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A pre-study for CEDR

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Abstract

This report includes the gathered information in a CEDR pre-study, with the objective to list the relevant safety, manoeuvrability, infrastructure and environment related criteria for longer and/or heavier vehicles. Furthermore, research areas that should be further investigated for development of a harmonized performance based standards for assessing longer and/or heavier vehicles access to a road network, are identified.

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Denna rapport innehåller samlad information från en CEDR förstudie med målet att lista relevanta säkerhets-, manövrerbarhets-, infrastruktur- och miljörelaterade kriterier för längre och/eller tyngre fordon. Dessutom identifieras forskningsområden som bör utredas ytterligare för att utveckla harmoniserade prestandabaserade kriterier för bedömning av längre och/eller tyngre fordons tillgång till ett vägnät.

Titel:	Prestandabaserade kriterier för tunga fordon med vikt och/eller dimensioner som överskrider de angivna gränserna i direktivet 96/53/EC – En förstudie för CEDR
Författare:	Sogol Kharrazi (VTI) Robert Karlsson (VTI)
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Preface

Many of the member organizations within Conference of European Directors of Roads (CEDR) are interested in development of harmonized performance based standards for the infrastructure, with respect to vehicle combinations with weight and/or dimensions exceeding the specified limits in the directive 96/53/EC. Their emphasis is not on determining whether longer and/or heavier vehicles should be allowed on a given road network or not, but on developing a harmonized framework for objective evaluation of the suitability of the infrastructure for such vehicles. In this scope, Swedish Transport Administration and Norwegian Public Road Administrations commissioned the Swedish National Road and Transport Research Institute, VTI, to conduct a pre-study and literature review on this topic. The objective of the pre-study is to list the relevant safety, infrastructure and environment related criteria for longer and/or heavier vehicles and to identify research areas that should be further investigated.

The authors would like to thank Thomas Asp and Petter Åsman at Trafikverket and Henning Fransplass and Elin Norby at Statens vegvesen for their valuable cooperation during the course of the project.

Linköping, September 2015

Sogol Kharrazi

Quality review

External peer review was performed by Thomas Asp, Trafikverket, and Henning Fransplass, Statens vegvesen. Sogol Kharrazi has made alterations to the final manuscript of the report. The research director, Jonas Jansson, examined and approved the report for publication in October 2015. The conclusions and recommendations expressed are the author's/authors' and do not necessarily reflect VTI's opinion as an authority.

Kvalitetsgranskning

Extern peer review har genomförts av Thomas Asp, Trafikverket, och Henning Fransplass, Statens vegvesen. Sogol Kharrazi har genomfört justeringar av slutligt rapportmanus. Forskningschef Jonas Jansson har därefter granskat och godkänt publikationen för publicering i oktober 2015. De slutsatser och rekommendationer som uttrycks är författarens/författarnas egna och speglar inte nödvändigtvis myndigheten VTI:s uppfattning.

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Summary

Performance based standards for vehicle combinations with weight and/or dimensions exceeding the specified limits in the Directive 96/53/EC – A pre-study for CEDR

by Sogol Kharrazi (VTI) and Robert Karlsson (VTI)

The predominant worldwide regulatory principle used for regulation of heavy vehicles is prescriptive regulations with explicitly defined and quantified mandates. The common approach is setting limits on the vehicle weight and length to ensure safety and to protect infrastructure. However other approaches are also in use; for instance in Australia, Canada, and New Zealand, Performance Based Standards (PBS) are implemented. Under a PBS approach, 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.

Many of the member organizations within Conference of European Directors of Roads (CEDR) are interested in development of a harmonized PBS for infrastructure, which can be used for objective assessment of suitability of the road infrastructure for vehicle combinations with weight and/or dimensions exceeding the specified limits in the directive 96/53/EC. This report is the outcome of a pre-study which reviews the existing legislations imposing limitation on weight and dimensions of heavy vehicles in Sweden, Norway and Europe. Furthermore, it discusses performance measures for safety and manoeuvrability of Longer and/or Heavier Vehicles (LHVs) and relevant infrastructure and environmental aspects.

When investigating the performance of heavy vehicles with respect to safety and manoeuvrability measures, both vehicle design and infrastructure design should be considered; since they are highly related. If a heavy vehicle is to be permitted on a certain road network, features of the roads play an important role on the required level of performance from the vehicle. Therefore, in the provided list of relevant performance measures in this report, the corresponding influential infrastructure features are also listed. Similarly dynamics and design of vehicles to be traveling on a road, should be considered when constructing a road. One approach to address this, is to utilize reference vehicles for road design, which is applied in both Sweden and Norway.

The main infrastructure design features which should be considered with respect to LHVs are: grade, lane width, curvature, roundabout and intersection dimensions and crossfall. Other important infrastructure aspects are availability of parking and rest areas, tunnel safety, safety barriers, turn lane length, distance between a railroad crossing and intersection, sight distance at an intersection and regulation of traffic signals.

Heavier loads of LHVs can be compensated for by axle and tire configurations that reduce the loads on the pavement. Nevertheless, it is important to note that there are load history dependent deterioration mechanisms in the pavement structure. There are gaps in the knowledge of these effects and further investigations are required. Another important issue with regard to bearing capacity of a pavement, is its variance during a year. Thus, axle load limits can be adjusted with regard to seasonal changes, an approach which is implemented in e.g. Norway and Canada.

The primary part of the infrastructure that put restrictions on the allowed axle load and gross weight of heavy vehicles, to avoid excessive loading, are bridges. 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 account for the effects of LHVs on bridges is to consider more reference vehicles. This approach has been investigated by Swedish Transport Administration for vehicles with gross weight up to 74 ton. Another common approach, used e.g. in Australia and the United States, is to calculate the effects of the vehicle loading on the bridges by a bridge formula.

Sammanfattning

Prestandabaserade kriterier för tunga fordon med vikt och/eller dimensioner som överskrider de angivna gränserna i direktivet 96/53/EC – En förstudie för CEDR

av Sogol Kharrazi (VTI) och Robert Karlsson (VTI)

Den globalt dominerande regleringsprincipen för reglering av tunga fordon är normativa regelverk med uttryckligt definierade och kvantifierade mandat. Den vanligaste metoden är att sätta gränser för fordonets vikt och längd för att garantera säkerheten och skydda infrastrukturen. En annan metod som används i Australien, Kanada och Nya Zeeland, är 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.

Många av medlemsorganisationerna i Conference Europeenne des Directeurs des Routes (CEDR) är intresserade av att utveckla en harmoniserad PBS för infrastruktur som kan användas för att objektivt bedöma lämplighet av ett vägnät för fordonskombinationer med vikt och/eller dimensioner som överskrider de angivna gränserna i direktivet 96/53/EC. Denna rapport är resultatet av en förstudie som granskar befintliga lagstiftningar med begränsningar på vikt och dimensioner av tunga fordon i Sverige, Norge och Europa, och diskuterar prestandamått för säkerhet och manövrerbarhet av längre och/eller tyngre fordon (LHV) och relevanta infrastruktur- och miljöaspekter.

Vid utredning av tunga fordons prestanda med avseende på säkerhet och manövrerbarhet, bör både fordonsdesign och vägkonstruktion övervägas eftersom de är starkt relaterade. Vägars utformning spelar en viktig roll för den nivå av prestanda som krävs av fordonet. Därför så finns i den medföljande listan över relevanta prestandamått i denna rapport även motsvarande inflytelserika infrastrukturegenskaper. På samma sätt bör dynamik och konstruktion av fordon som färdas på väg övervägas vid konstruktion av en ny väg. Ett sätt att ta hänsyn till detta är att använda referensfordon vid vägutformning vilket appliceras i både Sverige och Norge.

De viktigaste infrastrukturegenskaperna som bör övervägas i förhållande till LHV:er är: lutning, körfältsbredd, radiestorlek i kurvor, cirkulationsplats- och korsningsdimensioner och tvärfall. Andra viktiga infrastrukturaspekter är tillgängligheten av parkeringar och rastplatser, tunnelsäkerhet, skyddsräcke, svängkörfältslängd, avståndet mellan en järnvägsövergång och korsning, sikt i en korsning och reglering av trafiksignaler.

Tyngre laster av LHV:er kan kompenseras av axel- och däckskonfigurationer som minskar belastningen på vägen. Men det är viktigt att notera att det finns historieberoende nedbrytningsmekanismer i vägbeläggningen vilket är ett område där det saknas tillräckligt med kunskap och ytterligare undersökningar krävs. En annan viktig aspekt när det gäller vägbärighet är dess varians under ett år. Således kan gränsvärden för axeltryck justeras med hänsyn till säsongsmässiga förändringar, en strategi som genomförs i till exempel Norge och Kanada.

Den huvudsakliga delen av infrastrukturen som sätter begränsningar på tillåtna axeltryck och bruttovikten för tunga fordon för att undvika överbelastning är broar. I Sverige bestäms bärigheten hos en bro genom att beräkna belastningseffekter och resulterande påfrestning med hjälp av referensfordon. Ett möjligt sätt att ta hänsyn till effekterna av LHV:er på broar är att använda flera referensfordon. Denna metod har undersökts av Trafikverket för fordon med totalvikt upp till 74 ton. En annan vanlig metod, som används till exempel i Australien och USA, är att uppskatta effekterna av fordonets belastning på broar med en broformel.

1. Introduction

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 such an 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 than prescriptive regulations, which encourages innovative novel products. 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).

In this report, first the existing legislations which impose limitation on weight and dimensions of heavy vehicles are reviewed and compared within Sweden, Norway and Europe. Other relevant legislations with respect to safety and environmental effects of the heavy vehicles are also presented. Then performance measures for safety and manoeuvrability of Longer and/or Heavier Vehicles (LHV) are discussed which is followed by the relevant infrastructure and environmental aspects.

2. European, Swedish and Norwegian Legislations

In this section relevant legislations within Europe, Sweden and Norway are compared and reviewed. It should be noted that two types of European legislations are cited in this review: regulations and directives. The difference is that a regulation has general application and is applicable in all member states, while directives set out general rules to be transferred into national law by each country as they deem appropriate (EC 2015).

The following definitions, in accordance to defined terms in the Dir 96/53/EC, are used in this report:

- **Motor vehicle:** any power-driven vehicle which travels on the road by its own means.
- **Semitrailer:** any vehicle intended to be coupled to a motor vehicle in such a way that part of it rests on the motor vehicle with a substantial part of its weight and of the weight of its load being borne by the motor vehicle, and constructed and equipped for the carriage of goods.
- **Trailer:** any vehicle intended to be coupled to a motor vehicle excluding semi-trailers, and constructed and equipped for the carriage of goods.
- **Articulated vehicle:** a vehicle combination consisting of a motor vehicle coupled to a semitrailer.
- **Road train:** a vehicle combination consisting of a motor vehicle coupled to a trailer.

2.1. Weight Limits

The weight limit for international traffic in EU, stated in the Dir 96/53/EC, depends on the number of axles of the vehicle/vehicle combination (EC 1996). In Sweden the weight limit depends on the axle distance (between the foremost and rearmost axles in the vehicle/vehicle combination); there are additional limits for the motor vehicle based on the number of axles (Sweden 1998). Norway has a more detailed approach; there are weight limits for a vehicle based on the vehicle type and number of axles. Furthermore, there are weight limits for the vehicle combination, based on the combination type and axle configuration (Norway 2013). The vehicle weight limits in EU, Sweden and Norway are summarized and compared in Table 1.

Table 1. Vehicle weight limits (ton) in EU, Sweden and Norway

	EU	Sweden	Norway
Motor vehicle	**18/25(26)*/32** for 2/3/4 axles	**18/25(26)*/31(32)*** for 2/3/4 axles	**19/26/26-32*** for 2/3/4 axles (based on wheelbase)
Semitrailer/Trailer	**18/24** for 2/3 axles	**GVW/GCW table** based on axle distance for all vehicles/vehicle combinations; some specific values for drawbar trailers (33-36), also based on axle distance	**10/18,20/24,27** for centre-axle trailer & semitrailer with 1/2/3 axles **20/28/30** for drawbar trailer and dolly with semitrailer with 2/3/4 axles
Vehicle combination	**36/40** For road trains with 4/5 axles **36(38)[1]/40(44)[2]** For articulated vehicles with 4/5 axles [1] if the semitrailer axle distance is bigger than 1.8m and the driving axle is fitted with twin tyres and air suspension [2] if carrying a 40-foot ISO container as a combined transport operation	**GVW/GCW table, max 60** based on axle distance	**GCW table, max 50 (60 for timber transport & modular vehicle)** based on combination type, number of axles and distance between motor vehicle rearmost axle and trailer foremost axle

* If driving axle is fitted with twin tyres and a) air suspension (or equivalent) or b) drive axle load does not exceed 9.5 t

2.2. Axle Load Limits

The approach toward axle load limits and the actual limits are comparable in EU, Sweden and Norway; however, in Norway the reference axle distance has a finer mesh, see Table 2. In Sweden and Norway the axle load limits depend on the road bearing capacity; Sweden has three categories of bearing capacity and Norway has four (Sweden 1998, Norway 2013). The provided values in Table 2 are for the roads with highest bearing capacity.

Table 2. Axle load limits (ton) in EU, Sweden and Norway

	EU (Dir 96/53/EC)	Sweden BK1	Norway BK10
Single Axle Load			
Axle that is not a driving axle	10	10	10
Driving axle	11.5	11.5	11.5
Bogie Load			
d < 1 m (0.8 for Norway)	11 (11.5)*	11.5	10
1 <= d < 1.3 m (between 0.8-1.19 & 1.2-1.29 m for Norway)	16	16	15 & 16
1.3 <= d < 1.8 m	18	18	18
1.3 <= d < 1.8 m and driving axle is fitted with twin tyres and a) air suspension (or equivalent) or b) drive axle load does not exceed 9.5 ton	19	19	19
d >= 1.8 m	20	20	20
Triple Axle Load			
d < 1.3 m (less than 1 & between 1.00-1.29 for Norway)	21	21	16 & 22
d >= 1.3 m	24	24	24

* For driving axle

2.3. Length Limits

Length of single vehicles in EU is regulated in the R (EU) No 1230/2012 which is also applied in Norway (not for timber transport), and also in Sweden, but only for modular vehicles (EC 2012), see Table 3. Length of vehicle combinations in Europe are regulated in the Dir 96/53/EC. 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 (EC 1996); a modular combination is a vehicle combination that consists of vehicle units defined in Annex I of the directive.

Table 3. Vehicle dimension limits (m) in EU, Sweden and Norway

	EU	Sweden	Norway
Motor vehicle	**12**	**12** (only modular)	**12**
Semitrailer	**12** kingpin to rear **2.04** kingpin to front corner	**12** kingpin to rear **2.04** kingpin to front corner (only modular)	**12** kingpin to rear **2.04** kingpin to front corner
Trailer	**12**	**12** (only modular)	**12** (not timber transport)
Vehicle combination	**16.5** (articulated vehicle) **18.75** (road train)	**24** **25.25** (modular)	**17.5** (articulated vehicle) **19.5 (**road train) **24** (timber transport) **25.25** (modular)
Width	**<= 2.55 (2.6)***	**<= 2.55 (2.6)***	**<= 2.55 (2.6)***
Height	**<= 4.0**	**Not regulated**	**Not regulated**

* For conditioned vehicles (vehicles fitted with a bodywork with insulated walls of at least 45 mm thick)

In Sweden the overall length limit is 25.25 m for a modular vehicle combination and 24 m for other combinations (Sweden 1998). The length limit of a vehicle combination in Norway depends on the road category; the largest value is 19.5 m with exception of 24m for timber transport and 25.25 m for modular vehicles which are allowed on parts of the road network (Norway 2013). The vehicle length limits in EU, Sweden and Norway are summarized and compared in Table 3. Additional constraints on the loading length and axle distance of road trains are listed in Table 4 .

Table 4. Additional constraints on the loading length and axle distance of road trains

	EU	Sweden	Norway
Loading length behind the cabin	**15.65**	**21.86** (modular)	**15.65**
From foremost point of the loading area to the rear end of the vehicle	**16.4**	**22.9** (modular)	**17.15**
From rear axle of the motor vehicle to the front axle of the trailer	**>= 3**	**>= 3, 4, 5** (based on axle configuration)	**>= 3**

2.4. Manoeuvrability and Traction

In the R (EU) No 1230/2012, there are extra criteria that indirectly impose restrictions on the dimensions and load distribution of the vehicle to ensure manoeuvrability and traction (EC 2012). These regulations and their counterparts in Swedish and Norwegian legislations are listed in Table 5.

Table 5. Restrictions imposed by manoeuvrability and traction criteria

	EU	Sweden	Norway
Outer & inner circle radius of the swept area in a 360° turn	**12.5 & 5.3** semitrailer is deemed to comply if wb <= $[(12.5\text{-}2.04)^2 - (5.3 + w)^2]^{0.5}$	**12.5 & 5.3** (motor vehicle) **12.5 & 2** (modular vehicle) deemed to comply if axle distance <= 22.5m & trailer wheelbase <= 8.15m	**12.5 & 5.3** **12.5 & 2** (timber transport) **13 & 2 in a 180° turn** (modular vehicle)
Rear swing out in a turn with radius of 12.5 m	**<= 0.8 (1.0) m** (motor vehicle) based on rearmost axle type **<= 1.2 m** (articulated vehicle) Stated in Dir 97/27/EC	**Not regulated**	**<= 0.8 (1.0)m** (motor vehicle) based on rearmost axle type **Not regulated** (vehicle combination)
Steering axles load	**>= 20% of GVW**	**>= 20% of GVW**	**>= 20% of GVW**
Driving axles load	**>= 25% of GCW** Stated in Dir 96/53/EC, for international traffic	**Not regulated**	**Not regulated**
Engine power	**>= 5 kW/t of GCW**	**>= 5kW/t of GCW** (GCW <= 44 t) **>= 220+2(GCW-44) kW** (GCW > 44 t)	**>= 5.15 kW/t of GCW** (GCW <= 40 t) **>= 206 kW** (GCW > 40 t)
Gradeability	**>= 12 %** starting five times within five minutes at a grade (with maximum load)	**>= 12%** starting five times within five minutes at a grade (with maximum load, up to 44 ton)	**>= 12 %** starting five times within five minutes at a grade (with maximum load)

2.5. Brakes

Braking performance of heavy vehicles is another relevant issue that is extensively addressed in the existing regulations in Europe, and is also applied in Sweden and Norway. In the R (EC) No 661/2009, which addresses the type approval of vehicles and their components, the UNECE regulation no 13 is listed as the regulation which should be followed for the brakes (EC 2009b). ECE R13 includes criteria on deceleration, braking efficiency, parking ability on a grade and braking stability on a straight path and on a split friction surface, summarized in Table 6 (UNECE 2008).

Furthermore, in the R (EC) No. 661/2009, the mandatory fitment of a number of active safety systems, including electronic stability control systems (ESC), advanced emergency braking systems (AEBS) and lane departure warning systems (LDWS) for heavy vehicles are included. In addition to the motor vehicles, the ESC system should also be fitted to trailers and semitrailers with air suspension and with less than four axles (EC 2009b). The detailed technical requirements for AEBS and LDWS are stated in R (EU) No. 347/2012 and R (EU) No. 351/2012, respectively.

Table 6. Heavy vehicles brake regulation in Europe

Criteria	**Required level of performance**
Braking deceleration	**5 m/s2** (from 60 km/h with engaged engine) **4 m/s2** (from 90 (80) km/h* with disengaged engine) **4 m/s2** (from 60 km/h, after 20 repeated braking from 60 to 30 km/h) **3.3 m/s2** (from 60 km/h, after 6 km continuous braking)
Braking efficiency, ratio of achievable deceleration to the ideally supported deceleration by the tyre/pavement friction	**>=75%** (on roads with friction coefficient of 0.8 & 0.3 with an initial speed of 50 km/h)
Braking stability on a straight path	**Judged Subjectively** (in a 4 m/s2 deceleration from 90 (80) km/h*)
Braking stability on a split friction surface, measured by required steering correction	**< 240° (120°)**** (from 50 km/h on a surface with kH>0.5, kH/kL>2)
Parking ability on a grade	**>=18 %** (single vehicle loaded up to GVW) **>=12 %** (vehicle combination loaded up to GCW, with unbraked trailer)

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

2.6. Exhaust Emission

The exhaust emission regulation for heavy vehicles in Europe is stated in the R (EC) No 595/2009, which is normally called Euro VI. The main regulation is complemented with the commission regulations R (EU) No 582/2011 and R (EU) No 133/2014, which stipulate all technical details regarding test procedures, measurement instruments and administrative procedures. Euro VI has been applied in both Sweden and Norway.

The emission limits in Euro VI, which are listed in Table 7, has been in effect since 31 Dec 2013 for all new engines. 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 (EC 2009a, EC 2011, EC 2014a).

Table 7. Euro VI emission limits

	CO (mg/kWh)	**THC (mg/kWh)**	**NMHC (mg/kWh)**	**CH4 (mg/kWh)**	**NOX (mg/kWh)**	**NH3 (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

2.7. Vehicle and Tyre Noise

The vehicle noise regulation in Europe are stated in the R (EU) No 540/2014, which replaced the directive 70/157/EEC in April 2014 and is similar to the UNECE regulation no 51, rev 3. The procedure for measuring the vehicle noise is based on the ISO 362:2007 pass-by-noise standard, where 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 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. The new limits for heavy vehicles with engine power more than 250 kW are 82, 81, and 79 dB for the three phases, in effect in year 2016, 2020(2022) and 2024(2026) respectively. There are two different dates because new vehicle types and first registration are not treated equally (EC 2014b).

The tyre noise level limits are laid down in the European regulation R (EC) No 661/2009, which 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); the implementation time for original-equipment tyres is 2016 (EC 2009b). 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; when reaching the recording section, the vehicle should be in neutral gear with the engine switched off. The vehicle and tyre noise limits in Sweden and Norway are same as the ones laid down in the European regulations, see Table 8.

Table 8. Heavy vehicle and Tyre noise limits in Europe

	Heavy Vehicle	**Normal Tyre**	**Traction Tyre**
Noise limit [db]	82, 81, 79*	73**	75**

*Limits for the three phases **Plus 1db for winter tyres

3. Safety and Manoeuvrability of LHVs

In the previous section the existing regulations on heavy vehicles in Europe, Sweden and Norway were reviewed. These regulations address the conventional heavy vehicles with a limited length and weight (18.75m/44t in EU and 25.25m/60t in Sweden and Norway). Thus, to ensure safety and manoeuvrability of LHVs, if allowed on the road, extra requirements are needed. One possible approach is to use Performance Based Standards (PBS), which has been implemented in Australia, Canada and New Zealand. 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.

Here, the relevant performance measures with respect to safety and manoeuvrability of heavy vehicles found in the literatures, current regulations and existing PBS approaches are reviewed. They can be categorized into the four groups of traction, tracking, stability and braking, based on the practical goals they address. This categorization is adapted from the goals used by (Fancher, et al 1989). In the following sections, each of these categories are reviewed.

When investigating the performance of heavy vehicles with respect to safety and manoeuvrability measures, both vehicle design and infrastructure design should be considered; since they are highly related. If a heavy vehicle is to be permitted on a certain road network, features of the roads play an important role on the required level of performance from the vehicle. Likewise when building a new road, the characteristics of the heavy vehicles to be driven on it, put demands on how it should be designed. Therefore, in the provided list of performance measures in the upcoming sections, the influential infrastructure features for each measure, if relevant, are listed along with their nominal values in Sweden and Norway as examples.

3.1. 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 the traction group. The existing European regulation on engine power, driving axle loads and gradeability belongs to this category. In Table 9, the relevant performance measures with respect to traction and the corresponding influential infrastructure features are listed. The nominal values for Sweden and Norway are from (Trafikverket 2012a, Statens vegvesen 2013).

Table 9. Performance measures that address traction of heavy vehicles

	Performance measure	Influential infrastructure feature
Traction	**Startability** Measure of vehicle ability to commence from rest on an upgrade road	**Road grade** Sweden: 6-8% main roads, 10% minor roads Norway: 6% **Friction** Sweden (winter maintenance): 0.35 main roads, 0.25 minor roads Norway (winter maintenance): 0.25 main roads, 0.20 minor roads
	Gradeability Measure of vehicle ability to maintain acceptable speed on an upgrade road	**Road grade** Sweden: 6-8% main roads, 10% minor roads Norway: 6% **Friction** Sweden (winter maintenance): 0.35 main roads, 0.25 minor roads Norway (winter maintenance): 0.25 main roads, 0.20 minor roads
	Acceleration capability Measure of vehicle ability to accelerate from rest with an acceptable level of acceleration	**Friction** Sweden (winter maintenance): 0.35 main roads, 0.25 minor roads Norway (winter maintenance): 0.25 main roads, 0.20 minor roads

3.2. 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 the tracking group. The existing European regulation on swept area and rear swing out belongs to this category.

In Table 10, the relevant performance measures with respect to tracking and the corresponding influential infrastructure features are listed. The nominal values for Sweden and Norway are from (Trafikverket 2012a, Trafikverket 2012b, Statens vegvesen 2013). Road surface friction is important for these measures as well, but it is not repeated in the table.

Table 10. Performance measures which address tracking of heavy vehicles

	Performance measure	Influential infrastructure feature
Traction	**Tracking ability on a straight path** Measure of deviation of the towed units from the prescribed path on an uneven straight road with a crossfall	**Lane width** Sweden: 3.5-3.75m highway, 3.0-3.75m main roads, 2.75-3.25m minor roads Norway: 3.25-3.5m depending on speed limit **Crossfall** Sweden: 2.5-5.5% Norway: Min 2%
	Frontal swing Measure of deviation of front outer corner of the vehicle from the prescribed path in a tight turn at low speeds	**Reference roundabout dimensions (outer and inner circles)** Sweden: 12.5 m - 2.5 m Norway: 12.5 m – 2.5 m **Reference intersection dimensions (available width in a 90° turn)** Sweden: 8.5 m Norway: No guidelines
	Tail swing Measure of deviation of rear outer corner of the vehicle units from the prescribed path in a tight turn at low speeds	**Reference roundabout dimensions (outer and inner circles)** Sweden: 12.5 m - 2.5 m Norway: 12.5 m – 2.5 m **Reference intersection dimensions (available width in a 90° turn)** Sweden: 8.5 m Norway: No guidelines
	Low-speed offtracking/swept path Measure of deviation of the towed units from the prescribed path in a tight turn at low speeds	**Reference roundabout dimensions (outer and inner circles)** Sweden: 12.5 m - 2.5 m Norway: 12.5 m – 2.5 m **Reference intersection dimensions (available width in a 90° turn)** Sweden: 8.5 m Norway: No guidelines
	High-speed steady-state offtracking Measure of deviation of the towed units from the prescribed path in a turn at high speeds	**Road curvature** Sweden: Minimum 100-1200 m depending on speed limit Norway: Minimum 125-800 m depending on speed limit **Lane width*** Sweden: 3.5-3.75m highway, 3.0-3.75m main roads, 2.75-3.25m minor roads Norway: 3.25-3.5m depending on speed limit
	High-speed transient offtracking Measure of deviation of the towed units from the prescribed path in a sudden manoeuvre at high speeds	**Lane width** Sweden: 3.5-3.75m highway, 3.0-3.75m main roads, 2.75-3.25m minor roads Norway: 3.25-3.5m depending on speed limit

* There are guidelines on how much a lane width should increase in a curve, based on the curvature.

3.3. 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 the stability group. The requirement on steady-state rollover threshold of tank vehicles in Europe, according to the UNECE regulation no 111, and ESC fitment belongs to this category.

In Table 11, the relevant performance measures with respect to stability are listed. They are not as closely related to the infrastructure features as the previous categories, thus only the description of the measure is provided in the table. However, road surface friction plays an important role for the stability related measures as well.

Table 11. Performance measures which address stability of heavy vehicles

	Performance measure
Stability	**Steady-state rollover threshold** Measure of maximum severity of the steady turn, i.e. lateral acceleration, which the vehicle can sustain without rolling over
	Load transfer ratio Measure of the proximity of a wheel lift-off in a sudden manoeuvre
	Rearward amplification Measure of the amplification of motions (e.g. yaw rate or lateral acceleration) in the rearmost unit in a sudden manoeuvre
	Yaw damping coefficient Measure of quickness of decay of towed units oscillations after a sudden manoeuvre
	Friction demand of steer tyres Measure of excessive understeering risk, i.e. demanded friction at steer tyres, to overcome the resistance of other axles, in a tight turn at low speeds
	Friction demand of drive tyres Measure of jackknife risk, i.e. demanded friction at drive tyres, to overcome the resistance of trailer axles, in a tight turn at low speeds

3.4. 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 the braking group. As mentioned earlier, this category is addressed within the European regulations rather comprehensively.

In Table 12, the relevant performance measures with respect to braking and the corresponding influential infrastructure features are listed. The nominal values for Sweden and Norway are taken from (Trafikverket 2012a, Statens vegvesen 2013).

Table 12. Performance measures which address braking performance of heavy vehicles

	Performance measure	Influential infrastructure feature
Braking	**Braking deceleration** Measure of stopping distance	**Friction** Sweden (winter maintenance): 0.35 main roads, 0.25 minor roads Norway (winter maintenance): 0.25 main roads, 0.20 minor roads
	Braking efficiency Ratio of achievable deceleration to the ideally supported deceleration by the tyre/pavement friction	**Friction** Sweden (winter maintenance): 0.35 main roads, 0.25 minor roads Norway (winter maintenance): 0.25 main roads, 0.20 minor roads
	Braking stability on a straight path Measure of required space during a heavy brake	**Lane width** Sweden: 3.5-3.75m highway, 3.0-3.75m main roads, 2.75-3.25m minor roads Norway: 3.25-3.5m depending on speed limit **Friction** Sweden (winter maintenance): 0.35 main roads, 0.25 minor roads Norway (winter maintenance): 0.25 main roads, 0.20 minor roads
	Braking stability in a turn Measure of required space during a heavy brake in a turn	**Road curvature** Sweden: Minimum 100-1200 m depending on speed limit Norway: Minimum 125-800 m depending on speed limit **Lane width*** Sweden: 3.5-3.75m highway, 3.0-3.75m main roads, 2.75-3.25m minor roads Norway: 3.25-3.5m depending on speed limit **Friction** Sweden (winter maintenance): 0.35 main roads, 0.25 minor roads Norway (winter maintenance): 0.25 main roads, 0.20 minor roads
	Braking stability on a split friction surface Measure of vehicle controllability by the driver when it is braked on a road with split friction	**Friction** Sweden (winter maintenance): 0.35 main roads, 0.25 minor roads Norway (winter maintenance): 0.25 main roads, 0.20 minor roads
	Parking ability on a grade Measure of vehicle ability to stay still on a graded road	**Road grade** Sweden: 6-8% main roads, 10% minor roads Norway: 6% **Friction** Sweden (winter maintenance): 0.35 main roads, 0.25 minor roads Norway (winter maintenance): 0.25 main roads, 0.20 minor roads

* There are guidelines on how much a lane width should increase in a curve, based on the curvature.

3.5. Extra safety features

In addition to the listed performance measures, applicability and effectiveness of demanding extra safety features on LHV vehicles for ensuring safe performance should be explored. Examples of such safety features are full EBS functionally on all units for faster braking response and splash guards for decreasing risks associated with overtaking.

4. Infrastructure aspects of LHVs

In this section, effects of heavy vehicles on the infrastructure are discussed. Important aspects to consider are road design (geometry and position of roadway elements), pavement design, bridge design, tunnel design and road services.

4.1. Road design

Road design requirements are stated in regulatory documents ensuring function based on 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. Examples of geometrical constraints are road width, free height and available area at intersections.

The infrastructure features that should be considered when studying the safety and manoeuvrability of heavy vehicles were listed in the previous section. Similarly dynamics and design of vehicles to be traveling on a road, should be considered when constructing a road. In practice, several reference vehicles are used for road design. In Figure 1 reference vehicles used in Norway and reference heavy vehicles in Sweden are shown. The two reference heavy vehicles used for road design in Sweden are a tractor-semitrailer and a truck-dolly-semitrailer. Tractor-semitrailer is used in design of intersections and swept area needed in curves, while the latter is used to determine the required space for turn lanes and parking lots (Trafikverket 2012b). If LHVs are to be allowed on a road network, the reference heavy vehicles for the road design should be updated accordingly. For instance, the minimum length of left-turn lanes at intersections in Sweden is currently 30 m, which can accommodate a truck-dolly-semitrailer and a passenger car; this minimum length should be increased in future if LHVs are to be allowed on a road network. Another example is the distance between a railroad crossing and intersection, which also has a minimum length of 30m in current road design guidelines.

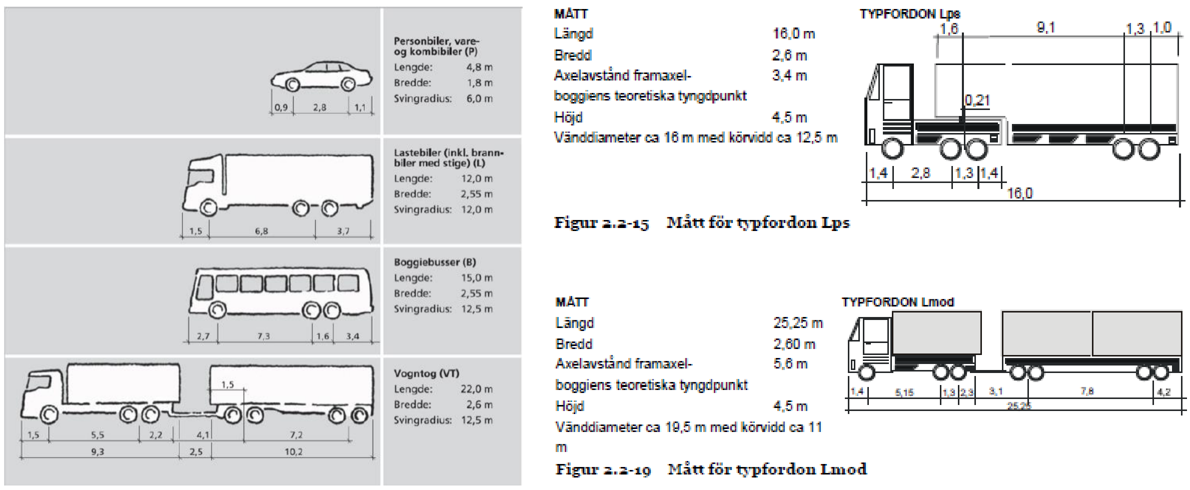

Figure 1. Left: *Reference vehicles for the Norwegian road network (Statens vegvesen 2013).*
Right: *reference heavy vehicles for the Swedish road network (Trafikverket 2012b)*

The main infrastructure design features which were discussed in previous section are: grade, lane width, curvature, roundabout and intersection dimensions, crossfall and friction. Turn lane length and distance between a railroad crossing and intersection have been also mentioned. Other important infrastructure features which should be mentioned are the sight distance and signalized intersections. Longer vehicles might require more time to pass an intersection, this means that the available sight distance at an intersection should be sufficient for an LHV; in case of a signalized intersection, the calculation of required time for departing the intersection, used to regulate the traffic signals, should be updated with regard to longer vehicles.

4.2. Pavement design

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.

Heavier loads of LHVs can be compensated for by axle and tire configurations that reduce the loads on the pavement. Nevertheless, it is important to note that there are load history dependent deterioration mechanisms in the pavement structure. Examples are:

- Viscous rheological behaviour of bitumen bound materials which means that asphalt concrete subject to multiple loads in short intervals will not be able to regain shape between loads.
- Soil sensitivity to repeated loading which leads to reduced resistance to permanent deformation.

There are gaps in the knowledge of these effects. However, plans to investigate both of these aspects in Sweden are in place.

It should be noted that the bearing capacity of roads differ very much during a year, depending on precipitation, temperature, drainage conditions, etc. A frozen pavement and a pavement during the thawing period represent two extreme bearing capacity situations. Consequently, there are time periods when load restrictions could be eased and there are time periods when traffic loads can be very detrimental to a pavements condition. This has been reflected in vehicle weight or axle restrictions in some countries. For instance in Norway some axle load restrictions are lifted during the frozen winter period. In some provinces in Canada, additional weight is allowed to be carried during a defined period of freeze-up in winter; some provinces allow winter weights for all vehicles, while others allow them only for a specific commodity, such as timber. Furthermore, all provinces in Canada impose spring weight restrictions during the thaw period; however, the onset and duration varies widely (NCHRP 2010).

Another issue is the vehicle vibration and its possible effects on the residential areas along the road. Vibrations from heavy vehicles influencing residential areas are mainly related to number of axles, axle loads, suspension, vehicle speed and road surface evenness (Hunaidi, 2000). A potential problem might be very heavy vehicles travelling at high speed on soft soil (clay) and weak pavements. Loads from several axles may interfere at a certain distance and cause greater vibrations than expected based on individual axle loads.

4.3. Bridge design

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 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 LHVs. Therefore the allowed traffic load is calculated for each individual vehicle and bridge when dispensations are issued in Sweden.

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 2. It should be noted that in a new regulation, in effect since June 2015, the maximum gross weight on BK1 roads has been increased to 64 ton for heavy vehicles with axle distance of 20.2 m or higher.

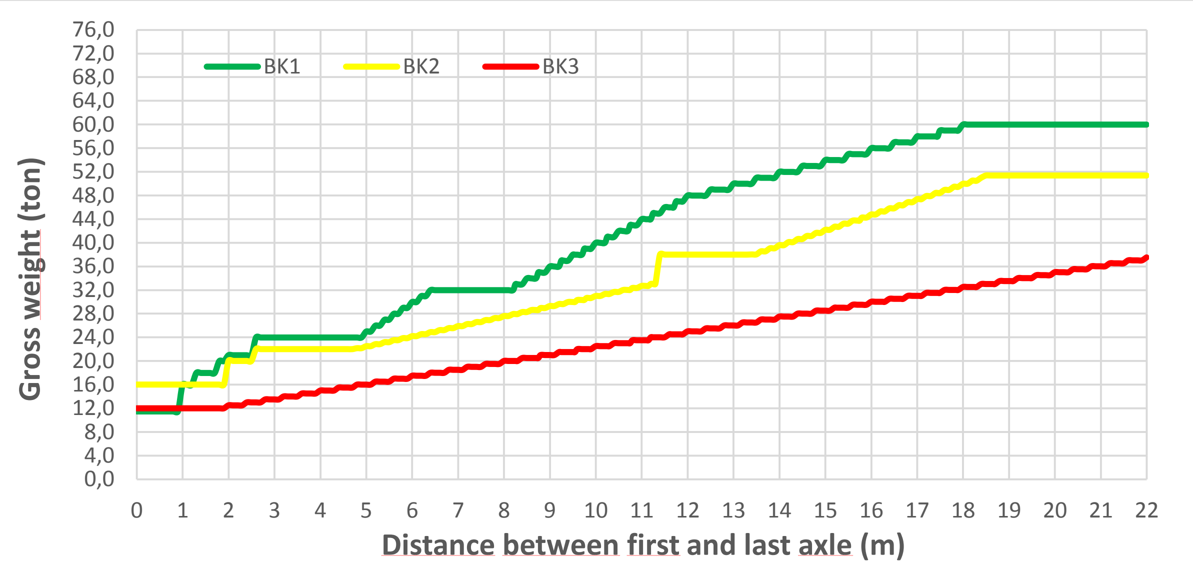

Figure 2. Permissible gross weight vs. distance between first and last axle of the vehicle, for the three bearing capacities (Trafikverket 2014)

One possible approach to account for the effects of LHVs on bridges is considering more reference vehicles and updating the gross weight curve accordingly. This approach has been investigated by Swedish Transport Administration for vehicles with gross weight up to 74 t and is presented in (Trafikverket 2014). Another common approach, used e.g. in Australia and the United States, is to calculate the effects of the vehicle loading by bridge formulae. A bridge formula advises some limits on the total mass based on the axle configuration of the vehicle, namely axle spacing, and in some cases, number of axles.

4.4. Tunnel design

Space in tunnels is certainly very expensive and safety is a major concern. There are a range of issues and scenarios that should be investigated which involve LHVs, direct or indirect. Direct if the vehicle is for example malfunctioning or indirect if other problems occur and the vehicle need to adapt to the situation, for example by turning or reversing. The following aspects need to be further investigated when regulating LHVs:

- Emergency parking space requirements
- Turning possibilities inside long tunnels and reversing abilities in case of emergency
- Overtaking of heavy vehicles in tunnels, sway and tunnel space
- Risk of fire, discussed in (OECD 2011)
- Potentially dangerous situations involving transport of dangerous substances

4.5. Vehicle restraint systems

Another relevant issue for heavier vehicles, is suitability of vehicle restraint systems, which can be divided into safety barriers, terminals/transitions and crash cushions. Safety barriers are guardrails designed to prevent vehicles from leaving the road. These should comply with the EN 1317-5 standard, which include product requirements. EN 1317-2 states the containment level classes, of which H1-H4 are the most demanding. H1 is required to contain a rigid truck of 10 ton colliding with an incident angle of 15 degrees and 70 km/h, while H4 is required to contain a 30 ton rigid truck, or 38 ton articulated vehicle, both colliding with an incident angle of 20 degrees and 65 km/h. The EN 1317 standard also include safety zone requirements, which may also be affected by heavier vehicle allowances. One can conclude that the weight of vehicles used in the Nordic countries today exceed the limits set in the EN 1317 (Statens vegvesen 2014).

4.6. Road service

Availability of road services, such as parking and rest areas, is of importance for longer 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. Control stations and places to apply snow chains are other examples of facilities that require space to accommodate vehicles.

4.7. Ferry traffic

Ferries are important to some links in Norway due to its geography and cannot be neglected. However, this topic has not been included in the scope of this pre-study.

5. Environmental aspects of LHVs

The existing European environmental regulations, namely exhaust and noise emissions described previously, are already performance based. These regulations are also in effect in Sweden and Norway. Thus, the main issue with respect to LHVs is whether the existing regulations are suitable for them as well, or not. Some of the main issues to be investigated are:

- Is it adequate to mandate an exhaust emission limit in accordance to Euro VI for LHVs?
- 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 LHVs due to the fact that a long heavy vehicle combination is equipped with more tyres?

5.1. Fuel consumption

No fuel consumption/CO2 regulation for heavy vehicles is available in Europe yet. However, the Commission has recently set out strategy to curb CO2 emissions of heavy vehicles and has developed a test procedure to measure their fuel consumption and CO2 emissions. The test procedure is based on tests of the individual components of the vehicle and simulations of the fuel consumption and CO2 emissions of the entire vehicle (UniGraz 2012). 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 CO2 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 m3-km, to reflect the fuel consumption or CO2-emissions per transported amount of goods.

One possible approach to address the LHVs fuel consumption, is to consider them in the prospective regulations, e.g. in determining the typical mission profiles and the fuel consumption limits. Another issue which should not be neglected is the alternative powertrains and fuels.

6. Conclusions

In this report, the existing legislations which impose limitation on weight and dimensions of heavy vehicles are reviewed and compared within Sweden, Norway and Europe. Additionally, performance measures for safety and manoeuvrability of LHVs and relevant infrastructure and environmental aspects are discussed.

When investigating the performance of heavy vehicles with respect to safety and manoeuvrability measures, both vehicle design and infrastructure design should be considered; since they are highly related. If a heavy vehicle is to be permitted on a certain road network, features of the roads play an important role on the required level of performance from the vehicle. Therefore, in the provided list of relevant performance measures in this report, the corresponding influential infrastructure features are listed, along with their nominal values in Sweden and Norway as examples. Similarly dynamics and design of vehicles to be traveling on a road, should be considered when constructing a road. One approach to address this, is to utilize reference vehicles for road design, which is applied in both Sweden and Norway.

The main infrastructure design features which should be considered with respect to LHVs are: grade, lane width, curvature, roundabout and intersection dimensions and crossfall. Other important infrastructure aspects are availability of parking and rest areas, tunnel safety, safety barriers, turn lane length, distance between a railroad crossing and intersection, sight distance at an intersection and regulation of traffic signals.

Heavier loads of LHVs can be compensated for by axle and tire configurations that reduce the loads on the pavement. Nevertheless, it is important to note that there are load history dependent deterioration mechanisms in the pavement structure. There are gaps in the knowledge of these effects and further investigations are required. Another important issue with regard to bearing capacity of a pavement, is its variance during a year. Thus, axle load limits can be adjusted with regard to seasonal changes, an approach which is implemented in e.g. Norway and Canada.

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. 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 account for the effects of LHVs on bridges is to consider more reference vehicles. This approach has been investigated by Swedish Transport Administration for vehicles with gross weight up to 74t. Another common approach, used e.g. in Australia and the United States, is to calculate the effects of the vehicle loading on the bridges by a bridge formula.

The existing European environmental regulations, also in effect in Sweden and Norway, are already performance based. Thus, many of these regulations can be applied to LHVs as well. In some cases some adaptations might be required; for instance in the case of the prospective European regulation on fuel consumption, LHVs should be considered when determining the typical mission profiles and the fuel consumption limits.

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HEAD OFFICE
LINKÖPING
SE-581 95 LINKÖPING
PHONE +46 (0)13-20 40 00

STOCKHOLM
Box 55685
SE-102 15 STOCKHOLM
PHONE +46 (0)8-555 770 20

GOTHENBURG
Box 8072
SE-402 78 GOTHENBURG
PHONE +46 (0)31-750 26 00

BORLÄNGE
Box 920
SE-781 29 BORLÄNGE
PHONE +46 (0)243-44 68 60

LUND
Medicon Village AB
SE-223 81 LUND
PHONE +46 (0)46-540 75 00

vti