010).

The first two PBS demonstration projects were implemented in forestry industry, more specifically within Sappi Forests Ltd and Mondi Business Paper which are two major timber growers and paper companies in South Africa. The vehicles were designed and manufactured to comply with the Level 2 safety standards of the Australian PBS system and went into operation in November and December 2007. Both Sappi and Mondi vehicles were a truck-dolly-semitrailer combination; The Sappi PBS vehicle was 27 m long with total mass of 67.5 t, while the Mondi PBS vehicle had an overall length of 24 m and total mass of 64.1 t, see Figure 3.4. The following extra safety features were incorporated in the design of one or both of the Sappi and Mondi vehicles:

- ABS and EBS
- Air suspension
- Pneumatic straps (self-tightening) for load securement
- Lift axles
- Underslung drawbar
- On-board load cells for payload control
- Central tyre inflation
- Vehicle tracking system
- Anti-rollover devices
- Special driver training

The PBS demonstration results showed a number of improvements in performance of both Sappi and Mondi vehicles compared with the 22 m baseline (legal) vehicle. This has resulted in the approval of 58 additional permits for PBS demonstration vehicles in South Africa, most of which are operating in the forestry transport sector (Nordengen 2010, Nordengen 2012).

4. Safety and Manoeuvrability

In this chapter the safety and manoeuvrability related performance measures, which were found in existing PBS approaches or studies on performance of heavy vehicles, are described. They are categorized into 4 groups based on the practical goals they address (adapted from the goals used by Fancher, et al 1989):

Traction: The heavy vehicle should be able to start motion, maintain motion and attain a desirable level of acceleration; measures that can be used to assess the vehicle performance with respect to these goals are listed in this group.

Tracking: The rear end of the vehicle and all the units within the vehicle combination should follow the path of the front end of the vehicle with adequate fidelity; measures that can be used to assess the vehicle performance with respect to this goal are listed in this group.

Stability: The vehicle should be stable, attain directional control and remain upright during manoeuvring; measures that can be used to assess the vehicle performance with respect to these goals are listed in this group.

Braking: The vehicle should safely attain a desirable level of deceleration during braking; measures that can be used to assess the vehicle performance with respect to this goal are listed in this group.

It should be noted that the coupling strength is not considered here, since there is a recent ISO standard, ISO 18868:2013, in which the formulae to calculate the performance requirement for the coupling equipment in different vehicle combinations, including HCT vehicles, are provided.

Another issue which is not addressed in this section, but should be investigated in another project, is the possible associated risk with overtaking of long heavy vehicles and the required measures. A study on overtaking of 30 m long HCT vehicles has been conducted by the Swedish road and transport research institute, VTI, which showed no significant risk; however, it was concluded that HCT vehicles might have a small negative effect on overtaking situations and that further field studies are required (Andersson et.al, 2011).

4.1. Traction

The performance measures that address the traction issue of the heavy vehicles are:

- Startability
- Gradeability
- Acceleration capability

The description of these performance measures follows.

4.1.1. Startability

A heavy vehicle should be able to commence from a standing start on an upgrade road, otherwise it can become a risk and an inconvenience to the other road users.

Test method

From a standing start on a slope having an upgrade not less than the specified grade, the vehicle being assessed must commence and maintain steady forward motion. Steady forward motion on the specified grade is achieved when the vehicle's speed is either constant or increasing for a distance of at least 5 m (NTC 2008).

4.1.2. Gradeability

A heavy vehicle should be able to maintain acceptable speed on an upgrade road, otherwise it delays the other vehicles travelling in the same direction and increases the traffic congestion, which in turn can lead to an accident.

The vehicle-related factors that determine gradeability also influence startability. However, a vehicle may be designed to maximize gradeability at the expense of its startability performance or vice versa (geared low or high) (NTC 2008).

Test method

With the vehicle being assessed in forward motion on a slope having an upgrade not less than the specified grade, steady forward motion must be attained at a speed at least equal to the specified minimum speed. Steady forward motion is achieved when the vehicle's speed is either constant or increasing for a distance of at least 5 m (NTC 2008).

4.1.3. Acceleration capability

A heavy vehicle should be able to accelerate from rest with an acceptable level of acceleration, otherwise it will require too long time to clear areas such as intersections and railway crossings. Long clearance times will delay the traffic flow and can impose safety risks, especially if the sight distances are inadequate.

Test method

From a standing start the vehicle being assessed must accelerate, changing through the gears as required, over a specified distance within a time less than the specified maximum value (NTC 2008).

4.2. Tracking

The performance measures that address the tracking issue of the heavy vehicles are:

- Tracking ability on a straight path
- Frontal swing
- Tail swing
- Low-speed offtracking
- High-speed steady-state offtracking
- High speed transient offtracking

The description of these performance measures follows. The term "prescribed path", used in the provided descriptions, refers to the path of the outer front wheel or the front outer corner of the hauling unit.

4.2.1. Tracking ability on a straight path

When a heavy vehicle is travelling at high speed on a straight road with a crossfall and uneven surface, the towed units do not follow the prescribed path exactly and will undergo some small lateral excursions. The ability of the towed unit to follow the prescribed path is called tracking ability and is desirable. In other words, the vehicle's swept path should be limited while travelling at high speed on a straight road with a crossfall and uneven surface; otherwise it might encroach into adjacent lanes or interfere with roadside objects (Prem et al. 2000). Tracking ability on a straight path improves by higher cornering stiffness of tyres, shorter wheelbase, and fewer articulation points (NRTC 2002).

Test method

The vehicle being assessed must travel on a defined straight road segment, with a crossfall not less than a specified value, at a certain speed. The vehicle must be driven in a normal manner and follow a straight path as closely as possible and the tracking ability, i.e. total swept width, should be less than the specified maximum value (NTC 2008). In case of simulation, a realistic road surface based on measured road profiles should be used (Prem et al. 2000).

4.2.2. Frontal swing

When a heavy vehicle negotiates a turn at low speeds, front outer corner of the vehicle units, including the hauler unit, track outboard the prescribed path. The maximum distance between the path of the front outer corner of any of the vehicle units and the prescribed path is the frontal swing and should be limited. Frontal swing is an indicator of the potential intrusion into adjacent lanes or interference with the roadside objects and decreases with shorter front overhang and shorter wheelbase (NTC 2008).

Test method

The vehicle being assessed must be driven through a specified turn, defined by the turn radius and the arc segment, at a low speed, and the frontal swing should not exceed a certain value. Various turn radius and arc segments have been adopted in different PBS approaches, such as:

- 90° circular arc of 12.5 m radius is used in Australian PBS (NTC 2008)
- 180° circular arc of 12.5 m radius is used in New Zealand (LTSA 2002)

4.2.3. Tail swing

When a heavy vehicle negotiates a turn at low speeds, during the initial and final stages of the turn, the rear outer corner of the vehicle units track outboard the prescribed path. The maximum distance between the path of the rear outer corner of any of the vehicle units and the prescribed path during the initial and final stage of the turn is the tail swing and should be limited. For conventional vehicles tail swing is only significant during the initial stage of the turn; but for trailers with steerable axles, it should be tested both on the initial and final stage of the turn. Tail swing is an indicator of the potential intrusion into adjacent lanes or interference with the roadside objects and decreases with shorter rear overhang (NRTC 2008).

Test method

The vehicle being assessed must be driven through a specified turn, defined by the turn radius and the arc segment, at a low speed, and the tail swing should not exceed a certain value. A 90° circular arc of 12.5 m radius has been used in Australia and New Zealand (NTC 2008, LTSA 2002).

4.2.4. Low-speed offtracking/swept path

When a heavy vehicle negotiates a turn at low speeds, rear end of the vehicle track inboard the prescribed path. The maximum distance between the path of the rearmost axle of the vehicle and the prescribed path is called low-speed offtracking and should be limited. In some approaches the vehicle swept path is used instead of offtracking. Low-speed offtracking/swept path is an indicator of the potential intrusion into adjacent lanes or interference with the roadside objects and decreases with more articulation points and shorter wheelbase (NRTC 2002).

Test method

The vehicle being assessed must be driven through a specified turn, defined by the turn radius and the arc segment, at a low speed, and the low-speed offtracking should not exceed a certain value. Various turn radius and arc segments have been adopted in different PBS approaches, such as:

- 90° circular arc of 12.5 m radius is used in Australian PBS (NTC 2008)
- 120° circular arc of 12.5 m radius is used in New Zealand PBS (NTZA 2013)
- 90° circular arc of 11 m radius is used in Canadian PBS (Woodrooffe 2012)
- 360° circular arc of 12.5 m radius is used in Sweden (VV 1997)

4.2.5. High-speed steady-state offtracking

When a heavy vehicle negotiates a steady turn at high speeds, rear end of the vehicle track outboard the prescribed path. The maximum distance between the path of the rearmost axle of the vehicle and the prescribed path is called high-speed steady-state offtracking and should be limited. High-speed steady-state offtracking is an indicator of the potential intrusion into adjacent lanes or interference with the roadside objects.

Test method

The vehicle being assessed must be driven through a specified turn, defined by the turn radius, at a specified speed, and the high-speed steady-state offtracking should not exceed a certain value. Various speed and turn radius have been adopted in different PBS approaches and studies, such as:

- Negotiating a turn of 393 m radius at 100 km/h (lateral acceleration of 0.2 g) is used in Canadian PBS (Woodrooffe 2012)
- Negotiating a turn of 366 m (1200 ft) radius at speed of 88.5 km/h (55 mph – lateral acceleration of 0.17 g) was used by Fancher, et al. 1989.

4.2.6. High-speed transient offtracking

During a sudden manoeuvre at high speeds, the rear end of the heavy vehicle track outboard the prescribed path. The maximum distance between the path of the rearmost axle of the vehicle and the prescribed path in a dynamic manoeuvre is called high-speed transient offtracking and should be limited. In some studies path of the rear end of the last unit is considered instead of the rearmost axle, for the sake of fair comparison, due to different positioning of the axles in different combinations (Kharrazi 2013). High-speed transient offtracking is an indicator of the potential intrusion into adjacent lanes or interference with the roadside objects and decreases with longer wheelbase and increased cornering stiffness of tyres (NRTC 2002).

Test method

The vehicle being assessed must execute a sudden manoeuvre such as a lane change. In Australian PBS, a single lance change (SLC) performed at 88 km/h with a peak lateral acceleration of 0.15 g at the front axle of the hauling unit is used, which is based on the ISO SLC (14791) (NTC 2008). In some US studies, the SAE SLC (J2179) is used (Winkler & Fancher 1992). SAE J2179 is now harmonized with ISO 1479. In Sweden a double lane change manoeuvre at speed of 80 km/h, with lateral displacement of 3m and a peak lateral acceleration of 1.75 m/s^2 has been used (Nordström & Nordmark 1981).

4.3. Stability

The performance measures that address the stability issue of the heavy vehicles are:

- Steady-state rollover threshold
- Load transfer ratio
- Rearward amplification
- Yaw damping coefficient
- Handling quality (understeer/oversteer)
- Friction demand of steer tyres in tight turns

- Friction demand of drive tyres in tight turns

The description of these performance measures follows.

4.3.1. Steady-state rollover threshold

A vehicle negotiating a turn is subjected to an overturning moment that is proportional to the lateral acceleration. The steady-state rollover threshold (SRT) is the maximum severity of the steady turn, i.e. lateral acceleration, which a vehicle can sustain without reaching the rollover threshold. This performance measure is affected powerfully by the loading condition of the vehicle (better stability with decreased height of centre of gravity) and has been strongly linked to rollover accidents of heavy vehicles (Winkler et al. 2000, Muller et al. 1999), see section 3.6 on crash rates. The SRT performance measure is also used for regulation of tank vehicles in Europe, according to UNECE regulation no 111 (UNECE 2001).

Test method

The vehicle being assessed must be driven on a circular path with slowly increasing speed until a vehicle unit (or a roll-coupled unit) rolls over; the measured lateral acceleration at the point of rollover is the steady-state rollover threshold. Alternatively, a tilt table can be used where the vehicle is placed on a tilt table and gradually titled until it rolls. It should be noted that the accuracy of the tilt table procedure decreases as the tilt angle increases, however up to tilt angles of 27° , corresponding to SRT of 0.5 g, the test accuracy is acceptable and most heavy vehicles have a SRT value below 0.5 g (Latto 2001).

4.3.2. Load transfer ratio

The load transfer ratio (LTR) is a measure of the roll stability of a heavy vehicle and characterizes how close a vehicle gets to rolling over in a dynamic manoeuvre. It measures the fractional change in the load carried on the left and right side tyres, which indicates the proximity of a total lift off. This measure can be expressed as an average value, as in eq. 3.1, for all axles. Some tractors may have low roll stiffness of the steer axle. It then has a negligible effect and may be exclude. (Ervin & Guy 1986). An alternative approach is to calculate LTR for each axle separately, i.e. no wheel lift off may occur. LTR has a value of 0 when the vehicle is at rest and will rise to a value of 1 when all of the vehicle/axle load transfers to one side.

$$\frac{\sum|F_L-F_R|}{\sum(F_L+F_R)} \qquad (3.1)$$

Test method

Same test method as for the high-speed transient offtracking can be used, i.e. performing a sudden manoeuvre such as lane change at high speed.

4.3.3. Rearward amplification

In a sudden manoeuvre at high speeds, the lateral motion of the hauling unit of a heavy vehicle combination is amplified increasingly by each successive unit; this phenomenon is called rearward amplification and is a matter of concern for vehicle combinations with more than one articulation point. Rearward amplification is defined as the ratio of the peak value of a motion variable of interest for the rearmost unit to that of the hauling unit; it is usually given in terms of lateral acceleration or yaw rate. This performance measure indicates the increased risk for a swing out or rollover of the last unit compared to what the driver is experiencing in the towing unit. Rearward amplification improves with fewer articulation points, more forward location of coupling points, longer wheelbase and higher cornering-stiffness of tyres (Prem et al. 2000).

Test method

Same test method as for the high-speed transient offtracking can be used, i.e. performing a sudden manoeuvre such as lane change at high speed. It should be noted that the maximum rearward amplification occurs at different steering frequency for various heavy vehicle combinations. Thus, it is advised that the manoeuvring should be performed for a range of frequencies and the worst case be selected for fare comparison (Ervin & Guy 1986). In the Australian approach, a steer frequency of 0.4 Hz is used instead of finding the worst frequency as suggested in ISO 14791 (NTC 2008).

4.3.4. Yaw damping coefficient

After performing a severe manoeuvre, the swinging or yaw oscillations of the towed units in heavy vehicle combinations decay with various rates. The yaw damping coefficient is a measure of how quickly these oscillations settle down and is defined as damping ratio of the least damped articulation joint of the heavy vehicle combination. Yaw damping ratio of an articulation joint is determined from the amplitudes of the articulation angle of subsequent oscillations. Low yaw damping coefficient result in prolonged swinging of the towed units and can lead to loss of control or collision with a vehicle in an adjacent lane or roadside object (NTC 2008). Yaw damping coefficient improve with longer wheelbase and increased cornering stiffness of tyres (NRTC 2002).

Test method

The vehicle being assessed, must be driven at certified speed and steered with a pulse input, e.g. in accordance to the pulse input method in ISO 14791. The damping of the articulation angles shall be determined during free oscillations of the vehicle combination.

4.3.5. Handling quality

Handling quality (under/oversteer) refers to the responsiveness and ease of directional control of the heavy vehicle, which is related to the understeer/oversteer behaviour of vehicle. El-Gindy and Woodrooffe at 1990 proposed a “three-point” method based on the handling diagram of the vehicle, as a measure of the handling quality of the vehicle. The three-point method can be summarized as follows (NRTC 2001-1):

- First point: the understeer coefficient at lateral acceleration of 0.15 g, should be within a recommended range.
- Second point: the lateral acceleration at which the vehicle switches from understeer to oversteer should be higher than a certain value.
- Third point: the understeer coefficient at a certain, rather high, lateral acceleration should be higher than the critical understeer coefficient.

In some studies, the single value of understeer coefficient at lateral acceleration of 0.25 g is considered as a measure of handling quality, such as in (Ervin & Guy 1986), where it is referred to as the steady-state yaw stability.

In the study by Fancher, et.al, in 1989, the steering sensitivity, that is, the rate of change of steering angle with respect to lateral acceleration, evaluated at 55 mi/h and lateral acceleration of 0.3 g is used as a measure of handling quality.

Test method

The handling diagram of the vehicle being assessed should be obtained, e.g. by driving at constant speed and slowly increasing the steering input, more information about the handling diagram of a vehicle can be found in (Pacejka 2004).

4.3.6. Friction demand of steer tyres in tight turns

For a heavy vehicle negotiating a tight turn at low speed, loss of steerability might occur if the demanded friction at the steer tyres for maintaining the desired path, exceeds the available friction. This measure pertains the resistance of widely spread drive axles to travelling around a tight turn which will result in a higher demand for side force at the steer axle. In such situations the vehicle will exhibit extreme understeer behaviour and plough straight ahead which can lead to collisions. The friction demand of steer tyres is defined as the friction coefficient demanded by the steer tyres of the hauling unit in a prescribed 90° low speed turn.

Test method

The vehicle being assessed must be driven through a specified turn, defined by the turn radius and the arc segment, at a low speed, and the required friction should not exceed a certain value. In the Australian PBS, a 90° circular arc of 12.5 radius is used (NTC 2008).

4.3.7. Friction demand of drive tyres in tight turns

A heavy vehicle negotiating a tight turn at low speed, might exhibit a jackknife, if the demanded friction at the drive tyres of the hauling unit exceeds the available friction. This measure pertains the resistance of widely spread axle set in the trailers to travelling around a tight turn which will result in a higher demand for side force at the drive axles of the hauling unit. The friction demand of drive tyres is defined as the friction coefficient demanded by the drive tyres of the hauling unit in a prescribed 90° low speed turn.

Test method

Same test method as for the friction demand of steer tyres can be used, i.e. negotiating a tight turn at a low speed.

4.4. Braking

There are quite a few measures which address the braking performance of the heavy vehicles, many of which already exist in Swedish/European regulation, which are based on ECE R13 (UNECE 2008). The described performance measures herein are:

- Braking deceleration/stopping distance
- Braking efficiency
- Braking stability on a straight path
- Braking stability in a turn
- Braking stability on a split friction surface
- Parking ability on a grade.

4.4.1. Braking deceleration/stopping distance

A heavy vehicle should be able to achieve high levels of deceleration to have a short stopping distance. The performance measure that address this aspect of a heavy vehicle performance, can be either defined as the desirable deceleration level or maximum stopping distance. The deceleration performance after repeated or continuous braking (fade test) is also important.

Test method

Using a full-pedal brake application the vehicle is stopped from a certain speed and the deceleration/stopping distance is measured. In EU regulation braking from speeds of 60 and 90 km/h is used for single braking; while, for fade braking test, only deceleration from 60 km/h, after 20 repetitions of braking from 60 to 20 km/h or continuous braking for 6 km, is considered (UNECE 2008). In US regulation braking from speed of 60 mph (95.5 km/h) is used (FMVSS 2012).

4.4.2. Braking efficiency

A heavy vehicle should effectively utilize the tyre/pavement friction to be able to stop quickly in a stable manner and avoid wheel locking. If the front wheels lock, the vehicle will not be responsive to steering, if the rear wheels of the hauling unit lock, a jackknife may occur and if the wheels of the towed units lock, a trailer swing may happen. Braking efficiency is a measure that address this aspect of a heavy vehicle performance and is defined as the ratio of achievable deceleration to the ideally supported deceleration by the tyre/pavement friction, in an emergency stop without locking any wheels (Fancher et.al, 1989).

Test method

The vehicle being assessed is braked from a certain speed to standstill. Braking efficiency must be more than the specified value. In Canada an emergency stop of 0.4 g deceleration is used (NCHRP 2010). In EU regulation, the braking efficiency is measured on road surfaces with a friction coefficient of 0.8 and 0.3 (or less) with an initial speed of 50 km/h (UNECE 2008).

4.4.3. Braking stability on a straight path

A heavy vehicle should be able to remain stable and stay in a straight path during heavy braking. This performance measure is incorporated in EU brake regulation and is also part of the Australian PBS.

Test method

The vehicle being assessed should be stopped from a certain speed, to achieve the defined assessment deceleration level on a straight path. The vehicle must stay within a certain wide lane. In the EU regulation, speed of 90 km/h with the deceleration level of 4 m/s2 is used (UNECE 2008). In the Australian PBS speed of 60 km/h with a range of deceleration levels from 0.2 to 0.4 g, depending on the combination type, is used.

4.4.4. Braking stability in a turn

A heavy vehicle should be able to brake heavily while negotiating a turn and stay in the desired path, i.e. within its traffic lane, during braking. This performance measure exist in the US regulations on air brake systems (FMVSS 2012).

Test method

Using a full-pedal brake application the vehicle is stopped from a certain speed on a specified turn, defined by the turn radius. The vehicle must stay within a certain wide lane. In the US regulations speed of 30 mph (48.3 km/h), turn radius of 500 ft (152 m) and a 12 ft (3.7 m) wide lane is used.

4.4.5. Braking stability on a split friction surface

A heavy vehicle should be controllable by the driver when it is braked on a road with split friction. This performance measure is used in the EU regulation and is defined as the maximum steering corrections required by the driver to keep the vehicle on a straight path. Furthermore, the wheels should not lock.

Test method

The right and left wheels of the vehicle being assessed should be situated on surfaces with differing friction coefficients (kH and kL), where kH > 0.5 and kH/kL > 2, then Using a full-pedal brake application the vehicle is stopped from a certain speed (50 km/h in EU regulation). The required steering corrections by the driver during the test should be less than a certain limit and no wheel locking should occur (UNECE 2008).

4.4.6. Parking ability on a grade

The parking brake of a heavy vehicle shall be able to hold the vehicle on a grade, in forward and reverse directions. This performance measure is defined as the maximum grade, on which a heavy vehicle can be parked using the parking brake.

Test method

The vehicle being assessed should be parked on a grade, in forward and reverse directions, using the parking brake. The vehicle should stay still on a certain grade.

4.5. Summary of performance measures

Table 4.1 provides a summary of the described performance measures and their corresponding required level of performance in the existing PBS approaches in Australia, New Zealand and Canada. It should be noted that part of the braking performance measures are listed separately in Table 4.2, since the corresponding listed levels of performance are based on the EU and US regulations.

Table 4.1. Safety and manoeuvrability measures and corresponding required level of performance in the PBS approaches in Australia, New Zealand and Canada.

	Performance measure	Australia*	New Zealand**	Canada
Traction	Startability	Achievable grade 15, 12, 10, 5 [%]	Based on Australian PBS	-
	Gradeability	Achievable grade 20, 15, 12, 8 [%] Viable speed on 1% grade 80, 70, 70, 60 [km/h]	Based on Australian PBS	-
	Acceleration capability	Travel time for 100 m 20, 23, 26, 29 [s]	Based on Australian PBS	-
Tracking	Tracking ability on a straight path	swept width at 90 km/h 2.9, 3.0, 3.1, 3.3 [m]	-	-
	Frontal swing	90° turn of 12.5 m radius 0.7 [m]	Based on Australian PBS	-
	Tail swing	90° turn of 12.5 m radius 0.3, 0.35, 0.35, 0.5 [m]	Based on Australian PBS	-
	Low-speed swept path (offtracking for Canada)	90° turn of 12.5 m radius 7.4, 8.7, 10.6, 13.7 [m]	120° turn of 12.5 m radius 7.6 [m]	90° turn of 11 m radius 6 [m]
	High-speed steady-state offtracking	-	100 km/h, 393m radius 0.6 [m]	100 km/h, 393m radius 0.46 [m]
	High-speed transient offtracking	ISO SLC, 88 km/h, 0.4 Hz 0.6, 0.8, 1.0, 1.2 [m]	Based on Australian PBS	ISO SLC, 88 km/h, 0.4 Hz 0.8 [m]

	Performance measure	Australia*	New Zealand**	Canada
Stability	Steady-state rollover threshold	0.35 [g]	Vehicle with ESC: 0.35 [g] Vehicle without ESC: 0.4 [g]	0.4 [g]
	Load transfer ratio	-	ISO SLC, 88 km/h, 0.4 Hz 0.6 [-]	ISO SLC, 88 km/h, 0.4 Hz 0.6 [-]
	Rearward amplification	ISO SLC, 88 km/h, 0.4 Hz 5.7 SRT (lateral acc.)	Based on Australian PBS	-
	Yaw damping coefficient	ISO 14791 - pulse input 0.15 [-]	Based on Australian PBS	-
	Handling quality	Yet to be defined	-	-
	Friction demand of steer tyres in a tight turn	90° turn of 12.5 m radius 80%	Based on Australian PBS	-
	Friction demand of drive tyres in a tight turn	-	-	90° turn of 11 m radius 0.1 (friction coefficient)
Brake	Braking efficiency	-	-	0.4 g braking 70%
	Braking stability on a straight path	60 km/h, 0.2-0.4g braking 2.9, 3.0, 3.1, 3.3 [m]	Based on Australian PBS	-

*Four values for different level of access to the road network
** In New Zealand, the PBS requirements are not formally specified in the regulations; however in practice, the regulators use Australian performance based standards with a few variations and additions to assess a vehicle.

Table 4.2. Braking performance measures and corresponding required level of performance in the EU and the US regulations.

Performance measure	EU (ECE R13)	US (FMVSS 121)
Braking deceleration/stopping distance	5 m/s2 from 60 km/h 4 m/s2 from 90 (80) km/h* 4 m/s2 from 60 km/h (after 20 repeated braking from 60 to 20 km/h at 3 m/s2) 3.3 m/s2 from 60 km/h (after 6 km braking)	76.2 m from 96.5 km/h
Braking efficiency	75%, 50 km/h, friction coefficients of 0.3 & 0.8	-
Braking stability on a straight path	Subjectively, 4 m/s2 braking from 90 (80) km/h*	-
Braking stability in a turn	-	3.7 m lane in a 152 m radius turn at 48.3 km/h
Braking stability on a split friction surface	SWA<240° (120°)**, kH>0.5, kH/kL>2, 50 km/h	
Parking ability on a grade	18 % slope, single vehicle, loaded up to GVW. 12 % slope, unbraked trailer, loaded up to GCW	20% slope

* Value in parenthesis is for tractors
** Value in parenthesis is for the first 2 seconds

4.6. Correlation between performance measures and crash rates

The correlation between vehicle performance measures and crash risk must be known in order to *quantify* the benefits associated with any performance measures introduced to improve vehicle stability (Mueller et al 1999). It is reasonable to assume that a vehicle that scores high in e.g. stability performance would have a lower risk of being involved in a stability-related crash. However there is very little published evidence to support this assumption. A few studies correlating stability performance measures with crash risk have been made on vehicle fleets in Australia (de Pont 2005) and New Zealand (Mueller et al. 1999). However, those vehicle fleets included no HCT vehicles.

A determination of the correlation between performance measures and crash rates for a given vehicle configuration requires its performance values and a sufficient number of crashes reported for the vehicle configuration in question. Values for a vehicle's performance measures are ideally determined by computer simulations or by physically testing the vehicle. However, cases will occur where the performance values of a crash-involved vehicle configuration have not been determined by either of these methods.

As a solution to this issue, linear regression techniques, in which simulation data for more than 50 vehicles formed the basis of the regression matrix, were used in the New Zealand study. The regression models were applied to the set of vehicles and their parameters that could be obtained from the database on vehicle configurations of the New Zealand vehicle fleet, as well as the database on rollover or loss-of-control crashes involving heavy vehicles. By this method, distributions of a performance measure for both the general fleet and the crashed vehicles were obtained, from which the relative crash risk for different values of the performance measure could be estimated (Mueller et al. 1999).

By this methodology, the correlation between a number of performance measures and crash rates for three vehicle combinations were derived; B-trains, truck-trailers and tractor-semitrailers. Between 1996 and 1999, these vehicle combinations had been involved in a total of 161 rollover or loss-of-control crashes leading to fatal, serious/minor injury or property damage only (Mueller et al. 1999).

The examined performance measures were static rollover threshold, high-speed transient offtracking, dynamic load transfer ratio, yaw damping ratio, rearward amplification and high-speed steady-state offtracking. However, for the last two, it was not possible to obtain a satisfactory regression fit. The analysis results, Table 4.3, show that in all cases, except high-speed transient offtracking, the proportion of vehicles not meeting the target performance standard is greater among the crashed vehicles than among the fleet. These results indicate a clear correlation between poor performance and crash rate. In the case of yaw damping ratio, the relationship has high uncertainty because only a small number of vehicles do not meet the target.

Table 4.3. Poor performance and crash rate correlation in New Zealand (Mueller et al. 1999).

Performance measure	Target Value	Fleet performance*	Crashed vehicle*
Static rollover threshold	>= 0.35 g	15%	40%
Dynamic load transfer ratio	<= 0.6	35%	58%
High-speed transient offtracking	<= 0.8 m	0	0
Yaw damping ratio	>= 0.15	1.2%	4.7%

* Percentage of the vehicles for which the target value is not met

The relative crash rates in Figure 4.1 were obtained by dividing the static rollover threshold distribution for the crash involved vehicles by the SRT distribution of the whole fleet. The base line or average crash rate is one. It can be seen that as the SRT increases, the crash involvement rate decreases. Vehicles with an SRT of 0.3 g or less have more than 3 times the average rollover crash rate. Similar plots were obtained with respect to the rest of investigated performance measures. It was shown that the worst performing vehicles with respect to dynamic load transfer ratio (>=0.7) have roughly 3 times the crash rate of those vehicles which meet the minimum target values (0.6). All vehicles surveyed had high-speed transient offtracking values below the maximum target value of 0.8 m. However, the relative crash rate trend showed that the accident rate increases with an increasing offtracking.

The more general accident studies on heavy vehicles, specifically HCT vehicles, are reviewed in the next chapter.

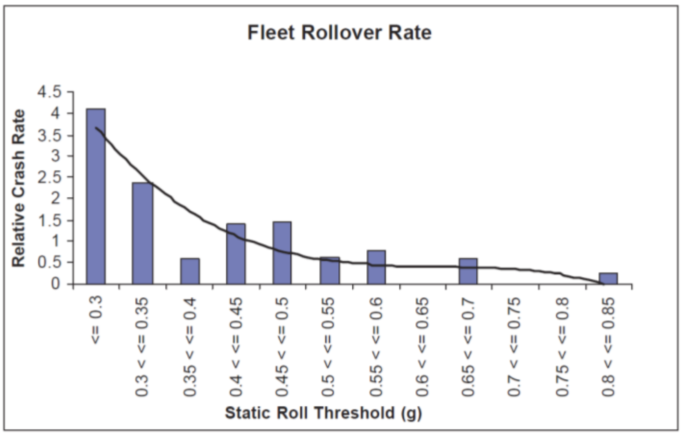


Figure 4.1. Crash involvement rate with respect to SRT (Mueller et al. 1999).

5. Heavy Vehicle Accidents

In order to identify accident types in which heavy vehicles, specifically HCT vehicles, are overrepresented, the conducted studies on heavy vehicle accidents in different countries were reviewed; the review outcomes are summarised in this chapter.

5.1. Europe

In Sweden and Finland, heavy vehicles based on European Modular System (EMS), with maximum length of 25.25m and a gross vehicle weight of 60 t, are allowed on the road network. While these EMS vehicles are not regarded as HCTs in Sweden and Finland, they would be in other European countries. In recent years the Netherlands, Denmark, Germany and Norway have trialled EMS vehicles (DRD 2011, Eidhammar et al. 2009, MIE, 2011).

During the trials in the Netherlands and Denmark with EMS vehicles only a few accidents were reported. The accidents were judged to be more or less typical heavy vehicle accidents and could not be attributed to the characteristics of the vehicles under trial (DRD 2011, MIE 2011).

During the EMS trials in Netherlands between 2007 and 2010, 54 accidents were reported which resulted in property damage only, except two with minor occupant injuries. Among the factors contributing to the accidents, none could be attributed directly to the characteristics of the EMS vehicles. There were however indications of indirect interactions between the vehicle length and adverse weather and road surface, and other drivers' misjudgement of the length at lane changes, entrance ramps and during overtaking. It was however pointed out that such situations and accidents also occur with conventional heavy vehicles. The number of accidents with EMS vehicles were also too low to determine if some accidents are more common for EMS than conventional vehicles (MIE 2011).

In Denmark there were 408 registered EMS vehicles in 2010. Between 2008 and 2010, four accidents were reported, whereof two with actual EMS vehicles. This accident number was lower than expected in comparison with the average accident involvement of heavy vehicles. However, the EMS-vehicle travelled mostly on larger and safer roads which may explain the difference. The conclusion was that the sample from the test period was too small for evaluating the safety of the EMS vehicles based on the accident data (DRD 2011).

In a recent study, Balint et al. (2013) analysed Swedish accident data involving heavy vehicles from the years 2003-2012. Average crash rates showed that the rates for fatal or severe crashes decrease with increasing length, and that the group of long combinations (18.76 – 25.25 m) had the lowest crash rate, see Table 5.1. The authors had no available data on loading and thereby weight of the vehicles involved, and was not able to control for road type. The observed crash rates are therefore influenced by the exposure patterns and it cannot be excluded without further investigation that the lower accident rate for "long" combinations reflects that such combinations typically travelled on safer roads. Nevertheless, based on the available data, the study did not find any evidence that long combinations, exceeding 18.75 m, would be less safe than the conventional vehicles.

Table 5.1 Rates of fatal or severe crashes in Sweden between 2003 and 2012 for heavy vehicles categorized by length.

	Combination length [m]			
	Short (< 12)	**Medium (12.01 – 18.75)**	**Long (18.76 – 25.25)**	**All**
Number of fatal or severe crashes	1 466	390	509	2 290
Vehicle Kilometres Travelled (billion km)	10.72	7.01	11.69	29.42
Crash rate (fatal or severe crashes /billion km)	137	56	44	78

5.2. North America

In this section the heavy vehicle accident studies in Canada, the United States and Mexico are summarised.

5.2.1. Canada (Alberta)

In Canada there are three types of HCT vehicles which are referred to as: Turnpike Doubles (37 m), Triple Trailer combinations (35 m) and Rocky Mountain Doubles (31 m), see Figure 5.1. The maximum allowed gross weight of an HCT vehicle in Canada is 62.5 t with 8 axles, and they are operated under permit in certain Provinces (Alberta, Saskatchewan, Manitoba and Quebec). The three HCT vehicle types are generally restricted to travel on four lane highways on a designated road network; however Rocky Mountain Doubles are also permitted on a few undivided two-lane highways (Woodroffe 2001).

The province Alberta in Canada has more than 40 years of experience of operation with HCT vehicles. The road network in Alberta where HCT vehicles are permitted is about 3000 km which corresponds to approximately 20% of the primary highway network. Overall, the HCT vehicles in Alberta account for about one percent of all heavy vehicles involved in fatal, injury and property damage collisions. From a crash rate perspective, HCT vehicles as a group has the best safety performance of all vehicle types. The severity outcome of HCT vehicle collisions on their designated network is lower than that of other vehicle types. Taking traffic exposure into consideration, HCT vehicles has a lower crash rate per 100 million VKT than other vehicle types (Kenny et al. 2000, Woodroffe 2001, Montufar et al. 2007).

Woodroffe (2001, 2004) concluded that the high safety performance of HCT vehicles in Alberta is highly related to the strict permit conditions. These include selective routing, restrictions on vehicle speed, restricted time of day operation, enhanced driver qualifications requirements and operating restrictions for adverse road and weather conditions.

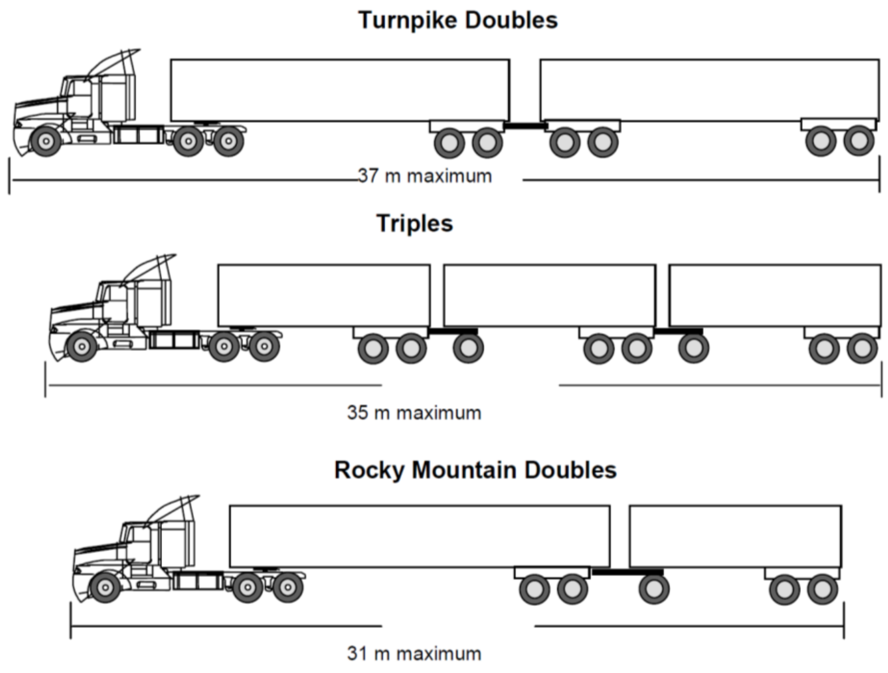


Figure 5.1 Illustration of typical HCT vehicles in Canada (Woodroffe 2001).

5.2.2. United States

In the United States HCT vehicles also comprise the Rocky Mountain Double, the Turnpike Double, and the Triple, but with somewhat shorter trailers than their Canadian equivalents. HCT vehicles are permitted on designated routes in twelve states in the US, and in contrast to Canada, they are allowed an increased mass over the usual legal limits (OECD 2009).

Carson (2007) writes that the prior studies that have focused on vehicle configuration and accident involvement have been criticized for not controlling for the effects of vehicle size and weight and that the reported results may reflect the combined effects of configuration and size/weight. Furthermore, no studies were found that considered the effects of increased vehicle size on safety levels. However, the literature consistently showed a general trend for decreased crashes but increased severity with increasing vehicle gross weight. There is a probable increased safety risk for speeding and excessive weight, but there is little data to support this.

Craft (2000) reports that of the 17,191 heavy vehicle combinations involved in fatal accidents in the United States from 1991-1996, 221 (1.3 percent) were HCT vehicles and concludes that HCT vehicles were not significantly “more or less safe” than other heavy vehicle combinations. Assessing the relative safety of HCT vehicles in the US by means of crash rates is problematic due to the lack of reliable data on heavy vehicle configurations involved in collisions as well as the lack of exposure data (Scopatz & DeLucia 2000, Carson 2007).

5.2.3. Mexico

Mexico allows HCT vehicles consisting of double trailers; one of the common combination is an A-double (tractor-semitrailer-dolly-semitrailer) with a gross vehicle weight of 66.5 t and length of 39 meters. The A-double must display a sign on the rear, indicating that it is a double length trailer in use. Mexico does not place special road restrictions on HCT vehicles other than those already in place for conventional tractor-trailers (OECD 2009).

A recent analysis of crashes involving heavy vehicles was conducted by the ANTP (National Private Fleets Association). ANTP represents about 10% of the private fleet companies. The results showed that crashes per million kilometres as well as crashes per tonne-kilometres were lower for tractors with two trailers than for tractors with one trailers and rigid trucks (ANTP 2014).

5.3. Australia

In a recent investigation in Australia (Austroads 2014), crash rates of PBS vehicles, obtained using a survey within the PBS vehicles operators, are compared with the general heavy vehicle accident rates provided by the National Transport Insurance (NTI). Over 40% of the “for hire” heavy vehicles market in Australia is insured by NTI, which uses the following accident categorization for recording the heavy vehicle accidents:

- Minor accidents, cost less than $5000.
- Moderate accidents, cost $5000 to $15000.
- Serious accidents, cost $15000 to $50000.
- Major accidents, cost greater than $50000.

The operator survey was conducted across an estimated 26% of the Australian PBS vehicle populations and included 65 fleets who are operating over 600 PBS vehicles. The survey accident data in many instances could be crossed checked to insurance incidents through vehicle identification numbers, allowing an external validation of the survey results.

The main findings of the investigation is presented in Table 5.2; the accident rates per 100 million km for tractor/rigid-truck combinations (grouped based on the hauling unit which can be either a tractor or a rigid truck) are provided, along with a weighted total. The weighting factors are based on the surveyed PBS vehicles; truck combinations accounted for 31% of the surveyed kilometres travelled, while tractor combinations accounted for 69%. Across all accident types, the PBS vehicles have performed better than the general heavy vehicles, reflecting a 63% reduction in major accidents on a weighted fleet basis, the corresponding figure for combined serious and major accidents is 76%.

There have been other accident investigations in Australia where performance of B-doubles (tractor-link trailer-semitrailer) are compared with single articulated vehicles. B-doubles were introduced in Australia in 1984. B-doubles are generally permitted a length of 26 metres and gross combination mass of 68.5 t, and have extensive network access, including major roads in urban areas. Between 1996 and 2006, the number of B-doubles increased almost tenfold (from 1,265 to 11,400) whilst there was little growth in the number of other heavy vehicle combinations, from 54,198 to 58,200. (OECD 2009, Pearson 2009).

Pearson (2009) cites a study that reports a comparison of crash statistics for single articulated vehicles and B-doubles between 1994 and 2003. Of the total number of crashes, 329 fatal crashes were associated with single articulated vehicles and 2 fatal crashes were associated with B-doubles, and for the crashes with serious injuries, the numbers were 1420 and 13 respectively. The study did not include exposure data so crash rates could not be calculated. Pearson (2009) states that the main advantages with the introduction of B-doubles are the reduction in exposure and the stability advantages of the B-double configuration, particularly the roll coupling between trailers.

The recent report by the Australian National Truck Accident Research Centre (NTARC) showed similar trends; according to NTARC (2013), the single articulated vehicle share of the freight task has fallen, from 39% in 2005 to 21% in 2011. This share has been taken by heavier rigid combinations and B-doubles. Nevertheless, single articulated vehicles are overrepresented in the heavy vehicles crash incidents in 2011, accounting for 37.9% of large losses. B-doubles is the safer alternative and are only involved in 23.6% of large truck crash incidents, while they account for 45% of the freight task in tonne kilometres.The authors mention that the tighter engineering hurdles that have to be achieved for the PBS approvals plus the added management focus (such as more experienced driver and restrictions to higher capacity road network) are the probable cause for the significant lower accident rate of the PBS vehicles (Austroads 2014).

Table 5.2 Accident rates per 100 million km for PBS heavy vehicles versus general heavy vehicles (Austroads 2014).

	Combination type	Minor	Moderate	Serious	Major	Serious + Major
General heavy vehicles	Tractor combination (69%)	21	22	16	13	29
	Rigid truck combination (31%)	42	34	19	7	26
	Weighted total	**27.5**	**25.7**	**16.9**	**11.1**	**28**
PBS heavy vehicles	Tractor combination (69%)	8	2	2	5	7
	Rigid truck combination (31%)	20	26	4	2	6
	Weighted total	**11.7**	**9.4**	**2.6**	**4.1**	**6.7**

5.4. South Africa

Nordengren (2012) summarised the experiences of PBS demonstration vehicles in the forestry sector; for the period September 2009 to March 2012, 5 crashes involved PBS vehicles and 77 crashes involved standard heavy vehicles. The average crash rate of the PBS vehicles (0.69 per million kms) was a factor of 6.7 less than the average crash rate of the standard vehicles (4.59 per million kms). According to Nordengren (2012), one of the contributing factors to this improved safety performance is the fact that the drivers of the PBS vehicles are more experienced than the drivers of the standard vehicles.

6. Environment

In this chapter the existing regulations on performance of heavy vehicles with respect to environment are described; these regulations are generally performance based already, which is valid for the ones described in this chapter, namely exhaust emissions, fuel consumption and noise. In the followings, first the regulation on exhaust emissions in Europe, the United States and Japan are presented which is followed by the fuel consumption regulations; finally the existing limits on vehicle and tyre noise are explained.

6.1. Exhaust emissions

The common way of regulating exhaust emissions of heavy vehicles, is to specify limits for the gaseous and particulate pollutants in the exhaust gas. In comparison to passenger cars and light duty vehicles where emission limits is distance based (per km), emission regulations for heavy vehicles worldwide is engine-based and the emission limits are expressed per produced work (per kWh) in a given test cycle. The main reason for this approach is that heavy vehicles are produced in smaller numbers but in great numbers of variants. Therefore the type approval for emissions is related to the engine which then can be installed in a number of different vehicle configurations with different weight where the same emission requirements apply as long as the vehicle falls under the heavy duty emission legislation.

6.1.1. Europe

The exhaust emission regulation for heavy vehicles in Europe is stated in EU regulation No 595/2009 which is normally called Euro VI. The main regulation is complemented with the commission regulations EU No 582/2011 and EU No 133/2014, which stipulate all technical details regarding test procedures, measurement instruments and administrative procedures. With Euro VI the World Harmonized Heavy Duty Test procedure (WHDC) including the transient (WHTC) and steady state (WHSC) test cycles where introduced in Europe (EC 2009b, EC 2011, EC 2014a).

In Euro VI, ‘gaseous pollutants’, which are the exhaust gas emissions of carbon monoxide (CO), nitrogen oxides (NO_X expressed in NO_2 equivalent), hydrocarbons (HC) and ammonia (NH_3), plus ‘particulate pollutants’ are addressed. Particulate pollutants are components of the exhaust gas which are removed from the diluted exhaust gas at a maximum temperature of 325 K (52 °C) by means of filters. For diesel engines the most critical emissions are NO_X and particulates. Since the Euro I stage was introduced in 1992 the NOx emission limit have been decreased with 95% and the particulate emission limit with more than 97%, see Figure 6.1.

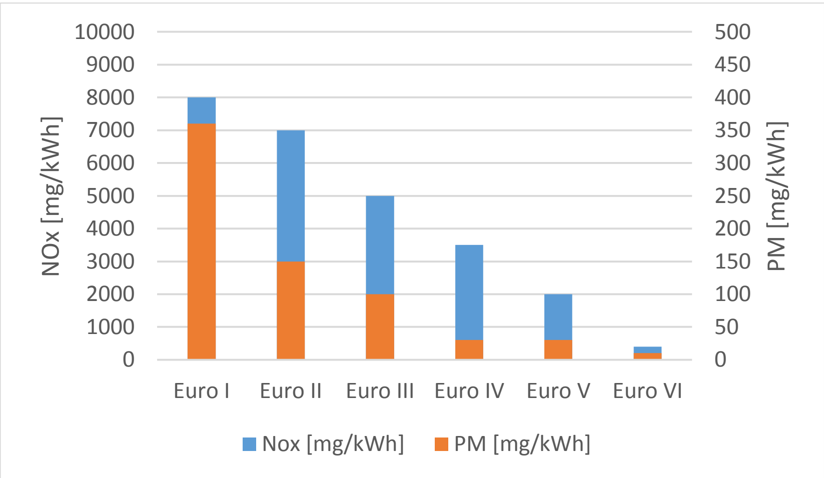


Figure 6.1. Emission limits of NOx and PM for HD engines from Euro I to Euro VI (Trafikverket 2014).

Table 6.1. Euro VI emission limits.

	CO (mg/kWh)	THC (mg/kWh)	NMHC (mg/kWh)		CH_4 (mg/kWh)	NO_X (mg/kWh)	NH_3 (ppm)	PM mass (mg/kWh)	PM number (#/kWh)
Compression Ignition (WHSC)	1500	130				400	10	10	8.0×10^{11}
Compression Ignition (WHTC)	4000	160				460	10	10	6.0×10^{11}
Positive Ignition (WHTC)	4000		160		500	460	10	10	6.0×10^{11}

CO: carbon monoxide, THC: total hydrocarbon, NMHC: non-methane hydrocarbons, CH_4: methane, NO_X: nitrogen oxides, NH_3: ammonia, PM: particulate matter, ppm: parts per million

The emission limits in Euro VI, listed in Table 6.1, has been in effect since 31 Dec 2013 for all new engines; some Euro VI provisions, including OBD and certain testing requirements are phased-in by 2016/2017 (EC 2014a). The exhaust emissions are measured with respect to two driving cycles: World Harmonized Steady state Cycle and World Harmonized Transient Cycle, which have been created to cover typical driving conditions in Europe, USA, Japan and Australia.

WHSC consists of number of speed and power modes, which cover the typical operating range of HD engines, and defined ramps between these modes, see Figure 6.2 . The parameters of the WHSC are given in Table 6.2, the total running time is 1895 s (Dieselnet 2014). WHSC test procedure, described in UNECE regulation no 49 and adapted by Euro VI, consists of a hot start test following engine preconditioning at WHSC mode 9 (UNECE 2013).

The WHTC is a second by second sequence of normalized speed and torque values with several motoring segments and total duration of 1800 s. Normalized engine speed and torque values over the WHTC cycle are shown in Figure 6.3 (Dieselnet 2014). WHTC test procedure, described in ECE R49 and adapted by Euro VI, consists of a cold start test following either natural or forced cool-down of the engine, a hot soak period and a hot start test (UNECE 2013).

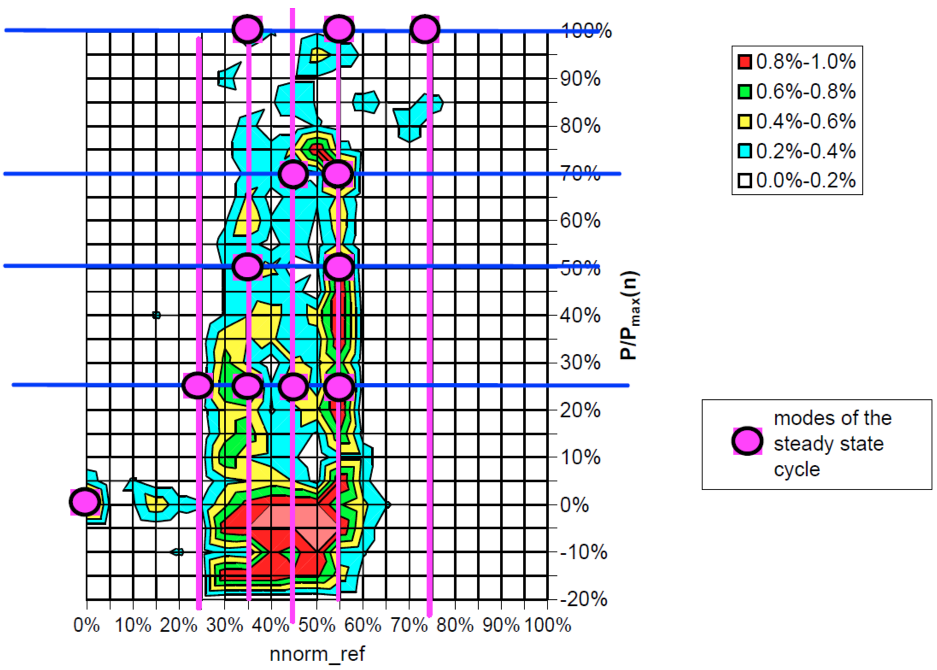


Figure 6.2. Modes of the world harmonized stationary cycle (Schulte et al. 2004).

Table 6.2. WHSC modes.

Mode	Normalized speed (%)	Normalized load (%)	Mode length (Including 20s ramp)
0	Motoring	-	-
1	0	0	210
2	55	100	50
3	55	25	250
4	55	70	75
5	35	100	50
6	25	25	200
7	45	70	75
8	45	25	150
9	55	50	125
10	75	100	50
11	35	50	200
12	35	25	250
13	0	0	210

Euro VI regulation additionally introduced off-cycle emissions (OCE), for which the World-harmonized Not-To-Exceed (WNTE) Methodology, as described in ECE R49, was adapted. In WNTE methodology, a control area is defined on the engine which shall include all operating speeds between the 30th percentile cumulative speed distribution over the WHTC test cycle and all engine load points with a torque value greater than or equal to 30 per cent of the maximum torque value produced by the engine. The control area shall be divided into 9 grids for engines rated below 3000 rpm and 12 grids for engines with rated speed above 3000 rpm. The testing involves random selection of three grid cells and emission measurement at 5 points per cell, the applicable emission limits are:

- CO: 2 000 mg/kWh
- THC: 220 mg/kWh
- NOX: 600 mg/kWh
- PM: 16 mg/kWh

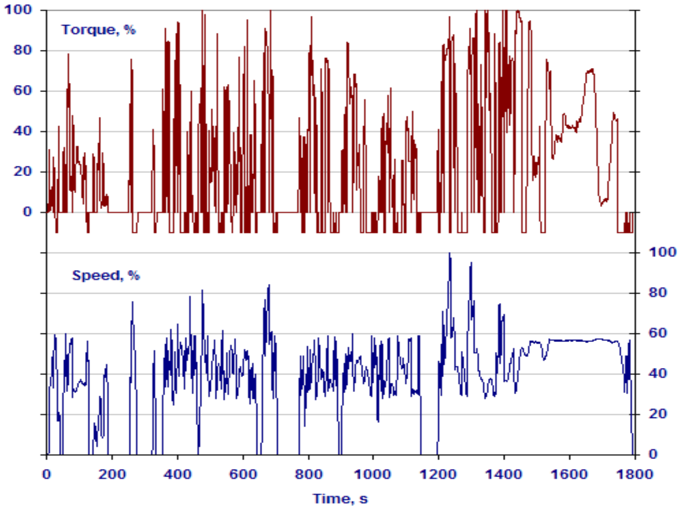


Figure 6.3. World harmonized transient cycle (Dieselnet 2014).

Another important new feature of Euro VI is use of Portable Emission Measurement System (PEMS) procedure for in-use emission testing, to ensure that the vehicle emissions are not only limited in conditioned laboratory tests, but also in real world operation. The testing can be done in a wide range of ambient and engine operation conditions. The testing is conducted over a mix of urban (0-50 km/h), rural (50-75 km/h) and motorway (> 75 km/h) conditions, with exact percentages of these conditions depending on vehicle category; 45% urban, 25% rural, and 30% motorway for N1 and N2. 20% urban, 25% rural and 55% motorway for N3. First in-use test should be conducted at the time of type approval testing and it shall be repeated at least every 2 years over the useful life period of the engine (EC 2011, DELPHI 2013).

The pass or fail decision in the PEMS procedure is based on a statistical calculation using moving averaging window method. In this method, the mass emissions are calculated for sub-sets of the complete data set, the length of these sub-sets being determined so as to match the engine CO_2 mass or work measured over the reference laboratory transient cycle. Conformity factors are used in the emission calculations to account for the fact that in PEMS testing the conditions are not exactly like the laboratory testing. Furthermore deterioration factors adds margin to the emission limits due to the fact that the components deteriorate over time (EC 2011).

In Euro VI the importance of unrestricted access to vehicle repair information is also highlighted. A great proportion of such information is related to on-board diagnostic (OBD) systems and their interaction with other vehicle systems. Stricter OBD requirements are included in Euro VI and the commission has appointed CEN, the European Committee for Standardization, to develop a common European standard for the format of vehicle OBD and vehicle repair and maintenance information.

Sweden

In Sweden an in-service test program for heavy vehicles has been established which is administered by the Swedish Transport Agency; approximately 10 vehicles are tested each year (Transportstyrelsen 2011).

The purpose of the test program is to perform an independent test to assess the durability requirement in the type approval legislation for exhaust emissions. All vehicles are tested on road in accordance with the PEMS test protocol, introduced in Euro VI, including urban, suburban and highway driving. Some of the vehicles are also tested on chassis dynamometer. The selection of the vehicles has this far been based on Euro IV and Euro V emission standards. For the coming years there will be more Euro VI vehicles tested in the programme as the number of available vehicles is increasing on the market.

6.1.2. United States

In the United States there are two set of standards: Environmental Protection Agency (EPA) or federal standards and the California standards, the two have been harmonized since 2004.

US exhaust emission regulation is also engine based as in Europe, meaning that the regulations do not require that complete heavy vehicle be chassis certified. The emissions should be measured with respect to the Federal Test Procedure (FTP) transient cycles which was developed to take into account a variety of heavy vehicle and bus driving patterns in American cities, including traffic in and around the cities on roads and expressways. There are two FTP transient cycles, one for diesel engines and one for gasoline engines, described below.

Heavy duty diesel transient cycle (HDDTC) consists of four phases, including (1) New York Non Freeway (NYNF) phase typical of light urban traffic with frequent stops and starts, (2) Los Angeles Non Freeway (LANF) phase typical of crowded urban traffic with few stops, (3) Los Angeles Freeway (LAFY) phase simulating crowded expressway traffic in Los Angeles, followed by (4) a repetition of the first NYNF phase. The variation of normalized speed and torque with time is shown in Figure 6.4.

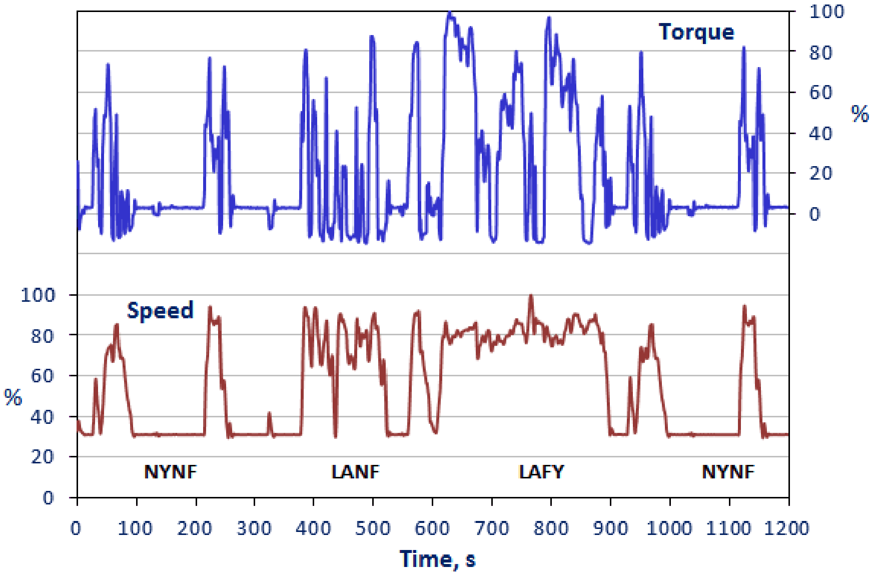


Figure 6.4. Heavy duty diesel transient cycle (Dieselnet 2014).

The average load factor of the FTP cycle is roughly 20-25% of the maximum engine power available at a given engine speed. The equivalent average vehicle speed is about 30 km/h and the equivalent distance travelled is 10.3 km for a running time of 1200 s. Heavy duty diesel engines tested on the HDDTC cycle produce medium to high exhaust gas temperatures. Generally, the temperature is at a medium level between 250 and 350°C, but there are hot sections with temperatures reaching as high as 450°C. (DELPHI 2013) An equivalent driving cycle is used for the gasoline engines, called Heavy duty Gasoline transient cycle (HDGTC). The EPA emission standards for model year 2007 and later heavy duty engines, which have been adopted by the California ARB as well, are presented in Table 6.3 (EPA 2014).

Similar to the European regulations, in the US engine-based regulation, there are extra additional testing requirements in addition to the FTP transient cycle testing, namely: Supplemental Emission Test (SET) and Not-to-Exceed (NTE) testing.

Supplemental Emission Test is used to ensure that the emissions are also controlled during steady state type driving. SET is a 13-mode steady-state test with emission limits equal to the FTP transient test limit and has the same operating modes and weighting as the European Stationary Cycle (ESC), additionally, the transition between the modes is defined. The SET test is characterized by high average load factors and very high exhaust gas temperatures. The SET modes are listed in Table 6.4, where speeds A, B and C are defined based on the highest and lowest engine speeds.

Table 6.3. US emission limits for engine-based certification

	CO g/bhp-hr (mg/kWh)	NMHC g/bhp-hr (mg/kWh)	NO_X g/bhp-hr (mg/kWh)	PM mass g/bhp-hr (mg/kWh)	Idle CO % exhaust gas flow
Diesel engine	15.5 (20777)	0.14 (187)	0.2 (268)	0.01 (13)	0.5
Gasoline engine	14.4 (19302)	0.14 (187)	0.2 (268)	0.01 (13)	0.5

CO: carbon monoxide, NMHC: non-methane hydrocarbons, NO_X: nitrogen oxides, PM: particulate matter

Table 6.4. Supplemental emission test modes.

Mode	Speed	Normalized load (%)	Mode length (including 20s ramp)
1	Warm idle	0	190
2	A	100	193
3	B	50	239
4	B	75	237
5	A	50	123
6	A	75	120
7	A	25	123
8	B	100	214
9	B	25	238
10	C	100	191
11	C	25	122
12	C	75	120
13	C	50	122
14	Warm idle	0	168

Not-to-Exceed (NTE) testing was introduced to make sure that heavy-duty engine emissions are controlled over the full range of speed and load combinations commonly experienced in use. In NTE test, the engine is required to maintain emissions below a limit of 1.5 x FTP standards during engine operation within a broad range of speed and load points below the engine torque curve (the Not-To-Exceed Control Area) (Dieselnet 2014). NTE testing has been introduced in the world harmonized regulation as WNTE, described in previous section; however, in the US it is a method used for on road testing while in Europe it is a lab-based test procedure.

6.1.3. Japan

Similar to EU and the US, the exhaust emission regulation for heavy vehicles in Japan is engine-based. The pollutant limits in Japanese regulation, listed in Table 6.5, are measured in JE05 (also known as ED12) driving cycle. JE05 is a transient test based on Tokyo driving conditions and is defined through vehicle speed versus time. The duration of JE05 is 1829 s, the average speed is 26.94 km/h and the maximum speed is 88 km/h, see Figure 6.5 (DELPHI 2013).

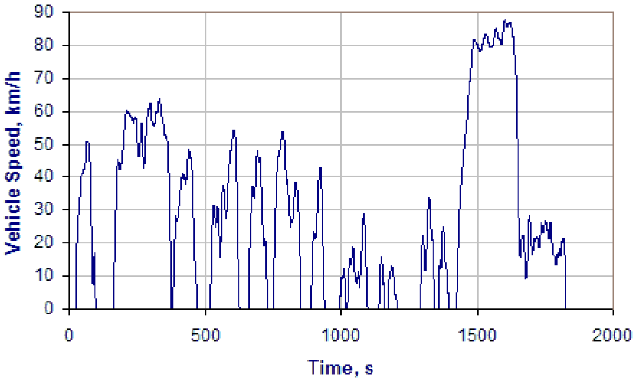


Figure 6.5. JE05 Driving cycle (Dieselnet 2014)

Table 6.5. Japanese exhaust emission standards

	CO (g/kWh)	NMHC (g/kWh)	NOx* (g/kWh)	PM (g/kWh)
Diesel engine	2.22	0.17d	0.7	0.01
Gasoline engine	16	0.23	0.7	0.01

* NOx is planned to be reduced to 0.4 g/kWh for GVW>7.5 from 2016.

6.1.4. Other countries

The exhaust emission and fuel consumption regulation in other countries are mainly based on EU regulation, while some countries have adapted the US or Japanese regulations. For instance, Canadian emission standards are based on the US regulations, while Australian standards are based on European regulations with acceptance of selected US and Japanese standards. The long term policy is to fully harmonize Australian regulations with UNECE standards.

Emission standards in many Asian countries (such as China, India, Thailand and Singapore) as well as South American countries (such as Argentina, Brazil, Peru and Chile) are based on European regulations, however in most cases an older EU regulation (EU III-EU V) is in effect (Dieselnet 2014).

6.2. Fuel consumption

6.2.1. Europe

Unlike for passenger cars and light duty vehicles, no fuel consumption/CO_2 regulation for heavy vehicles is available in Europe yet. However, the Commission has recently set out strategy to curb CO_2 emissions of heavy vehicles and has developed a test procedure to measure their fuel consumption and CO_2 emissions. The test procedure is based on tests of the individual components of the vehicle and simulations of the fuel consumption and CO_2 emissions of the entire vehicle. In order to better reflect real world conditions the procedure will include a number of different mission profiles typical for different categories of heavy vehicles. The CO_2 limits and the most suitable metric unit are yet to be decided. However, the likely metrics for the procedure are per tonne-km and per m^3-km, to reflect the fuel consumption or CO_2-emissions per transported amount of goods.

In the proposed CO_2 certification procedure for heavy vehicles in (UniGraz 2012) the results for fuel consumption and CO_2 emissions shall be simulated by a standardized software tool, the “VECTO (Vehicle Energy Consumption calculation Tool)”. This tool shall be provided by the regulatory authority, which is also responsible for the maintenance of the software and for updates of the tool according to updated regulations. Vehicle manufacturers and possibly, at a late stage, body and trailer manufacturers as well as component suppliers shall make use of the model to perform their own simulations to evaluate the fuel efficiency of different heavy vehicle configurations and – as the main purpose – to declare the CO_2 emissions to the type approval authority.

The first step of the proposed CO_2 certification is to allocate correct vehicle segment to the vehicle. A vehicle segment is defined by the (1) vehicle class and (2) mission profile. For each segment, the following values are defined in the simulator:

- CO2 test cycle (different test cycles have been developed for different vehicle missions to define typical driving situations for most of the heavy vehicles).
- Reference loading
- Norm body for the measurement of the aerodynamic drag
- If a truck is tested as a rigid truck only or as a truck and trailer combination (Optional)

6.2.2. US

In 2011, a regulatory program to reduce greenhouse gases and improve fuel efficiency of medium and heavy-duty vehicles in the US was published with effective start in 2014. The proposed rule was established by the U.S. Environmental Protection Agency and the Department of Transportation's National Highway Traffic Safety Administration (NHTSA).

In the published rule, differentiated standards are adopted for nine sub-categories of combination tractors based on three attributes: weight class, cab type and roof height. The standards include CO_2 limit (g/ton-mile) and Fuel consumption limit (gal/1000 ton-mile) which are identical based on an emission factor of 10,18 grams of CO_2 per gallon of diesel fuel, see Table 6.6 (EPA 2011).

As compared to the baseline values (average 2010 tractors), the adopted standards represent an average improvement in GHG emissions of 17 percent for diesel vehicles and 12 percent for gasoline vehicles. The agencies estimate that consequently the CO_2 emissions will be reduced by nearly 270 million metric tonnes and about 530 million barrels of oil over will be saved during the lifetime of the vehicles sold from 2014 to 2018. This translates to a net benefit of $49 billion to society (EPA 2011).

The vehicle standards are checked by using a simulation model, called Greenhouse Gas Emissions Model (GEM). The drive cycles used in the GEM for the CO_2/Fuel Consumption calculation are the California Air Resource Board transient vehicle cycle and two steady-state simulation cycles, one at 55mph and one at 65 mph speed.

Furthermore, the new regulation compliments the engine-based pollutant regulatory (Table 6.3) by adding three more pollutant to be measured, namely: CO_2, CH_4, and N_2O. The CO_2 limit for 2017 model year is 480 g/bhp-hr (644 g/kWh), while the limits for both N_2O and CH_4 are 0.05 g/bhp-hr (67 mg/kWh) (UniGraz 2012).

Table 6.6. US CO2/Fuel consumption standards for 2017 model year

	CO_2 (g/ton-mile)			Fuel consumption (gal/kton-mile)		
	Low roof	**Mid roof**	**High roof**	**Low roof**	**Mid roof**	**High roof**
Day cab class 7	104	115	120	10.2	11.3	11.8
Day cab class 8	80	86	89	7.8	8.4	8.7
Sleeper cab class 8	66	73	72	6.5	7.2	7.1

6.2.3. Japan

The Japanese regulation for fuel consumption of heavy vehicles, called the TRIAS, was already published in 2007. However, the standards will be in effect form April 2015.

The test procedure in TRIAS is a combined engine testing and vehicle simulation where the engine testing (same as exhaust emission testing - JE05) provides the input data for the simulation model. In the complete vehicle simulation three pre-defined test cycles are used. The first cycle is City Running Mode which covers a distance of 13.28 km. The second cycle is the intercity running mode which operates at a steady state speed of 80 km/h but with an instantaneous change in the vertical slope of the road with overall length of 38.2 km. The third cycle is the urban part of the city running with overall length of 2.88 km.

The standards are given for different classes of truck and tractors, based on the GVW. The fuel consumption limit is 4.04 km/l and 2.01 km/l for trucks, respectively tractors, with GVW larger than 20t (UniGraz 2012).

6.3. Noise emissions

6.3.1. Vehicle noise

The vehicle noise regulation in Europe are stated in EU regulation no 540/2014 which replaced the directive 70/157/EEC in April 2014 and is similar to the UNECE regulation no 51, rev 3.

In the directive 70/157/EEC, the procedure for measuring the vehicle noise was based on ISO 362:1998 pass-by-noise standard. In ISO 362:1998, the noise of heavy vehicles is measured with the vehicles accelerating with wide open throttle (WOT) on various gear settings past two microphones (one on either side), with an approach speed of 50 km/h (or 3/4 of the rated engine speed, whichever is the lower). The highest noise level, subtracted by 1 dB (to take account for inaccuracies in the measurement tools) and rounded down to the nearest integer, is retained as the final result. The measurement is done on the ISO surface 10844. The noise limit for heavy vehicles with engine power more than 150 kW was 80 db. (EC 2007, UNECE 2011)

The ISO 362 Standard was revised in 2007 with the objective of attuning to real-life situations. The new revision, ISO 362:2007, includes a combination of WOT and constant speed tests with stricter controls on gearing and operating conditions. However vehicles with a power to weight ratio under 25 (in general all heavy vehicles) are not subject to the constant speed test (LMS International 2014). Following the ISO 362 revision, ECE R51 has been revised and the new EU regulation no 540/2014 has been published.

The new regulation for vehicle noise adopts the ISO 362:2007 as the testing procedure and proposes new noise limits to be implemented in 3 phases. . Phase 1 has to be reached 2 years after publication, phase 2 in 6/8 years and phase 3, 10/12 years after publication. There are two different dates because new vehicle types and first registration are not treated equally. The new limits for heavy vehicles with engine power more than 250 kW (changed from 150W due to dramatic changes in the engine powers) are 82, 81, and 79 dB for the three phases, respectively (EC 2014b).

Since the test method in the new regulation has changed, it is not possible to directly compare limit values from the new regulation with the old ones. However, conducted tests on 178 heavy vehicles, which were all certified according to the old noise limits, showed that 18% of them did not pass the phase 1 limit of the new regulation; corresponding figures for the phase 2 and phase 3 limits are 50% and 100%, respectively (Glowczewski 2012).

Other countries

The ECE R51 regulation has been adapted in most of the member countries, the significant exceptions are the USA and Canada, who have their own testing standards and limits. In the USA regulations, the SAEJ366 pass-by-noise test is used, which includes both an acceleration test and a deceleration test. Other differences are the track layout and the distance between the microphones and the centreline. India, China, Brazil and other nations indirectly adhere to UNECE regulations in part, without being full signatories, allowing them more flexibility as their economies develop (LMS International 2014).

6.3.2. Tyre noise

Major noise source for heavy vehicles at speeds higher than 50 km/h is tyre noise (Sandberg 2012). Therefore, the legislation on the tyre noise play an important role in regulating the noise emission of heavy vehicles.

The first direct limitation of tyre noise in EU was specified in Directive 2001/43/EC; however, the specified limits were too high that it only eliminated very exceptional tyres in the market. In fact, according to a review in (FEHRL 2006), the emitted noise from 75% of C3 tyres tested in period 2000-2004 was 3db below the limit and for 50% of tyres, it was 5db below the limit. Therefore the European commission, appointed FEHRL to make a comprehensive study of tyre noise and published new set of tyre requirements in Regulation EC 661/2009 based on the FEHRL proposals. The new noise limits for heavy vehicles tyres (C3) are presented in Table 6.7, which are 2db (1db) higher than the proposed values by FEHR. For special use tyres, the specified limits shall be increased by 2 dB and for snow tyres by 1dB (EC 2009a, FEHRL 2006).

The new tyre noise regulation has been in effect since November 2012 for the so-called replacement tyres (tyres sold as replacement to the original-equipment tyres on new vehicles), whereas the implementation time for original-equipment tyres is 2016.

The tyre noise emissions should be measured in a coast-by-noise test, where the vehicle is travelling at high speed on a specified road surface (ISO 10844) and when reaching the recording section, the vehicle should be in neutral gear (coasting) with the engine switched off. The maximum recorded noise level, rounded down to the nearest integer is retained as the final result.

The following truck tyre categories are excluded from the regulations (Sandberg 2012):

- Retreaded tyres
- Tyres produced before July 2012
- Professional off-road tyres

Table 6.7. Limits on noise emission of heavy vehicles tyres

Tyre type	Limit in EC 661/2009	Decrease compared to 2001/43/EC	Limit proposed by FEHRL
Normal	73*	3	71
Traction	75*	3	73

* An additional 1db is allowed for winter tyres

Concerns about the current tyre noise regulation

Although the regulation EC 661/2009 is improved relative to the directive 2001/43/EC, there are still concerns about the current regulations on tyre noise of heavy vehicles, summarized below:

- The European Commission implemented higher noise limits that those proposed by FEHRL study; given the very liberal limits in 2001/43/EC, the reductions of 3 dB in EC 661/2009 are relatively small (Sandberg 2012).
- The ISO 10844 is a fine graded surface with maximum stone size of 8mm and due to its smooth texture it is not representative of the rougher surface commonly found on high speed roads. (FEHRL 2006). The existing studies show a poor correlation between the noise levels measured on the ISO surface and on actual roads; e.g. a study by SP on nine different C3 tyres showed that the measured noise on the road surface were 4-10 dB higher than the measured value on the ISO surface (Jansson 2007 cited in Sandberg) . In the study by FEHRL, it was proposed to use a test surface based on 10-11 mm aggregate (FEHRL 2006).
- Winter truck tyres, which will be increasingly used in the Nordic countries, are given an extra 1-2 dB allowance in the noise limits, on top of the requirement for traction tyres. However it can be expected that the winter tyres will not only be used in winter time and not just on drive axles, as in practice they will be moved to trailer axles in spring and summer, although with lower tread depths (Sandberg 2012).
- The excluded tyres from the regulations count for about 50% of truck tyres on roads (Sandberg 2012)
- A special problem with truck tyres is that they exhibit tonal properties (sound energy concentrated at one or a few frequencies) if the treading is not randomized (most truck tyres have randomized treading patterns). In the coast-by testing, conservative tonality effect will be detected. A proposal is to use drum tests instead where the tonality will be easy to measure (Sandberg 2012).

Tyre rolling resistance

In the EC 661/2009 regulation, in addition to the tyre noise emission, rolling resistance of truck tyres is also addressed. The tyre rolling resistance coefficient is measured in accordance with ISO 28580 and the corresponding limits for heavy vehicles tyres is 6.5 kg/ton, which shall be increased by 1 kg/ton for snow tyres.

7. Infrastructure

In this chapter, effect of heavy vehicles on the infrastructure are discussed. Important aspects to consider are road design (geometry and position of roadway elements), pavement design (design of pavement structure), bridge design, tunnel design and road services. The first section is dedicated to pavement where a brief description of the pavement design and deterioration mechanisms are provided, and the existing regulations on heavy vehicles with respect to their impact on the pavement are described. In the bridge section, the existing formulas and methods for analysing the effect of heavy vehicle on the bridges and calculating the maximum allowed load are presented. Finally, in the last section a brief overview of the relevant aspects of road and tunnel design, as well as road services is provided.

7.1. Pavement

This section provides a background on how regulations for vehicle configuration can be set up. The basic hypotheses drawn upon here are that:

- On the one hand simple relationships as the fourth power law rule can be very useful to create PBS for vehicle loads but
- On the other hand it is of utmost importance to understand risks associated with vehicle loading on pavements, to be able to avoid excess damage.

Heavy vehicles lead to deterioration of pavements mainly by increasing cracking of bound layers and rutting of all layers in the pavement and the subgrade. The degree of deterioration is dependent on the load characteristics, pavement design (type and configuration of layers), climate conditions and performance of each pavement and subgrade layer. Heavy vehicles are one of many sources of deterioration. Alongside with heavy vehicles, pavements deterioration is influenced by cars with studded tyres and climatic effects as well as inherent inferior properties of the pavements. It is therefore difficult to be more precise on exact origin of damages observed in the field.

To be able to create PBS for vehicle loads on pavements it is crucial to understand mechanisms leading to serious damages and thus design criteria that can rule out the occurrence. This is done in two steps. First the pavement function and design is described including material behaviour and deterioration. Secondly, the main deterioration mechanisms and their relationship to heavy loads are described. Lastly, the existing regulations are discussed.

7.1.1. Pavement structure

A typical Swedish pavement structure configuration is presented in Figure 7.1. The layer thicknesses are mainly dependent on traffic loads and risk of uneven frost heave and thaw weakening. The properties of each layer is in turn dependent on a number of mechanisms and functional requirements such as friction, aqua planning, durability, heat conduction, frost heave, drainage, water susceptibility, etc. Bituminous bound layers usually comprise a thickness in total from a minimum of 45 mm to a maximum around 260 mm, depending on the flow of heavy traffic.

Subgrade materials

The levelled foundation for the pavement is called subgrade and consists of in situ or on site soil. The purpose of the pavement layers is to prevent damages in the subgrade materials. Therefore the pavement needs to be designed in such a way that the stresses and strains from traffic are distributed over an adequately large area. Inferior subgrade soil may be replaced or improved. The performance of the subgrade can also be improved by drainage and protection from climate actions. One way of protection is to use a soil with acceptable properties that can replace subgrade soils that are sensitive to frost heave, a so called protection layer.

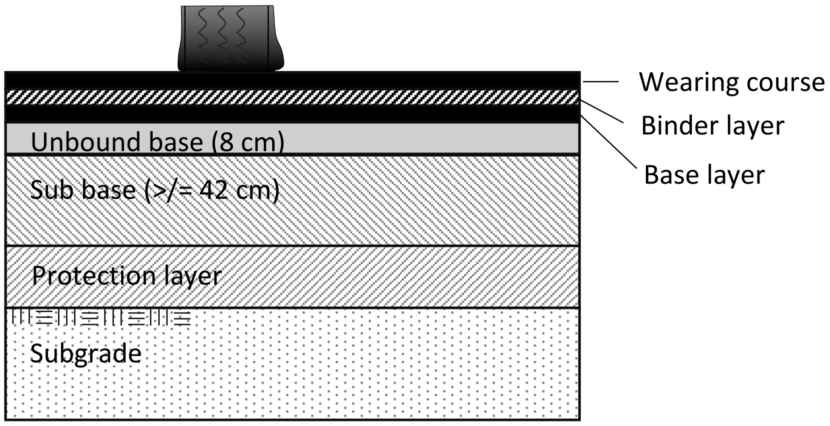


Figure 7.1. Typical pavement structures for flexible (asphalt concrete) pavement. For rigid (cement concrete) pavements the binder layer does not exist.

In the context of heavy vehicles it is important to remember that traffic loads are not negligible in the subgrade. In an attempt to illustrate this, contributions to vertical stresses from the weight of materials and traffic loading is calculated by simplified models and assumptions based on an ordinary pavement and traffic loading (25 kN load on each tyre and no distance between). This simplified model shows that traffic load will generate substantial contributions to the stress levels in the pavement well below 2 meters; not accounting for other factors such as dynamic contributions to loads, see Figure 7.2.

Although geotechnical problems such as slope stability and settlements are generally a matter for static analysis not including effects of heavy vehicles, there are sensitive soils that may be severely affected by dynamic loads and vibrations.

In the US design guide for asphalt pavements, MEPDG, the equation below is used for prediction of permanent deformations in unbound materials. This has been calibrated for Swedish conditions against HVS (Heavy Vehicle Simulator) results.

$$Rutting = \sum_{i=1}^{n} \varepsilon_0 e^{-\left(\frac{\rho}{N}\right)^{\beta}} \cdot \varepsilon_r \cdot \Delta h_i \qquad (5.1)$$

where ε_0, ρ, β are constants, N the number of passes of axles giving raise to resilient strain ε_r, which is summarized over layers with thickness Δh. This equation implies that rate rutting is proportional to the load applied within certain limits.

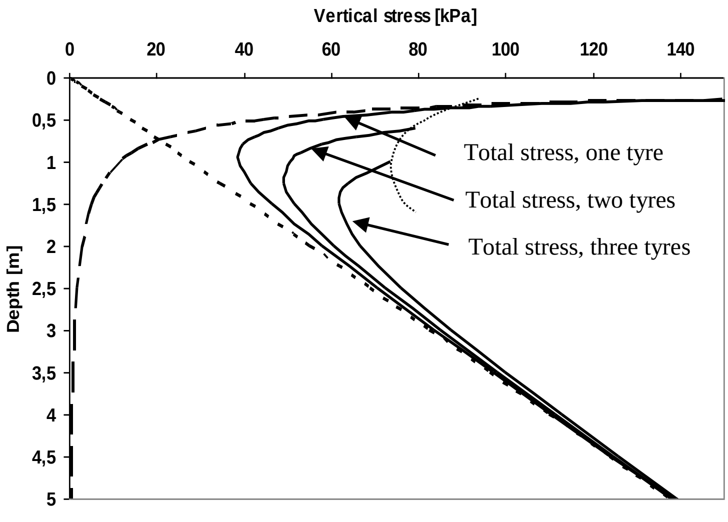


Figure 7.2. Simplified illustration of contribution from static traffic load and pavement weight on vertical stresses.

Aspects of freezing and thawing also needs to be considered. Regulations on traffic loads are common during thawing since bearing capacity reach their lowest levels during this period. On the other hand, frozen pavements have extremely high bearing capacity.

Unbound materials

Unbound materials in pavements are normally crushed aggregate or uncrushed stone material taken from site or transported from quarries, so called granular materials. In some areas of Europe, coarse granular materials are scarce and finer materials such as sands are used instead. From a performance point of view, unbound materials are fundamentally dependent on its gradation (size distribution), particle properties (strength, durability), water content and surrounding pressure on the material (confining pressure, which is a function of previous compaction and support from surrounding materials).

From a heavy load point of view, it is of particular interest how heavy loads influence the development of permanent deformations and, consequently, the important contribution from unbound layers to rutting. Several researchers have concluded that at low levels of stress, an equilibrium level of permanent strain can be reached. At higher stresses, however, permanent strains may gradually increase until failure is reached in the material (i.e. rapid growth of deformations). It appears that unbound granular materials experience a load threshold level, as reported by many researchers. Figure 7.3 illustrates the sensitivity of unbound granular materials to stress conditions under traffic loading and the presence of a threshold limit for loading with respect to development of permanent deformations contributing to rutting. Stresses applied to a sample in loading cycles with slightly different stress paths (a.) as defined from ordinary normal stresses (b.) generates very different permanent strains and deformations during cyclic loading (c.) so that a threshold level defined by the peak *q/p* is indicated (d.).

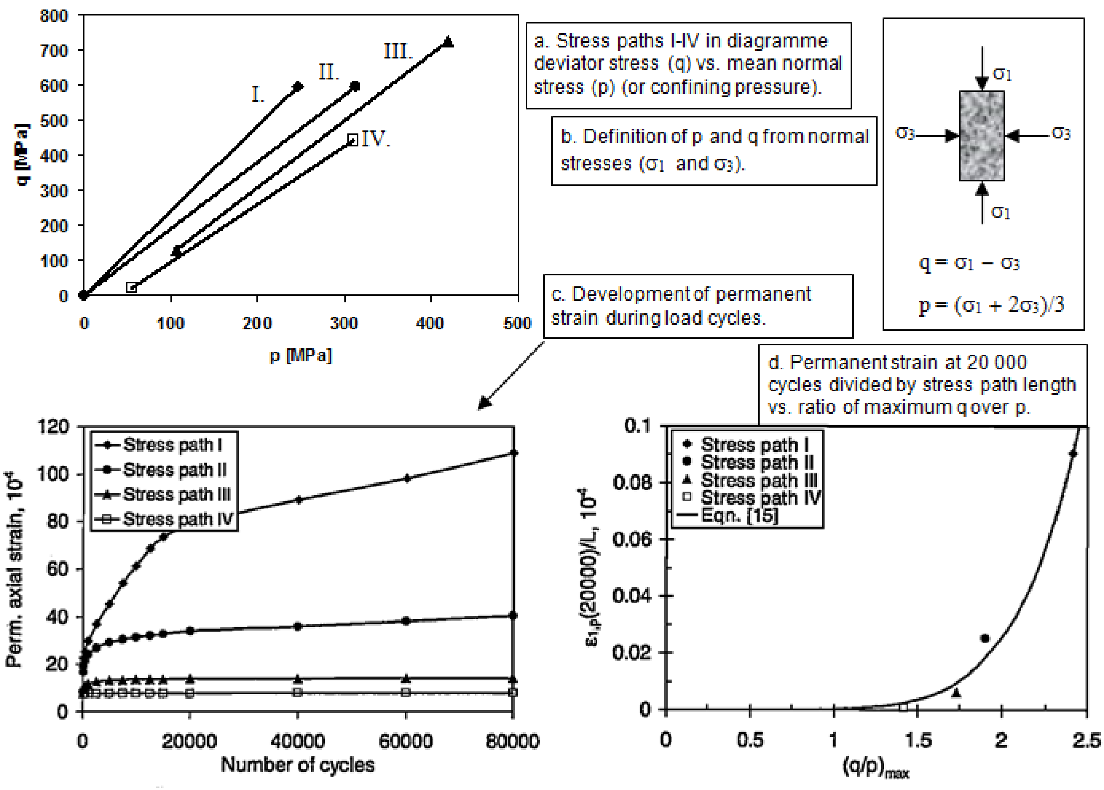


Figure 7.3. Dependency of stress conditions on development of permanent deformations and the load threshold limit (Lekarp & Dawson 1998, Lekarp et al. 2000). Note the importance of the relation between stresses on permanent deformation.

The aforementioned fundamental description of behaviour of granular materials cannot be directly converted into a deterioration law (such as the fourth power law) without major simplifications but points out several important features of unbound granular materials. Unfortunate combinations of high loads or improper load configurations, weak or damaged bound layers and subgrade, and conditions in the unbound material itself may cause severe damage to a pavement. It is for example the reason why pavements with steep ditch slopes cannot be loaded by trucks near the edge without edge faults (no pressure holding back from pavement side). Overloading at the wrong time in the wrong place may lead to severe damage far beyond any fourth power law (such as during thawing). However, on high strength, high volume roads, the likelihood of being close to the threshold levels are probably very low and in that case associated with an already developed damage.

Bituminous bound materials

Bituminous bound materials consist of aggregate, filler, bitumen and sometimes different types of additives. These materials are in popular parlance called "asphalt concrete" while in practice, the products and methods used are actually quite broad and complex. Bitumen gives the bound layers flexible properties, which significantly reduce the requirements on the unbound layers compared to rigid cement bound layers. Any further technical details are not given here but it is important to state that performance of different types of "asphalt concrete" differs quite a lot and that extra performance costs accordingly. For performance reasons, bituminous bound materials for pavement construction are usually divided into:

- Wearing course – the surface layer with the purpose of withstanding wear and climatic action, as well as creating a surface with good characteristics regarding friction, drainage, noise and visual properties
- Binder layer – an intermediate layer which can withstand deformations
- Base layer – bottom asphalt concrete layer which can withstand both deformations and numerous cyclic loads (fatigue).

Fatigue and rutting are two deterioration mechanisms occurring directly in the asphalt concrete as a consequence of traffic. There exist numerous publications on both issues. A review is impossible to fit into this context and the follow only aims at picturing mechanisms.

Fatigue in asphalt concrete is often described in terms of number of cycles to failure at a certain stress or strain level. Typically, after laboratory testing of asphalt concrete, linear relationships are obtained for the parameters log (N = number of cycles) vs. log (ε or σ = strain or stress level). Reported slopes (b) of this relationship is usually between 3 and 5 (i.e. log $N = b \cdot \log \varepsilon + a$, where a is a constant). With some mathematics one can conclude that

$$N = a \cdot \varepsilon^{b} \tag{5.2}$$

which is a direct parallel to the fourth power law (if b = 4). It appears that the fourth power law is feasible for pavements which are maintained due to fatigue deterioration. Another proof of the effects of cycling loading on asphalt concrete is given by fracture mechanics. Fracture mechanics is a discipline in science where the development of cracks in materials during repeated loading are modelled and explained. It has been theoretically shown by different researchers that b is between 3 and 4 (Medani & Molenaar 2000, Lee et al. 2003, Molenaar 2007).

Rutting on the other hand show a different response to traffic loading, compared to fatigue. In the US M-E Design Guide, as an example of generally accepted relationship for deformation, the following relationship between resilient strain (non-permanent), εr, and plastic strain (permanent), ε_p is provided (NCHRP 2004):

$$\frac{\varepsilon_p}{\varepsilon_r} = k_1 \cdot 10^{-3,4488} \cdot T^{1.5606} \cdot N^{0.479244} \tag{5.3}$$

where k_1 is a parameter dependent on asphalt concrete thickness, T is temperature and N is number of vehicle passes. Keeping these parameters equal, one can conclude that the permanent deformation is linear to the resilient response, which is approximately linear to the traffic load for limited ranges. Hence, there is no fourth power law in this case. It is then a linear relationship between axle load and permanent deformations leading to rutting.

Asphalt concrete is viscoelastic, which means that its response to load is time dependent and develops a time history. Asphalt concrete is also believed to heal some damage over a period of resting time. Therefore, there is a slight difference between for example passes of three single axles and one pass of a triple axle with the same axle loads. This is illustrated in Figure 7.4 where the increasing top transversal strain should be noted. Even though the extra top strain is estimated to 14 % in this case, a damage law with a power factor between 3 and 4 will result in between 48 and 69 % more damage for the last passage compared to the first (cf. eq. 5.2). Another consequence of viscoelasticity is the considerable time needed for the transversal strain to return to near its original level (which in theory is never totally reached). Similarly another consequence of viscoelasticity is that lower speed of vehicles lead to larger deformations as the transversal strain evolves over a longer period of time, but this will not have a significant effect in the context of heavier vehicles if it is assumed that a given total load is transported by given maximum axle loads.

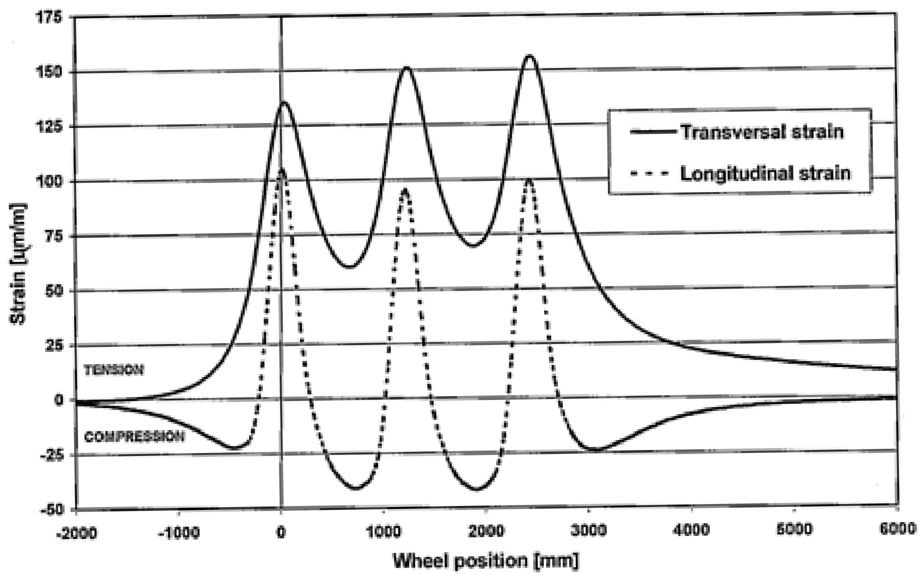


Figure 7.4. Calculated strains at the bottom of asphalt concrete layers during passing of triple axle (Nilsson 1999). Observe that remaining viscous deformations lead to increased top strain for the last axle and a slow recovery after loading.

Cement bound materials

Similar to asphalt bound materials, cement bound materials are used in wearing courses and base layers. The pavements are then referred to as rigid pavements. Furthermore, cement, lime or other hydraulic binders can be used to improve properties of subbase and subgrade materials, which give them more rigid properties. Cement concrete has no relaxation abilities and consequently no viscous deformations. Flexible joints at sufficiently short spacing are needed to account for the always appearing deformations in lower layers and keep internal stresses at an acceptable level. Temperature variations and corresponding vertical temperature gradients are one source of internal stresses. Cement concrete may also be subject to fatigue and ageing. Fatigue due to temperature and traffic loads is used as a pavement design criteria. Ageing and durability is an important topic since rigid pavements usually are demanded a long service life to be cost efficient compared to flexible pavement with much shorter maintenance intervals.

7.1.2. Loads from heavy vehicles and their influence on pavements

Loads from vehicles are transferred to the pavement surface by the contact area of tyres. Therefore, axle loads, tyre configuration and tyre properties are of great importance to deterioration. At the road surface in the wheel paths, the loads of single tyres are of importance. Further down in the pavement and the subgrade, several loads from multiple tyres and axles may overlap and be of importance to the total stresses and strains.

The loads from vehicles vary substantially from the ideal load distribution as a consequence of dynamic effects and uneven distribution of goods.

Tyre properties are important to which contact pressure that develop between tyre and road surface, such as tyre pressure, pattern with contact area and design of tyres that are relevant to how load forces are distributed through the tyre. The distribution of tyre contact pressure on the road surface will influence the deterioration in the upper layers by locally high shear stresses and strains in both vertical and horizontal directions.

Cracking

Cracking appear in bound materials as a result of repeated loading, often referred to as fatigue. At least three different categories of fatigue related cracks can be defined: top-down cracking, bottom-up and alligator cracking. Alligator cracking is generally related to thin bituminous layers, i.e. low volume roads, and mainly occur during cold or wet conditions. Bottom-up and top-down cracking are directly related to high repeated stresses and strains occurring at the top and bottom of the bituminous bound layers. Bottom-up cracks can directly be attributed to the tensile stresses and strains occurring below tyres. Top-down cracking is more complex and related to high repeated tensile and shear stresses and strains occurring beside the tyres as well as loading, climate and properties of wearing course materials.

Related to allowance of longer and heavier vehicles; since crack appears in the upper one or two decimetres redistribution of loads on several axles and tyres will significantly reduce deterioration by cracking. However, as earlier stated, multiple loads during a short period will give rise to slightly higher degradation than what a purely additive model would suggest, for example due to viscoelastic effects.

Rutting

Rutting appears in all pavement and subgrade layers as a result of compaction or redistribution of the materials. Changing shape of bound layers as result of rutting in unbound layers below is part of the process of rutting. Ideally, most compaction in pavement and subgrade should have been taken care of during construction but experience show that traffic will cause some compaction and that climatic effects may lead to the pavement materials becoming susceptible to compaction. Heavy loads may lead to higher degree of compaction at greater depths in the pavement and subgrade. Tyre configuration and axle load may influence compaction of materials near the surface. Likewise, loads and tyre configuration will influence the shear stresses and strains that are responsible for redistribution of materials at all levels.

Regarding effects of longer and heavier vehicles, distribution of loads on several axles significantly reduces rutting in pavement layers. The potential problem of softening of soils by increased pore pressures from repeated traffic loading is not well known, even though evidence for the mechanism has been presented. The mechanism is similar to that happening during for example earthquakes but the load characteristics are too different to apply results directly.

Modelling of rutting due to heavier vehicles are possible and directly related to the loads and consequently the distribution of axles and tyres with the resulting contact pressures and areas.

Critical condition approach

Pavement deterioration is generally seen as a continuous development in properties and condition. If design, construction and maintenance of pavements and traffic loads are following regulations, this is generally true and the aforementioned development of rutting and cracking is prevailing. However, in the context of allowing longer and heavier vehicles it might be of interest to notice how critical conditions and factor interaction can lead to severe deterioration during a short period. These critical conditions needs to be considered in the PBS framework.

In combination with heavy traffic, some critical conditions for flexible pavements are:

- Cold (stiff) surface and wet (weak) subgrade. Often the case during thawing. Great risk for cracking of asphalt concrete.
- Hot (soft) asphalt concrete and wet (weak) subgrade. Often the case during rainy summers on poorly drained pavements. Great risks for excess rutting.
- Frequent slow traffic on hot (soft) asphalt concrete pavements.
- Frequent axle loads on soils that can build up high pore pressure, which result in low bearing capacity and low resistance to deformation.

One example of critical condition for rigid pavements is rapidly heated surface (creating a large temperature difference to lower layers) and heavy traffic. Slabs are poorly supported in the centre and experience great stresses.

7.1.3. Modelling of damages caused by heavy vehicles

For the purpose of estimating the relative deterioration of different axle loads an approach relating the deterioration of a specific axle load to that of a standard axle load is commonly used. The deterioration or expected life length of a standard axle can then be estimated by simple tables, performance models or advanced mechanistic models. The most well-known relationship is the so called “fourth power law” which is expressed mathematically as follows:

$$\frac{N_{ref}}{N_x} = \left(\frac{W_x}{W_{ref}}\right)^4 \qquad (5.4)$$

where W_x and W_{ref} are axle loads and N_x and N_{ref} are the corresponding number of load applications. The exponent 4 in the fourth power law was found in the AASHO Road Test, carried out in USA during 1958-1960. However, it was not strictly constant in that test but varied from about 3.6 to 4.6. Later experimental and theoretical research has indicated greater variability in the exponent, but has not been conclusive. When individual distress modes are considered, different exponent values are found. For instance, COST 334 reports that cracking of bituminous layers has a value of $4 - 7$, permanent deformation of the subgrade has an exponent of perhaps $3 - 4$ and permanent deformation of bituminous layers a value of $1 - 2$. As these values depend on many factors (a.o. material variations) and are not fully known, the stated values should be regarded as “best estimates” (COST 2001). However, the conclusions stated by COST 334 can also be questioned, especially during critical conditions when stresses and strains are approaching the limiting strengths, such as when heavy loads are passing sections experiencing thawing or flooding. It is therefore important that road managers ensure that critical conditions are avoided, at least on medium and highly trafficked roads. Consequently, these roads should have exponent values less than 5. The exact exponent value will then be dependent on which layer that is critical to distress and finally causing need for maintenance.

To formulate the effect of dynamic loads due to vertical motion of the body and the wheel hop, usually a so-called Dynamic Load Coefficient (DLC) is used. Relative to the static load, DLC is about 5-10% for well-damped suspensions and can goes up to 20-40% for poor-damped suspensions (Bosma et al. 2012).

Another important factor that influence the pavement wear caused by heavy vehicles is the tyre characteristics. The relative pavement wear for different tyres at equal loads is commonly formulated in form of a Tyre Configuration Factor (TCF). The TCF proposed in COST 334 for primary rutting, derived using regression analysis with 295/80R22.5 tyre as reference, is expressed as (COST 2001):

$$TCF = \left(\frac{b}{470}\right)^{-1.65}\left(\frac{2R}{1059}\right)^{-1.12}(pressure\ ratio)^{1.42} \qquad (5.5)$$

7.1.4. Existing regulations

Limiting the axle loads is a widely used approach for controlling the effect of heavy vehicles on pavements. In the Australian PBS, in addition to the axle load limits, there are maximum limits on the gross mass of the vehicle and the tyre inflation pressure, in order to control the pavement horizontal loading and pressure distribution. It should be noted that the gross mass limits in the Australian PBS, which depend on the number of driving axles, are higher than the existing prescriptive regulations in Australia.

In Sweden, axle load limits are used which depend on the bearing capacity (BK) of the road (three classes) and the axle configuration, see Table 7.1 (Transportstyrelsen 2010). These regulations is here discussed from the above described knowledge of deterioration mechanisms and modelling.

For bitumen bound layers dividing a 11.5 t load on twice as many tyres will lead to approximately $2(5.75/10)^4 = 22$ % of damage compared to a single 10 t load (based on the fourth power law above). A 20 t bogie axle with a long distance between tyres will correspond to a damage of slightly more than twice that of a single 10 t axle (due to viscoelastic effects above). Considering all other uncertainties, twice the damage is probably enough to describe the effect. At high road surface temperatures and slow vehicles speed the approximation will no longer be valid. The same analysis can be applied to triple axles. Deterioration of bitumen bound layers a comparably thin compared to axle dimensions and will consequently be very dependent on tyre properties.

Table 7.1 Axle load limits (tonne) in Sweden.

	BK1	BK2	BK3
1. Axle load			
a. Axle that is not a driving axle	10	10	8
b. Driving axle	11.5	10	8
2. Bogie load			
a. The distance between the axles is less than 1.0 m.	11.5	11.5	11.5
b. The distance between the axles is 1.0 m or more but not 1.3 m.	16	16	12
c. The distance between the axles is 1.3 m or more but not 1.8 m.	18	16	12
d. The distance between the axles is 1.3 m or more but not 1.8 m and the driving axle is fitted with twin wheels and pneumatic/equivalent suspension or the driving axles are fitted with twin wheels and the weight on no axle exceed 9.5t	19	16	12
e. The distance between the axles is 1.8 m or more.	20	16	12
3. Triple axle load			
a. The distance between the outer axles is less than 2.6 metres.	21	20	13
b. The distance between the outer axles is 2.6 metres or more.	24	22	13

For unbound materials, dividing a load on several tyres will reduce the stresses and strains in the upper pavement layers. However, further down in the pavement and subgrade loads from several tyres will overlap, depending on the distance between tyres and the load distribution ability of the pavement layers. At a sufficient depth the deformation from traffic loads will diminish since the extra stresses and strains are very small, especially compared to the static stress from the weight of materials. To analyse how the distance between tyres influence deterioration, permanent deformations can be calculated using the MEPDG equation, since the increase in strain level of the combined strains are fairly small. Permanent deformations in unbound layers are a good measure of the extra cost of maintenance that is caused by heavy loads with respect to deterioration in unbound layers. The example distance between bogie tyres in the Swedish regulations seems to comply well with permanent deformations calculated by the Swedish Transport Administration strain computing software, "PMS Objekt".

7.2. Bridge

Bridges are the primary part of the infrastructure that put restrictions on the allowed axle load and gross weight of heavy vehicles, to avoid excessive loading of the bridges. A number of different bridge types exist such as slab, slab frame, girder, box girder, arch, truss, cable stayed, suspension and composite bridges. The load bearing mechanisms differ between these bridges and they show a variety in materials, spans and overall geometries. Many bridges are very short and not affected by allowing longer vehicles. Deterioration of shorter bridges is therefore more dependent on axle and tire configuration.

The structural strength is achieved by components consisting of concrete, reinforced concrete, steel structures and steel cables, which are joined together by components. The difference in static function and material types lead to a difference in sensitivity to longer and heavier vehicles. Therefore the allowed traffic load is calculated for each individual vehicle and bridge when dispensations are issued in Sweden. These calculations are made in two different ways. In the first one the load intensity of the dispensation vehicle is compared with the load intensity of the reference vehicles. For most of the bridge types, a second calculation is also made to compare the load effect of the dispensation vehicle with the load effect of the reference vehicles, where the actual influence lines for each bridge is used in the calculations. The most favorable calculation is valid. In some cases lower safety margins are considered in the bearing capacity calculation of bridges when granting dispensations; since, there exist more information about the actual axle load and configuration of the vehicle. Furthermore, the granted dispensation is for a limited time.

In Sweden the bearing capacity of a bridge is determined by calculating the load effects and resulting stresses using reference vehicles, taking into account the bridge condition and its weight and other loads. The reference vehicles that are used in the bearing capacity calculations of bridges were originally nine vehicles selected in 1980s, named "*a*" to "*i*". The reference vehicle list were expanded later in two stages with three (*j*, *k* and *l*) and two more vehicles (*m* and *n*). Currently the bearing capacity calculation of bridges is based on all 14 reference vehicles, "*a*" to "*n*", described in the regulation TDOK 2013:267, version 1.0 (Trafikverket 2013). The reference vehicle "*a*" is used to determine the value for the permissible single axle load, while reference vehicles "*b*" to "*n*" are used to determine the permissible bogie axle load and the gross weight. The permissible gross weight versus axle distance is calculated by considering every axle distance in the reference vehicles and its corresponding sum of axle weight, see Figure 7.5. The permitted values for the axle load and the bogie load have evolved from 6 t and 10 t in the 1950s, respectively, to 8 t and 12 t in 1967 and 10t and 16t in 1974 and finally to current limits of 12 t and 18 t, in place since 1992. In 1980s, the bearing capacity calculation was conducted for all existing bridges. Individual calculation was conducted for every bridge made before the Second World War, while for other bridges stereotyped calculations were performed, considering that these bridges were designed for significantly higher loadings.

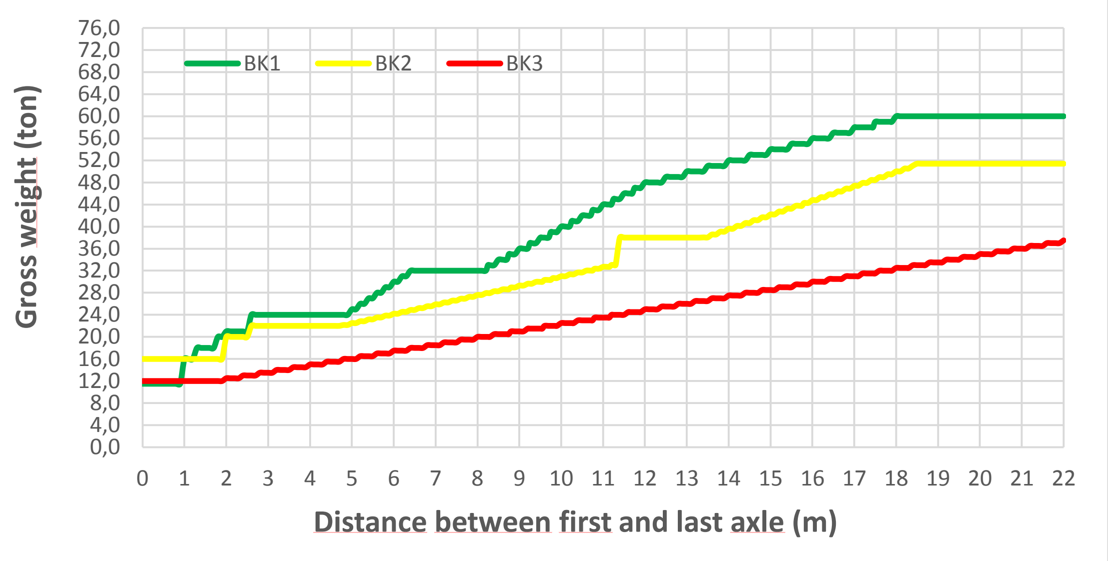


Figure 7.5. Permissible gross weight vs. distance between first and last axle of the vehicle, for the three bearing capacities (Trafikverket 2014).

7.2.1. Bridge formula & MERRV

Bridge formulae are widely used for estimating the effect of heavy vehicle loadings on bridges and advising some limits on the total mass based on the axle configurations, namely axle spacing, and in some cases, number of axles. In Table 7.2, some examples are provided.

Table 7.2 Examples of bridge formulae used for regulation of heavy vehicles loading.

Country	**Bridge Formula**	**Notes**
Australia (NTC 2008)	Access to the PBS level 1 road network M = 3L + 12.5 for M <= 42.5 t M = L + 32.5 for M >= 42.5 t Access to the PBS level 2 road network M = 3L + 12.5 for M <= 46.5 t M =1.5L + 29.5 for M >= 46.5 t Access to the PBS Level 3-4 road network M = 3L + 12.5 for all M	L [m] = distance between the extreme axles of any two axle groups M [ton] = total gross mass on the axles within that distance L
United States (USDoT 2000)	W = 500 [L N / (N - 1) + 12 N + 36]	W [lb] = maximum weight on any group of two or more consecutive axles L [ft] = distance between the extremes of the axle group N = number of axles in the axle group
South Africa (SADoT 2009)	M1 = 2100 L + 18000 For abnormal load vehicles M2 = EW (6.850 + 0.00145 AD)	L [m] = distance between the centres of extreme axles of any two axle groups M1 [kg] = maximum combined mass on all the axles within the distance L M2 [kg] = Allowable maximum mass of the group of axles EW [mm] = Effective Width AD [mm] = Distance between the centre of the first axle of any group of axles to the centre of the last axle of the group

In the Australian PBS, a bridge formula is used to avoid excessive loading of the bridges by HCT vehicles, as described in Table 7.2. However, during the development of infrastructure PBS, another measure was also considered, called Bridge standard Maximum Effect Relative to Reference Vehicle (MERRV). The MERRV measure may be described as the maximum bending moment and shear force induced in a set of representative (or route specific) bridges measured relative to a reference vehicle. This alternative, which was later excluded from the Australian PBS, has some similarities with the Swedish approach for granting dispensations.

7.3. Other infrastructure aspects

Here other relevant infrastructure aspects with respect to HCT vehicles, namely road design, safety barriers, tunnel design and road services, are briefly described.

Road design requirements are stated in regulatory documents ensuring function based on for example typical traffic situations, several reference vehicles, design speed, physics (dynamics, friction), aesthetics, reliability, safety, costs and driver behaviour and needs. These functional needs are stated in the documents as performance based or geometrical constraints, such as road width, free height and available area in junctions. Geometrical characteristics of the roads should be considered when investigating manoeuvrability and safety of HCT vehicles with respect to the measures described in Chapter 4.

Suitability of existing safety barriers for HCT vehicles should also be investigated. It should be noted that the highest containment level of barriers specified in the current European standards is H4b, which involves an impact test with a 38 tonnes vehicle with an impact speed of 65 km/h and an impact angle of 20° (OECD 2011).

HCT vehicles do not impose further geometrical requirements on the tunnel design than the road design, except for emergency parking areas in long tunnels. However, tunnels are subject to extensive safety considerations which should be taken into account when investigating effect of HCT vehicles. For instance, tunnels should be properly equipped to ensure that the risk of fire do not increase by allowing passage of HCT vehicles. Risks associated with heavy vehicles in tunnels is discussed in (OECD 2011).

Another relevant infrastructure aspect is availability of road services such as parking and rest areas for HCT vehicles. As stated in (Hjort & Sandin 2012), driver fatigue is the cause of an essential part of single vehicle accidents with heavy vehicles, which signify the importance of access to sufficient rest areas.

8. Discussions

8.1. Safety and manoeuvrability

In work package 2 a list of selection criteria, by a board of experts within the field, were prepared as a basis for discussions and selection of relevant performance measures. Discussions were held to decide which one of the gathered safety and manoeuvrability related performance measures, described in Chapter 3, should be included in the preliminary set of performance measures to be investigated thoroughly in this project, via simulations and test track experiments. The selection criteria are:

- They shall be valid with respect to the traffic issues of heavy vehicles
- Preferably, they shall be based on existing standards
- They shall be simple and robust
- They shall be measurable in full-scale vehicle tests
- They shall be compatible with European regulations
- Redundancy shall be avoided (with respect to the traffic issue to be captured)

The preliminary selected performance measures are discussed in the following subsections. An important aspect of the study is to investigate each of these measures with respect to both high and low friction surfaces, where tyre characteristics and tyre modelling play an important role. Existence of correlations between the performance on high and low friction surfaces should be investigated. A preliminary list of heavy vehicle combinations to be modelled and studied by simulations, are provided in Appendix. The list cover both existing fleet in the Sweden and prospective HCT vehicles.

8.1.1. Traction, tracking and stability

For the measures in the traction, tracking and stability categories, it was concluded that all the listed measures in Table 4.1 should be considered for further investigation, except handling quality which reckoned not to have a robust definition and not to be directly related to safety hazards or a specific issue for HCT vehicles. It is anticipated that some of the listed measures are highly correlated; however, this should be verified by the investigation results, before a measure can be eliminated. The anticipated correlated measures are:

- High speed steady-state offtracking and the tracking ability on straight path; the difference is the level of lateral acceleration the vehicle is exposed to.
- Rearward amplification, load transfer ratio and high speed transient offtracking; rearward amplification of both lateral acceleration and yaw rate will be investigated.
- Startability, gradeability and acceleration capability. For high speed gradeability, more than one grade should be checked based on the road characteristics in Sweden.

Furthermore, frontal swing, tail swing and low-speed offtracking will be investigated in the same manoeuvres, and if possible, will be replaced by one measure which cover all aspects of cornering at low speed. The manoeuvres will be based on the Swedish road characteristics.

8.1.2. Braking

For the measures addressing the braking performance of the heavy vehicles, it is reckoned that the existing measures in ECE R13 regulations are also suitable for the HCT vehicles; thus, only braking stability in a turn, which does not exist in the ECE R13, will be included in the upcoming investigations. However, to verify the suitability of ECE R13 regulation for HCT vehicles, some braking tests with a selection of HCT vehicles should be conducted to verify that certifying each unit separately, which is the case in ECE R13, is sufficient to assure an acceptable braking performance of the complete vehicle. Furthermore, the possibility of inclusion of an exemption for HCT vehicles with regard to parking ability on a grade should be deliberated. To be more specific, ECE R13 demands that the parking brake on the towing unit of a vehicle combination should be able to hold all the connected trailers (unbraked) on a 12% slope; possibility of altering the regulation so that the parking brake on the trailers can be also utilized to pass the regulation should be considered.

Another brake related issue of the HCT vehicles, which is not discussed in the reviewed literature, is the down-grade holding capability, i.e. the ability of a fully loaded vehicle to maintain a certain constant speed on a specified down-grade in different road conditions (Sadeghi 2013). The necessity of adding a measure for addressing the down-grade holding to the Swedish PBS should be assessed.

In Table 8.1 the selected safety and manoeuvrability performance measures, to be further investigated within the "PBS for HCT in Sweden" project, are listed.

Table 8.1 Performance measures to be further investigated within the "PBS for HCT in Sweden" project.

	Performance measure*
Traction	Startability
	Gradeability
	Acceleration capability
Tracking	Tracking ability on a straight path
	Frontal swing
	Tail swing
	Low-speed swept path
	High-speed steady-state offtracking
	High-speed transient offtracking
Stability	Steady-state rollover threshold
	Load transfer ratio
	Rearward amplification
	Yaw damping coefficient
	Friction demand of steer tyres in a tight turn
	Friction demand of drive tyres in a tight turn
Braking	Braking stability in a turn

* The performance measures are defined in Chapter 4

8.1.3. Extra safety features

Applicability and effectiveness of demanding extra safety features on HCT vehicles for ensuring safe performance should be explored. Examples of such safety features are active safety systems, e.g. Electronic Stability Control (ESC), full EBS functionally on all units for faster braking response and splash guards for decreasing risks associated with overtaking.

8.2. Environment

In Chapter 4, the existing European regulations, also in effect in Sweden, on exhaust and noise emissions and prospective regulations on fuel consumption were presented. As mentioned, they are all already performance based regulations, thus, the main issue with respect to HCT vehicles is whether the existing regulations are suitable for them as well or not. Some of the main questions and concerns to be investigated are:

- Is it adequate to mandate an exhaust emission limit in accordance to Euro VI for HCT vehicles?
- What is a suitable metric for the prospective fuel/energy consumption limits of HCT vehicles and what should be the allowed limits?
- The vehicle noise is verified for the powered unit (truck/trailer), not the whole vehicle combination. However in reality, the noise level of a truck/trailer hauling just one trailer or multiple trailers is not the same due to the differences in the engine load, number of axles and aerodynamics.
- Should the tyre noise limits be different for HCT vehicles due to the fact that a long heavy vehicle combination is equipped with more tyres?

8.3. Infrastructure

The main pavement deterioration mechanisms and their relationship to heavy loads, as well as bridge bearing capacity calculations were described in Chapter 5. In summary the followings recommendations with respect to HCT vehicles should be considered:

- To comply with the existing load regulations
- Divide loads on axles that give less damage than if carried by single 10 t axles
- Divide loads on tyre configurations that give less damage by comparing the total permanent deformation in unbound layers with deformation caused by the same load on single 10 t axles, for example using the MEPDG equation and strains calculated by PMS Objekt or equivalent.
- If needed, a critical condition approach should be used which better address some specific issues that cannot be modelled with current state of knowledge in research. For instance, the current knowledge is not sufficient to estimate effects during passes of multiple heavy loads on wet subgrade prone to building up high pore pressures. This particular effect is currently under investigation in an ongoing project at the mine road connecting Kaunisvaara near Pajala (Erlingsson & Carlssom 2014).
- The effect of HCT vehicles on bridges should be investigated. One possible approach is considering more reference vehicles and updating the gross weight curve, Figure 7.5, and maybe even introducing more categories in the road network. This approach has already been investigated by Swedish Transport Administration for vehicles with gross weight up to 74 t and is presented in (Trafikverket 2014).
- Other aspects such as suitability of safety barriers, tunnel safety and availability of resting areas should be considered.

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Appendix

Table A.1 Preliminary list of heavy vehicle combinations to be modelled and studied in the project

	Heavy Vehicle Combination	**Axle configurations***
1	Tractor-Semitrailer	TR1+1-ST3 TR1+2-ST3
2	Tractor-Link trailer-Semitrailer (B-double)	TR1+1-LT2-ST3 TR1+2-LT2-ST3 TR1+2-LT3-ST3
3	Tractor-Semitrailer-Center axle trailer	TR1+1-ST3-CT2 TR1+2-ST3-CT2
4	Tractor-Semitrailer-Dolly-Semitrailer (A-double)	TR1+1-ST3-DY2-ST3 TR1+2-ST3-DY2-ST3
5	Tractor-Link trailer-Link trailer-Semitrailer (B-triple)	TR1+2-LT2-LT2-ST3 TR1+2-LT3-LT3-ST3
6	Truck-Center axle trailer	TK1+2-CT2 TK1+3-CT3
7	Truck-Full trailer	TK1+2-FT2+2 TK1+2-FT2+3 TK1+3-FT2+3
8	Truck-Dolly-Semitrailer	TK1+2-DY2-ST3 TK1+3-DY2-ST3
9	Truck-Center axle trailer-Center axle trailer	TK1+2-CT2-CT2 TK1+2-CT3-CT3
10	Truck-Dolly-Link trailer-Semitrailer (Truck B-double)	TK1+2-DY2-LT2-ST3 TK1+2-DY2-LT3-ST3 TK1+3-DY2-LT3-ST3

* **TR**=Tractor, **TK**=Truck, **ST**=Semitrailer, **CT**=Center axle trailer, **LT**=Link trailer, **FT**=Full trailer, **DY**= Dolly
The number following each unit name (i+j) indicates number of axles at the front (i) and number of axles at the rear (j).
For units with a single axle group, only one number is given.

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