Greening and Safety Assurance of Future Modular Road Vehicles

Book of Requirements

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HTAS EMS project consortium

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Executive Summary

Recent megatrends can be distinguished which have a strong impact on logistic and transport concepts. Such megatrends are typically related to climate change, growing transport demand, urbanisation and scarcity of resources. The resulting logistic and transport concepts are intermodal transport, European Modular System (EMS) and hub & spoke systems (H&S). For the transport modes there is a need for multiples of loading units. This has motivated a consortium, consisting of automotive industry partners, knowledge institutes and universities to investigate these trends with the objective of developing new vehicle concepts that meet the following requirements:

- Significant reduction of CO_2 emission per unit payload
- Meeting the (future) needs of logistic companies in terms of flexibility, efficiency and TCO (total cost of ownership)
- Based on existing modules to facilitate intermodality (rail-road-water-air)
- Possible usage across Europe for cross-border long-distance road transport
- Compatibility with the existing infrastructure
- Designed/evaluated by using performance-based standards

Longer and heavier vehicles (LHVs) allow combinations of existing loading units (multiples), resulting in longer and sometimes heavier vehicle combinations with the potential for reducing cost and environmental impact per unit load, reducing road space for transport of the same amount of goods and complying with hub & spoke logistic concepts where vehicle systems can be split and loading units can be delivered separately into city areas.

However, current vehicle regulations vary. EU-wide regulations, country-specific regulations as well as upcoming vehicle regulations (improving aerodynamics and energy efficiency) allow different vehicle combinations. Nonetheless the use of longer and heavier vehicles is permitted only in a few countries.

The requirements for new vehicle concepts, the possible potentials of LHVs and the existing conditions provide a guideline for the further investigations:

- Need for smart, clean and profitable transport
- Leading to a transport system with an efficient combination of logistic and transport concepts
- Legalised by an EU-wide regulation with the ability to operate within the current infrastructure

A comparison of these points with the existing and upcoming legal framework leads to the conclusion that this framework does not support the coming need for multiples of loading units.

To overcome the conflict with respect to the coming need for multiples of loading units a selection of vehicle combinations is made to be used for further analysis and comparison regarding performance, fuel consumption and CO_2 impact per unit load and total cost of ownership. This selection covers standard vehicle combinations that meet the 96/53/EC regulation as well as existing LHVs. The selection is based on common loading unit lengths, and all LHVs comply with 60 tonne GVW.

To overcome the conflict with respect to the existing and upcoming legal framework a new European legal framework based on PBS (performance based standards) is proposed. PBS includes safety standards with a distinction between four different groups: stability, dynamic performance, powertrain and manoeuvrability. In addition, PBS includes standards with respect to infrastructure use, i.e. standards to guarantee that no extra damage will result from the use of the specific vehicle combination compared to already accepted ones. The positive effect of the use of PBS in countries such as Canada and Australia, and the potential being expected in other countries and by a growing share of institutes, was the reason for proposing a new legal framework, based on PBS. This study uses existing PBS frameworks as a starting point with modifications to account for typical European conditions.

The vehicle combinations selected are subjected to the proposed PBS, for which a special simulation environment has been developed and validated by extensive experiments for different LHV combinations.

The analyses regarding the stability and dynamic performance PBS show that all LHVs are in the range of the standard vehicle configurations and satisfy limits that are acceptable with reference to European infrastructure dimensions - or can be modified to satisfy these limits by application of technological improvements through air suspension, active steering strategies, roll-coupling between vehicle articulations, or raising the roll-centre. Other options are modifying the axle positions or increasing the number of axles. The powertrain standard refers to startability, maintaining a certain speed on a slope, and acceleration capability. This depends on the gradients to be expected and can easily be adjusted by increasing mainly the HP (horsepower) per unit vehicle weight, or by changing the number of driven axles. For some vehicle combinations the manoeuvrability PBS requires steerable axles to meet the manoeuvrability limits as set by the 96/53/EC regulation.

Considering the burden on the infrastructure, the analyses show that LHVs may constitute a comparable or even lower burden than standard vehicle combinations. Overtaking provision is worse due to the increased length. Under side wind impact some LHVs perform well, while others are poorer than standard vehicle configurations. Axle distance, air suspension and the number of axles are the parameters that can be altered to improve the performance.

Fuel consumption and CO_2 emissions per unit payload were determined using a special validated simulation tool. The comparison of the LHVs one to one with the standard configurations already shows an improvement. However, one LHV will not replace one standard vehicle, and different options are considered for replacing a fleet of standard vehicle combinations by LHVs on the basis of the same number of loading units. Replacing standard vehicles by LHVs with the same loading unit yields the best results; the potential CO_2 emission is between 24 and 38% lower. Replacement by different loading units results in a potential improvement of 4 to 11%.

In a similar way, a comparison is made on the total cost of ownership, including all direct and indirect costs “associated with an asset or acquisition over its entire life cycle”. Again the comparison of replacement of standard vehicles by LHVs shows an improvement. Starting from a constant level of payload units, the potential cost reduction is 30 to 50% with the same loading units and 15 – 20% with different loading units.

These results show that, within the framework of the transport task, high improvements are feasible but that it is important to choose the right loading units and the right vehicle combination in order to tap the potentials.

On the basis of all of these results, the analysis tools developed and applied as well as the experiments conducted an investigation is carried out to determine vehicle combinations that are optimal with respect to safety performance and infrastructure burden (PBS based), fuel consumption and TCO. A proposal for new vehicle concepts and a validation on the weakest PBS of LHVs as well as on green and profitable transport shows high potential for meeting the future demand regarding logistic flexibility, efficiency, sustainability and TCO without compromising safety and infrastructure impact. These concepts are compatible with existing infrastructure and are based on existing payload units to facilitate transfer between different transport modes. In order to allow such vehicles on the road, a proposal for a new, performance-based EU-wide legal framework is necessary; this should be based on existing experience with such regulations in countries like Canada and Australia and adjusted to match European conditions.

Introduction

This document "Greening and Safety Assurance of Future Modular Road Vehicles - Book of Requirements" is the result of an international project with various partners working together to develop a coherent view on European future long distance road transport for the year 2020 and beyond. The project partners are:

- Eindhoven University of Technology, located in Eindhoven, the Netherlands
- HAN University of Applied Sciences, located in Arnhem, the Netherlands
- MAN Nutzfahrzeuge AG, located in Munich, Germany
- DAF Trucks N.V., located in Eindhoven, the Netherlands
- TNO Industry and Technology, located in Helmond, the Netherlands
- D-Tec Trailers B.V., located in Kesteren, the Netherlands
- WABCO, located in Rotterdam, the Netherlands

The TU/e and HAN are educational institutions, MAN and DAF are leading truck manufacturers, TNO is a large research organisation, D-TEC is a SME producing innovative trailers and WABCO is a leading supplier of safety and vehicle control systems. The HTAS-EMS project was started October in 2010 and is completed by October 2014. The project has been financed by the Dutch Ministry of Economic Affairs and has Eureka status. The acronym EMS is an abbreviation of European Modular System. EMS is a concept allowing combinations of existing loading units (modules) into longer and sometimes heavier vehicle combinations to be used on parts of the road network. The dimensions of the modules are standardized, supporting intermodal freight transport (switching between truck, train and ship).

The HTAS EMS project takes up the challenge to describe the ideal EMS vehicle, first taking the present LHV (Longer and Heavier vehicles) as a basis and considering current and near future solutions, and thereafter focusing on new more innovative and efficient vehicle concepts for the mid-term future beyond 2020. New analysis methods and proposals for a modified legal framework will be developed. This Book of Requirements is one of the results of the HTAS-EMS project. The aim is to develop new vehicle concepts meeting the following requirements:

- reduction of CO_2 emissions by 35%
- meeting the (future) needs of logistic companies
- based on existing modules, to facilitate intermodality (rail-road-water)
- possible usage across Europe for cross-border long-distance road transport
- compatibility with the existing infrastructure (with no, or very minor, local adaptations)
- designed/evaluated by using performance-based standards

With an analysis of environmental trends and a look outside Europe, a range of vehicle combinations based on current standard vehicles was selected and a proposal for a new legal framework developed. The analysis shows three different important features which must be met by the vehicle combinations: they have to be smart, clean and profitable. To evaluate these features the vehicle combinations have been simulated, tested and calculated as to their safety, environment and cost aspects. In this way the vehicle combinations could be validated, use cases compared and requirements for future concepts defined. The next steps are the validation within pilot projects with selected customers and a further elaboration of the proposed legal framework at European level.

With this document we attempt to provide a coherent and realistic vision on future long distance road transport within Europe and hope it can be a source of inspiration for the people involved in the field. It is also clear that the actual implementation of these ideas in Europe is a very complex, political and time consuming process.

This Book of Requirements is split into three parts. First the environmental trends and current legal framework will be discussed in Part I. After reviewing this it becomes clear that the future challenges cannot be met within the existing European legal framework.

In Part II various existing vehicle combinations that can handle multiple loading units, and that may be suitable to operate within Europe, are selected. In some parts of the world these types of vehicles are already operating and the accompanying legal framework of these countries is discussed. Typically the approach is based not only on prescribing (maximum) dimensions and weights, but also considers the actual vehicle performance. A set of performance based standards applicable to the European context will be defined.

In Part III the vehicle combinations will be analysed using the proposed European performance based standards to ensure safety. Furthermore the environmental impact and economic viability will be checked. Within the proposed new legal framework the vehicle layout can be optimised further and three future concept vehicles are proposed, that meet the future challenges regarding logistics, profitability and environmental impact.

Part I. Environment and legal framework

In Part I the consequences of megatrends on logistic and transport concepts are set against the current and upcoming legal framework. A summary will be given first. For more detailed information please turn to chapters 2, 3 and 4.

Megatrends are trends that must be taken into account for imagining possible futures. First the megatrends which have an influence on transport are defined:

- Climate change: Global warming is becoming a serious problem; the transport sector needs to act.
- Transport and mobility: Growing transport demand and congestions need to be dealt with.
- Urbanisation: Cities will grow because of urbanisation, more efficient transport systems are needed.
- Scarcity of resources: Transport efficiency is needed because of the scarcity of oil and the growing demand for it.

These megatrends issue in logistic and transport concepts. These logistic concepts are intermodal transport, European Modular System (EMS) and hub & spoke systems (H&S). The transport concepts there require multiples of loading units.

Logistic concepts
All megatrends point to the need for intermodal transport and EMS. Intermodal transport is the movement of goods in the same loading unit where at least two modes of transport are used. Use of intermodal transport has already been encouraged since the introduction of the 92/106/EEC regulation in 1992. If operators comply with the requirements of this regulation, they qualify for tax reduction or reimbursement. This is done to reduce the problems of road congestion, environment and safety. The use of different modes for transport is growing. Despite this, the performance of intermodal logistic chains still needs to be optimised to reduce the carbon dioxide (CO_2) emission from transport as stated in the white paper from the European Commission.

EMS is being introduced in Europe to improve the efficiency of transport and to reduce its environmental impact. It is a concept that allows combinations of existing loading units (multiples) on vehicles which may be used on some parts of the road network. This results in longer and sometimes heavier vehicle combinations. Research shows that EMS is in conformity with all defined megatrends. It is allowed in a few countries in the EU.

Due to urbanisation the volume of deliveries per day will increase. This has given rise to hub & spoke systems. A hub & spoke system has hubs outside the city. From these hubs the products are sorted to the spokes in the city. From the spokes the last mile deliveries are done. This concept results in high frequency of services, an efficient distribution system and lower costs for the users. Various companies are already using hub & spoke systems.

The concepts described above are already being used in current logistics. To cope with the future megatrends a vision for an efficient logistic system which combines these logistic concepts is described. To be efficient the transport in this system needs to be smart, clean and profitable. Smart transport relates to the general safety of vehicle combinations and their suitability for the European infrastructure. Clean transport is CO_2-efficient transport, while profitable transport is low-cost transport. This system is explained in Fig. 0-1.

First the types of transport (urban and interurban) and segments (city, distribution, long-haul and international long-haul) are shown based on the distances travelled. Between the combinations of segments a hub and a hub & spoke system are located. Between these systems there is the possibility of shifting between modes, as shown in Fig. 0-1. Compared with current hub (& spoke) systems the geographical positions selected for these hubs are closer to the different modes, the right techniques are employed and the right combination of modes is used. Furthermore, use of the hub & spoke system is expanded so that several companies work together in one hub & spoke system.

If EMS is to be introduced into this system it first needs to be widely adopted in the EU so that it can be used for international long-haul transport. Only then, by using different modes up to the borderline of an urban environment, will the full potential of EMS be exploited. Here the use of multiples of loading units is of importance because they are needed for switching loading units between modes.

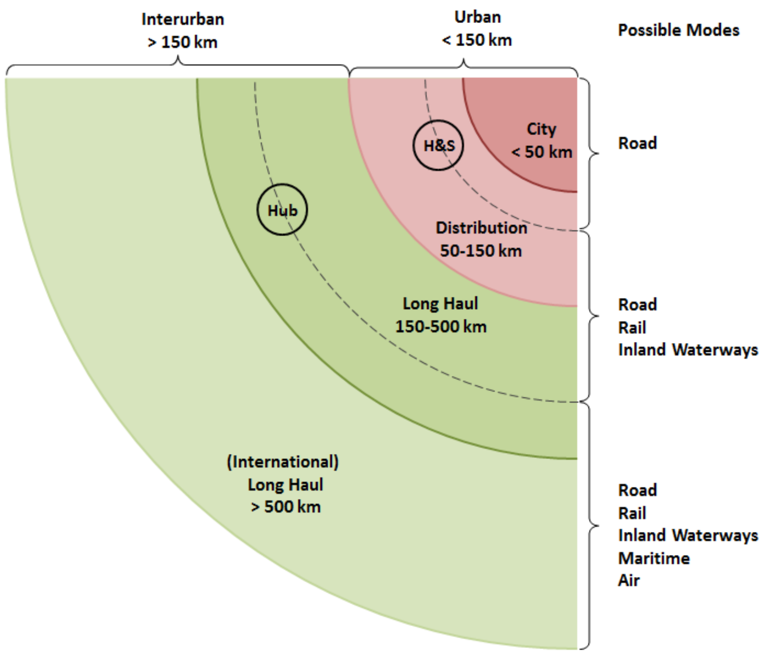

Fig. 0-1 Vision of logistic concepts (principle).

Transport concepts

With respect to transport concepts the megatrends issue in the need for multiples. Transport concepts consist of pallets and loading units. With respect to pallets research shows that the Euro Pallet will remain dominant in Europe. Despite this it is not expected that the dimensions of the International Organization for Standardization (ISO) container will change. The containers of the future will therefore be those which are compatible with other existing dimensions.

This vision requires multiples of current loading units. With use of multiples the efficiency of transport is increased. Multiples serve the logistic concepts. It is proposed that the number of multiples be based on a total vehicle length of approximately 33 m. This figure is taken because a vehicle concept must be able to make a complete turn at a roundabout if it is to be driven in the current infrastructure.

Infrastructure and vehicle regulations
There is an EU-wide agreement on infrastructure for certain roads. Nonetheless there are also country-specific regulations which take precedence and are often different from the EU-wide agreement. With respect to vehicle regulations there are EU-wide, country-specific and upcoming vehicle regulations. Here too there are differences between EU-wide and country-specific regulations. Sweden, Finland and the Netherlands have already agreed on the use of 25.25 m long and 60t trucks, whereas this is not allowed in general in Europe for cross-border transport. With respect to upcoming regulations Denmark, Germany and Belgium are in the test phase for or in discussion about Longer and Heavier Vehicles (LHVs).

The most important upcoming regulation was proposed on 15th April 2013 by the European Commission as an amendment of Directive 96/53/EC. The goal of this change is to improve the aerodynamics of vehicles and their energy efficiency, while continuing to improve road safety, and to achieve this within the limits imposed by the geometry of road infrastructures.

Conflict and solution
If this vision for the logistic and transport concepts is set against the infrastructure regulations and (upcoming) vehicle regulations, the following conflict emerges:

The current and upcoming legal framework does not support the coming need for multiples of loading units.

To solve this conflict two solutions will be given in Part II:

- Smart, clean and profitable vehicle combinations which can handle multiples within the existing infrastructure.
- A proposal for a new EU-wide legal framework which allows the use of multiples within the existing infrastructure.

1 Environmental trends

The transport world is changing. Megatrends have been identified that influence the future development of logistic and transport concepts. In this chapter these topics will be discussed. First the megatrends with respect to transport are described in paragraph 1.1. Paragraphs 1.2 and 1.3 respectively describe the current and future logistic and transport concepts which result from these megatrends. Furthermore a vision for each concept is described.

1.1 Megatrends

This paragraph describes the megatrends which influence transport. 'Megatrends are trends that alter business and society in a profound and lasting fashion, over decades rather than years. They have an impact on every one of us. They fundamentally alter the opportunities and risks for companies. In short, they are those trends that we must always take into account when imagining possible futures.'[1]

The megatrends that influence transport are: climate change, transport & mobility, urbanisation and scarcity of resources. As a consequence of these megatrends the need for cost-efficiency is increasing. This is described as a last part of this paragraph.

Climate change

Since the 1990's the global temperature has been increasing. This temperature increase is reaching a problematic level. The average temperature from 2001 up to 2011 was 14.48° C, whereas the maximum average temperature that homo sapiens has survived is 15.3° C. [2, 3] Furthermore an increase in natural disasters due to the climate change has been noticed.[4]

To slow down the climate change the international community has set the target of keeping global warming below 2° C compared with the temperature in 1990 (13.5° C[5]).[6] To achieve this 2° C target it is necessary that between 2000 and 2050, the total amount of carbon dioxide (CO_2) emissions should not exceed 1000 to 1500 billion tonnes. It is estimated that since 2000 420 billion tonnes of CO_2 have been generated, while the global CO_2 emission is still increasing. If the global increase in CO_2 emission continues, the 1500 billion tonnes will be exceeded in the next two decades.[7]

In 2011 75% of all goods transport in the European Union (EU) was handled by road transport.[8] In view of this it is not surprising that road transport is responsible for 17% of the total CO_2 emissions in the EU. Transport is also the only major sector in the EU in which the total Greenhouse Gas (GHG) emissions are still growing - by 29% between 1990 and 2009.[9]

[1] Berger, R. (2012). *Thoughts Megatrends.* München: Roland Berger School of Strategy and Economics. Page 5.

[2] NOAA National Climatic Data Center. (2012, December). *State of the Climate: Global Analysis for Annual 2012*. Retrieved August 13, 2013, from NOAA National Climatic Data Center: http://www.ncdc.noaa.gov/sotc/global/2012/13

[3] Sinn, H.-W. (2012). *Das grüne Paradoxon. Plädoyer für eine illusionsfreie Klimapolitik.* Berlin: Econ-Verlag. Page 44.

[4] Münchener Rückversicherungs-Gesellschaft. (2013). *Natural Catastrophes 2012 World Map.* München. Slide 4-5.

[5] Sinn, H.-W. (2012). *Das grüne Paradoxon. Plädoyer für eine illusionsfreie Klimapolitik.* Berlin: Econ-Verlag. Page 47.

[6] European Commission. (2011). *White Paper: Roadmap to a Single European Transport Area - Toward a competitive and resource efficient transport system.* Brussels. Page 3.

[7] Olivier, J., Janssens-Maenhout, G., & Peters, J. (2012). *Trends in global CO2 emissions; 2012 Report.* The Hague/Bilthoven: PBL Publishers. Page 6-7.

[8] Eurostat. (2013, June 14). *Modal split of freight transport*. Retrieved September 9, 2013, from Eurostat: http://epp.eurostat.ec.europa.eu/tgm/refreshTableAction.do?tab=table&plugin=1&pcode=tsdtr220&language=en

[9] Schroten, A., Warringa, G., & Bles, M. (2012). *Marginal abatement cost curves for Heavy Duty Vehicles.* Delft: CE Delft. Page 5.

Taking road transport as a whole, 26% of the CO_2 emissions is due to Heavy Duty Vehicles (HDVs). HDVs are defined as trucks and buses and are used in different segments. For these different segments market shares and CO_2 emissions are shown in Fig. 1-1 and Fig. 1-2 respectively. From these figures it can be concluded that 38% of the total long-haul HDVs are responsible for 63% of the total CO_2 emissions of HDVs. This shows that the long-haul sector is responsible for most CO_2 emissions from HDVs and that making improvements here will be effective.

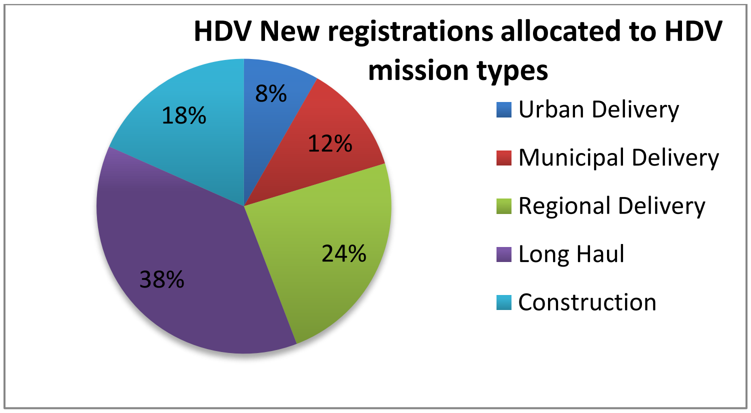

Fig. 1-1 Market shares of truck segments from newly registered HDVs.[10]

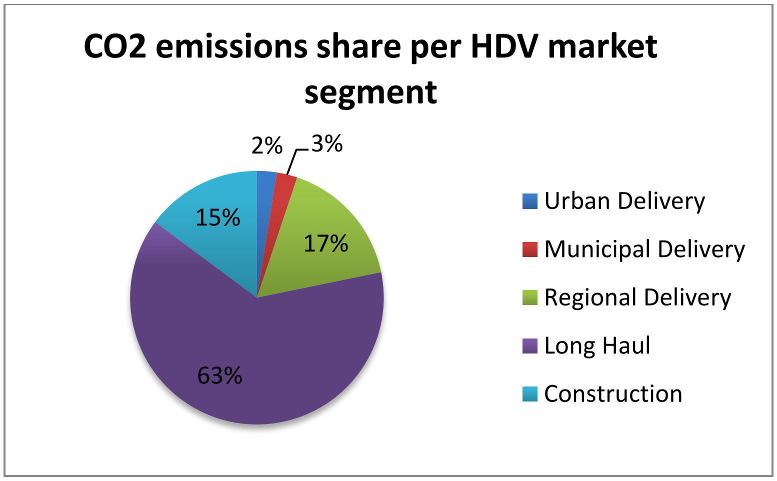

Fig. 1-2 CO_2 emissions share per HDV market segment.[11]

[10] Hausberger, S., & et all. (2012). *Reduction and Testing of Greenhouse Gas Emissions from Heavy Duty Vehicles - LOT 2.* Graz. Page 172.

[11] Hausberger, S., & et all. (2012). *Reduction and Testing of Greenhouse Gas Emissions from Heavy Duty Vehicles - LOT 2.* Graz. Page 175.

The above statements show that action is needed in the road transport sector with respect to CO_2 emission. If the 2° C target is to be met, the transport sector must reduce its emissions. A reduction of at least 60% in GHGs by 2050 with respect to 1990 is required from the transport sector by the European Commission. For 2030 the goal for transport will be to reduce GHG emissions to around 20% below their 2008 level.[12] These targets are shown as a graph in Fig. 1-3.

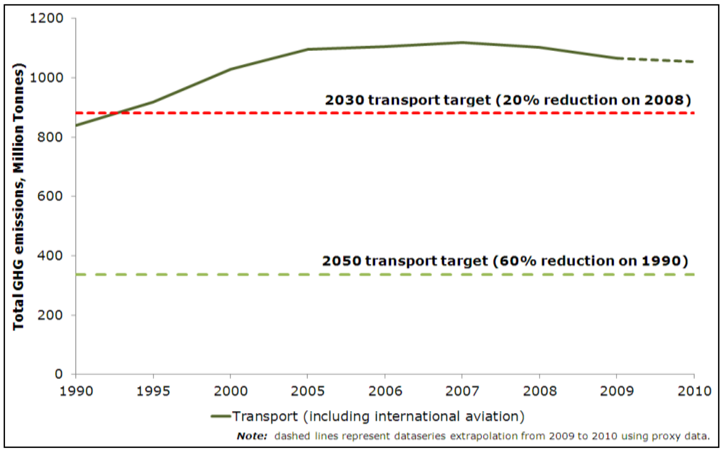

Fig. 1-3 Yearly GHG emission targets regarding transport for 2030 and 2050.[13]

Not only the European Commission but also the European Automotive Manufacturers' Association (ACEA) sets goals with respect to CO_2 emission. The ACEA is an organisation in which different automotive companies cooperate. Together with these companies it has set the target of decreasing the fuel consumption of modern trucks by an average of 20% per t-km by the year 2020. This will be in comparison with Euro V vehicles in 2005.[14]

Transport and mobility

The demand for transport is changing: since 1970 European freight transport has increased by approximately 70% up to 1997.[15] By 2030 it is expected that the total freight transport volumes will grow by approximately 38% with respect to 2011.[16] Furthermore, congestion is a problem due to the growth of transport within the existing, or in some cases non-existent, infrastructure. Currently congestion costs amount to 1% of the total EU Gross Domestic Product (GDP) every year.[17] Both the increasing demand for transport and the congestion problem are a call for more efficient transport.

[12] European Commission. (2011). *White Paper: Roadmap to a Single European Transport Area - Toward a competitive and resource efficient transport system.* Brussels. Page 3.

[13] European Environment Agency. (n.d.). *Trends and targets: EU-27 GHG emissions - Eps file*. Retrieved August 9, 2013, from European Environment Agency: http://www.eea.europa.eu/data-and-maps/figures/trends-and-targets-eu-27/trends-and-targets-eu-27

[14] ACEA. (2008, September 23). Commercial vehicle manufacturers push fuel efficiency and environmental protection with "vision 20-20". Retrieved August 28, 2013, from ACEA: http://www.acea.be/index.php/news/news_detail/commercial_vehicle_manufacturers_push_fuel_efficiency_and_environmental_pro

[15] Commission of the European Communities. (1997). *Intermodality and intermodal freight transport in the European Union .* Brussels. Page I.

[16] European Commission. (2011). *Impact Assessment – accompanying document to the White Paper.* Brussels. Page 137.

[17] European Commission. (2013, May 17). *Clean transport, Urban transport*. Retrieved August 20, 2013, from Mobility and transport: http://ec.europa.eu/transport/themes/urban/urban_mobility/

Urbanisation

World population is growing. In 2011 the world had a population of seven billion people.[18] The figure is expected to rise to over eight billion in 2030.[19] The growth will be in the urban areas because of the natural population growth, rural-urban migration and administrative changes. These administrative changes may entail the incorporation of suburban areas or neighbouring towns into a larger city or the foundation of a completely new city.[20]

The urban population is expected to grow globally by 40% by 2030 with respect to 2010. The population in rural areas is expected to stay the same in this period. This would mean that in 2030 around 60% of the world's population will be living in urban areas. The highest rates of population growth for the period 2010 up to 2030 are expected in Africa and Asia – 52% and 16% respectively. In the EU the population will grow by only 1%. Urban areas will nevertheless grow by 4% between 2010 and 2030, whereas the rural population will remain approximately unchanged.[21] Because of this London will become a mega-city like Paris, which is already a mega-city (city with at least 10 million inhabitants).[22] Alongside these mega-cities many areas will become agglomerations, which will face the same challenges as the mega-cities.

Due to urbanisation in Europe there will be an urgent need for more efficient and effective freight transport systems that not only provide and dispose goods but also tackle environmental issues such as noise, air pollution, vibration and visual intrusion.[23]

Scarcity of resources

Society and business will be faced by a rising shortage of energy resources – in particular fossil oil – and raw materials. Regardless of the question as to when the world will really run out of oil, the era of cheap oil (and other resources) is certainly over. New oil extraction techniques will increase the supply, but they will also lead to an increase in the global oil price. As oil becomes scarce, these new techniques will become profitable. Higher energy efficiency and reduction of demand are necessary to dampen the oil price increase or to postpone the discussion about running out of oil.[24]

According to the International Energy Agency, road transport will remain the transport mode with the highest energy consumption – it will account for around three-quarters of the transport sector's total energy demand in 2035.[25] Road freight transport will be responsible for almost 40% of the increase in global oil demand between 2011 and 2025 in the New Policies Scenario. Despite this dramatic increase in oil demand, a significant improvement in the fuel economy of trucks has already been considered in this scenario – i.e. all possible reduction measures have to be considered to further reduce the demand for oil from the road freight sector.[26]

[18] United Nations Population Fund. (2011). *The State of World Population 2011.* New York: UNFPA. Page ii.

[19] United Nations. (2012). *World Urbanization Prospects : The 2011 Revision. CD-ROM Edition - Data in digital form (POP/DB/WUP/Rev.2011).*

[20] *World Urbanization Prospects, the 2011 Revision*. (n.d.). Retrieved 11 7, 2013, from United Nations, Department of Economic and Social Affairs: http://esa.un.org/unup/Documentation/Definition-Problems_1.htm

[21] United Nations. (2012). *World Urbanization Prospects : The 2011 Revision. CD-ROM Edition - Data in digital form (POP/DB/WUP/Rev.2011).*

[22] United Nations. (2012). *World Urbanization Prospects - The 2011 Revision.* New York: United Nations. Page 7.

[23] Taniguchi, E. (2012, October 29). *The Future of City Logistics*. Retrieved August 16, 2013, from Delevering Tomorrow: www.delevering-tomorrow.com/the-future-of-city-logistics/

[24] Berger, R. (2012). *Thoughts Megatrends.* München: Roland Berger School of Strategy and Economics. Page 22 – 25.

[25] Inernational Energy Agency. (2012). *World Energy Outlook 2012.* Paris: OECD Publishing. Page 63.

[26] Inernational Energy Agency. (2012). *World Energy Outlook 2012.* Paris: OECD Publishing. Page 91, 94-96.

Cost-effectiveness
The increasing need for cost-effectiveness is a consequence of the megatrends described above. As road transport is already a business with low profits, cost-effectiveness is becoming even more important.

Taxes for cars are changing due to climate change. The European Commission wants to 'move towards full application of "user pays" and "polluter pays" principles and private sector engagement to eliminate distortions, including harmful subsidies, generate revenues and ensure financing for future transport investments.'[27] For road transport this would mean a tariff structure based on recovery of road wear and tear (damage or deterioration resulting from ordinary use), noise and pollution costs.[28] This will also be taken into account for toll roads. As a result there is an increasing need for cost-effectiveness in the transport sector.

Over the past decades the demand for transport has been linked to the development in the GDP. When the GDP is growing, more transport is needed.[29] In the last few years, however, this link has been less pronounced. Possible reasons are the dematerialisation of the economy and growing regional trade patterns. Despite this weakening link the demand for transport will increase in the future.[30] Due to this, total costs and pollution will increase. This too results in the need for cost-effectiveness.

Finally, the scarcity of resources will lead to higher oil prices. Cost-effectiveness is also needed because of these higher prices.

1.2 Logistic concepts
The megatrends described in paragraph 1.1 will result in specific logistic concepts. These concepts are intermodal transport, EMS and hub & spoke systems. In paragraph 1.2.1 the connection between the megatrends and new logistic concepts is explained. Intermodal transport, European Modular System (EMS) and hub & spoke systems are considered. In paragraph 1.2.2 a vision for a logistic system that combines intermodal transport, EMS and hub & spoke systems in an efficient way is described.

1.2.1 Logistic concepts due to megatrends
In this paragraph intermodal transport is explained with its connection with the megatrends. Then EMS is described. Finally the connection between urbanisation and hub & spoke systems is explained.

Intermodal transport
The megatrends climate change, transport demand, urbanisation and scarcity of resources all point to one logistic concept: intermodal transport. To explain the term intermodal transport first the meaning of modes is explained and elaborated on. Intermodal transport is then described with its current developments.

Modes of transport
Modes are the different types of transport that can be used. The five modes used by the European Commission are the following: Road, Rail, Inland Waterways, Maritime and Air.[31]

[27] European Commission. (2011). *White Paper: Roadmap to a Single European Transport Area - Toward a competitive and resource efficient transport system.* Brussels. Page 11 and 30.

[28] European Commission. (2011). *White Paper: Roadmap to a Single European Transport Area - Toward a competitive and resource efficient transport system.* Brussels. Page 29.

[29] *Freight transport demand (CSI 036) - Assesment published Jan 2011*. (2011, January). Retrieved December 10, 2013, from European Environment Agency: http://www.eea.europa.eu/data-and-maps/indicators/freight-transport-demand-version-2/assessment

[30] Sessa, C., & Enei, R. (2009). *EU Transport demand: Trends and drivers.*

[31] *Transport modes*. (2012, 11 9). Retrieved 10 30, 2013, from European Commission: http://ec.europa.eu/transport/modes/

'Road infrastructures are large consumers of space with the lowest level of physical constraints among transportation modes. However, physiographical constraints are significant in road construction with substantial additional costs to overcome features such as rivers or rugged terrain. Road transport systems have high maintenance costs, both for the vehicles and infrastructures. They are mainly linked to light industries where rapid movements of freight in small batches are the norm. Yet, with containerisation, road transportation has become a crucial link in freight distribution.

Railways consist of a fixed track to which vehicles are bound. They have an average level of physical constraints linked to the types of locomotives, and a low gradient is required, particularly for freight. The construction and maintenance of rail tracks is expensive. Heavy industries are traditionally linked with rail transport systems, although containerisation has improved the flexibility of rail transport by linking it with road and maritime modes. Rail is by far the land transport mode offering the highest capacity.

Because of the physical properties of water conferring buoyancy and limited friction, Maritime and Inland Waterways transport is the most effective mode to move large quantities of cargo over long distances. Main maritime routes are composed of oceans, coasts, seas, lakes, rivers and channels. Maritime transport has high terminal costs, since port infrastructures are among the most expensive to build, maintain and improve. High inventory costs also characterise maritime transport. More than any other mode, maritime transport is linked to heavy industries, such as steel and petrochemical facilities adjacent to port sites.

Air routes are practically unlimited, but they are denser over the North Atlantic, inside North America and Europe and over the North Pacific. Air transport constraints are multidimensional and include the site (a commercial plane needs about 3.300 meters of runway for landing and take-off), the climate, fog and aerial currents. More recently, air transport has been accommodating growing quantities of high value freight and is playing a growing role in global logistics.'[32]

In Europe the grams of CO2 per tkm are lowest for Maritime and Rail transport, 14 and 21 g/tkm respectively in 2011. Inland Waterways and Road produced 61 and 75 g/tkm respectively in 2011.[33] Despite these results road transport currently has a modal share of 77.7% in the EU. Rail and Inland waterways respectively have a modal share of 16.9 and 5.4%.[34] Despite the fact that road transport has the highest CO_2 emission per t/km it also has the highest modal share. This is because road transport possesses significant advantages over other modes. 'The capital cost of vehicles is relatively small. This produces several key characteristics of road transport. Low vehicle costs make it comparatively easy for new users to gain entry, which helps ensure that the trucking industry, for example, is highly competitive. Low capital costs also ensure that innovations and new technologies can diffuse quickly through the industry. Another advantage of road transport is the high relative speed of vehicles, the major constraint being government-imposed speed limits. One of its most important attributes is the flexibility of route choice, once a network of roads is provided. Road transport has the unique opportunity of providing door-to-door service for both passengers and freight. These multiple advantages have made cars and trucks the modes of choice for a great number of trip purposes, and have led to the market dominance of cars and trucks for short-distance trips.'[35]

[32] Rodrigue, J.-P., Slack, B., & Comtois, C. (2013). *Transportation Modes: An Overview*. Retrieved 11 8, 2013, from The Geography of Transport Systems: http://people.hofstra.edu/geotrans/eng/ch3en/conc3en/ch3c1en.html

[33] Specific CO2 emissions data for road, rail and inland shipping transport, 1995-2011 from TREMOVE v3.3.1. Specific CO2 emissions data for air and maritime transport, 1995-2011 from TRENDS.

[34] Progtrans. (2012). *World Transport Reports Edition 2012/2013.* Progtrans AG. Page 274.

[35] Rodrigue, J.-P., Comtois, C., & Slack, B. (2006). *The geography of transport systems.* New York: Routledge. Page 101 – 103.

Intermodal transport

Intermodality is defined in different ways. The European Conference of Ministers of Transport (first) and the European Commission (second) define it as:

- 'The movement of goods in one and the same loading unit or road vehicle, which uses successively two or more modes of transport without handling the goods themselves in changing modes.'
- 'Intermodality is a characteristic of a transport system that allows at least two different modes to be used in an integrated manner in a door-to-door transport chain.'[36]

These two definitions together characterise intermodality as follows:

The movement of goods in one and the same loading unit or road vehicle, whereby at least two different modes are used in an integrated manner in order to complete a door-to-door transport chain, without handling the goods themselves in changing modes.

One example would be the delivery of green (coffee) beans. 'The green beans are delivered to the Brazilian port of Santos in 60 kilo bags. Once arrived, the beans are mechanically loaded into a container, fitted with what is called a liner bag (a plastic bag with the dimensions of a container, hooked up in the corners of the box). The container is shipped to Antwerp (Belgium) and transhipped in the port on to a barge, after which it continues its journey to Amsterdam. In the Netherlands some containers go via rail to Leeuwarden from Amsterdam, the remainder is forwarded to Harlingen by barge. From Harlingen and Leeuwarden the containers with coffee beans are trucked to the coffee-roasting factory in Joure where the beans are processed.'[37]

Since 1992 the 92/106/EEC regulation has been in force. This regulation describes requirements for intermodal transport. If operators comply with these requirements, they qualify for tax reductions or reimbursements. This is done to reduce the problems of road congestion, environment and safety.[38] Research shows that intermodal transport using rail and road transport has been growing over the last few years. The number of containers shipped by rail from European ports too is growing.[39]

To reduce the CO_2 emission the European Commission has stated three future goals for optimizing the performance of multimodal logistic chains in freight transport (see below). This also shows that intermodal transport is seen by the European Commission as a way towards more efficient transport.

- 30% of road freight over 300 km should shift to other modes such as rail or waterborne transport by 2030, and more than 50% by 2050, facilitated by efficient and green freight corridors. To meet this goal will also require appropriate infrastructure to be developed.
- A fully functional and EU-wide multimodal TEN-T 'core network' by 2030, with a high quality and capacity network by 2050 and a corresponding set of information services.
- By 2050, connect all core network airports to the rail network, preferably high-speed; ensure that all core seaports are sufficiently connected to the rail freight and, where possible, inland waterway system.'[40]

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[36] Commission of the European Communities. (1997). *Intermodality and intermodal freight transport in the European Union .* Brussels. Page 5.

[37] C.J. de Vries. (n.d.). *Intermodal transport from a dutch perspective.* Dutch Inland Shipping Information Agency.

[38] European Commission. (1992). *Directive 92/106/EEC*

[39] International Union of Railways. (2012). *2012 Report on Combined Transport in Europe.* Paris: International Union of Railways (UIC) - Railway Technical Publications (ETF). Page 29 and 78-81.

[40] European Commission. (2011). *White Paper: Roadmap to a Single European Transport Area - Toward a competitive and resource efficient transport system.* Brussels.

The TEN-T core network is a European transport network across 28 member states to promote growth and competitiveness. 'The new policy establishes, for the first time, a core transport network built on 9 major corridors: 2 North-South corridors, 3 East-West corridors; and 4 diagonal corridors. The core network will transform East-West connections, remove bottlenecks, upgrade infrastructure and streamline cross border transport operations for passengers and businesses throughout the EU. It will improve connections between different modes of transport and contribute to the EU's climate change objectives.'[41]

EMS

The megatrends climate change, transport demand, urbanisation and scarcity of resources result in the logistic concept: EMS.

In Europe EMS is being introduced to improve the efficiency of road transport and to reduce its environmental impact. EMS is a concept that allows combinations of existing loading units (multiples) on vehicles which may be used on some parts of the road network. This results in longer and sometimes heavier vehicle combinations and will lead to a need for fewer vehicles to transport the same amount of goods. An example of EMS is the use of three 20 foot containers in the Dutch (deep-sea) container market. Normally two 20 foot containers are allowed to be transported by a simple vehicle combination.

EMS is already used in Sweden, Finland and the Netherlands, and trials are in progress in several countries in Europe. Regulations and trials are discussed in paragraph 2.2. Different studies have been made based on trials and existing regulations. The potential CO_2 saving potential from EMS is shown in Table 1-1 according to a number of different studies. All studies see a CO_2 emission reduction, which obviously is beneficial for slowing down climate change.

Furthermore, EMS trucks will occupy less road space to transport the same amount of goods. Estimates indicate that more than one-fourth of road space may be saved with EMS.[42] This is necessary in view of the growing congestion problem and the rising demand for transport.

Beside this cities will grow due to urbanisation. With use of EMS large trailers can bring all multiples outside the cities, and the loading units can be delivered separately.[43] EMS results in less fuel consumption, better t/km performance and fewer trucks. This means a reduced need for resources. Moreover studies have been done with respect to the cost-reduction potential of LHVs. These studies show that the saving potential is positive, see Table 1-1.

A last important item with respect to EMS is the shift of market share from Rail and Inland Waterways to Road due to EMS. A modal shift can have a severe impact on transport density and revenue per mode. Various studies have examined this, and Table 1-2 shows the results. A distinction is made between facts and estimates for the future. As can be seen in the table, there will be a limited modal shift. This is because Road, Rail and Inland Waterways currently have their own specific types of goods and therefore only compete on the level of their mutual freight sectors.

Despite this it is possible for intermodal transport to expand the share of mutual goods because of the collaboration between the modes.

[41] European Commission. (2013, 10 15). *Mobilty and Transport*. Retrieved 12 4, 2013, from European Commission: http://ec.europa.eu/transport/themes/infrastructure/index_en.htm

[42] Aurell, J., & Wadman, T. (2007). *Vehicle combinations based on the modular concept.* Page 20-21.

[43] Frost & Sullivan. (2013). *Delivering to Future Cities - Mega Trends Driving Urban Logistics.* Page 1.

Table 1-1 Saving potential for LHVs in different studies.

Study	CO_2 saving potential	Cost reduction potential
Fewer trucks improve the environment. Three Short Become Two Long, if the EU Follows the Example Set by Sweden and Finland.[44]	20%	-
Improved Performance of European Long Haulage Transport.[45]	15%	23-24%
Longer and Heavier Vehicles in the Netherlands. Facts, figures and experiences in the period 1995-2010.[46]	11%	25-38%
40t-EuroCombi. Ergebnisse der wissenschaftlichen Begleitung des Pilotprojektes in Thüringen.[47]	18%	-
Auswertung des niedersächsischen Modellversuchs zum Einsatz von „GigaLinern“.[48]	33%	-
Vehicle combinations based on the modular concept.[49]	18%	-

Table 1-2 Modal shift from rail and IWW to road for different studies.

Study	Market share loss in tkm		Fact or estimation
	Rail	IWW	
Monitoringsonderzoek vervolgproef LZV. (Netherlands-specific)[50]	1.4-2.7%	0.2-0.3%	Fact
Inzet van langere en/of zwaardere vrachtauto's in het intermodaal vervoer in Nederland. (Netherlands-specific)[51]	2.0-5.0%	0.1-0.2%	Estimation
Longer and/or Longer and Heavier Goods Vehicles (LHVs) – a Study of the Likely Effects if Permitted in the UK. (United Kingdom-specific)[52]	8.0-18.0%	22.0-54.0%	Estimation
Longer and Heavier Vehicles for freight transport (Europe-specific)[53]	2.1%	-	Estimation for 2020

[44] Ramberg, K. (2004). *Fewer Trucks Improve the Environment. Three Short Become Two Long, if the EU Follows the example set by Sweden and Finland.*

[45] Backman, H., & Nordström, R. (2002). *Improved Performance of European Long Haulage Transport.* Stockholm: TFK.

[46] Rijkswaterstaat. (2010). *Longer and Heavier Vehicles in the Netherlands.* Directorate General for Public Works and Water Management.

[47] Hils, P., & Adler, U. (2010). *40t-EuroCombi.*

[48] Friedrich, B., Hoffmann, S., & Bräckelmann, F. (2007). *Auswertung des niedersächsischen Modellversuchs yum Einsatz von "GigaLiner" .*

[49] Aurell, J., & Wadman, T. (2007). *Vehicle combinations based on the modular concept.*

[50] Hagen, G., Götz, N., Lieshout, R., & Rosenberg, F. (2006). *Monitoringsonderzoek vervolgproef LZV.* Arnhem : ARCADIS Ruimte & Mulieu BV.

[51] Dings, J., & Klimbie, P. (2000). *Inzet van langere en/of zwaardere vrachtauto's in het intermodaal vervoer in Nederland.* Oude Delft: Centrum voor energiebesparing en schone technologie.

[52] Knight, I., Newton, W., Mc Kinnon, A., & et al. (2008). *Longer and/or Longer and Heavier Goods Vehicles (LHVs).* Berkshire: IHS.

[53] Christidis, P., & Leduc, G. (2009). *Longer and heavier vehicles for freight transport.* Luxembourg: Office for Official Publications of the European Communities.

Hub & spoke systems
Due to urbanisation the logistic concept hub & spoke systems could be a beneficial solution for the growing demand for deliveries.

Based on the global current amount of deliveries of goods per dweller per day and the growing population in urban areas the volume of deliveries will be 500 million in 2025. To meet that kind of volume, logistics companies must consolidate their deliveries and polarise their fleets.[54] Some companies are already using hub & spoke systems. It is expected that there will be an increase in their use for logistics in cities.

A hub & spoke system has hubs outside the city. From these hubs the products are divided to the spokes into the city. From the spokes the last mile deliveries will be done, see Fig. 1-4. Last mile deliveries are defined as the last deliveries that are not private. These are, for example, deliveries from the main warehouse (spoke) to the receiving person. Another example of a last mile delivery would be the transport of supermarket products to the supermarket.

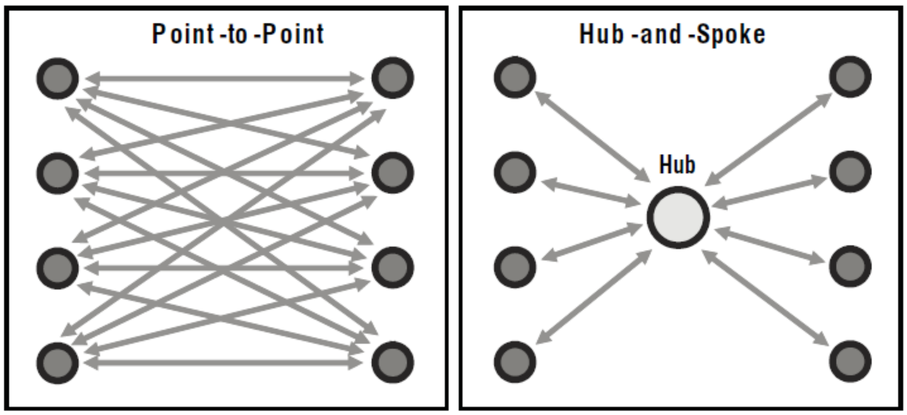


Fig. 1-4 Point-to-point and hub & spoke principle.[55]

The use of a hub & spoke system results in the following main advantages over point-to-point service:

- 'Economies of scale on connections by offering a high frequency of services. For instance, instead of one service per day between any two pairs in a point-to-point network, four services per day could be possible.
- Economies of scale at the hubs, enabling the potential development of an efficient distribution system since the hubs handle larger quantities of traffic.
- Economies of scope in the use of shared transhipment facilities. This can take several dimensions such as lower costs for the users as well as higher quality infrastructures.'[55]

Currently hub & spoke systems are used by various companies. Companies which are working in mail delivery, supermarket food delivery etc. are the best known for their hub & spoke usage. This way of organising the hub & spoke system is already demonstrating its benefits.

[54] Frost & Sullivan. (2013). *Delivering to Future Cities - Mega Trends Driving Urban Logistics.* Page 1.

[55] Rodrigue, J.-P., Comtois, C., & Slack, B. (2006). *The geography of transport systems.* New York: Routledge. Page 48.

1.2.2 Vision of logistic concepts in the future

To be able to cope with the future trends the logistic concepts (intermodal transport, EMS and hub & spoke systems) need to be used in the most efficient way. A vision for an efficient logistic system which combines these logistic concepts is described. To be efficient the transport in this system needs to be smart, clean and profitable. Smart transport is considered as the general safety of vehicle combinations and their suitability for the European infrastructure. Clean transport is seen as CO_2-efficient transport. Profitable transport is considered as low-cost transport. The transport system is explained in Fig. 1-5.

Before the vision is described, first the different types of transport and segments need to be considered. With respect to the different transport types a distinction is made between urban and interurban transport. Here urban transport is below 150 km, interurban transport is above 150 km. Within these two types of transport four different transport segments can be placed: City, Distribution, Long-Haul and (International) Long-Haul. Here too the segments are defined by a trip length in kilometres.

The vision is that between combinations of segments there are two efficient hub systems with the possibility of switching between modes. Between the (international) Long-Haul and Long-Haul segments there is only a hub for switching between modes. Between the Distribution and City segments there is a hub & spoke system. The possibility of switching between modes depends on the segment combination. The different modes per segment combination are shown in Fig. 1-5.

An efficient hub system is seen as a hub where shifting between modes is done efficiently and effectively. This means that the geographical position of these hubs is chosen close to the different modes and that the right techniques and the right combination of modes is used. An efficient hub & spoke system permits switching between modes, but transport to spokes is possible too. However, use of hub & spoke systems must be expanded from the current status: hub & spoke systems are currently mainly used by companies separately from each other. If this were to be expanded so that companies work together in one hub & spoke system, efficiency would be increased.

EMS needs to be widely adopted in the EU if the efficiency of road transport is to be improved. EMS is already applied in Sweden, Finland and the Netherlands. These countries alone are not enough to exploit the full potential of this solution. When EMS is widely adopted in the EU it can be used for international long-haul transport. Only then, by using different modes up to the borderline of an urban environment, will the full potential of EMS be tapped. Here the use of multiples of loading units is of importance because this is needed for an efficient transfer of loading units between the modes.

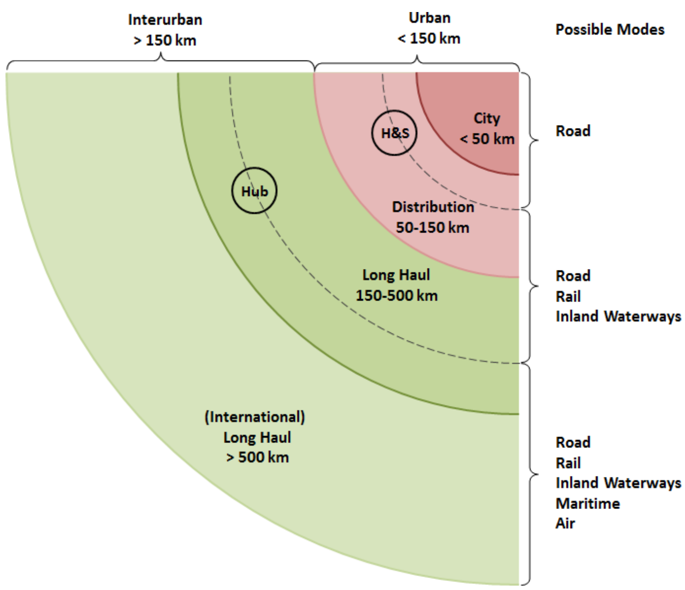


Fig. 1-5 Vision of logistic concepts (principle).

1.3 Transport concepts

Not only the megatrends described in paragraph 1.1 lead to new logistic concepts – efficiency too is a topic which influences future transport concepts. Transport concepts consist of packaging and loading units. For packaging, only pallets are considered because they are the only packaging products that affect loading units. In paragraph 1.3.1 the current and future transport concepts are described. Paragraph 1.3.2 outlines the vision for transport concepts in the future.

1.3.1 Transport concepts due to megatrends

The focus of this paragraph will be on the influence of transport changes on road transport. The current and future transport concepts are described. This paragraph is based on the reports Szylar (2012) and Meijer (2011), research part of the HTAS EMS project.

Current transport concepts

In this part first the current pallets are described. Then the different loading units will be explained and elaborated on.

Pallets are often used for road and rail transport but hardly at all in maritime transport because of the loss of capacity due to the bottom plate. In the EU there are three major pallet types in use, the Euro pallet being the dominant pallet type:

- Euro pallet, 80x120 cm.
- North America pallet, 100x120 cm.
- Asia pallet, 110x110 cm.

Currently three different loading units are most used in the EU: International Organization for Standardization (ISO) containers, C-series swap bodies and semi-trailers. First all these loading units are explained with their pros and cons. These pros and cons are based on Table 1-3 and Table 1-4, which give information regarding weight utilisation and dimensions of the loading units discussed. Fig. 1-6 then gives an overview of the different loading units and their possibilities regarding transport by road, rail, water or air.

The ISO containers are ideal for combined transport via road, rail and water, see Fig. 1-6. This is due to their standardised dimensions and stacking ability, see Table 1-4. It is also possible to combine multiples with ISO containers. For example, two 20 foot containers make one 40 foot container, see Table 1-4. Beside the ISO containers there are some other container sizes, such as the 45 foot pallet-wide container.

All ISO-sized containers are ineffective with regard to Euro pallets, especially compared to swap-bodies and semi-trailers. This is due to their internal dimensions. On the other side ISO containers can handle a large number of kilograms per cubic meter, see Table 1-4.

The C-series swap bodies are optimised to transport Euro pallets (Table 1-3) and can be used within road and rail transport, see Fig. 1-6. The loading units cannot normally be stacked.[56] Due to this, they are not attractive for water transport. The bodies are equipped with techniques that allow all C-series to fit on the same trailers and wagons. The twist lock positioning for the swap-bodies and the 20 foot ISO containers is the same so that trucks, trailers and wagons can carry both loading unit types. C-series swap bodies have the lowest cargo weight per cubic meter of the three loading unit types considered.

[56] Jeschke, S. (2011). *Global Trends in Transport Routes an Goods Transport: Influence to Future International Loading Units.* Page 18-19.

A semi-trailer can be used in road and rail transport without lifting. This makes this trailer efficient for road and rail transport. There are different transferring techniques for intermodal use; these are summarised in Appendix A. If semi-trailers are to be suitable for the combination of road, rail, and water transport, they need to be equipped with special parts. These entail 400 - 500 kg extra weight, which means a lower payload.[57] The special equipment mostly consists of reinforcements to permit lifting with cranes at terminals. In 2006 less than 3% of semi-trailers were equipped with the equipment needed to make them suitable for use in combined transport over rail and water.[58]

Semi-trailers have approximately the same pallet efficiency as the C-series swap bodies. They can carry more weight than C-series swap bodies, but they are not allowed to carry relatively as much weight as a 20 foot container per cubic meter, see Table 1-3 .

Table 1-3 Utilisation figures from loading units used in the EU.

Loading unit	Tare weight	Max. weight	Max. Payload	Internal volume	Ideal utilisation	Max. pallets	Floor utilisation	Ref.
	[kg]	[kg]	[kg]	[m³]	[kg/m³]	Euro pallets		
20' ISO	2080	24000	21920	33,2	660,8	11	76%	59
40' ISO	3900	30480	26580	65,7	404,8	25	87%	
40' ISO high cube	4150	30480	26330	76,1	346,1	23	78%	
45' pallet wide	4300	34000	29700	84,3	352,4	33	96%	60
C715	2520	16000	13480	43,8	308,0	17	88%	61
C745	2620	16000	13380	45,6	293,2	18	95%	
C782	2720	16000	13280	47,9	277,0	19	90%	
13.6 m semi-trailer	6250	39000	32750	87,0	376,5	33	94%	62
10.5 m semi-trailer	8820	33000	24180	56,4	428,8	20	91%	63

Table 1-4 External and internal dimensions of commonly used loading units.

Loading unit	External [mm]			Internal [mm]			Ref.
	Length	Width	Height	Length	Width	Height	
20’ ISO	6069	2362	2590	5944	2337	2388	57
40’ ISO	12192	2438	2591	12014	2289	2388	
40’ High cube ISO	12192	2438	2896	11963	2362	2692	
45’ pallet wide	13716	2500	2775	13553	2426	2563	58
C 715	7150	2550	2725	7010	2490	2507	59
C 745	7450	2550	2725	7310	2490	2507	
C 782	7820	2550	2725	7680	2490	2507	
13.6 m semi-trailer	13620	2550	2700	13620	2480	2575	60
10.5 m semi-trailer	10536	2550	2848	10086	2090	2675	61

[57] Roeser, M., & Bollig, S. (2013). Lang-LKW muss nich kranbar sein. *DWZ, Nr. 07*, 4.

[58] Jeschke, S. (2011). *Global Trends in Transport Routes an Goods Transport: Influence to Future International Loading Units.* Page 17-18.

[59] MCT Shipping Service. (n.d.). *Container Types & Specifications.*

[60] *45 ft Pallet Wide Container*. (n.d.). Retrieved 11 9, 2013, from Atoz Containers: http://www.atozcontainers.be/45ft%20Pallet%20Wide%20Container.html

[61] BSC Containersystem e.K. (2012, 6 1). *Cargoboxen*. Retrieved 11 9, 2013, from Containersystem: http://www.containersystem.de/cargobox.html

[62] Krone. (2012). *SDP 27 eLB4-CS.*

[63] Burgers Carroserie B.V. Aalsmeer. (2013). *10.55m box.*

Fig. 1-6 Loading units currently used per mode of transport. [64]

Future transport concepts

It is expected that the Euro pallet will remain the dominant pallet in Europe. It is not expected that the ISO container will change because of this dominance. This has different reasons. First, the ISO container is used worldwide and not only in Europe. Secondly, the ISO container is used in maritime and inland waterways transport, where only a small share of the goods is palletised.

With respect to loading units, the best way to arrive at a transport system that is as efficient as possible would be to have a standardised freight carrier for road, rail and water. Unfortunately, standardisation of all freight carriers is impossible at the moment. This is due to the immense investments required in infrastructure, which is perceived as very difficult to achieve in the future due to various, often contradicting, industry-specific demands of stakeholders.

The future containers are seen as those which are compatible with other already existent dimensions. Therefore, combinations, multiples and fractions of current dimensions are regarded as desirable. For example, a new regulation which promotes 45 foot pallet-wide containers was proposed by the European Commission in April 2013. With this container it is easier to switch between road, rail and water to enhance intermodality. Furthermore, it is 15 cm longer than the commonly used 13.6 m long semi-trailers, which results in higher efficiency. This proposal needs to be adopted by the European Parliament and the member states before it becomes law.[65]

[64] Jeschke, S. (2011). *Global Trends in Transport Routes an Goods Transport: Influence to Future International Loading Units.* Page 17.

[65] European Commission. (2013). *Proposal for a directive of the european parliament and of the council.* Brussels. Page 5.

For the ACEA too increasing the efficiency of transport is an important topic. The ACEA created a list of requirements which future loading units should meet. The loading units have to meet certain demands from the logistic service providers within the framework of international transport:

- 'The container is usable for combined transport with water and rail.
- It can be top and bottom-handled to make it possible to swap it at all kinds of swapping places. This will lead to higher efficiency.
- It has 3 openable sides: top, side and front. This will lead to easier access and it can be used for more sorts of freight to transport.
- It is theft-proof, can send and receive radio signals and is load-safe.
- It is stackable by high factors so that it can also be used in water transport.
- The internal volume and the height are optimised for higher productivity.
- It is foldable when empty, which reduces the size for making empty trips. This also means that more folded loading units can be placed on top of each other. It has to fold and unfold as fast as possible.
- It permits 10 foot multiple up to 60 foot.'[66]

1.3.2 Vision for transport concepts in the future

The coming move from 40 to 45 foot containers described in the previous section is positive for long-haul transport. With this move, the 45 foot container, which is often used in maritime transport, can also be used in road transport. This is beneficial for the efficiency of intermodal transport. Unfortunately, it does not result in optimisation for modal transport. As stated in paragraph 1.2.2, transport requires multiples of currently used loading units.

The need for multiples of standard loading units during road transport needs to be realised. To do this, vehicle combinations need to become longer and yet still be able to manoeuvre in the current infrastructure. As the most difficult manoeuvre in the current infrastructure, where the length plays an important role, a complete 360 degree turn at a roundabout is chosen. For the dimensions of the roundabout the 96/53/EC regulation is followed: it has an inner radius of 5.3 m and an outer radius of 12.5 m.

For the total vehicle length, the limit is set to approximately the circumference of the inner radius, which is 33 m. This is the worst-case manoeuvre on this roundabout. Of course it is a simplified view that the truck can describe a smooth circle. That is why the limit is set to approximately 33 m with the chance to deviate from this value depending on the loading units.

Beside the total vehicle length the maximum trailer length is taken into account. Fig. 1-7 shows how this is calculated. The blue rectangle represents the trailer. The dimensions of the European roundabout radius (inner circle 5.3 m, outer circle 12.5 m) are taken into account. For the trailer width 2.6 m is assumed. This is the maximum width permitted for trailers. This results in the dimension of 7.9 m. The figure shows that the maximum half-trailer length is 9.7, m which results in a maximum total length of 19.4 m. All trailers considered are within this limit.

[66] Jeschke, S. (2011). *Global Trends in Transport Routes an Goods Transport: Influence to Future International Loading Units.* Page 21.

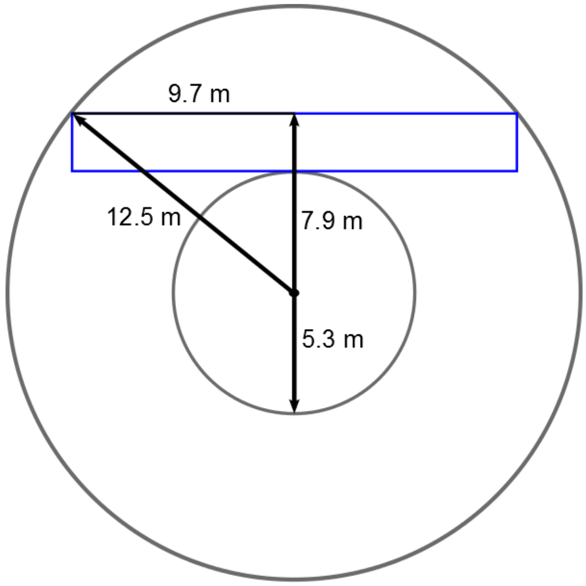


Fig. 1-7 Maximum trailer length on European roundabout.

In Table 1-5 it is shown which number of multiples of the same loading units is possible when the length of the total vehicle concept is extended to approximately 33 m. The loading unit length too is shown. From the table it is clear that with an extension to approximately 33 m there are far more possibilities with multiples.

Table 1-5 Possible multiples of standard loading units for a maximum vehicle combination length of approximately 33 m.

Loading unit	20' ISO	C715	C745	C782	10.5 m Semi	40' ISO	13.6 m Semi	45'
Multiples	4	4	3	3	2	2	2	2
Loading unit length [m]	24.3	28.6	22.4	23.5	21.1	24.4	27.2	27.4

2 Legal framework

In this chapter the legal framework with respect to road transport will be discussed. In paragraph 2.1 the regulations regarding infrastructure in Europe are described. Paragraph 2.2 describes EU-wide, country-specific and upcoming vehicle regulations.

2.1 Infrastructure regulations

Without infrastructure transport is not possible. In this paragraph the different regulations regarding infrastructure in Europe are summarised.

There are multiple important routes in the EU. For an efficient road network the United Nations Economic Commission for Europe (UNECE) has reached an agreement on international traffic arteries. These roads are numbered with the E-road numbering.[66]

In this agreement different aspects of road design in the EU are agreed upon. Though the document considers many aspects of road design, only the most important aspects will be discussed here.

First of all a distinction is made between three different road types:

'*1. Motorways*
Motorway means a road specially designed and built for motor traffic, which does not serve properties bordering on it, and which:

- *Is provided, except at special points or temporarily, with separate carriageways for the two directions of traffic, separated from each other by a dividing strip not intended for traffic or, exceptionally, by other means;*
- *Does not cross at level with any road, railway or tramway track, or footpath; and*
- *Is specially sign-posted as a motorway.*

2. Express roads
An express road is a road reserved for motor traffic accessible from interchanges or controlled junctions only and which:

- *Prohibits stopping and parking on the running carriageway(s); and*
- *Does not cross at level with any railway or tramway track, or footpath.*

3. Ordinary roads
An ordinary road is one open to all categories of users and vehicles. It may have a single carriageway or separate carriageways.'[67]

For these roads a range of recommended speeds are defined. Beside this, for these roads the minimum traffic lane width on a straight alignment should be 3.5 m.

Basic minimum road parameters are prescribed depending on the speed. Maximum and minimum radii and gradients are prescribed for the different speeds. These variables are shown in Appendix B, paragraph 'European regulations'. Despite these EU regulations there are also differences between road design regulations in Europe. Paragraph 'Country-specific regulations' of Appendix B summarises the infrastructure standards. This is done for the most important countries which have the two main transport routes from North to South and two main transport routes from West to East.

It must be noted that this agreement only gives geometrical guidelines. No guidelines are given with respect to loads.

[67] United Nations Economic and Social Council . (2008). *European agreement on main international traffic arteries.* Page 32-33

2.2 Vehicle regulations

There are different regulations in Europe regarding vehicles. These regulations will be discussed first. Furthermore there are country-specific regulations. These will also be taken into account. Last, upcoming regulations in the EU are explained to see in what direction the regulations will be going.

EU-wide regulations

For the international traffic within Europe there are regulations about maximum dimensions and weights for vehicle combinations and minimum requirements. These are written in Directives 96/53/EC and 97/27/EC. They are recognised by the EU 27, which allows combinations that meet these rules in international cross-border transport. These regulations take precedence for national road transport, but every country is free to adapt them.

Directive 96/53/EC prescribes for certain road vehicles within the community the maximum authorised dimensions in national and international traffic. The maximum authorised weights in international traffic are also prescribed.[68] Directive 97/27/EC prescribes masses and dimensions of certain categories of motor vehicles and their trailers. Furthermore it describes the minimal requirements for the applications.[69]

The maximum lengths of vehicle combinations are as stated in Table 2-1.

Table 2-1 Maximum allowed vehicle sizes. [70]

Unit	Maximum length [m]
Motor vehicle other than a bus	12.00
Trailer	13.60
Articulated vehicle (motor vehicle coupled to a trailer)	16.50
Road train (motor vehicle coupled to a semi-trailer)	18.75
Articulated bus (consisting of two rigid sections connected to each other by an articulated section)	18.75
Bus with two axles	13.50
Bus with more than two axles	15.00
Bus + trailer	18.75

The maximum width of the trailers for normal vehicles is 2.55 m. For superstructures of conditioned vehicles (superstructures specially equipped for the carriage of goods at controlled temperatures and whose side walls, inclusive of insulation, are each at least 45 mm thick), it is 2.6 m.[71] Fig. 2-1 and Fig. 2-2 show the relevant dimensions for road trains and articulated vehicles respectively. The relevant maximum dimensions from Table 2-1 are also shown in these pictures. Furthermore the following regulations on dimensions are shown:

- 'Maximum distance measured parallel to the longitudinal axis of the road train from the foremost external point of the loading area behind the cabin to the rearmost external point of the trailer of the combination is 16.4 m.'[72]
- 'Maximum distance measured parallel to the longitudinal axis of the road train from the foremost external point of the loading area behind the cabin to the rear-most external point of the trailer of the combination, minus the distance between the rear of the drawing vehicle and the front of the trailer is 15.65 m.'[73]

[68] European Commission. (1996). *Directive 96/53/EC.* Page 1.

[69] European Commission. (1997). *Directive 97/27/EC.* Page 1.

[70] European Commission. (1996). *Directive 96/53/EC.* Page 11.

[71] European Commission. (1996). *Directive 96/53/EC.* Page 11.

[72] European Commission. (1996). *Directive 96/53/EC.* Page 12.

[73] European Commission. (1996). *Directive 96/53/EC.* Page 12.

- 'The distance between the rear axle of a motor vehicle and the front axle of a trailer must not be less than 3.00 m.'[74]
- 'Maximum distance between the axis of the fifth-wheel king pin and the rear of a semi-trailer is 12.0 m.'[75]
- 'The distance measured horizontally between the axis of the fifth-wheel king pin and any point at the front of the semi-trailer must not exceed 2.04 m.'[76]
- The maximum height of any vehicle combination is 4.0 m.[77]

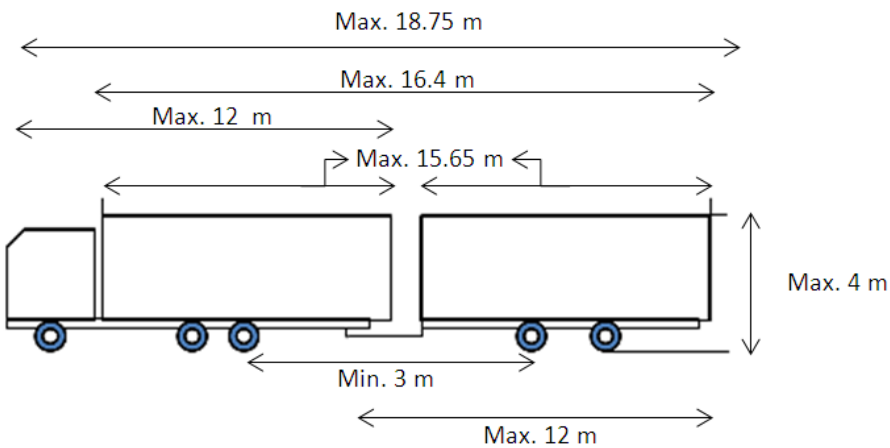


Fig. 2-1 Prescribed dimensions for road trains.

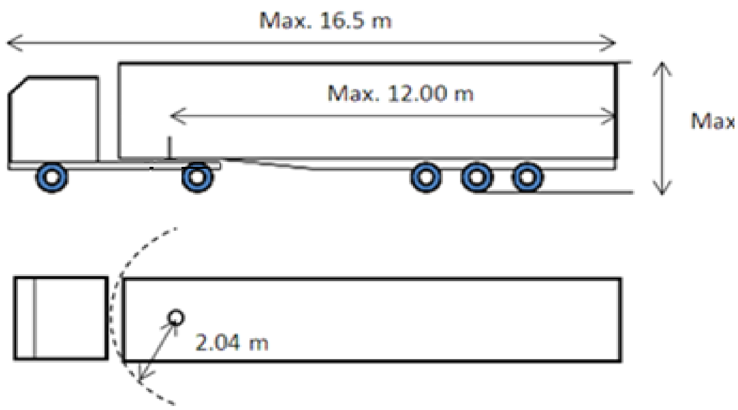


Fig. 2-2 Prescribed dimensions for articulated vehicles.

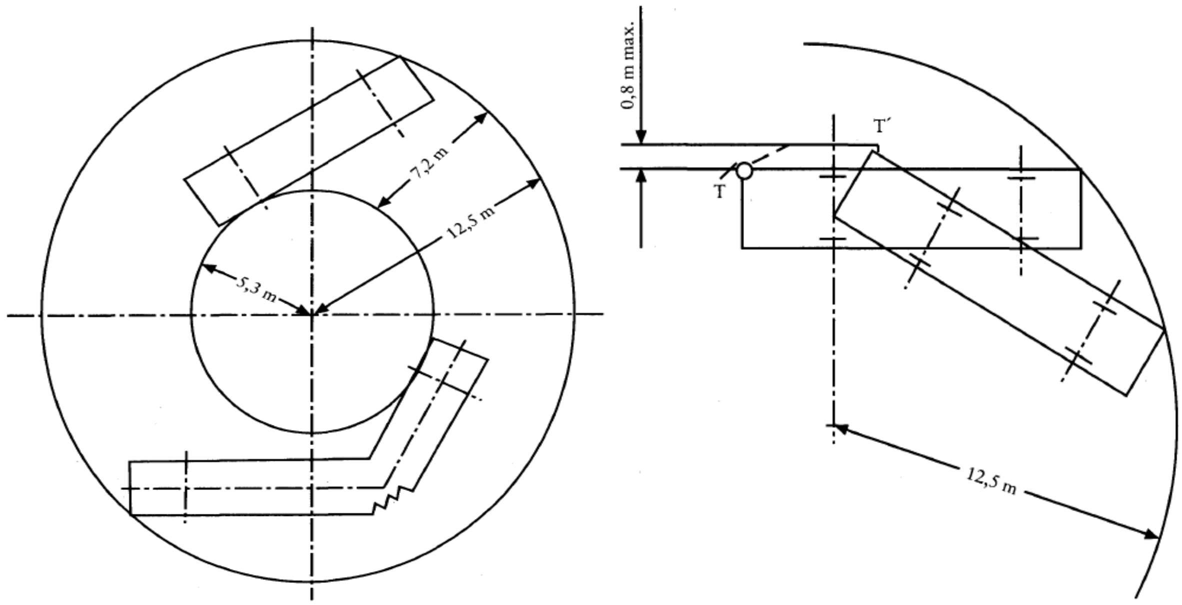
[74] European Commission. (1996). *Directive 96/53/EC.* Page 14.

[75] European Commission. (1996). *Directive 96/53/EC.* Page 11.

[76] European Commission. (1996). *Directive 96/53/EC.* Page 14.

[77] European Commission. (1996). *Directive 96/53/EC.* Page 11.

Regarding the manoeuvrability, 'any motor vehicle or vehicle combination which is in motion must be able to turn within a swept circle having an outer radius of 12.50 m and an inner radius of 5.30 m.' [78] This is shown in Fig. 2-3 (a). Furthermore no part of a rigid vehicle may exceed the circle by more than 0.8 m, see Fig. 2-3 (b).[79] In case of a retractable axle in lifted position, or loadable axle in the unloaded condition, the 0.8 m from Fig. 2-3 (b) is replaced with 1.0 m.[80]



(a) (b)

Fig. 2-3 Radius circle of 12.5 – 5.3 m (a) and allowed tail swing of a vehicle in a 12.5 m radius circle (b). [81]

Not only manoeuvrability but also permissible weights per vehicle type and axle configuration are prescribed by the European Commission. Depending on the type of vehicle combination the permissible axle weight is prescribed (see Appendix C). These permissible weights of the vehicles and axle (groups) are meant to prevent high damage to roads and bridges.

Country-specific regulations

In the previous section a summary is given regarding the EU-wide legislations with respect to vehicle combinations. Beside these there are also special regulations in different countries. Sweden, Finland and the Netherlands have already agreed on the use of 25.25 m long and 60t trucks. The use of LHVs in these countries is defined by special regulations and permits.[82, 83, 84]

[78] European Commission. (1996). *Directive 96/53/EC.* Page 11.

[79] European Commission. (1997). *Directive 97/27/EC.* Page 13.

[80] European Commission. (1997). *Directive 97/27/EC.* Page 13.

[81] European Commission. (1997). *Directive 97/27/EC.* Page 13.

[82] Aurell, J., & Wadman, T. (2007). *Vehicle combinations based on the modular concept.* Page 19.

[83] Aurell, J., & Wadman, T. (2007). *Vehicle combinations based on the modular concept.* Page 19.

[84] Beleidsregel keuring en ontheffingverlening LZV. (2012). *Staatscourant*.

Upcoming EU regulations
Currently there are multiple tests and proposed regulations with respect to trucks. In this part these tests and proposed regulations will be discussed. First information will be given on the status on implementing longer and/or heavier vehicles in Europe. Then new proposals from the EU will be discussed.

LHVs in Europe
In Europe the use of LHVs is an important topic. Table 2-2 shows which countries in Europe are testing longer and/or heavier vehicle combinations or discussing such tests. Also the maximum length and Gross Combined Weight (GCW) is shown. In other countries trials or discussions are in progress. Unfortunately their status is not clear.

Table 2-2 European countries in discussion or testing phase for LHVs.

Country	Maximum length [m]	Maximum GCW [t]	Test phase	In discussion
Denmark[85]	25.25	60	Until end 2016	
Germany[86]	25.25	44	Until end 2016	
Belgium[87 88]	25.25	60		x

Denmark started testing LHVs in 2008. The project was planned until 2011 but has been extended until 2016. In 2011 the approximate number of LHVs was 450 and growing. 1700 km of road was part of the trial at that time. [89] The most important findings of the research until now are:

- 'The Danish Government supports the use of Eco-Combis in cross-border transport between countries of *mutual agreement* and on *suitable roads*.
- Eco-Combis seem to have an equal or better use of load-capacity than regular trucks. This is important as the advantages of Eco-Combis are only fully realised if their larger load-capacity is actually utilised.
- The average total weight of Eco-Combis on Danish roads is about 40 tonnes (a weight of up to 60 tonnes is allowed) with an average axle load of about 6 tonnes. As a result, Eco-Combis do not seem to have a significant effect on wear-and-tear on roads in Denmark.
- A return on investments of 2.60 DKK per invested 1 DKK is approximated for 2016. The positive results of the analyses can mainly be ascribed to the savings on transport costs and, to a lesser extent, the reduced carbon emissions associated with the use of Eco-Combis.
- Calculations show that there is a potential 15 percent reduction of CO2 emissions in situations where two Eco-Combis can replace three regular road trains. Regarding traffic noise, the effect of Eco-Combis is very limited and estimated as unnoticeable to the human ear.'[90]

[85] Danish Ministry of Transport . (undated). *The Danish Eco-Combi Trial - Eco-Combis in Denmark 2008 - 2011 and beyond.* Rosendahls. Page 6.

[86] Verband der Automobilindustrie. (2013). *Der Feldversuch Lang-LKW - Eine Zwischenbilany.* Initiative für Innovative Nutzfahrzeuge. Page 8 and 32.

[87] Mobiliteitsraad van Vlaanderen. (2013). *Jaarverslag 2012.* Brussel. Page 12.

[88] Belga. (2013, July 19). *Proefproject met supertrucks opnieuw stapje dichterbij*. Retrieved August 20, 2013, from Skynet: http://www.skynet.be/nieuws-sport/nieuws/politiek/artikel/991721/proefproject-met-supertrucks-opnieuw-stapje-dichterbij

[89] Danish Ministry of Transport . (n.d.). *The Danish Eco-Combi Trial - Eco-Combis in Denmark 2008 - 2011 and beyond.* Rosendahls.

[90] Danish Ministry of Transport . (n.d.). *The Danish Eco-Combi Trial - Eco-Combis in Denmark 2008 - 2011 and beyond.* Rosendahls.

Germany is doing similar tests to Denmark but with a maximum of 44 t per truck. At the time of writing 43 LHVs are in use in Germany in seven regions. All trucks have additional safety systems like distance control, lane change control, lane keeping assist, rear identification and visibility. The result of this research so far is a fuel consumption reduction of 15 – 30% per t-km with respect to a normal truck. The effect on wear-and-tear on roads is also smaller because the individual axle loads are lower.[91]

In Belgium a test phase has been agreed upon, but the council of state still has to agree with the plans. Furthermore a recommendation has to be given by the “mobiliteitsraad”, which is a strategic board that gives recommendations regarding mobility.

Proposal of European parliament on future trucks

On 15th April 2013 the European Commission proposed an amendment of Directive 96/53/EC. The goal of this change is to improve the aerodynamics of vehicles and their energy efficiency, while continuing to improve road safety, within the limits imposed by the geometry of road infrastructures. [92]

For trucks the following is proposed:

- ‘To grant derogations from the maximum dimensions of the vehicles for the addition of aerodynamic devices to the rear of the vehicles or to redefine the geometry of the cabs for tractors. These derogations open up new prospects for manufacturers of tractors, lorries and trailers but must meet certain requirements, on which is not to increase the load capacity of the vehicles.
- Streamlining of cabs must also improve the drivers’ field of vision, and thus save around 400 lives each year in Europe. The drivers’ comfort and safety will also be increased.
- The proposed Directive plans to authorise a weight increase of one tonne for vehicles with an electric or hybrid propulsion, to take account of the weight of batteries or the dual motorisation, without prejudice to the load capacity of the vehicle.
- Enable inspection authorities to better detect infringements and harmonise administrative penalties that apply to them.
- Allowing a derogation of 15 cm in the length of trucks carrying 45-foot containers, which are increasingly used in intercontinental and European transport.’[93] See also paragraph 1.3.1 section ‘Future transport concepts’.

This proposal needs to be adopted by the European Parliament and member states before becoming law. It is expected that the new trucks could be seen on the road between 2018 and 2020.[94]

[91] Verband der Automobilindustrie. (2013). *Der Feldversuch Lang-LKW - Eine Zwischenbilanz.* Initiative für Innovative Nutzfahrzeuge. Page 1-11.

[92] European Commission. (2013). *Proposal for a directive of the european parliament and of the council.* Page 1-2. Brussels.

[93] European Commission. (2013). *Proposal for a directive of the european parliament and of the council.* Brussels. Page 5.

[94] European Commission. (2013, July 29). *New EU Rules for safer and more environmental lorries*. Retrieved August 20, 2013, from European Commission: http://ec.europa.eu/commission_2010-2014/kallas/headlines/news/2013/04/lorries_en.htm

3 Future transport and logistic concepts compared with legal framework

In this chapter the visions with respect to logistic and transport concepts from Chapter 1 and the legal framework with respect to infrastructure and vehicle regulations from Chapter 2 are compared.

In Chapter 1 logistic and transport concepts are described which arise because of megatrends. For these concepts visions were stated. These visions are summarised in the following points:

- There is a need for smart, clean and profitable transport.
- Smart, clean and profitable transport leads to an efficient transport system in which intermodal transport, EMS and hub & spoke systems are efficiently combined.
- To combine intermodal transport, EMS and hub & spoke systems efficiently there is a need for an EU wide regulation which permits use of multiples of loading units for road transport.
- To be able to carry multiples of loading units in the current infrastructure, vehicle combinations need to be extended to lengths of approximately 33m.

Taking into account the current and upcoming vehicle regulation mentioned in Chapter 2 and comparing this with the vision stated above a conflict arises:

The current and upcoming legal framework does not support the coming need for multiples of loading units.

To resolve this conflict two solutions will be given in Part II:

- Smart, clean and profitable vehicle combinations which can handle multiples within the current infrastructure.
- A proposal for a new EU-wide legal framework which allows the use of multiples within the existing infrastructure.

Part II. Vehicle combinations and new legal framework

In Part II solutions for the conflict between upcoming vehicle regulations and the future vision on freight transport are explained in detail. The first solution consists of a proposal for new vehicle combinations which can handle multiples. The second solution is a proposal for a new EU-wide legal framework.

Vehicle combinations
14 different vehicle combinations are selected to get a good idea of how smart, clean and profitable they are. Two groups of vehicle combinations are considered: standard vehicle combinations that are legal across Europe and existing LHVs, both variants already in use in some European countries as well as proposed LHV combinations. These were selected to permit a good comparison when the performance of the different groups is assessed. The vehicles were selected based on their combination of loading units, GCW and length.

Proposal for new legal framework
To draw up a proposal for a new legal framework regulations outside Europe have been studied. Chapter 5 elaborates on the performance-based legal framework of Australia, Canada and New Zealand. Practice shows that this legal framework can be used for all vehicle combinations and has positive effects on safety and CO_2 emission compared with conventional legal frameworks.

A performance-based legal framework uses Performance-Based Standards (PBS) to demonstrate whether or not products and services meet specified goals and objectives. The vehicle combinations are classified on performance instead of weight and length.

Apart from research-based results that show the positive effects of PBS, different institutes too regard PBS as the new form for a European legal framework. For these reasons the proposal for the new legal framework is based on PBS. The Australian PBS is taken as a starting point because this regulation takes the differences in infrastructure into account by defining road classes. In Australia the infrastructure is divided into four different road classes. For each PBS it is stated what performance is required for driving on a road of a specified class.

The proposal is split into two subjects: road classes and PBS. Based on the usage of different segments the road classes are defined as ordinary roads, express roads and motorways, which is the same definition as that used by the UNECE. The explanation given by the UNECE per road type is a starting point, but detailed characteristics need to be defined by the road authorities.

The PBS are split up into safety and infrastructure standards. The safety standards again consist of four groups:

- Stability standards
- Dynamic performance standards
- Powertrain standards
- Manoeuvrability standards

Most PBS have been adopted from the Australian PBS, but newly developed standards which Australia does not take into account have also been added. For every PBS the source, requirements from the European regulation, a short description and the load conditions are defined.

For each standard the performance value per road class still needs to be defined. It is not possible to take the Australian values because the infrastructure there differs from European roads. Furthermore the origin of these values is not clear. On the basis of the existing regulations and infrastructure design only recommendations can be given for some performance values (see the EU requirement in tables). Despite this, however extensive research is still necessary to define all performance values.

4 Vehicle combinations

In chapter 3 the conflict between the upcoming vehicle regulation and the future vision in freight transport is described. One solution is to propose new vehicle combinations that can handle multiples. To be able to make a good comparison a distinction is made between standard vehicle combinations and existing LHVs. With these types of vehicle combinations conclusions can be drawn with respect to smart, clean and profitable transport between current and upcoming vehicle combinations. This is described in Part III.

For the choice of the vehicles a combination of loading units is taken into account. Only combinations which combine multiples of ISO containers or swap bodies and semi-trailers are considered because of intermodality. ISO containers are used by all modes, whereas swap bodies and semi-trailers are used only by rail and road. For the swap bodies only the C782 is used because this is the largest. If this swap body can be carried, the other sizes are possible too.

Table 4-1 shows the selected vehicle combinations with their origin, GCW and length. It is divided into the different vehicle combinations described below.

Standard vehicle combinations

For the standard vehicle combinations the very common European articulated vehicle and road train are used. These vehicles are within the 96-53-EC regulation for international transport as described in paragraph 2.2. Furthermore four vehicle combinations are added to the standard vehicle combination group. Combination 3A-II is important for comparison regarding safety, as this combination is known as an allowed critical combination. Combinations 13, 14 and 15 are added for the comparison regarding clean and profitable transport.

Existing LHVs

Most of the existing LHVs evaluated have their origin in the Netherlands. Combinations 4A, 5 and 6C are legally allowed LHVs in the Netherlands. Combination B is a widely used combination for transport of supermarket products in the Netherlands. Combination 6A is being used in the trials in Denmark. This concept was chosen because it is similar to 6C but uses different loading units. All these vehicles are within the maximum length limit of 25.25m and the GCW limit of 60t.

In the existing LHVs group three combinations (8C, 10A and 12A) longer than 25.25 m are also considered, since they represent the current trend of LHVs for the near future. These vehicle combinations still need to comply with the 60t maximum GCW. The 60t is chosen to permit easier comparison with the other LHVs and because, in the near future, 60 t is the most sensible GCW that can be expected. This GCW is allowed in the EU only by the Netherlands, Finland and Sweden. In these countries research has shown that this GCW does not cause additional damage to the roads.[95,96] First the other EU countries need to make the step to 60 t before higher GCWs can be expected.

Combination 8C consists of two 45 foot containers. Transport of one 45 foot container over road will be allowed in the near future. The combination of two 45 foot containers goes one step further. Combinations 10A and 12A show the next future combinations which carry multiple C782 swap bodies or a combination of C782 swap bodies and a 13.6m semi-trailer. This combination of loading units is preferable for the sake of EMS and intermodal transport.

For all vehicle combinations no active steering and no ABS is used. This is done to simulate the worst case behaviour.

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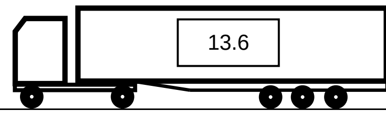
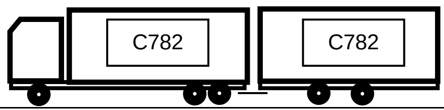
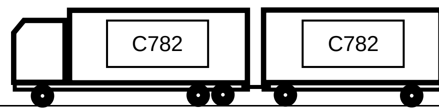
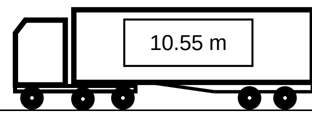
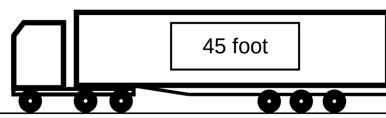
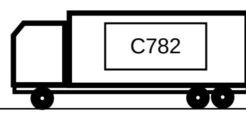
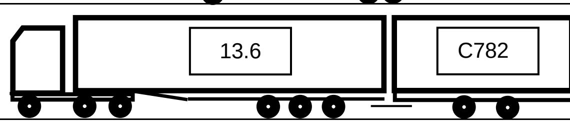
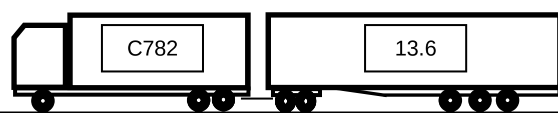
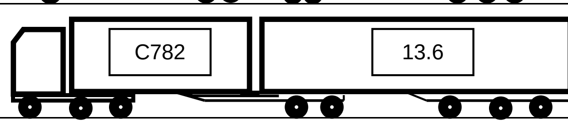
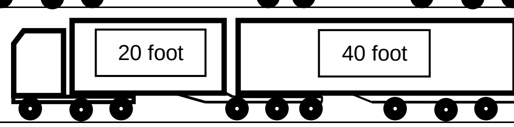
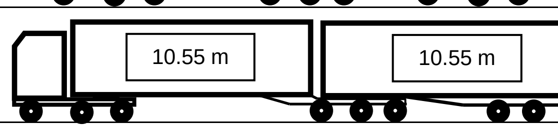
[95] Backman, H., & Nordström, R. (2002). *Improved Performance of European Long Haulage Transport.* Stockholm: TFK.

[96] Rijkswaterstaat. (2010). *Longer and Heavier Vehicles in the Netherlands.* Directorate General for Public Works and Water Management.

Table 4-1 Vehicle combinations to be analysed.

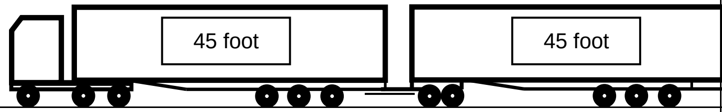
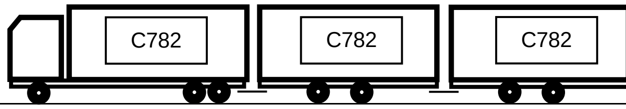
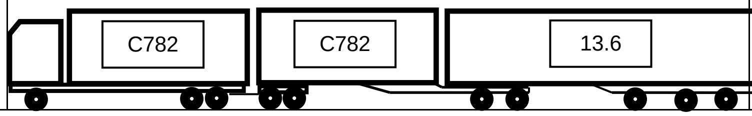
Type	Number	Picture	Origin	GCW	Length
standard vehicles	1B[97]		EU	40 t	16.4 m
	3A[97, 98]		EU	40 t	18.7 m
	3A-II		EU	40 t	18.7 m
	13		EU	40 t	13.88 m
	14		EU	40 t	17.05 m
	15		EU	40 t	10.17 m
existing LHVs	4A[98]		NL	60 t	25.25 m
	5[98]		NL	60 t	24.6 m
	6A[99]		DK	60 t	25.25 m
	6C[98]		NL	60 t	23.5 m
	B[100]		NL	60 t	25.25 m

[97] Aurell, J., & Wadman, T. (2007). *Vehicle combinations based on the modular concept.* Page 29.

[98] Kural, K., Besselink, I., Pauwelussen, J., & Nijmeijer, H. (2012). *Assesment of dutch longer and heavier vehicles with a performance based approach and its applicability to Europe.*

[99] Germanchev, A., & Eady, P. (2009). *Heavy vehicle benchmarking study.* Page 68.

[100] *Meer lading met minder ritten*. (2013). Retrieved 10 29, 2013, from Tielbeke: http://www.tielbeke.nl/nl/transport/transport-LZV

	8C[97]		EU	60 t	31.95 m
	10A[97]		EU	60 t	27.4 m
	12A[97]		EU	60 t	33.3 m

5 Proposal for a new legal framework

Chapter 3 made it clear that the current legal framework does not meet future demands. It was also stated that there is a need for smart, clean and profitable transport. A transport system is needed. The basis for such a system is the legal framework. Improvements are needed especially with respect to smart transport. In the EU the vehicle regulations focus only on masses and dimensions. It is therefore not clear whether a vehicle is really safe. Neither is it evaluated how the complete vehicle combination will perform in the infrastructure.

For the reasons stated above paragraph 5.1 describes regulations outside Europe which use a different form of legal framework. In paragraph 5.2 a proposal for a new legal framework in Europe, based on the information gained in paragraph 5.1, will be explained.

5.1 Regulations and legislations outside Europe

Longer and heavier vehicle combinations are already used in countries outside Europe. Countries with similar requirements for transport such as infrastructure, safety and environment are considered. This has led us to Australia, Canada and New Zealand. Canada was the first country to introduce a legal framework that was based not only on length and weight but also on the performance of the vehicle combinations. Australia and New Zealand introduced a performance-based framework later but have gained a great deal of experience with it in the meantime. Practice shows that the legal framework used in these countries is compatible with the use of LHVs and has positive effects regarding smart, clean and profitable transport[101,102]

In New Zealand the system has similarities with the EU but there are also performance indicators. In Canada and Australia Performance-Based Standards (PBS) form the legal framework. In general PBS state goals and objectives to be achieved and describe methods that can be used to demonstrate whether or not products and services meet the specified goals and objectives. The vehicle combinations are thus classified on performance instead of weight and length. For trucks this means that they are classified based on, for example, their stability, manoeuvrability, dynamics, powertrain and infrastructure. A short explanation of the different regulations for Canada, New Zealand and Australia is given.

New Zealand

In New Zealand HDVs are classified in the same way as in Europe. The maximum permitted weight of the combinations is the lead criterion. First the vehicle is classified as a light (A), medium (B) or heavy (C) goods vehicle. The trailer too is classified as a very light (A), light (B), medium (C) or heavy (D) trailer.[103] Based on the class both are restricted to certain maximum dimensions, turning circle, axle configurations, maximum axle loads, suspension, towing coupling point and stability minimums. These are all performance standards which the vehicle has to meet. A distinction is made between vehicle combinations and rigid vehicles.[104,105]

[101] Woodrooffe, J. (2012). *Performance-Based Standards and Indicators for Sustainable Commercial Vehicle Transport.* Michigan: Michigan Transportation Research Institute.

[102] Hassal, K., & Thompson, R. (2010). *Estimating the Benefits of Performance Based Standards Vehicles.*

[103] *What class is my vehicle*. (n.d.). Retrieved August 19, 2013, from NZ Transport Agency: http://www.nzta.govt.nz/vehicle/classes-standards/class.html

[104] NZTA. (2011). *Heavy trailers and combination vehicles.*

[105] NZTA. (2013). *Heavy rigid vehicles.*

Canada[106]

The Canadian PBS were introduced in the mid-1980s to harmonise the heavy vehicle weight and dimension regulations. The PBS system was developed to regulate size and weight within the context of the following objectives:

- To encourage the use of the most stable heavy vehicle configurations through the implementation of practical, enforceable weight and dimensions limits.
- To balance the available capacities of the national highway transport system by encouraging the use of the most productive vehicle configurations relative to their impact on the infrastructure.
- To provide the motor transport industry with the ability to serve markets across Canada using safe, productive, nationally acceptable equipment.

With these objectives in mind weight and dimension limits were set for vehicle configurations, which were evaluated against seven "performance measures". For a detailed description of these performance measures see Appendix D.

Australia[107]

PBS where introduced in Australia in 2007. The approach assesses the performance of the vehicle combination with respect to safety and infrastructure. It is a practically oriented set of rules that makes it possible to rank the performance of the vehicle combination from different perspectives. Generally speaking it does not matter what the vehicle looks like, how heavy or long it is; what matters is the performance of the vehicle combination in a number of different scenarios. Depending on the performance of the vehicle it may or may not drive on four different road classes.

As depicted in Fig. 5-1, the Australian PBS scheme is divided into two parts: infrastructure and safety. The infrastructure part contains in total four criteria assessing the performance of vehicles with respect to road and bridge damage. The safety part has 16 standards where the vehicle is assessed in longitudinal and lateral direction. These safety and infrastructure criteria are described in detail in Appendix D.

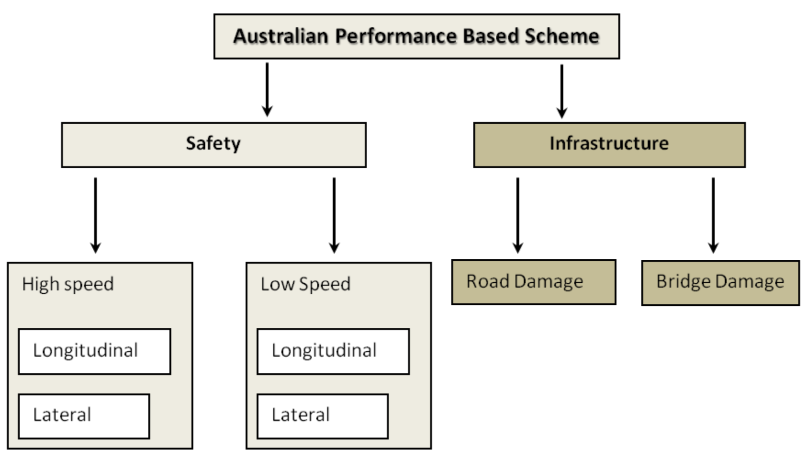


Fig. 5-1 Structure of the Australian PBS.

[106] Woodrooffe, J. (2012). *Performance-Based Standards and Indicators for Sustainable Commercial Vehicle Transport.* Michigan: Michigan Transportation Research Institute. Page 5-7.

[107] National Transport Commission Australia. (2008). *Performance based standards scheme. The standards and vehicle assesment rules.*

5.2 New European legal framework based on PBS

As described earlier a new legal framework is necessary because of the conflict between the current legal framework and the logistic and transport concepts needed to cope with future megatrends.

Paragraph 5.1 shows that the PBS system in Australia and Canada gives more flexibility with respect to weight and size. The vehicle combinations still need to comply with standards which prescribe the performance. In Canada research shows that the safety performance of LHVs is three to five times better than that of the standard tractor semi-trailer operating on identical roads.[108]

In Australia research estimates the effect of PBS between 2011 and 2030. Fatalities, CO_2 emission and vehicle operating cost savings are considered to determine the total benefit of PBS. The basis for the benefits of PBS are the Vehicle Kilometres Travelled (VKT). Due to the use of LHVs the reduction in vehicles in Australia between 2011 and 2030 is 28.3% for interurban transport and 21% for urban transport. This will result in a reduction in VKT of 25.2% and 19.1% for regional and urban transport respectively. Due to the reduction in VKT the number of fatalities and the CO_2 emissions will fall. The number of fatalities will also decrease because the safety performance of PBS vehicles is higher than that of non-PBS vehicles.[109]

Another important fact is that different institutes regard PBS as the new form for a European legal framework. Chalmers University opened a postdoctoral position with the purpose of drawing up a proposal for PBS for high-capacity transport in Sweden.[110] The ACEA presented the 18th Scientific Advisory Group (SAG) report about PBS at the transport policy event in 2012. In this document the PBS of Australia and Canada are considered, there is a discussion of PBS and conclusions are made. The main conclusions of this document are that PBS can help to meet the expanding need with respect to fuel and emission constraints In Europe. Furthermore, the use of EMS in a PBS framework has, according to the document, high potential. Lastly, it concludes that the Australian and Canadian PBS lack key performance indicators in their legal framework. The transport sustainability can be determined by measuring the fuel consumption, GHG emissions and achieved safety outcome.[111]

The positive effects of the use of PBS in Australia and Canada and the growing share of institutes that see PBS as the future for the European legal framework are the reasons why the proposal for the new legal framework is based on PBS. The Australian PBS with its approach of different road classes is taken as a starting point because the infrastructure in Europe is extremely varied.

To take the infrastructure into account a proposal for different road classes is worked out. This is explained in paragraph 5.2.1. Paragraph 5.2.2 elaborates on the PBS.

5.2.1 Road classes

Europe has differences in its infrastructure. It is not possible for all vehicle types to drive on all roads. To resolve this issue road classes are proposed. Depending on the performance of a vehicle it can drive on prescribed road classes. The three road classes are determined in Fig. 5-2. This figure represents not only the road classes but also a vision for future transport.

First a distinction is made between urban and interurban transport. Within these types of transport four different transport segments can be placed: City, Distribution, Long-Haul and (International) Long-Haul.

[108] Woodrooffe, J. (2012). *Performance-Based Standards and Indicators for Sustainable Commercial Vehicle Transport.* Michigan: Michigan Transportation Research Institute. Page 6.

[109] Hassal, K., & Thompson, R. (2010). *Estimating the Benefits of Performance Based Standards Vehicles.* Page 8-11

[110] *Vacancies at Chalmers University of Technology*. (October 2013). Abgerufen am Oktober 2013 von Postdoctoral position in Performance Based Standards for High Capacity Transport in Sweden: http://www.chalmers.se/en/about-chalmers/vacancies/Pages/default.aspx?rmpage=job&rmjob=1335

[111] Woodrooffe, J. (2012). *Performance-Based Standards and Indicators for Sustainable Commercial Vehicle Transport.* Michigan: Michigan Transportation Research Institute. Page 5-7.

Between these segments the vision places efficient hub systems with the possibility of switching between modes. This framework integrates the different types of roads defined by the UNECE in the European agreement on main international traffic arteries. Ordinary roads are used by the city and distribution segments. Express roads are used by the distribution and long-haul segments. Finally motorways are used by the international long-haul and long-haul segments.[112]

These types of roads are proposed as the different road classes for the new legal framework. The explanation given per road type by the UNECE is a starting point for parameters for the road types, see paragraph 2.1. It is nevertheless necessary that the detailed characteristics of the roads be defined by the road authorities.

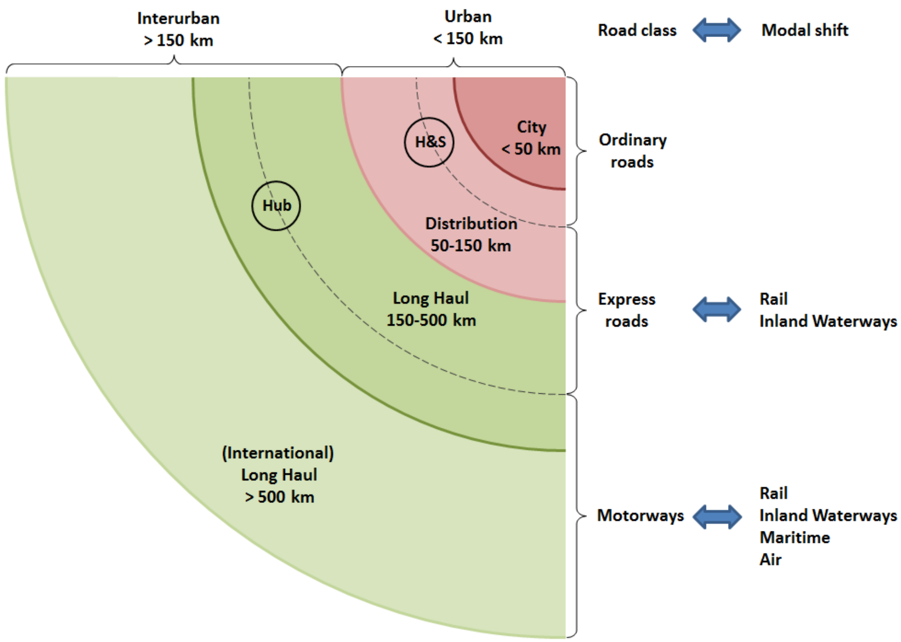


Fig. 5-2 Vision on use of segments by different modes for future transport.

[112] United Nations Economic and Social Council . (2008). *European agreement on main international traffic arteries.* Page 32-33

5.2.2 Performance-based standards

As described earlier, PBS state goals and objectives to be achieved and describe methods that can be used to demonstrate whether or not products and services meet the specified goals and objectives. In this paragraph a proposal is given for various PBS for European legislation on vehicle combinations.

A distinction is made between PBS for safety and infrastructure. The safety part contains standards that define whether a vehicle combination can drive safely on one of the defined road classes. The infrastructure part defines whether the vehicle combination can drive within the infrastructure without causing damage to it.

The safety standards are divided into four different groups:

- Stability standards (Table 5-1)
- Dynamic performance standards (Table 5-2)
- Powertrain standards (Table 5-3)
- Manoeuvrability standards (Table 5-4)

An explanation of the PBS is given in the tables. For every PBS the source, possible requirements for the European regulation, a short description and the load conditions are given. For these groups most PBS are based on the Australian legal framework, but for the manoeuvrability standards a 360° turn is added. This is seen as an important manoeuvre in the European infrastructure. Furthermore, if a PBS is dependent on infrastructure dimensions, the European values are taken instead of the Australian. Three PBS from the Australian framework are not taken into account: ride quality, handling quality and overtaking provision. For these PBS the results are not robust enough or they have not yet been defined.

For every safety standard the performance value per road class still needs to be defined. It is not possible to take the Australian values because the infrastructure there differs from European roads. The origin of these values is not clear either. Based on the existing regulations and infrastructure design recommendations can be made for some performance values (see EU requirement in tables), but despite this extended research is still necessary to define all performance values.

The infrastructure standards do not consist of groups. There are four different PBS. All of these have to do with damage on roads. For the infrastructure standards too extensive research is necessary to define performance values per road class. The infrastructure standards are shown in Table 5-5.

Safety

Table 5-1 Stability standards.

Standard	Source	EU requirement	Short description	Load conditions
Static rollover threshold	Australian PBS	None	The steady state level of lateral acceleration that a vehicle can sustain without rolling over during turning.	100%
Directional stability under braking	Australian PBS	UNECE agreement	The ability to maintain directional stability under braking	0 and 100%
Yaw damping coefficient	Australian PBS	None	The rate at which “sway” or yaw oscillations decay after a short duration steer input at the hauling unit	0 and 100%

Table 5-2 Dynamic performance standards.

Standard	Source	EU requirement	Short description	Load conditions
High-speed transient off-tracking	Australian PBS	UNECE agreement	The lateral distance that the last axle on the rearmost trailer tracks outside the path of the steer axle in a sudden evasive manoeuvre	0 and 100%
Tracking ability on a straight path	Australian PBS	UNECE agreement	The total swept width while travelling on straight path, including the influence of variations due to crossfall, road surface unevenness and driver steering activity	
Rearward amplification	Australian PBS	None	The degree to which the trailing unit(s) amplify the lateral acceleration of the hauling unit	

Table 5-3 Powertrain standards.

Standard	Source	EU requirement	Short description	Load conditions
Startability	Australian PBS	Directive 97/27/EC, point 7.9	The ability to commence forward motion on a specified upgrade.	100%
Gradeability A: Maintain Speed	Australian PBS	Directive 97/27/EC point 7.10	The ability to maintain speed on a specified upgrade.	
Gradeability B: Maintain Motion	Australian PBS	None	The ability to maintain forward motion on a specified upgrade.	
Acceleration capability	Australian PBS	None	The ability to accelerate either from rest or to increase speed on a road with no grade.	

Table 5-4 Manoeuvrability standards.

Standard	Source	EU requirement	Short description	Load conditions
Low-speed swept path	Australian PBS	Directive 96/53/EC point 1.5	The maximum width of the swept path in a prescribed 90° low-speed turn.	0 and 100%
Frontal swing	Australian PBS		The maximum width of the frontal swing swept path in a prescribed 90° low-speed turn.	
Tail swing	Australian PBS	Directive 97/27/EC point 7.6.2	The maximum outward lateral displacement of the outer rearmost point on a vehicle unit during the initial and final stages of a prescribed 90° low-speed turn.	
Steer tyre friction demand	Australian PBS	None	The maximum friction level demanded of the steer tyres of the hauling unit in a prescribed 90° low-speed turn.	
360° turn swept path	None	Directive 96/53/EC point 1.5.	This is the smallest radius a vehicle combination can make in a 360° turn. A vehicle has to be able to drive a complete round on a roundabout to prevent congestion on it. The minimum radius that the turn needs to be depends on the road class.	

Infrastructure

Table 5-5 Infrastructure standards.

Standard	Source	EU requirement	Short description	Load conditions
Pavement vertical loading	Australian PBS	96/53/EC	Limit the stress on the pavement layers below the surface of the road.	100%
Pavement horizontal loading	Australian PBS	None	The degree to which horizontal forces are applied to the pavement surface, primarily in a low-speed turn, during acceleration and on uphill grades.	
Tyre contact pressure distribution	Australian PBS	None	The minimum tyre width that is allowed, and the maximum pressure and pressure variation that is applied to the road surface by a single tyre or pair of tyres in a dual-tyred set.	
Bridge loading	Australian PBS	None	Check if the bridge loading is not exceeded by the vehicle combination.	

Part III. Validation of combinations on smart, clean and profitable transport

Now that the vehicle combinations have been selected and a proposal for a new legal framework described, Part III deals with validation of the combinations. Therefore a detailed look at the requirements of vehicle combinations is necessary. There are three stakeholders with interests in the efficiency of vehicle combinations: first the lawmakers, who require smart concepts that are safe and suitable in their circumstances. Second the environment with its interest in clean concepts, and last but not least the customer with his requirements for profitable concepts. For defining and proposing new vehicle concepts a balance between smart, clean and profitable transport must be achieved.

Validation on smart transport

For validation on smart transport a simulation tool has been developed. For each PBS the simulation scenario and the measured variables are explained. The results are shown, interpreted and compared for the various PBS groups: stability standards, dynamic performance standards, powertrain standards and manoeuvrability standards. The results show a preference for B-modules because of their stability and dynamic performance. Even though LHVs are already operating safely in countries like the Netherlands, Sweden and Finland, they have a lower performance in terms of low-speed manoeuvring than standard vehicle combinations.

Validation on clean transport

Clean transport is considered as CO_2-efficient transport. The CO_2 emissions, which are directly proportional to the fuel consumption, therefore have to be calculated. To arrive at realistic fuel consumption figures a simulation tool has been used, as well as a specified typical route for long-haul transport and an average loading of the vehicles. For a proper comparison use cases need to be defined using the assumption that the same load has to be transported – either by standard vehicles or by LHVs. The results show that the CO_2 emission is improved in almost all use cases with fuel-saving potentials between 4% and 11% for the replacement of different loading units and between 24% and 38% for combinations with the same loading units.

Validation on profitable transport

For validation on profitable transport the approach of Total Cost of Ownership is used. By considering all direct and indirect costs it gives an overview not only of the initial costs but also of all aspects of use at the customer. The costs have been calculated by using the data of an average fleet owner, the average loading and the calculated fuel consumptions. If the same uses cases as for clean transport are applied, improvements for all use cases can be detected. Mostly due to the different fuel savings and investment costs of LHVs compared to standard vehicles cost-saving potentials of 15% to 20% for different loading units and 30% to 50% for the same loading units are feasible.

Proposal for new concepts

As the validations show, it is very important to choose the right loading units and the right vehicle combination for smart, clean and profitable transport. They should be designed so their length allows accommodation of the loading units which will be popular in the future, and they should be both modular and intermodal. For substantial improvements in terms of transport efficiency future vehicle concepts should evolve from the current longer and heavier vehicle combinations by emphasising strong points and eliminating or improving the weak points in the performance. Technological improvements or changes in technical characteristics to meet the challenge of combining sufficient high-speed stability with good low-speed manoeuvrability are therefore necessary for new concepts.

6 Smart vehicle validation

In this chapter vehicle combinations proposed in chapter 4 are validated on smart transport. Smart relates here to the general safety of vehicle combinations and their suitability for the European infrastructure. To validate this smart transport the PBS proposed in Chapter 6 and additional standards are simulated. First, in paragraph 6.1, the software tool used is explained. In paragraph 6.2 the simulation procedure per PBS is explained and the results are discussed. Finally, paragraph 6.3 discusses the overall performance of the combinations and ways to improve this.

6.1 Software tool

A software tool was developed by the HAN University of Applied Science and Eindhoven University of Technology (TU/e). It was used during the project to simulate the performance of the various vehicle combinations. The modularity of the tool permits simulation of any vehicle combinations in different test scenarios. The simulation results were subsequently post-processed to obtain the performance characteristics of the vehicle.

The models were built by means of the Commercial Vehicle Library, which is a generic and modular vehicle model library consisting of trucks, trailers and components and was developed in SimMechanics (part of MATLAB/Simulink) by the TU/e. The software tool was designed with graphical user interfaces where the user can choose the tractive and towed units for creating the desired combination. For these units the values of their dimensions, such as the length, width and height, and the values of their weights need to be given as input.

To verify the results, the simulation models have been validated against the experimental data. The tests were carried out for two different vehicle combinations, and complete results were published in a journal article.[113]

6.2 Simulation results

The PBS given in Chapter 6 were simulated with use of the software tool. This was done for all vehicle combinations except the combinations 13, 14 and 15. This is because 1B, 3A-I and 3A-II are the most common or critical vehicles with respect to safety. Combinations 13, 14 and 15 are used in chapter 7 and 8 for validation of clean and profitable transport.

Based on the simulation results the combinations are assessed regarding their general safety and their suitability for the European infrastructure. In this section the safety PBS, infrastructure PBS and additional simulation standards are elaborated on in paragraphs 6.2.1, 6.2.2 and 6.2.3 respectively.

The simulations are based on the Performance-Based Standard Scheme of the National Transport Commission of Australia.[114] For a more detailed explanation please consult this reference. It must be mentioned that the necessary road geometry or road inputs for the PBS were changed to the European infrastructure geometry and road inputs. Alongside the explanation the simulation results are elaborated on.

[113] Kural, K., Prati, A., Besselink, I., Pauwelussen, J. et al., "*Validation of Longer and Heavier Vehicle Combination Simulation Models*," SAE Int. J. Commer. Veh. 6(2):2013, doi:10.4271/2013-01-2369

[114] National Transport Commission Australia. (2008). *Performance based standards scheme. The standards and vehicle assesment rules.*

6.2.1 Safety PBS

Firstly the explanation of the simulation scenario and measured variables is given. Furthermore the results are shown and interpreted for every PBS. The sections of this paragraph are based on the PBS groups. These groups are as mentioned in chapter 5.2.2: stability standards, dynamic performance standards, powertrain standards and manoeuvrability standards. Finally, possible improvements for the performance are discussed.

Stability standards

In this part the PBS static rollover threshold, directional stability under braking and yaw damping coefficient are explained and their results are interpreted. The loading cases per PBS are different and explained per PBS.

Static rollover threshold

This standard was introduced to manage the safety risk by limiting the rollover tendency of a vehicle participating in steady turns. The simulation is done with an initial speed of around 40 km/h. The path is circular and has a radius of 100 meters. The vehicle is fully loaded as the centre of gravity height is one of the most decisive factors for the performance. The highest steady state level of lateral acceleration that a vehicle can sustain without rolling over is determined. Final results are expressed as a fraction of achieved acceleration to gravitational acceleration. Hence higher values stand for better performance.

Fig. 6-1 shows the results for the static rollover threshold. It shows that all LHVs are in the range of the standard vehicle combinations. The combinations B, 8C and 12A have an even better performance. This is mainly influenced by the length of the vehicle and the number of articulations. Such a vehicle tends to slide rather than roll over, which results in a higher static rollover threshold.

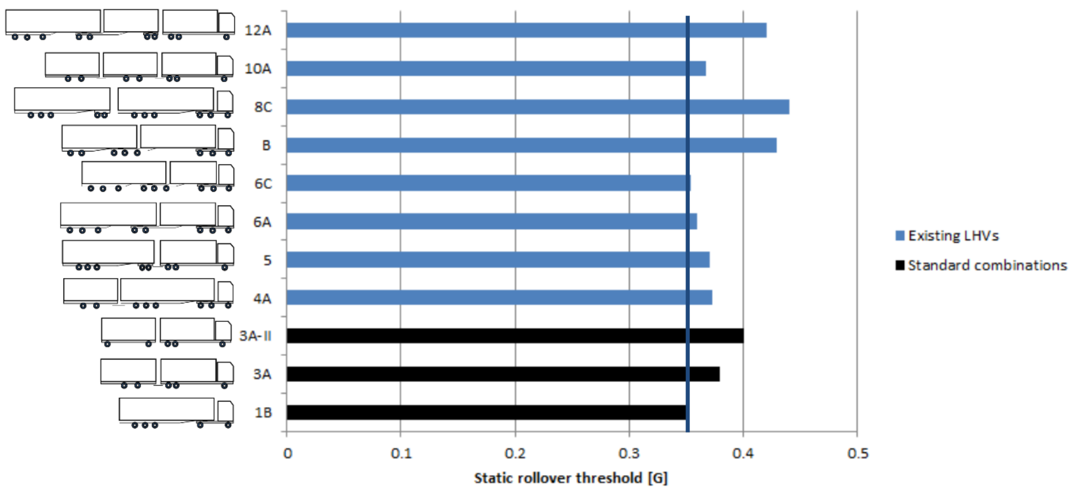


Fig. 6-1 Performance results for static rollover threshold per vehicle combination.

The static rollover threshold can be raised by increasing the number of axles, using air suspension, increasing the distance between the axles, using roll-coupled modules and/or increasing the roll centre height.

Directional stability under braking
This standard was introduced to manage the risk of vehicle instability during braking in a turn or on pavement across slopes. The vehicle must remain within the straight lane when braking. In the simulation the vehicle drives with a speed between 59 and 65 km/h on a straight lane. The deceleration is 0.37 g for every vehicle. Furthermore the simulation is carried out with the vehicle fully loaded and empty. The worst performance per PBS, which is the highest value, is taken for the results.

A simple braking system without ABS was used. Because of this the worst-case behaviour of the vehicle is considered. The tracking ability and deceleration are measured. The directional stability performance is expressed as the total width of envelope that the vehicle uses during the simulation. This is also called swept path.

As shown in Fig. 6-2 only concepts B and 8C are in the range of the standard vehicle combinations, though 6C, 10A and 12A also come close to the range of the standard vehicle combinations. This is due to the friction and normal force distribution. Beside this, an increased number of articulations might cause jack knifing during the braking if the friction varies between the axle groups. However, the simulations prove that vehicles are able to achieve the required deceleration even without ABS. Finally, all results are within a swept path of 3.5 m which is the average lane width in Europe. This proves that the performance is already within this limit.

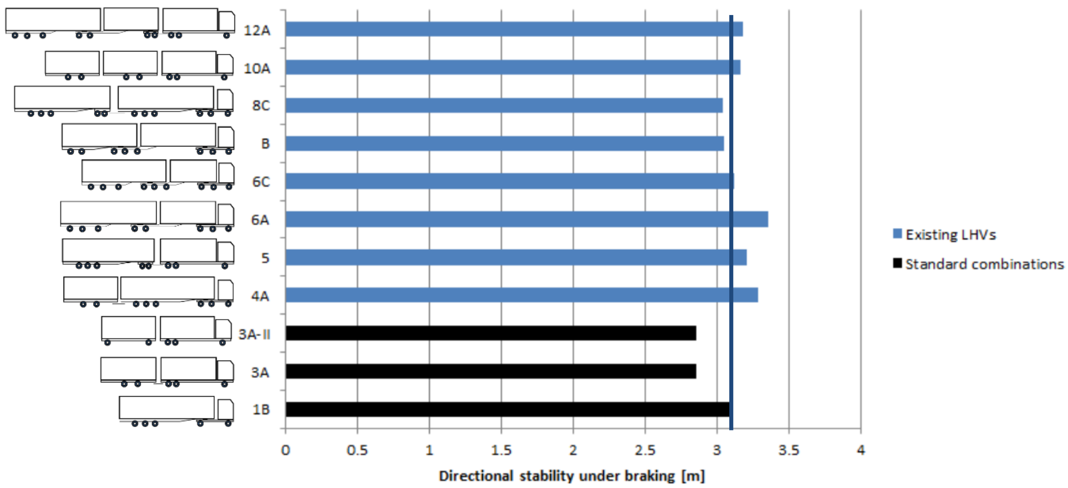


Fig. 6-2 Performance results for directional stability under braking per vehicle combination.

The directional stability under braking can be further improved with ABS and electric brake force distribution.

Yaw damping coefficient
This standard was introduced to manage the safety risk by requiring acceptable attenuation of any sway oscillations of rigid vehicles or between trailers of multi-articulated vehicles. The simulation was carried out with the vehicles fully loaded and empty. The worst performance per concept, which is the lowest value, is taken for the results. Attenuation of sway oscillations is done by measuring the decay of sway or yaw oscillation after a short-duration steer input defined in ISO 14791:2000(E). The speed is 88 km/h.

Fig. 6-3 shows that combinations 4A, B and 10A are not in the range of the standard vehicle combinations. Combinations 6A, 6C and 12A have B modules, which yield a better performance than the other combinations. This is due to the number of articulations and the distance between the kingpin and the axle groups. A higher number of articulations and a smaller distance between the kingpin and axle group is not favourable for the yaw damping. This is illustrated by cases 4A and 10A.

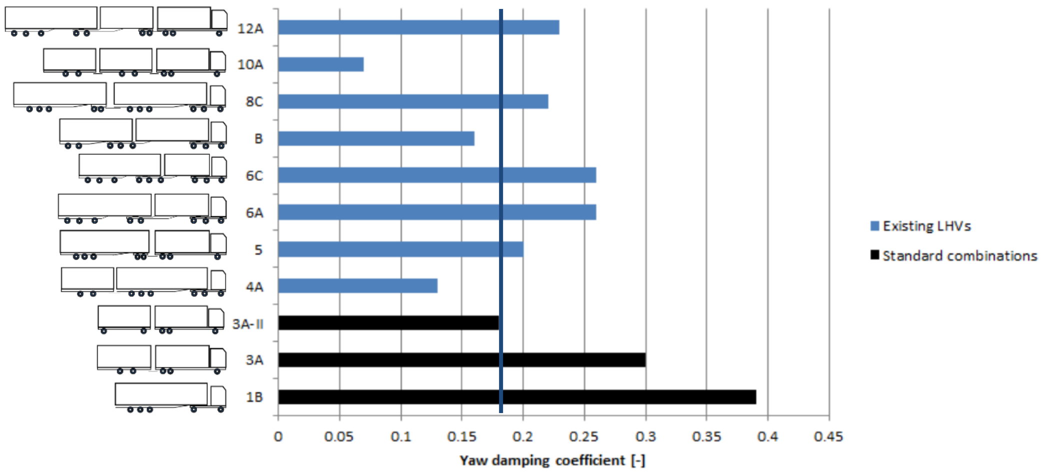


Fig. 6-3 Performance results for yaw damping coefficient per vehicle combination.

The yaw damping coefficient can be increased by different technological improvements such as air suspension, roll-coupled modules and increasing the roll-centre height.

Dynamic performance standards

In this part the PBS high-speed transient off-tracking, tracking ability on a straight path and rearward amplification are considered. All simulations were performed with the vehicles fully loaded and empty; the worst performance per concept is taken for the results

High-speed transient off-tracking

This standard was introduced to manage the safety risk by limiting the sway of the rearmost trailer in avoidance manoeuvres without braking, at highway speeds. A single lane change specified in ISO 14791:2000 is simulated at a speed of 88 km/h. The lateral displacement between the specified points on the rearmost axle of the rearmost vehicle is measured. The higher the value, the worse the result.

From Fig. 6-4 it is clear that only combination 5 is in the range of the performance of 1B and 3A. For the other combinations the performance is worse. The combinations which use a B module (concepts 6A, 6C and 12A) have performance ratings between 0.491 m and 0.564 m. The other combinations have performance ratings up to 1.324 m, which is significantly worse. This has to do with the important role of the number of articulations and the wheelbase of the prime mover. Hence vehicles B and 8C have the poorest performance compared to the other vehicles.

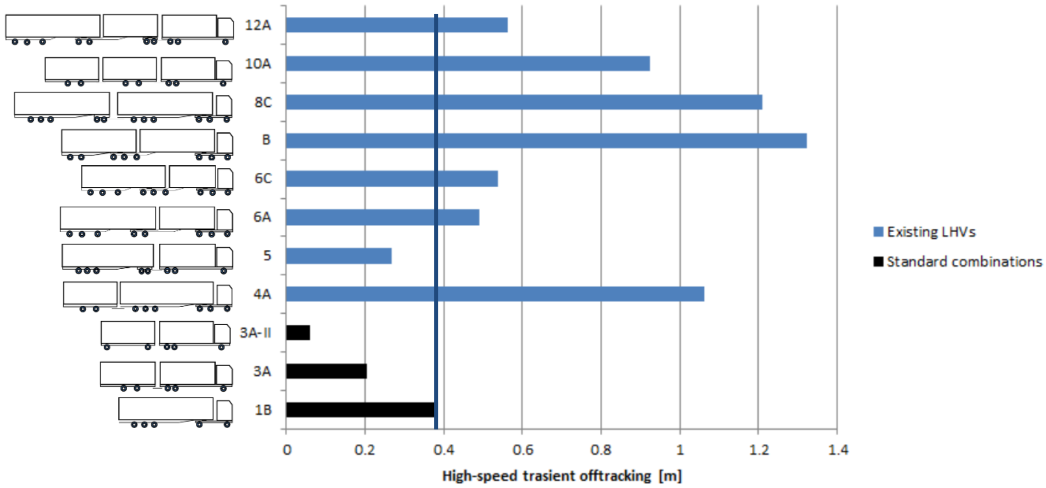


Fig. 6-4 Performance results for high-speed transient off-tracking per vehicle combination.

To improve the performance of the LHVs to a level within the standard vehicle combinations technological improvements are needed. The use of air suspension, active steering technologies, roll-coupled modules and increasing roll-centre height will have a positive influence on the performance.

Tracking ability on a straight path

This standard was introduced to manage the safety risk associated with lane width and sufficient lateral clearance to ensure that a vehicle remains within the lane. The test conditions provide for high speed on straight roads with uneven surfaces. The vehicle drives at least 1000 m at a minimum speed of 90 km/h. The road profile is based on a European highway, which is straight and banked. The swept path of the vehicle is measured. The higher the value, the worse the result.

The results in *Fig. 6-5* show that concept 6C has a better performance than the standard vehicle combinations. Concepts 5, 6A and 12A are close to the performance of these combinations. The performance is again, as in previous cases, influenced by the number of articulations and the wheelbase of the prime mover but also by the overall length of the combination. It should be noted that the difference between best and worst performance is only 20 cm. The worst performance combinations are thus still within the width of a European lane of 3.5 m.

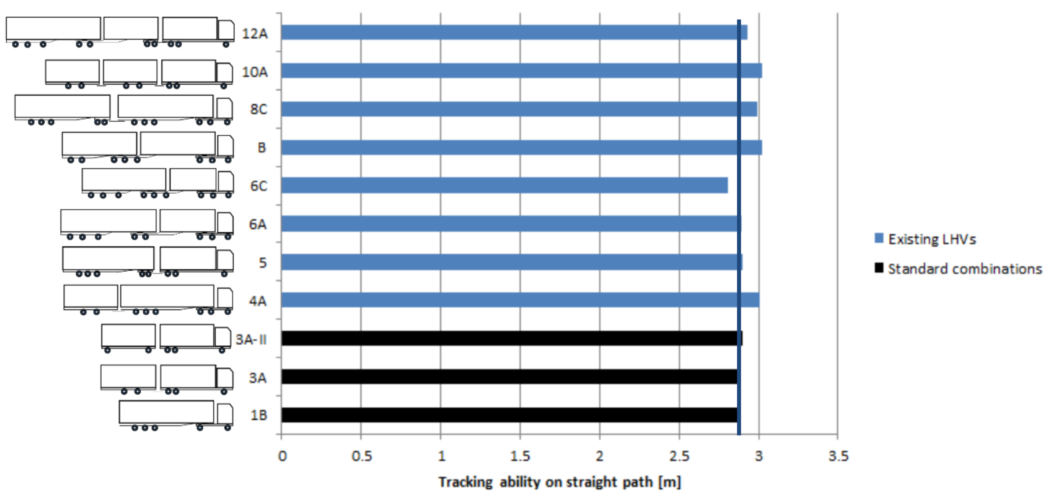


Fig. 6-5 Performance results for tracking ability on straight path per vehicle combination.

Increasing the distance between the axles, increasing the number of axles and decreasing the number of articulation points have a positive effect on the tracking ability of the LHVs.

Rearward amplification
This standard was introduced to manage the safety risk of a rollover of the last trailing unit during avoidance manoeuvres. In general one can expect amplification of the lateral acceleration from the prime mover towards the last trailing unit (as a whip). The manoeuvre is simulated by a single lane change specified in ISO 14791:2000, which is conducted at 88 km/h. The degree to which the trailing units amplify the lateral acceleration of the hauling unit is measured. Higher values represent worse results.

For this PBS concepts 5, 6C and 12A are within the ranges of the standard vehicle combinations. Concept 6A even has better performance. As with the high-speed transient off-tracking PBS, the combinations which use a B module (concepts 6A, 6C and 12A) have a better performance than the other combinations. This is because the amplification of lateral acceleration is coupled with the roll movement of the vehicle, although the distance between the articulation point and the centre of the axle group also plays a role. Hence the vehicles whose last coupling is realised as a drawbar incur the highest value of rearward amplification (10A and 4A).

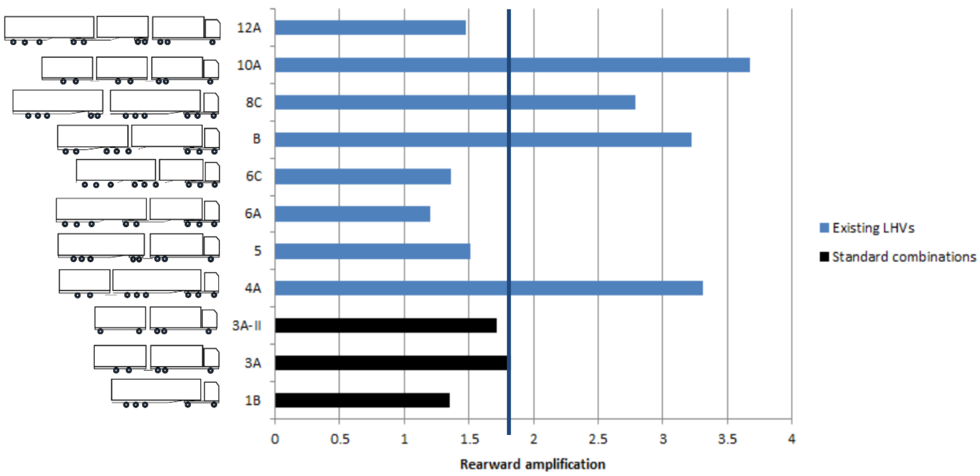


Fig. 6-6 Performance results for rearward amplification per vehicle combination.

The rearward amplification can be decreased with air suspension, roll-coupled modules and a higher roll centre.

Powertrain standards
In this part the PBS startability, maintain speed, maintain motion and acceleration capability are considered. All simulations were done with the vehicles fully loaded.

As the performance of the vehicle powertrain is mainly influenced by the engine characteristics, it should be noted that for the standard vehicles (1B, 3A-I and 3A-II) a 440 horsepower (HP) engine and for the LHVs a 540 HP engine was used. For the standard vehicles the second axle is driven. For the LHVs the second and third axles are driven.

Startability
This standard was introduced to manage the safety risk associated with starting on a grade. The vehicle is fully loaded. The simulation determines the maximum grade from which the vehicle can start and maintain forward motion. The higher the grade, the better the performance. The peak friction coefficient between tyre and road is assumed to be 0.8.

In terms of startability concepts 5 and 10A are able to drive up a steeper slope than the standard vehicle combinations, see *Fig. 6-7*. This relates to the fact that rigid trucks in general obtain better results than tractors due to a better load distribution that ensures sufficient vertical force on the driven wheels. The other combinations have a lower grade for startability. This is because the standard vehicles have 91 kg per HP and the LHVs have 111 kg per HP.

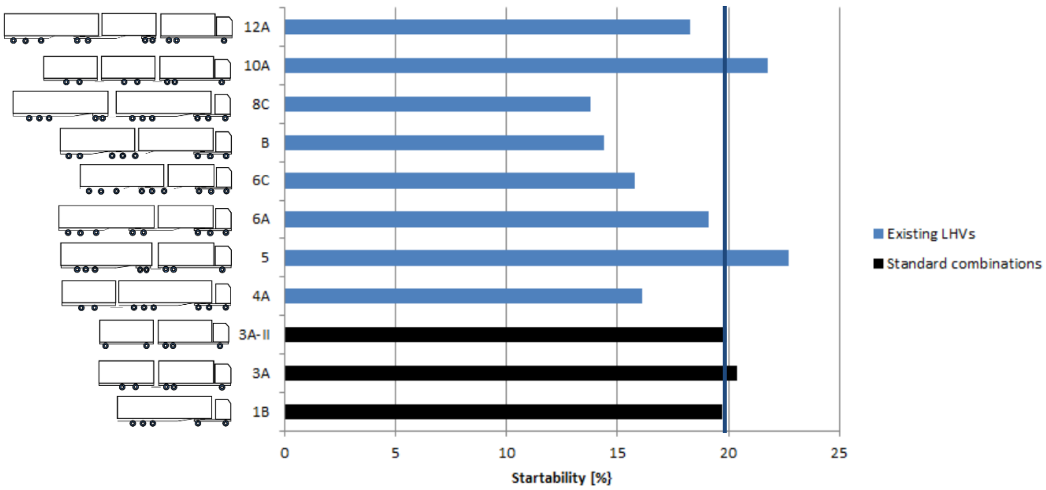


Fig. 6-7 Performance results for startability per vehicle combination.

If the LHVs are to match the performance of the standard vehicles, the number of HP per kg needs to be increased. The number of driven axles and the position of the king pin can also have a positive influence on the startability of the vehicle combinations.

Maintain speed

This standard was introduced to maintain a minimum speed on a specified uphill gradient. The applied gradients are 1% and 1.5%. On these grades the maximum speed in maximum gear is determined.

For a 1% slope it is clear that the standard vehicle combinations have the best performance, see Fig. 6-8. All the other combinations have the same maximum slope, which is lower than the standard vehicle combinations but close in range. For the 1.5% slope concept 3A-II has the best performance, 3A the worst, with the other combinations in-between with the same value. This is because 3A is capable of driving up at a higher gear but at the expense of speed.

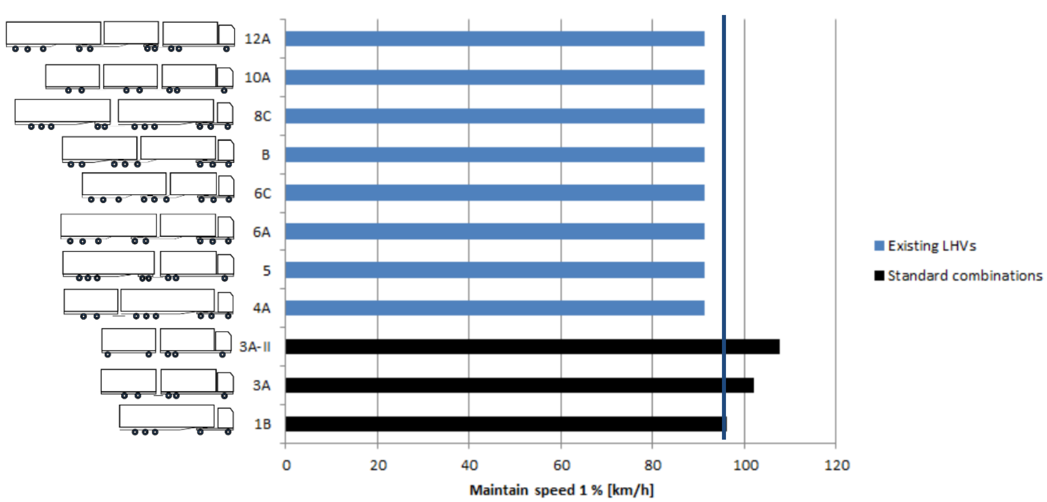


Fig. 6-8 Performance results for maintain speed at 1% slope per vehicle combination.

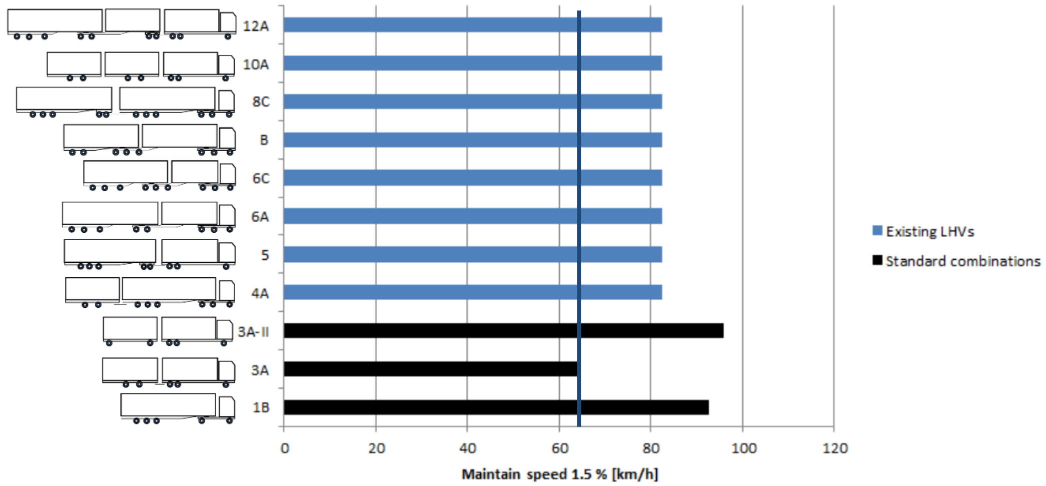


Fig. 6-9 Performance results for maintaining speed on a 1.5% slope per vehicle combination.

The improvements are the same as for startability.

Maintain motion

This standard was introduced to maintain a forward motion on an upgrade. With this the maximum upgrade is determined on which the vehicle can maintain forward motion. The higher the grade, the better the performance.

For this PBS concepts 5 and 10A are in the range of the standard vehicle combinations. The same reasoning applies here. The number of HP per kg has a great influence on this PBS.

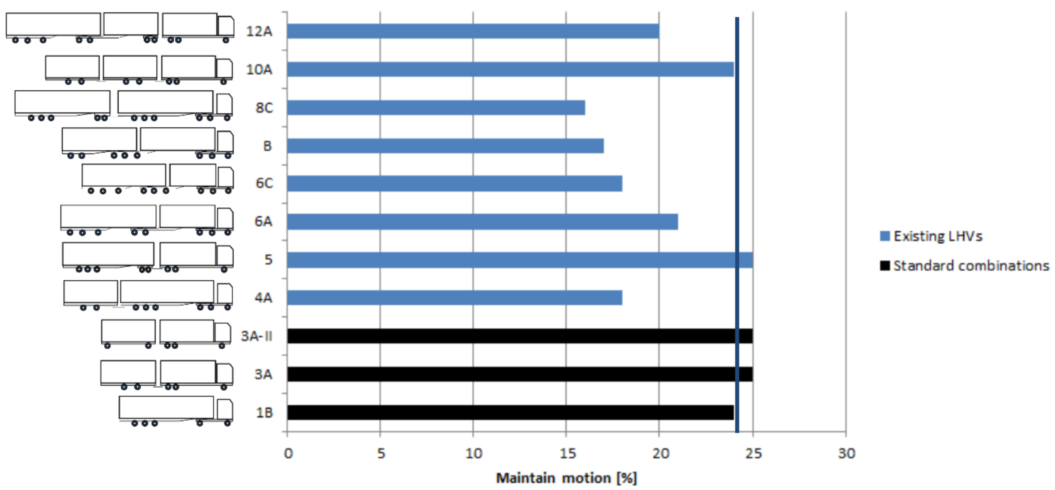


Fig. 6-10 Performance results for maintaining motion per vehicle combination.

Acceleration capability

This standard was introduced to manage the safety risk associated with travel through intersections and rail crossings. The simulation shows how much time it takes to travel 100 m on a flat, straight road. The shorter the time, the better the performance.

In this case all combinations come close to the performance of the standard vehicle combinations. If the performance is to be improved, however, the same improvements as for the other PBS in this group apply.

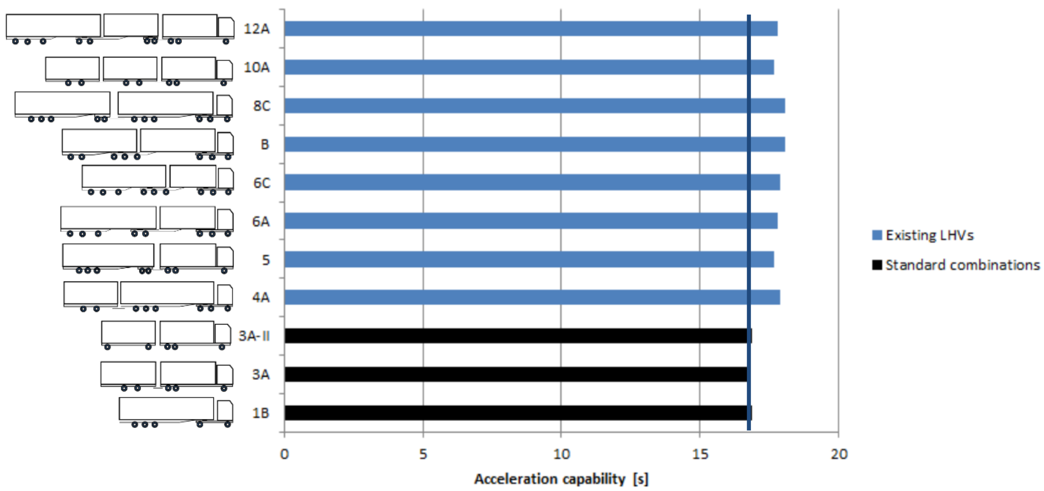


Fig. 6-11 Performance results for acceleration capability per vehicle combination.

Manoeuvrability standards

In this part the PBS low-speed swept path, frontal swing, tail swing, steer tyre friction demand and 360° turn swept path are considered. All simulations are carried out with the vehicles fully loaded and empty. The worst performance per vehicle is taken for the results.

Low-speed swept path

This standard was introduced to manage the safety risk associated with turns at intersections by limiting the road space required by a vehicle when making low-speed turns. The vehicle makes a prescribed 90 degree turn with 12.5 m radius at a speed of no more than 5 km/h. The swept path is measured. The higher the value, the worse the result.

Fig. 6-12 shows that none of the LHV combinations has a performance similar to that of the standard vehicle combinations. This is due to the length and to the number of unsteered axles. Beside this there is a clear interaction between high-speed dynamic standards and manoeuvrability. What is favourable for the dynamic standards (small number of articulations, long distance from articulation point to axle group) is not favourable for manoeuvrability.

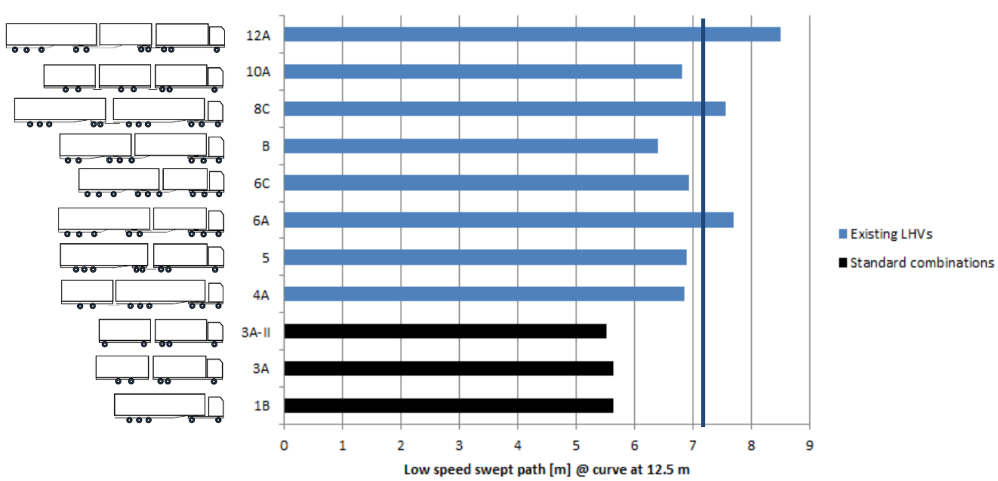


Fig. 6-12 Performance results for low-speed swept path per combination.

The low-speed swept path performance can be improved by active and passive steering systems, increasing the number of articulation points and decreasing the distance between the axles.

Frontal swing

This standard was introduced to manage the safety risk by limiting the road space requirement of a vehicle when making a tight turn at low speed. The vehicle makes a prescribed 90 degree turn with an 8 m radius at a maximum speed of 5 km/h. The frontal swing is measured; the higher the value, the worse the result.

For the frontal swing the performance of all LHVs is in the range of the standard vehicle combinations except for concept 5, see Fig. 6-13. However, this concept too comes close to the range of the standard vehicle combinations. The front overhang between the wheels of the prime mover and the front of the cabin is the most decisive factor. The number of articulations, wheelbase and tyre slip also play a role here. It can also be stated that vehicles with the largest frontal swing usually record lower values for the swept path (with respect to absolute length), as there is a link between the two.

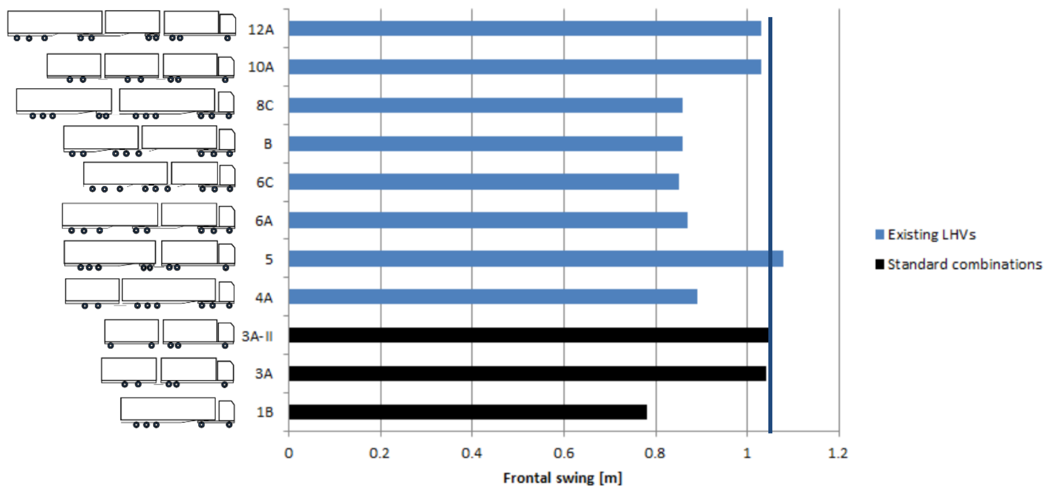


Fig. 6-13 Performance results for frontal swing per vehicle combination.

Tail swing

This standard was introduced to manage the safety risk by limiting the road space requirement of a vehicle when making a tight turn at low speed. The vehicle makes a prescribed 90 degree turn with an 8 m radius at a maximum speed of 5 km/h. The tail swing is measured; the higher the value, the worse the result.

For this PBS all combinations are in the range of the standard vehicle combinations, see Fig. 6-14. The tail swing is influenced mainly by the rear overhang. Here there is a similarity with the previous case in that vehicles with the largest tail swing usually record lower values for the swept path (with respect to absolute length) and vice versa. This is illustrated by concept 1B, which has the worst performance but the second smallest swept path.

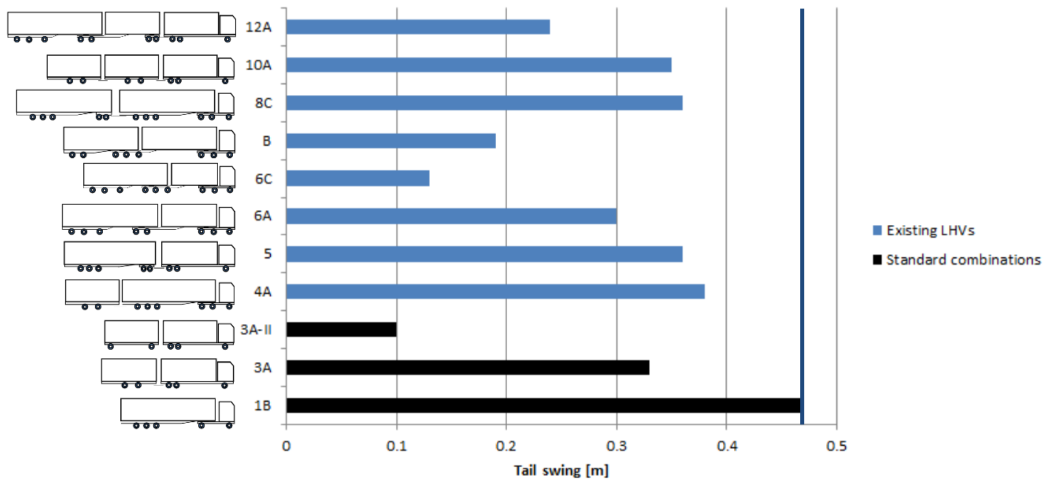


Fig. 6-14 Performance results for tail swing per vehicle combination.

The performance can be further improved by using active and passive steering systems.

Steer tyre friction demand
This standard was introduced to manage the safety risk by limiting the likelihood of a vehicle losing steering control when making a tight turn at low speed. The vehicle makes a prescribed 90 degree turn with an 8 m radius at a maximum speed of 5 km/h. The maximum friction level demand of the steered tyres of the hauling unit is measured. The performance is expressed as a percentage of the maximum available tyre/road friction limit; the higher the value, the worse the result.

Fig. 6-15 shows that concepts 5, B and 8C are in the range of the standard vehicle combinations, but all other combinations too come close to achieving the performance of the standard vehicles. The decisive factor for this PBS is the drag force caused by the side slip of non-steered axles. Here too benefit can be gained from using active and passive steering.

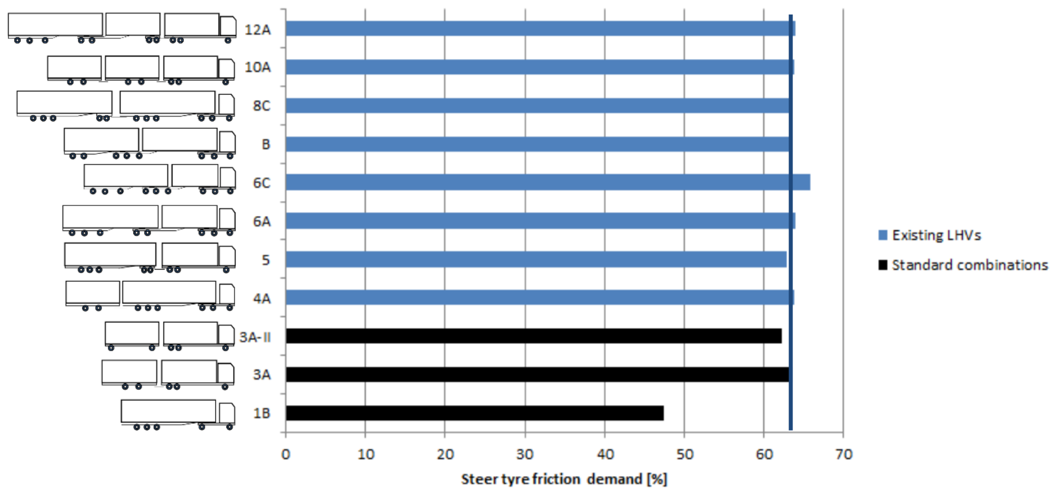


Fig. 6-15 Performance results for steer tyre friction demand per vehicle combination.

360° turn swept path

This simulation was added because a complete 360 degree turn is important in European infrastructure. A complete turn is simulated on a roundabout with an inner radius of 5.3 m and a street width of 7.2 m. These are the dimensions used in the 95/53/EC regulation. This simulation was carried out at a maximum speed of 5 km/h. No active steering is taken into account for the vehicle combinations in order to obtain worst-case performance. The swept path is measured; the higher the value, the worse the result.

Fig. 6-16 shows that the standard vehicle combinations are able to make a complete turn on the roundabout (performance <7.2 m). All other combinations are unable to make the complete turn, or even jackknife like concept 12A. It is clear that this has to do with the length and manoeuvrability problems of the LHVs. It points out the necessity of active steering for any LHV. Research has shown that the swept path can be reduced by more than 60% if an appropriate steer strategy is applied[115]. This would result in a performance which would satisfy the 96/53/EC regulation.

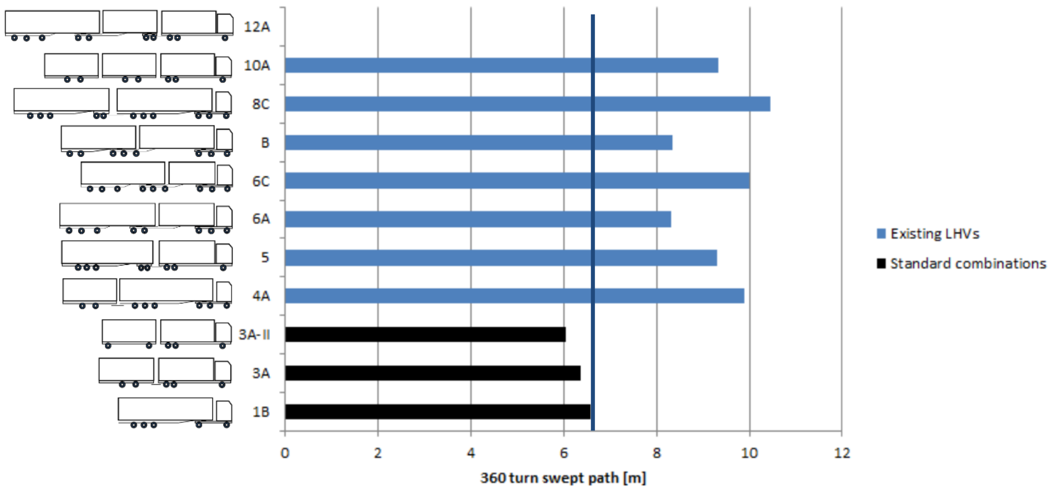


Fig. 6-16 Performance results for 360° turn swept path per vehicle combination.

6.2.2 Infrastructure PBS

The infrastructure PBS assessment consists of: pavement vertical loading, bridge loading, pavement horizontal loading and tyre contact patch pressure. However, the last two will be disregarded. Pavement horizontal loading holds for all combinations, as none of the driven axles exceeds 11.5 tonnes of vertical load. No concrete limits for the tyre road contact pressure are established in European legislation. However, as there are other EU regulations prescribing the tyre properties, it is considered that all tyres which are legally used are satisfactory for this assessment

A short explanation is given per PBS. All simulations are done with a fully loaded vehicle concept.

Pavement vertical loading

This standard was introduced to limit the stress on the pavement layers below the surface of the road. It is determined by the axle loads on the road. The higher the load, the worse the performance.

[115] Kandathil, J. (2012). *Improved command steering for a B-double truck combination.* Eindhoven University of Technology.

Fig. 6-17 shows only the highest axle load per vehicle combination. It shows that all combinations are in the range of the performance of the standard vehicle combinations. Concepts 6C, B, 8C and 12A achieve an even better performance. This is because the LHVs have more axles between which the GCW is divided. The axle loads are lower because of this.

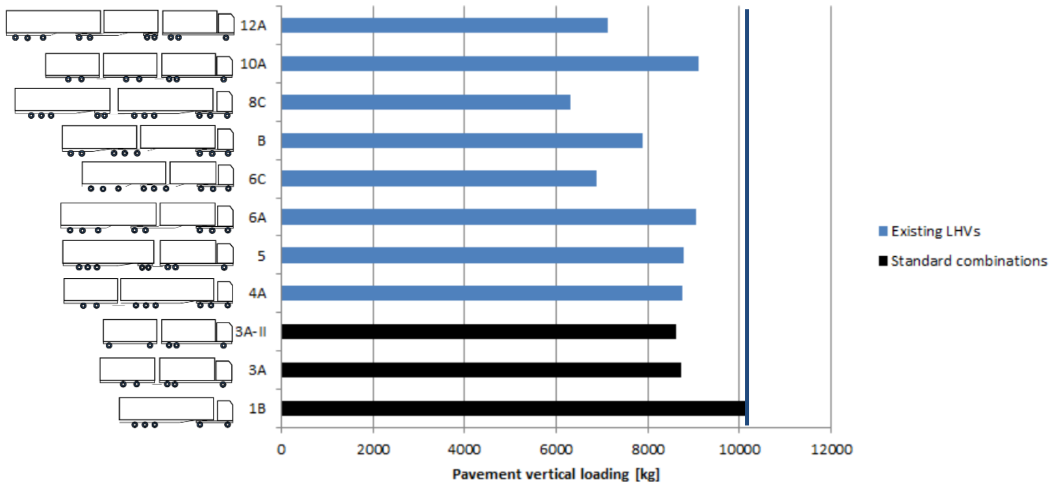


Fig. 6-17 Performance results for pavement vertical loading per vehicle combination.

Bridge loading

This standard was introduced to limit the impact on bridges. An empirical bridge formula from the Australian PBS is used to calculate this effect. As an input the minimum distance between the extreme axles or axle groups is used. From this the total gross mass on the axles within the given distance is determined. The results are used only for comparing the combinations. Further research is needed to define a formula for European bridges.

The results for the bridge loading show that five combinations are in the range of the standard vehicle combinations. The difference between the best and the worst is substantial. However, one can see that the weight and total length of the vehicle do not play a role. This shows that LHVs may have comparable or even better bridge loading than standard vehicle combinations.

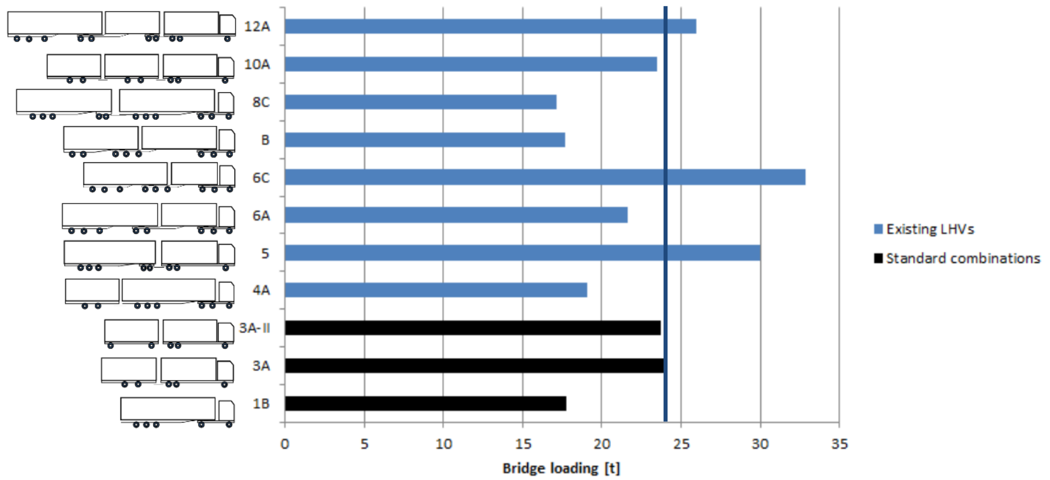


Fig. 6-18 Performance results for bridge loading per vehicle combination.

6.2.3 Additional simulation results

Overtaking provision and side wind tracking ability are simulated as additional results; these do not figure in the PBS assessment but should not be disregarded.

Overtaking provision

This was simulated to manage the safety risk in overtaking a vehicle combination. This standard is in the current PBS but not proposed in the legal framework. This is because overtaking should be taken into account, but not only on the basis of the total length of the vehicle. Now only the total length of the vehicle is taken into consideration as it is difficult to define an approach for the overtaking process.

Fig. 6-19 shows that the length of the vehicle combinations increases from the common standard vehicle combinations to the 12A combination. It is clear that none of the LHVs are in the range of the standard vehicle combinations.

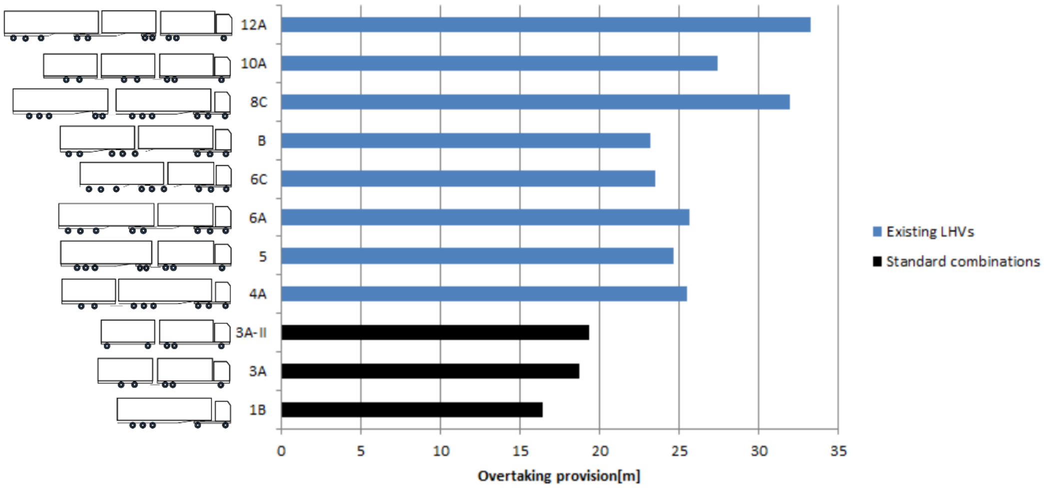


Fig. 6-19 Performance results for overtaking provision per vehicle combination.

Side wind tracking ability

This standard was introduced to manage the safety risk from a side wind during driving. Side wind can influence the driving behaviour dramatically and can even result in vehicle rollover. The swept path of the vehicle is simulated on a banked road with a side wind of 80 km/h which is attacking at an angle of 45 degrees with respect to the driving direction. The combinations are simulated empty and fully loaded. The worst result, which is the highest value, is taken into account.

From Fig. 6-20 it is clear that four combinations are within the range of the standard vehicle combinations and one is close to it. This has first of all to do with the fact that the area subject to the wind is larger in the other combinations. Furthermore, the number of articulations and the wheelbase of the prime mover are of importance.

Improvements for the LHVs for this PBS could be achieved by changing the distance between axles, altering the number of axles or using air suspension. This gives more stability to the vehicle combinations.

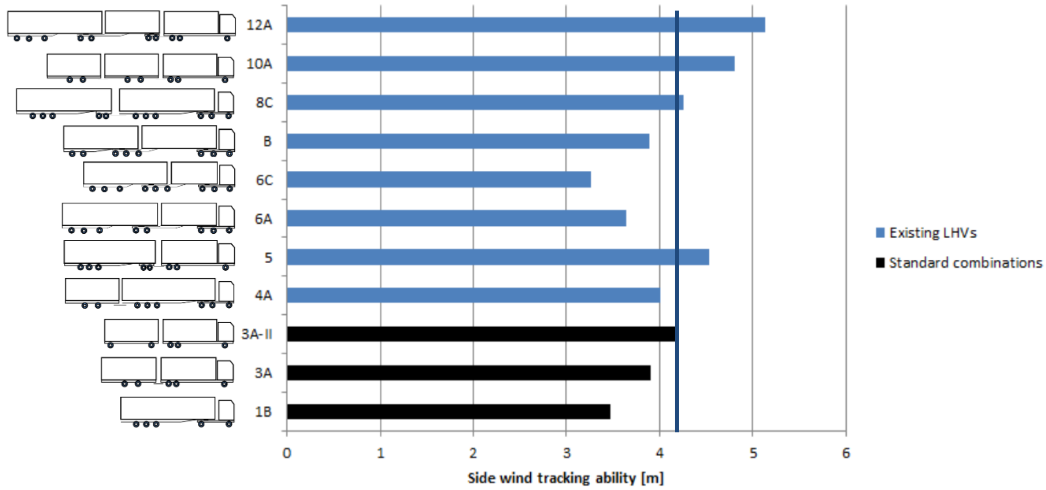


Fig. 6-20 Performance results for side wind tracking ability per vehicle combination.

6.3 Overall performance

In the previous paragraph the performance per PBS group is discussed. From the results it is clear that a combination of a C782 swap body and a 13.6 semi-trailer or a 20 and 40 foot container has the best performance when a set-up like combination 5 or 6 is used. Furthermore, B-modules have proved to be better for the stability and dynamic performance of the trailer.

The results have also shown that the performance of the LHVs is not always in the range of the standard vehicle combinations currently allowed on European roads. This is especially the case during low-speed manoeuvring. As proved by practice, the performance of the current LHVs is sufficient for operating safely in countries like the Netherlands, Sweden and Finland. To bring the performance closer to the range of the standard vehicle combinations technological improvements or changes in technical characteristics are necessary. In the previous paragraph it was already stated which improvements would be suitable per PBS. In Table 6-1 the effects on the different PBS of changes in technical characteristics or addition of technological improvements to a vehicle combination are summarised.

Table 6-1 The effect on the defined PBS of changing technical characteristics or adding technological improvements to a vehicle combination.

PBS / **characteristic**	Static rollover threshold	Directional stability under braking	Yaw damping coefficient	High-speed transient off-tracking	Tracking ability on a straight path	Rearward amplification	Startability	Gradeability	Acceleration capability	Low-speed swept path	Frontal swing	Tail swing	Steer-tyre friction demand	360 turn swept path	Pavement vertical	Pavement horizontal	Tyre contact pressure	Bridge loading	Side wind swept path
Increased engine torque							+	+	+							-			
Increased number of driven axles							+	+	+				+			-			
Increased number of axles	+		+	+	+	+				-				-	+				+
Application of air suspension	+		+	+	+	+													+
Application of braking control technologies		+																	
Increased distance between axles	+		+	+	+	+				-		-	-	-		-			+
Increased number of articulation points		-	-	-	-	-				+			+	+		+			-
Application of active steering axles			+	+	+	+				+		+	+	+		+			
Roll-coupled modules	+		+	+		+													
Increasing roll-centre height	+		+	+		+													+
Increasing the distance between axles and rear end of the trailer												-							
Increasing the length of towing bar			+	+	+														
Increasing the distance from steered axle to front of the cabin											-								
Increasing the distance from king pin to axle centre	+									-				-				+	

+ Positive influence

- Negative influence

7 Clean vehicle combination validation

In this chapter vehicle combinations are validated on clean transport. Clean transport is considered as CO_2-efficient transport. CO_2 emission is directly proportional to the fuel consumption. First the tool used to obtain the fuel consumption is explained in paragraph 7.1. Secondly, the results are given and the transport combinations are compared.

7.1 Fuel consumption tool

First, the fuel consumption per vehicle combination is calculated to obtain the CO_2 emission results. For the fuel calculation a MATLAB/Simulink model is used which takes into account longitudinal dynamics of vehicle combinations. A schematic of the tool is shown in Fig. 7-1. It consists of multiple processes which need different inputs for calculation.

For the route process the height profile, surface, velocity profile and stops need to be given. With respect to the driver process the starting condition, simulation step size, air temperature and air pressure are of importance. To run the engine process the engine specifications are needed. For the gearbox the ratios, efficiency and moment of inertia are used as inputs. For the axles the ratios, efficiency, moment of inertia, axle configuration and axle loads are also needed. The wheel process requires the wheel dimensions, resistance and moment of inertia. Lastly, for the resistance process the frontal area and drag coefficient are required.

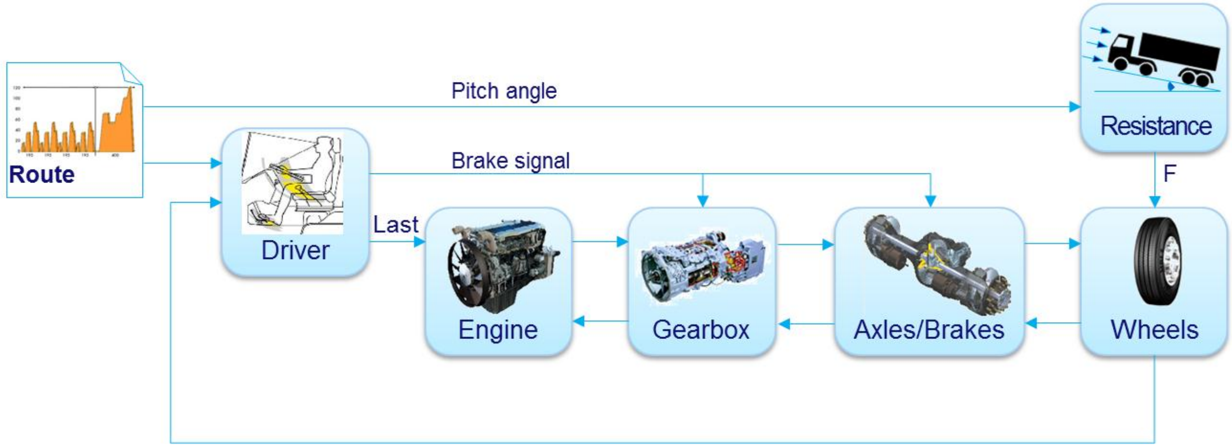


Fig. 7-1 Schematic of fuel consumption tool.

7.2 Simulation results

In this paragraph the assumptions for the calculations and the results of the fuel calculations are shown. Furthermore the CO_2 emission values based on the fuel calculations are presented.

Assumptions for calculations

All simulated vehicle combinations are based on technical specifications from which the inputs are defined in paragraph 7.1. This leaves only the route and the axle loads. For the axle loads the total weight of the vehicle combination is necessary.

Furthermore, for the fuel and CO_2 calculations the results are stated with respect to both weight and volume. For this too the vehicle weight is needed. The volume of freight is also of importance. The route, weight of the vehicle and volume of the freight are therefore explained in detail in this section.

Route
For the fuel simulation two routes are used. The first route goes from Munich to Leipheim in Germany over a distance of 102 km. This cycle is used for long-haul tests by MAN. The second route is an ACEA route for long-haul transport and has a total length of 108 km. In a few years' time this route will be used to measure and compare all trucks independent of the manufacturer. For these two routes the average fuel consumption is determined.

Weight
The axle loads depend on the tare weight of the vehicle combinations and the load of the freight (payload). The payload is determined by the tare weight subtracted from the GCW. In current transport the weight utilisation of vehicle combinations is 57% of the maximum allowed payload.[116] This value is valid only for the standard vehicle combinations.

The load distribution for LHVs is calculated from Table 7-1. For the standard vehicle combinations two types of combinations are considered: articulated vehicle (1B) and road train (3A-I). Starting from the weight utilisation of 57% the average payload is determined. From this the kilograms of average payload per square meter (based on length and width) of the container space are calculated for the standard vehicle combinations.

In the long-haul segment the shares of articulated vehicles and road trains are 86% and 14% respectively.[117] Based on these values an average weight utilisation of 423.22 kg/m^2 is determined. With this value the average payloads of the LHVs and the standard road train are determined. The utilisation is calculated as a percentage by dividing the average payload by the maximum payload.

Table 7-1 Weight utilisation of vehicle combinations.

Combination	Tare weight	Max GCW	Max payload	Average payload	Average GCW	Utilisation	
	[kg]	[kg]	[kg]	[kg]	[kg]	[kg/m^2]	[%]
1B	13817	40000	26183	14924	28741	441.84	57
3A	19279	40000	20721	16187	35466	423.22	78
13	18245	40000	21755	8921	27166	423.22	41
14	18725	40000	21275	13915	32640	423.22	65
15	13219	26000	12781	8093	21312	423.22	63
4A	21735	60000	38265	22389	44123	423.22	59
5	21953	60000	38047	22389	44341	423.22	59
6A	24415	60000	35585	22389	46803	423.22	63
6C	26305	60000	33695	17517	43822	423.22	52
B	29765	60000	30235	17843	47608	423.33	59
8C	30725	60000	29275	27830	58555	423.22	95
10A	25123	60000	34877	24280	49403	423.22	70
12A	30693	60000	29307	29307	60000	423.22	100

[116] Akerman, I., & Jonsson, R. (2007). *European Modular System for road freight transport - experiences and possibilities.* Stockholm: TFG.

[117] Based on MAN sale volumes for long haul

Volume

For the volume the same approach is taken as for the weight. Here, however, the utilisation of standard trucks with respect to volume is on average 82%. Again, based on this 82% the average volume of the standard vehicle combinations (1B and 3A-I) is determined. With the 86% to 14% split between articulated vehicles (1B) and road trains (3A-I) the value of 2.1 m^3 of freight per m^2 of container area is determined. The volume-related utilisation values are shown in Table 7-2.

Table 7-2 Volume utilisation of vehicle combinations.

Combination	Max volume	Average volume	Utilisation	
	[m^3]	[m^3]	[m^3/m^2]	[%]
1B	87	71	2,11	82
3A	96	80	2,10	84
13	56	44	2,10	79
14	84	69	2,10	82
15	48	39	2,10	82
4A	135	111	2,10	82
5	135	111	2,10	82
6A	135	111	2,10	82
6C	99	87	2,10	88
B	113	89	2,10	79
8C	169	138	2,10	82
10A	144	121	2,10	84
12A	183	152	2,10	83

Results

As stated before, the results are shown in terms of both weight and volume. These results are shown in Table 7-3 and Table 7-4 respectively. The average fuel consumption and CO_2 emission are the same for both tables.

The average fuel consumption is a direct result of the simulation tool. The number of litres of diesel used per 100 km is known for both routes, and the average of the two is taken. The CO_2 emission is determined using its proportional relationship to the fuel consumption. From DIN EN 16258 it is known that the CO_2 emission from tank to wheel is 2.67 kg CO_2/l.[118]

Based on the payload calculations in Table 7-1 the weight-related emission is expressed in grams CO_2 per tonne payload per km travelled. This is shown in Table 7-3 by comparing the standard vehicle combinations with the existing LHVs. It can be concluded that almost all LHVs have a better tonne per km performance. Only combinations 6C and B exceed the range of the standard vehicle combinations. This is due to the higher tare weight, which results in a smaller payload.

With respect to the volume-related performance the results are shown in grams CO_2 per m^3 freight per km travelled. This is shown in Table 7-4. Here the same conclusion can be drawn as for the weight-related results: almost all LHVs have a better m^3 per km performance. Only combinations 6C and B exceed the range of the standard vehicle combinations. This is due to the lower volume of the loading units.

[118] DIN EN 16258:2013-03

Table 7-3 Weight-related fuel consumption and CO_2 emission results.

Combination	Average fuel consumption	CO_2 emission	Payload	Gram CO_2 per tonne payload per km travelled
	[l/100km]	[g/km]	[ton]	[g/tkm]
1B	29.76	794.50	14.92	53.24
3A	34.06	909.31	16.19	56.18
13	29.76	794.50	8.92	89.07
14	34.30	915.85	13.92	65.82
15	24.73	660.38	8.09	81.60
4A	41.86	1117.58	22.39	49.92
5	42.50	1134.79	22.39	50.69
6A	43.74	1167.86	22.39	52.16
6C	42.16	1125.67	17.52	64.26
B	44.41	1185.85	17.84	66.46
8C	51.82	1383.67	27.83	49.72
10A	46.12	1231.48	24.28	50.72
12A	53.62	1431.77	29.31	48.85

Table 7-4 Volume-related fuel consumption and CO_2 emission results.

Combination	Average fuel consumption	CO_2 emission	Volume of freight	Gram CO_2 per m^3 freight per km travelled
	[l/100km]	[g/km]	[m^3]	[g/m^3km]
1B	29.76	794.50	71.32	11.14
3A	34.06	909.31	80.46	11.30
13	29.76	794.50	44.35	17.91
14	34.30	915.85	69.17	13.24
15	24.73	660.38	39.31	16.80
4A	41.86	1117.58	111.29	10.04
5	42.50	1134.79	111.29	10.20
6A	43.74	1167.86	111.29	10.49
6C	42.16	1125.67	87.07	12.93
B	44.41	1185.85	88.69	13.37
8C	51.82	1383.67	138.34	10.00
10A	46.12	1231.48	120.69	10.20
12A	53.62	1431.77	151.52	9.45

7.3 Comparison of use cases

To interpret the data a valuable comparison must now be made. Comparing the combinations one to one does not correspond to how LHVs will be used in practice. One LHV will not replace one standard vehicle. It is therefore determined how each LHV will replace the standard vehicle combinations. This is shown in Table 7-5.

Table 7-5 Replacement of standard vehicles by LHVs.

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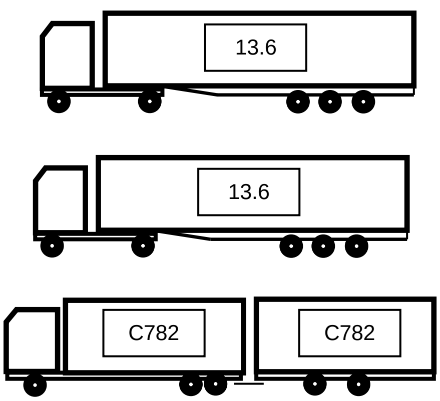
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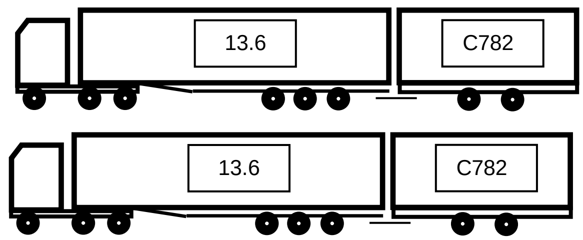
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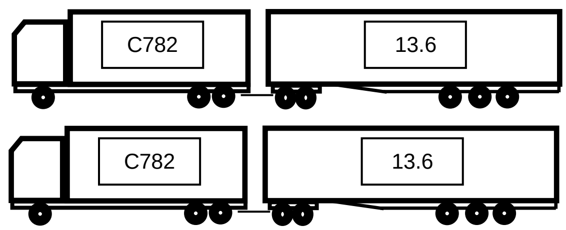
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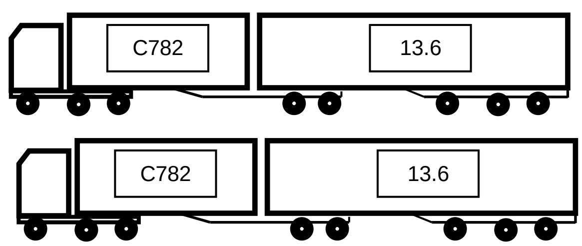
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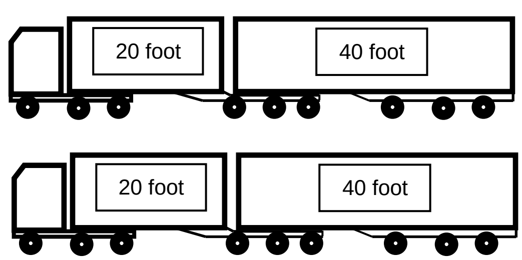
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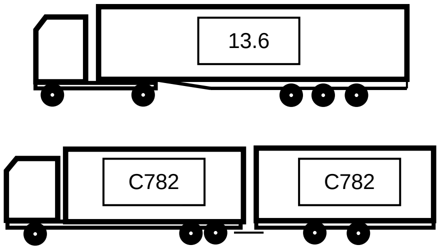
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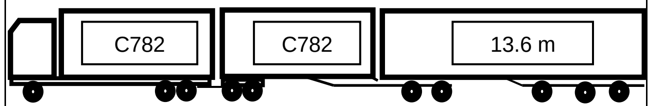
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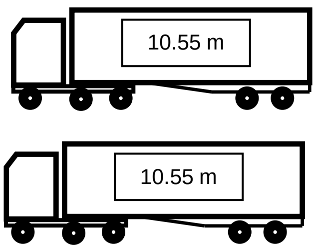
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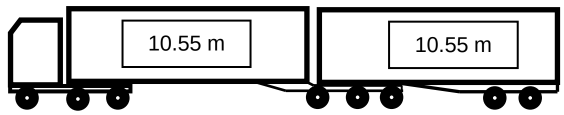
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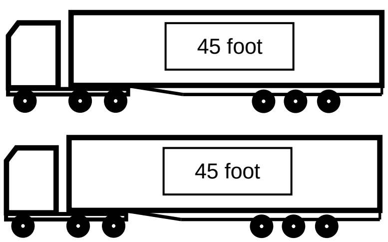
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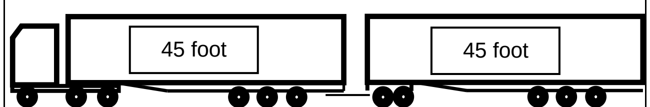
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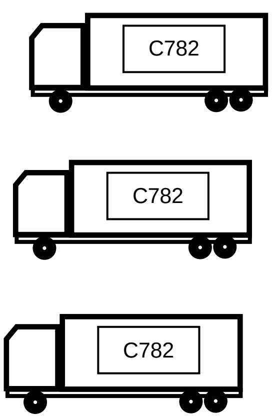
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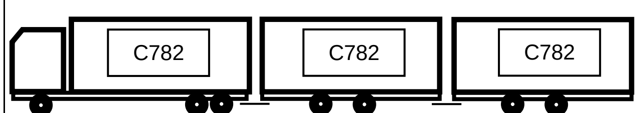
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Based on the comparison of use cases CO_2 emission is again expressed in terms of mass and volume. The results of these calculations are shown in Table 7-6 and Table 7-7 respectively.

For the weight-related comparison Table 7-6 shows that the CO_2 emission is improved for almost all use cases. The only exception is the replacement by two times combination 6C. This has a negative potential due to the higher weight of the loading units, which results in a lower payload.

It can also be concluded that combinations of the same loading units are the cleanest (1B, 8C and 10A). Here the potential is between 24 and 38%. For replacement with different loading units the potential is between 4 and 11%.

Table 7-6 CO_2 emission results per use case - weight-related.

Use case	Fuel consumption	CO_2 emission	Payload	Gram CO_2 per tonne payload per km travelled	Potential
	[l/100km]	[g/km]	[ton]	[g/tkm]	
2x 1B + 1x 3A	**93.57**	**2498.31**	**46.04**	**54.27**	
2x 4A	83.71	2235.16	44.78	49.92	8.02
2 x 5	85.00	2269.58	44.78	50.69	6.60
2x 6A	87.48	2335.72	44.78	52.16	3.88
2x 6C	84.32	2251.34	35.03	64.26	-18.41
1x 1B + 1x 3A	**63.81**	**1703.81**	**31.11**	**54.77**	
1 x 12 A	53.62	1431.77	29.31	48.85	10.79
2 x 13	**59.51**	**1589.00**	**17.84**	**89.07**	
1 x B	44.41	1185.85	17.84	66.47	25.37
2 x 14	**68.60**	**1831.70**	**27.83**	**65.82**	
1x 8C	51.82	1383.67	27.83	49.72	24.46
3x 15	**74.20**	**1981.15**	**24.28**	**81.60**	
1 x 10A	46.12	1231.48	24.28	50.72	37.84

For the volume-related comparison Table 7-7 gives the same overall results as the weight-related comparison. Here also the CO_2 emission is improved in all use cases except replacement by two times combination 6C. The potential of combinations of the same loading units is again between 24 and 39%. For replacement with different loading units this potential is between 6 and 16%.

Table 7-7 CO_2 emission results per use case - volume-related.

Use case	Fuel consumption	CO_2 emission	Volume of freight	Gram CO_2 per m^3 of freight per km travelled	Potential
	[l/100km]	[g/km]	[m^3]	[g/m^3km]	
2x 1B + 1x 3A	**93.57**	**2498.31**	**223.10**	**11.20**	
2x 4A	83.71	2235.16	222.57	10.04	10.32
2 x 5	85.00	2269.58	222.57	10.20	8.94
2x 6A	87.48	2335.72	222.57	10.49	6.29
2x 6C	84.32	2251.34	174.15	12.93	-15.45
1x 1B + 1x 3A	**63.81**	**1703.81**	**151.78**	**11.23**	
1 x 12 A	53.62	1431.77	151.52	9.45	15.82
2 x 13	**59.51**	**1589.00**	**88.69**	**17.92**	
1 x B	44.41	1185.85	88.69	13.37	25.37
2 x 14	**68.60**	**1831.70**	**138.34**	**13.24**	
1x 8C	51.82	1383.67	138.34	10.00	24.46
3x 15	**74.20**	**1981.15**	**117.94**	**16.80**	
1 x 10A	46.12	1231.48	120.69	10.20	39.26

8 Profitable vehicle combination validation

In this chapter the vehicle combinations are validated on profitable transport. For this the approach of Total Cost of Ownership is used. “Total Cost of Ownership is an estimation of all direct and indirect costs associated with an asset or acquisition over its entire life cycle.”[119] As such it gives an overview not only of the initial costs but also of all aspects of usage.

First the Total Cost of Ownership approach and the calculator are explained. Second results are given and the transport combinations are compared.

8.1 Total Cost of Ownership

Total Cost of Ownership (TCO) is a full-cost accounting methodology where all costs incurred by the customer in running his business are taken into account. As a result the costs per a defined base (e.g. year, operating day, kilometre, tonne-kilometre) for the customer's usage period can be calculated. In this way the operating companies obtain clear information about the composition of their transport costs and some idea of the required minimum price to charge for transporting freight.

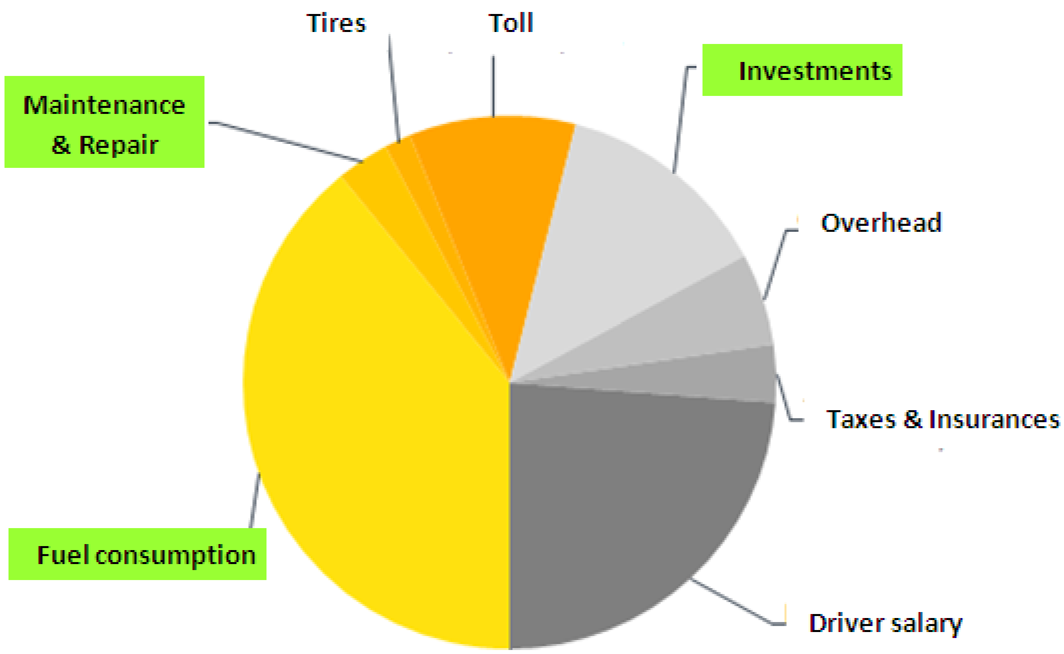


Fig. 8-1 Exemplary Total Cost of Ownership composition of a heavy duty vehicle.

[119] http://www.businessdictionary.com/definition/total-cost-of-ownership-TCO.html, visited on 26-03-2014.

8.1.2 TCO approach

The TCO calculation is a way of calculating the costs for a vehicle or a complete fleet as well as comparing different vehicles and business models. Different cost elements are taken into account; they can be allocated to seven main groups:

- Investment
- Taxes & Insurance
- Administration & Overhead
- Driver Salary
- Fuel & AdBlue Consumption
- Repair & Maintenance incl. Tyres
- Tolls & Fees

Apart from the cost elements some base data are integrated in the calculation to describe the kind of business or application; these include duration of the useful life, mileage, vehicle utilisation, number of loadings per day and operating days.

Depending how TCO is compared, different cost classifications are possible. For comparing different usages of the same or similar vehicles cost categories with a differentiation between fixed costs and variable costs are necessary. Fixed costs are costs that are dependent only on the useful life, whereas variable costs are mileage-dependent.

Table 8-1 Cost categories.

Fixed costs (Useful life dependency)	**Variable costs (Mileage dependency)**
Investment Taxes & Insurance Administration Driver	Fuel & AdBlue Consumption Repair & Maintenance (incl. Tyres) Tolls & Fees

For a comparison of different vehicles with the same use case it is helpful to take a closer look at the cost dependencies. The cost dependencies can be divided into three classes. First there are independent costs, which are the same for every vehicle and customer in the same line of business. Second there are manufacturer-dependent costs, which differ according to the choice of the product, and third the customer-dependent costs, which are highly dependent on the way the customer runs his business. Some cost elements, especially the operating costs, are dependent on both the manufacturer and the customer because they are influenced on the one hand by the technology and on the other hand by the way of utilisation.

Table 8-2 Cost dependencies.

<table>
<tr><th>Independent costs</th><th>Manufacturer-dependent costs</th><th>Customer-dependent costs</th></tr>
<tr><td rowspan="2">Taxes & Insurance
Tolls & Fees</td><td>Investment</td><td>Driver
Administration</td></tr>
<tr><td colspan="2">Fuel & AdBlue Consumption
Repair & Maintenance (incl. Tyres)</td></tr>
</table>

For a proper comparison not only the relevant data is important but also the premises, as most of the costs are country-specific. Comparisons made without knowing the boundary conditions are therefore not meaningful, i.e. a comparison should be based on the same premises.

8.1.3 TCO calculator

To obtain the TCO an Excel-based calculator is used which can take into account all relevant data. The results can be shown based on different factors such as costs per year or operating day or, with knowledge of the utilisation rate and number of loadings per day, as cost per tonne-kilometre.

Non-vehicle-specific fixed costs like taxes, insurance, driver salaries and administration costs are taken from publications or current market prices. Vehicle and vehicle-combination-specific costs are calculated according to the current market conditions.

8.2 Simulation results

In this paragraph the assumptions for the calculations and the results of the TCO calculations are shown.

Assumptions for calculations

All simulated vehicle combinations are based on the technical specifications, the defined mass and volume utilisations and the calculated fuel consumption rates. With this data and the remaining business model all cost elements can be defined.

The first part, the base data, defines the technical boundaries like type and model, payload and toll-relevant input like emission class and number of axles. These data are based on datasheets and technical specifications.

The fixed and variable cost elements – investment, maintenance and repair contract as well as tyres – are vehicle-combination-specific and based on typical market prices. Taxes and insurance too are dependent on the combination, but only on the number of trailers and dollies. By contrast, administration, driver training, driver wages and telematics as well as the fuel prices are constant cost elements for all vehicle combinations.

For comparing the same business model a typical route for intermodal transport needs to be chosen. A route from the port of Rotterdam to the destination Wolfsburg with toll fees in the Netherlands and Germany was therefore chosen. On this tour the vehicle drives for 96% of the trip on motorways, clocking up a yearly mileage of about 135,000 km with a useful life of 48 months with the first owner.

Results

The Total Costs of Ownership are shown in four different ways. First the costs are calculated independently of the utilisation as costs per year and per kilometre. In this way only the additional costs for the combinations are noticeable: i.e. a comparison on this base is not meaningful.

For a first comparison of the vehicle combinations it is necessary to break down the TCO by utilisation in relation to weight and volume, as the longer and heavier vehicle combinations are able to transport more goods than a standard vehicle.

Table 8-3 Weight-related Total Cost of Ownership.

Combination	TCO per year	TCO per km	Payload	Average utilisation	TCO per tonne payload per km travelled
	[€/year]	[€/km]	[ton]	[%]	[Ct/tkm]
1B	154,876.53	1.147	14.924	57.0	7.687
3A	164,761.61	1.220	16.187	78.1	7.542
13	164,576.22	1.219	8.921	41.0	13.668
14	171,136.48	1.268	13.915	65.4	9.111
15	140,646.57	1.042	8.093	63.3	12.877
4A	190,718.66	1.413	22.388	58.5	6.311
5	192,995.38	1.430	22.388	58.8	6.390
6A	195,747.53	1.450	22.388	62.9	6.478
6C	195,027.73	1.445	17.517	52.0	8.245
B	202,366.46	1.499	17.843	59.0	8.403
8C	217,508.71	1.611	27.830	95.1	5.787
10A	197,588.54	1.464	24.280	69.6	6.029
12A	220,966.42	1.637	29.307	100.0	5.585

Table 8-4 Volume-related Total Cost of Ownership.

Combination	TCO per year	TCO per km	Volume of freight	Average utilisation	TCO per m^3 freight per km travelled
	[€/year]	[€/km]	[m^3]	[%]	[Ct/m^3km]
1B	154,876.53	1.147	71.321	82.0	1.609
3A	164,761.61	1.220	80.459	83.9	1.517
13	164,576.22	1.219	44.345	78.6	2.751
14	171,136.48	1.268	69.169	82.1	1.832
15	140,646.57	1.042	39.312	82.0	2.650
4A	190,718.66	1.413	111.287	82.5	1.269
5	192,995.38	1.430	111.287	82.5	1.284
6A	195,747.53	1.450	111.287	82.5	1.303
6C	195,027.73	1.445	87.074	88.1	1.659
8C	217,508.71	1.611	138.337	82.1	1.164
10A	197,588.54	1.464	120.688	83.9	1.213
12A	220,966.42	1.637	151.516	82.9	1.080
B	202,366.46	1.499	88.691	78.6	1.691

A comparison of the standard vehicle combinations with the existing LHVs shows that all combinations are as profitable as the standard combinations or even more profitable. For combination 6C a higher tare weight of the containers combined with a lower volume (compared to the loading units of 6A) leads to an increase in the TCO. Similarly, for combination B, the higher investments and a lower payload result in higher TCO than with the other combinations. Even with these restrictions combinations 6C and B are within the range of the standard vehicle combinations.

8.3 Comparison of use cases

To interpret the data a valuable comparison for profitable transport like that for clean transport must be made. Therefore the same method is used: comparing the combinations one by one is not how LHVs will be used in practice. One LHV will not replace one standard vehicle. Again the replacement of standard vehicles by LHV's shown in Table 7-5 is applied.

Based on the comparison of use cases TCO is again expressed in terms of mass and volume. The results of these calculations are shown in Table 8-5 and Table 8-6 respectively.

Table 8-5 Total Cost of Ownership per use case - weight-related.

Use case	Payload	TCO per tonne payload per km travelled	Potential
	[ton]	[Ct/tkm]	
2x 1B + 1x 3A	**46.04**	**7.635**	
2x 4A	44.78	6.311	17.34%
2 x 5	44.78	6.390	16.31%
2x 6A	44.78	6.478	15.16%
2x 6C	35.03	8.245	-7.99%
1x 1B + 1x 3A	**31.11**	**8.719**	
1 x 12 A	29.31	5.585	26.61%
2 x 13	**17.84**	**13.668**	
1 x B	17.84	8.403	38.52%
2 x 14	**27.83**	**9.111**	
1x 8C	27.83	5.787	36.48%
3x 15	**24.28**	**12.877**	
1 x 10A	24.28	6.029	53.18%

For the weight-related comparison Table 8-5 shows that the TCO improves for all use cases. Replacement of different standard trucks by a longer and heavier truck using different loading units yields a TCO improvement of about 15 to 20%, in exceptional cases even up to 27%. Splitting and combining the same loading units on a longer and heavier truck makes it possible to improve the TCO by up to 35 to 40%. In exceptional cases, e.g. for combination 10A, an improvement of even 53% is possible, as here only one combination is needed instead of three vehicles.

Table 8-6 Total Cost of Ownership per use case – volume-related.

Use case	Volume of freight [m^3]	TCO per m^3 freight per km travelled [Ct/m^3km]	Potential
2x 1B + 1x 3A	**223.10**	**1.575**	
2x 4A	222.57	1.269	19.44%
2 x 5	222.57	1.284	18.48%
2x 6A	222.57	1.303	17.32%
2x 6C	174.15	1.659	-5.30%
1x 1B + 1x 3A	**151.78**	**1.560**	
1 x 12 A	151.52	1.080	30.78%
2 x 13	**88.69**	**2.751**	
1 x B	88.69	1.691	38.52%
2 x 14	**138.34**	**1.832**	
1x 8C	138.34	1.164	36.45%
3x 15	**117.94**	**2.650**	
1 x 10A	120.69	1.213	53.23%

Table 8-6 shows the volume-related comparison of the TCO. Again a TCO improvement can be detected for nearly all longer and heavier combinations.

For the use of different loading units there is a saving potential of 17 to 30%. Depending on the loading units even a deterioration is possible because of the use of payload-optimised loading units, which have a poorer volume-related performance.

Combination of identical loading units on a longer and heavier vehicle again leads to TCO improvements of 35 to 40%. With the focus on volume-optimised loading, units like combination 10A even have a potential for saving more than 50% of TCO.

As the results show, it is very important to choose the right loading units and the right vehicle combination if optimised TCO is to be achieved. This choice depends on the transport task and whether the focus is on mass or volume. In this way profitability can be improved by up to 50%.

9 Proposal for future vehicle concepts

In the preceding chapters the requirements from a logistics and environmental point of view have been analysed. A large number of vehicle combinations have been examined to evaluate their contribution to smart, clean and profitable transport. Beside this, ideas for a performance-based legal framework have been laid down. In this chapter a number of future concept vehicles, which meet these various requirements will be presented. The future concept vehicles should be considered as possible solutions, i.e. potential candidates for long-distance road transport within Europe. It is not the intention in this chapter to prescribe “the” exact future truck combination as a PBS-based framework allows innovation and many alternative solutions are possible.

9.1 General trends

Generally speaking, the future vehicle concepts should evolve from the current longer and heavier vehicle combinations, which were discussed in previous chapters. They should emphasise strong points and eliminate or improve the weak points in the performance. The vehicle concepts should be designed so that their length allows accommodation of multiple loading units, which will be preferred and popular in the future and allows them to be both modular and intermodal. With respect to modularity the loading units should be also interchangeable. This means that vehicle combinations should be composed in a way which allows the loading unit to be accommodated on any vehicle; this will lead to optimisation of the logistic process.

It will clearly result in elongation of the vehicles, a trend that is already present in the commercial-vehicle sector (see Fig. 9-1). However, longer mono-volume vehicles are still restricted by legislation; although they are easier to maintain and operate at distribution hubs than multiples of smaller units with equal capacity.

Fig. 9-1 Example of elongated semi-trailer.[120]

Furthermore for the future towed vehicles a balance needs to be found between the number of active elements and required vehicle performance, as their application in the transport market might be very difficult due to the initial investment and maintenance price accounted for the fleet owners.

As specified in the previous chapters, the 45 foot container and 745 swap body are seen as the loading units of the future. The maximum axle loads as prescribed by current legislation should not be exceeded, and the gross vehicle weight for the average utilisation as specified in previous chapters should not be more than 60 tonnes.

The intention is to specify the future concepts for both tractor and rigid truck in accordance with the matrix in Table 9-1.

[120] www.scania.com

Table 9-1 Loading unit vs. towing vehicle.

	tractor	rigid truck
45 foot container	2x 45 foot loading units	45 foot rigid truck with 45 foot loading unit
C745 Swap-body	-	C745 rigid truck with 2x C745 loading units(s)

In addition more attention should be given to aerodynamics, which will not be invasive in low speed manoeuvring, but provide reasonable reduction of air drag during long-haul operation. These devices may include:

Foldable Boat Tail – a device with a length of 1.25m in length at the back of the last vehicle is assumed. It opens only at high velocity and hence, as depicted in Fig. 9-2, does not influence the low-speed manoeuvrability and the tail swing.

Fig. 9-2 Example of foldable boat tail[121] and air inflated boat tail.[122]

Longer Cabin – the elongation of the prime mover's cabin will contribute not only to reduction of the air drag, but also increases the crash zones of the vehicle, which potentially results in safer vehicle. Besides that more space can be devoted to the driver comfort as well as packaging of necessary components (e.g. systems for emission reduction), which are nowadays problematic to accommodate in conventional cabin shape. If the elongation of the cabin is done properly and under suitable radius of the frontal cabin tip, it has no influence on the frontal swing of the vehicle combination during low speed manoeuvring. Both, the cabin and the graphical representation of available space during 12.5 m radius is depicted on the Fig. 9-3.

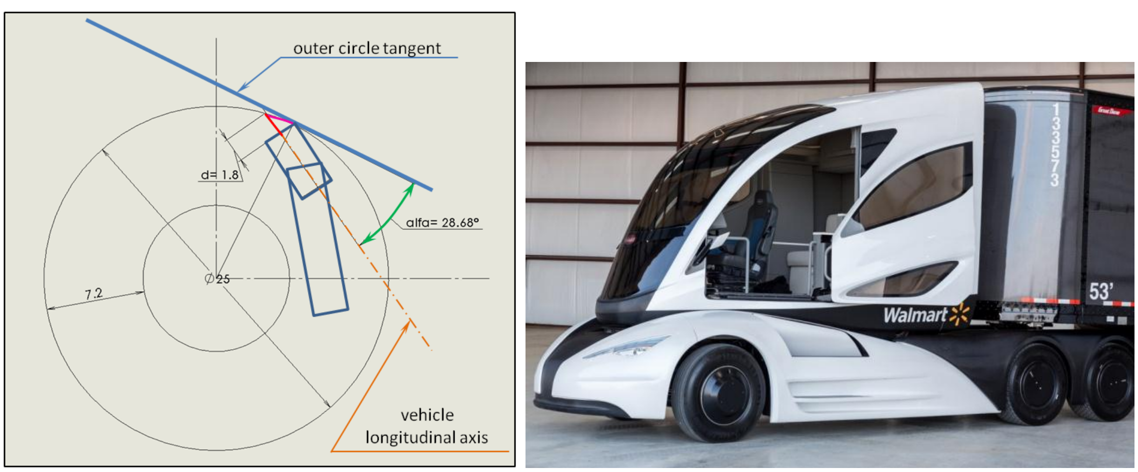


Fig. 9-3 Example of a longer and more aerodynamic cabin.[123]

[121] www.atdynamics.com/trailertail.htm
[122] www.aeroevolution.com

9.2 Future concept vehicles

On the basis of all the above-mentioned requirements we have specified 3 future concepts that will positively influence fuel consumption and emissions per unit of weight and volume.

Future Concept I – Swap-body Combo

Since use of the C-series swap-body is predicted to increase in the future Europe due to the high floor utilisation percentage and good interchangeability with a normal 20 foot container, one future concept has been designed to carry these types of loading units. A short survey among the partners of the project has revealed that the C745 swap-body has the greatest potential for the future. This concept has been envisaged as a normal truck towing a mechanically steerable dolly and a semi-trailer with a loading unit longer than usual in order to carry two 745 swap-bodies. The last axle of the semi-trailer is self-steerable, which improves the manoeuvrability performance.

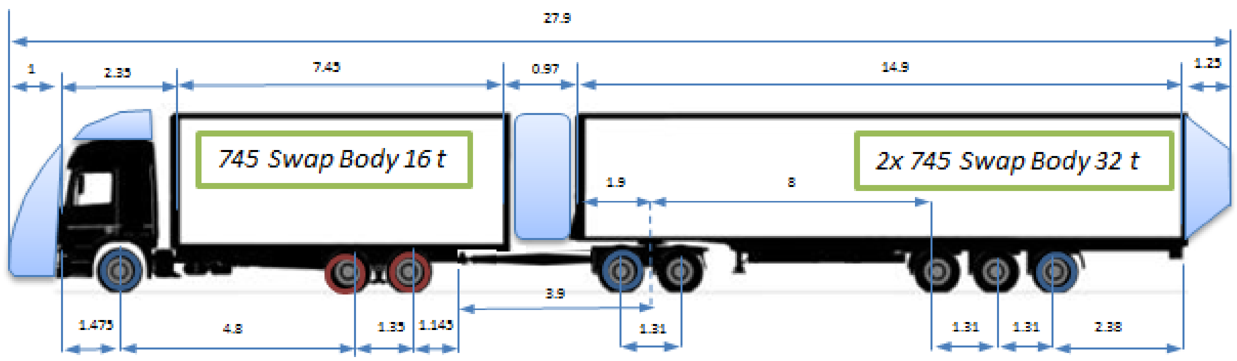


Fig. 9-4 Future Vehicle concept I.

Concept I can be easily decoupled in a hub & spoke system; the truck can reach the inner city, while the longer semi-trailer can be towed by a normal tractor to another destination or unhitched if needed. The vertical axle loads do not exceed the current values and are listed for fully loaded GVW in Table 9-2.

Table 9-2 Vertical axle loads when fully loaded.

	Truck			Dolly		Semitrailer		
Axle Number	I.	III.	IV.	I.	II.	I.	II.	III.
Axle Type	Steerable	Driven	Driven	Steerable	Rigid	Rigid	Rigid	Self-Steerable
Axle Vertical Load	7t	10.8t	10.8t	8t	8t	7.3t	7.3t	7.3t

For transporting three identical swap bodies, one can also employ a combination of tractor, semi-trailer and draw-bar trailer (listed and examined previously as 4A, see page 37), as the investment costs for fleet owners are minimal. Referring to the earlier described combination 4A, however, has the worst performance, and hence the above combination is preferred.

[123] www.news.walmart.com

Future Concept II

The second future concept is a combination of a tractor and two semi-trailers with self-steerable last axles which are able to carry 45 foot containers. The semi-trailers are interconnected by means of an adaptable steerable dolly. The dolly axles as well as the articulation point are locked at high speed; this substantially improves the high-speed stability performance compared to the combination 8C, which is always unlocked. Hence this feature will transform the combination into a very long B-Double.

At low speed the lock is released, and so the manoeuvrability performances are guaranteed thanks to the steerable dolly and extra articulation point. This dolly thus makes it possible to achieve the best performance for both low speed and high speed in one vehicle combination.

The dolly can be locked for example via wedges, which will lock the four-bar mechanism connecting the semi-trailer with the body of the dolly.

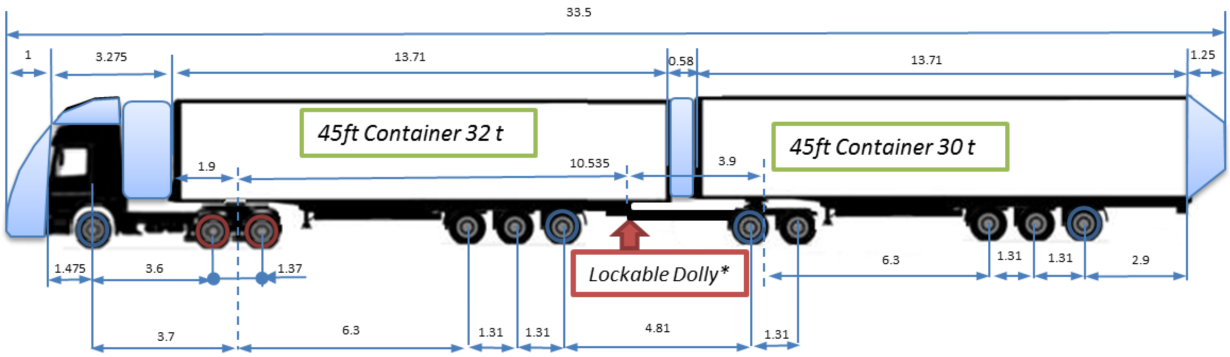


Fig. 9-5 Future Vehicle concept II.

Vertical axle loads for fully loaded GVW are listed in Table 9-3.

Table 9-3 Vertical axle loads when fully loaded.

	Tractor			B-Unit					Semitrailer		
Axle Number	I.	II.	III.	I.	II.	III.	IV.	V.	I.	II.	III.
Axle Type	Steerable	Driven	Driven	Rigid	Rigid	Self-Steerable	Steerable	Steerable	Rigid	Rigid	Self-Steerable
Axle Vertical Load	7.5t	8t	7.5t	7.8t	7.8t	7.8t	7.8t	7.8t	8t	8t	8t

Future Concept III - Transport Bus

The third concept can be understood as a transport bus which is able to accommodate 45ft containers. The bus has five axles (three steerable and two driven with twin tyres) and is connected via a dolly with a semi-trailer, which can also accommodate a 45ft container. The combination is very stable during high speed and provides sufficient traction force for startability and gradeability. Low-speed manoeuvrability is ensured through the first axle of the dolly, which is steerable (based on the articulation angle) and the last axle of the semi-trailer, which is self-steerable as in all previous concepts. The concept is depicted in Fig. 9-6 and axle loads are shown in Table 9-4.

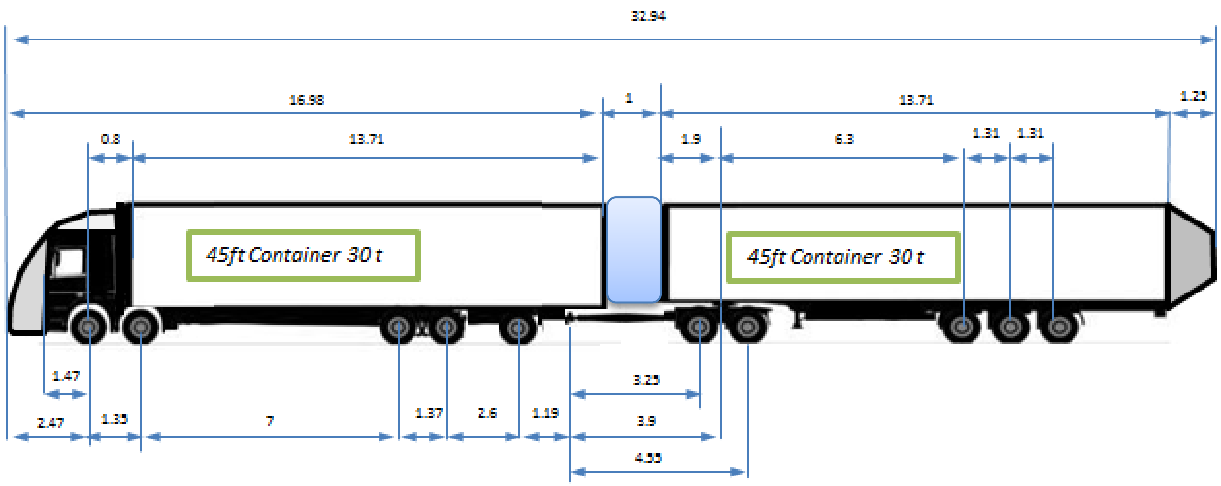


Fig. 9-6 Future Vehicle concept III.

Table 9-4 Vertical axle loads when fully loaded.

	Truck					Dolly		Semitrailer		
Axle Number	I.	II.	III.	IV.	V.	I.	II.	I.	II.	III.
Axle Type	Steerable	Steerable	Driven	Driven	Steerable	Steerable	Rigid	Rigid	Rigid	Self-Steerable
Axle Vertical Load	7t	6,8t	11,5t	11,5t	7,5t	8t	6,8t	8t	8t	8t

9.3 Validation on smart, clean and profitable transport

Validation on smart transport

To judge the stability, manoeuvrability and uphill performance of the future vehicle concepts the following crucial performance indicators have been selected:

- Low-speed swept path on 90 degree curve with 12.5 m radius
- Low-speed swept path on entire circle with 12.5 m radius
- Static rollover threshold
- Yaw damping
- High-speed transient off-tracking
- Rearward amplification
- Startability

All scenarios have been simulated in the same way as in previous chapters, so mutual benchmarking between vehicle combinations is possible. The performance of all three future vehicle concepts in each scenario is compared with the worst-performing legal vehicle combination (depicted in black) and the worst-performing current LHV combination (depicted in blue), and the results are discussed.

Fig. 9-7 and Fig. 9-8 illustrate the manoeuvrability performance of the vehicle combinations on curves with a radius of 12.5 m. In both cases all future vehicle concepts perform better than the worst vehicle from the current LHV group. Although the standard vehicle combinations achieve a better performance than all future concepts (FC), due to substantially shorter vehicle combination length, the FC I and FC III are still within the maximum allowed swept path width of 7.2 m. In addition it can be observed that appropriate selection of steering axles allows all FCs to negotiate an entire circle with radius 12.5 m, which however not possible for some of the current LHV's.

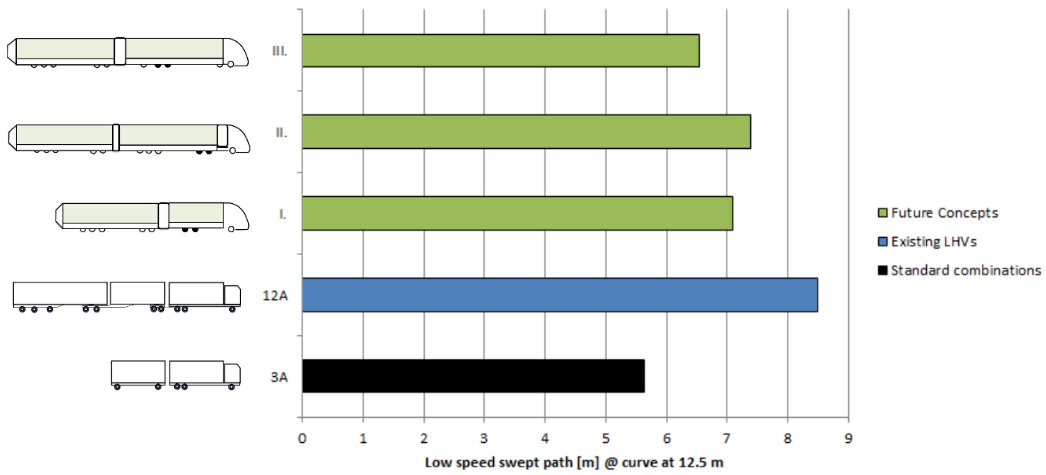


Fig. 9-7 Performance results for low-speed swept path of Future Concepts.

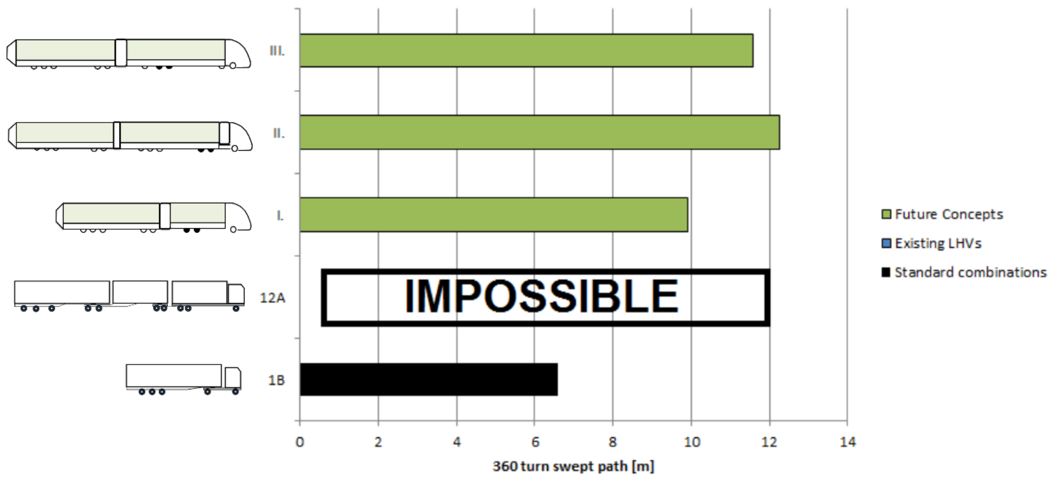


Fig. 9-8 Performance results for 360 turn swept path of Future Concepts.

In Fig. 9-9 the lateral stability performance for static rollover is shown. All combinations reached performance in the span 0.3g - 0.35g, which is quantitatively very similar performance ensuring sufficient stability. Note that there is not any rollover threshold limit established in EU legislation, as the threshold is mainly dependent on the type and height of the transported cargo. Hence majority of nowadays vehicle combinations have electronic rollover stability program which is activated around 0.3 g and vehicle is decelerated back to the safe region of operation.

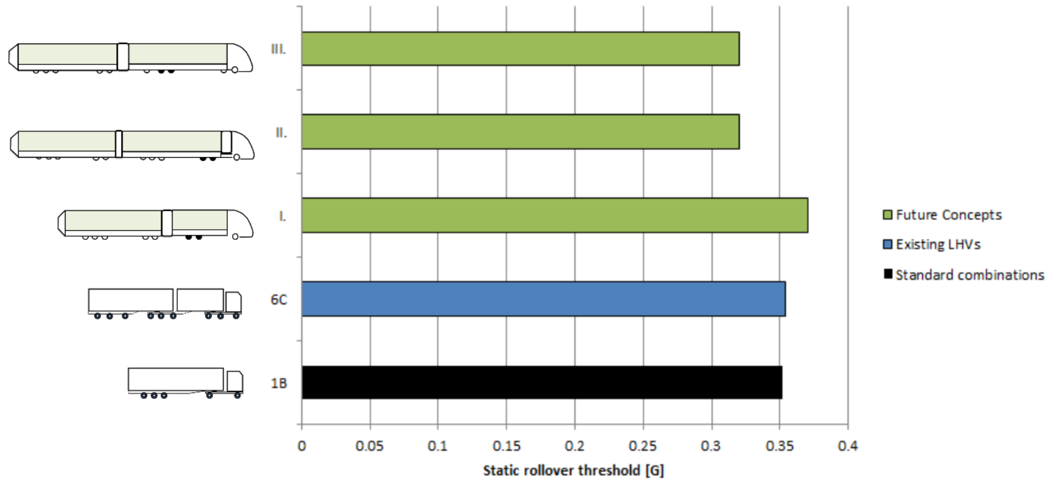


Fig. 9-9 Performance results for static rollover threshold of Future Concepts.

A dramatic difference can, however, be observed for the lateral dynamical stability, see Fig. 9-10 and 9-11. Particularly in yaw damping and rearward amplification, all FCs perform significantly better than other vehicles, which is due to their proper composition and sufficient length between the axle groups and kingpin. This performance is particularly important, as it ensures stability at high velocity if some dynamic or evasive steering manoeuvre is required.

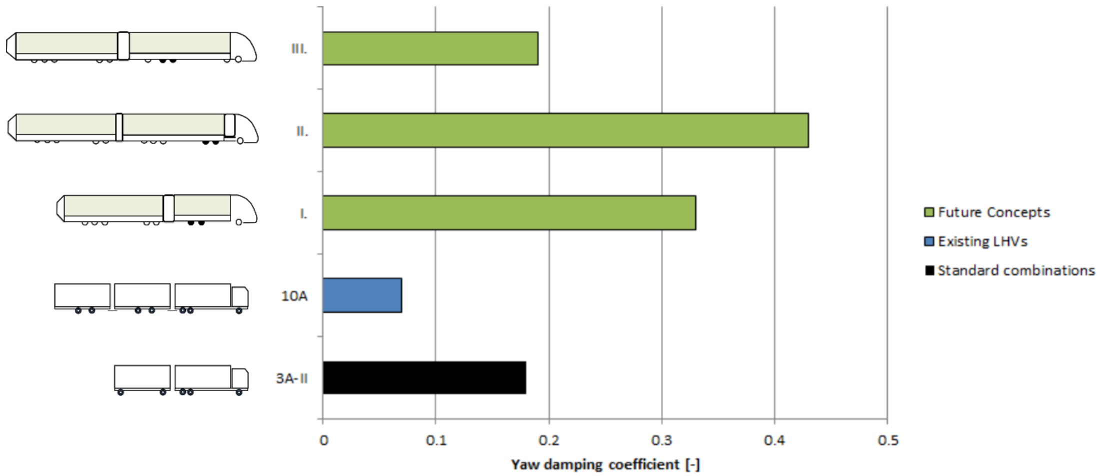


Fig. 9-10 Performance results for yaw damping coefficient of Future Concepts.

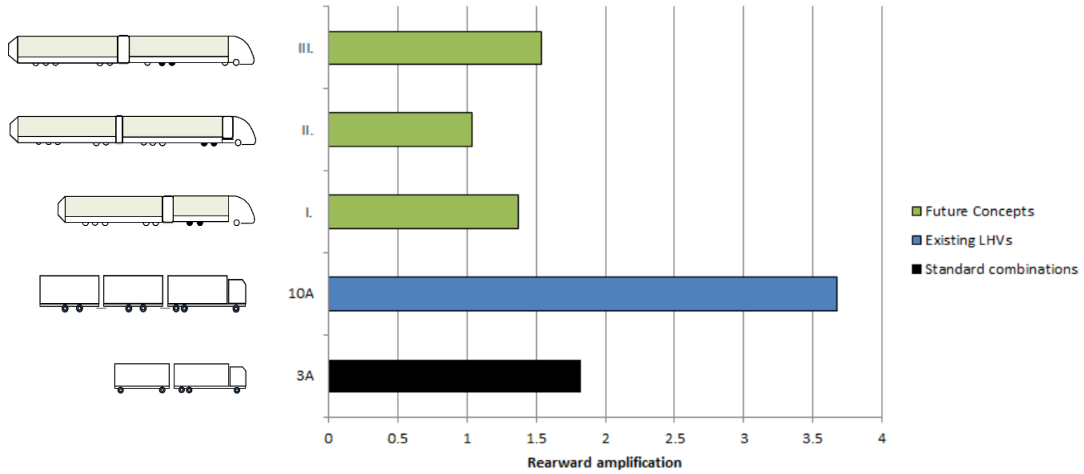


Fig. 9-11 Performance results for Rearward amplification of Future Concepts.

The last lateral dynamics assessment treats high-speed off-tracking, which is basically lateral path deviation of the last vehicle from the prime trajectory. This very important measure in fact quantifies the space needed by the vehicle combination during evasive manoeuvre. In Fig. 9-12 one can observe that no matter the overall length, all FC's are very strong in this measure and in case of FC-I and FC-III operates even better than European most frequent vehicle combination of tractor semitrailer.

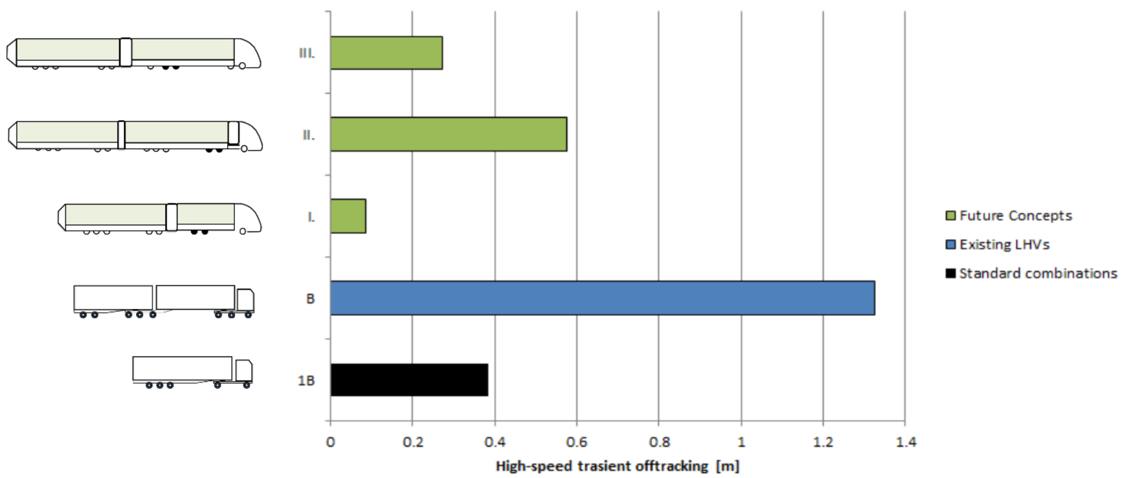


Fig. 9-12 Performance results for high-speed transient off-tracking of Future Concepts.

As shown in Fig. 9-13 the best startability performance is achieved by FC I followed by FC III. Although FC II and LHV 8C achieved only 14% this is still sufficient, as EU legislation prescribes a minimum startability of 12%.

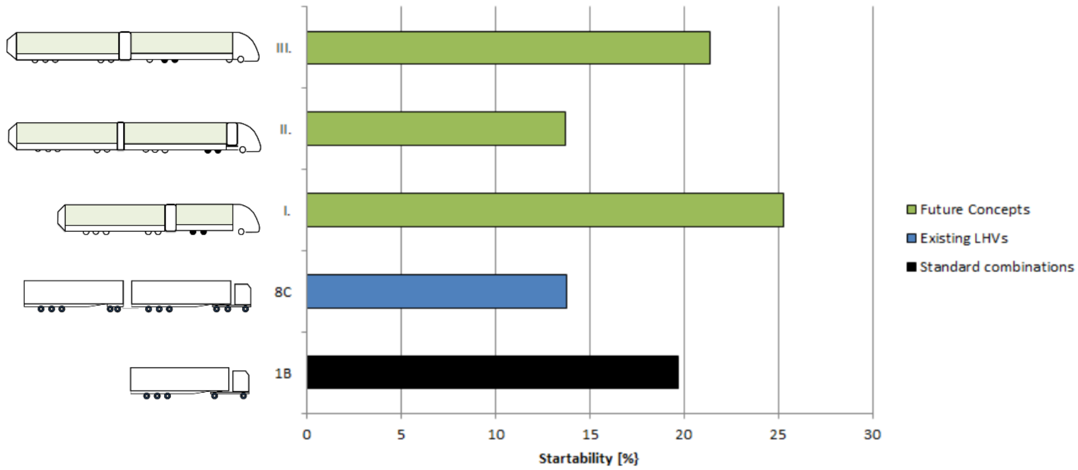


Fig. 9-13 Performance results for startability for Future Concepts.

The performance of the future vehicle concepts have been simulated and analysed. The mutual benchmarking of the new concepts with the worst performing legal vehicle combination (complying EC 96/53) and the worst performing current LHV combination results in better or comparable performance. The important result of this analysis underlines realistic and the even immediate feasibility of the usage of these three future concepts on the European roads at both high and low speed scenarios. To achieve such a performance a special support systems need to be however implemented on board as mandatory features, such as Anti-Roll Over or Active steering system. Although installation of such systems requires certain initial investment for the fleet owners, it pays back very quickly due to increased vehicle capacity as it is presented in the next section.

Validation on clean transport

For validation on clean transport again the fuel consumptions and the CO_2 emissions have been calculated. For this the same assumptions on route and average loading (weight and volume-related) were applied. For the average loading the weight and volume utilisation is shown in Table 9-5.

Table 9-5 Weight and volume utilisation of future concepts.

	Tare weight	Max GCW	Max payload	Average payload	Average GCW	Utilisation		Max volume	Average volume	Utilisation	
	[kg]	[kg]	[kg]	[kg]	[kg]	[kg/m^2]	[%]	[m^3]	[m^3]	[m^3/m^2]	[%]
FC-I	26743	60000	33257	23110	49853	423,22	69	137	115	2	84
FC-II	31720	60000	28280	27830	59550	423,22	98	169	138	2	82
FC-III	31058	60000	28942	27830	58888	423,22	96	169	138	2	82

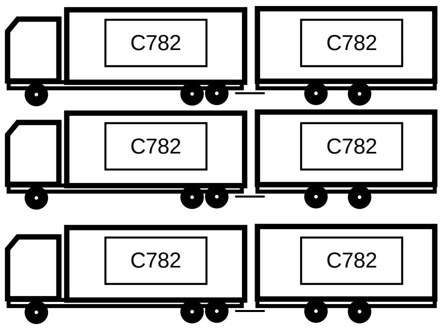
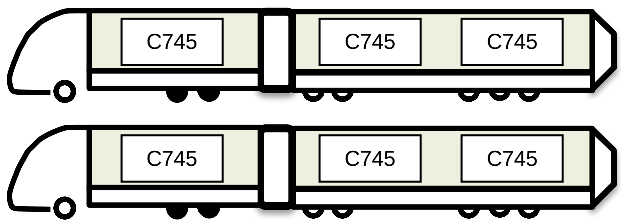
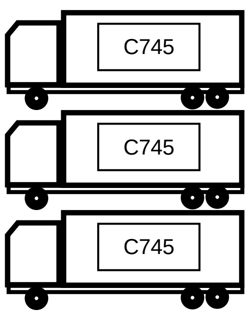
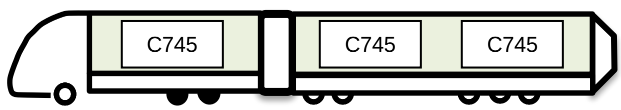
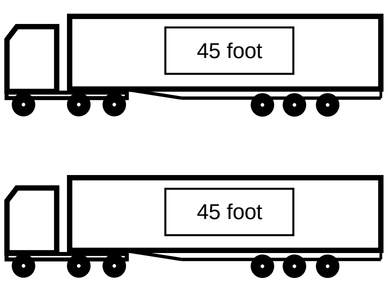
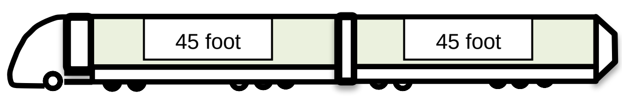
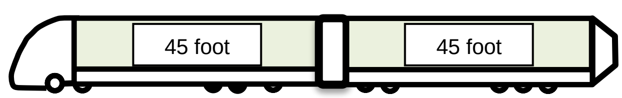
The results shown in Table 9-6 are weight and volume-related. Based on the payload calculations the weight-related emission is expressed in grams CO_2 per tonne payload per km travelled, whereas the volume-related performances are shown in grams CO_2 per m^3 freight per km travelled.

Table 9-6 Fuel consumption and CO_2 emission results.

	Average fuel consumption	CO_2 emission	Payload	Volume of freight	Gram CO_2 per tonne payload per km travelled	Gram CO_2 per m^3 of freight per km travelled
	[l/100km]	[g/km]	[ton]	[m^3]	[g/tkm]	[g/m^{3}km]
FC-I	44.56	1189.70	23.11	114.87	51.48	10.36
FC-II	51.60	1377.83	27.83	138.34	49.51	9.96
FC-III	51.29	1369.44	27.83	138.34	49.21	9.90

Again, for a proper comparison it is relevant to compare use cases and not vehicles one to one. For future concept I two different use cases are possible: a replacement of three articulated vehicles (combination 3A) by two new combinations or a replacement of three trucks with only one loading unit per truck (combination 15) by one new combination. For future concept II and future concept III a replacement of two road trains (combination 14) is possible. These use cases are listed in Table 9-7.

Table 9-7 Replacement of standard vehicles by Future Concepts.

Standard vehicle combination fleet	**Replaced by Future Concept**
3x 3A 	2x FC-I 
3x 15 	1x FC-I 
2x 14 	1x FC-II  1x FC-III 

Based on the comparison of use cases CO_2 emission is again expressed in terms of mass and volume. The results of these calculations are shown in Table 9-8 and Table 9-9 respectively.

Table 9-8 CO_2 emission results per use case - weight-related.

Concept combination	Fuel consumption	CO_2 emission	Payload	Gram CO_2 per tonne payload per km travelled	Potential
	[l/100km]	[g/km]	[ton]	[g/tkm]	
3x 3A	**102.17**	**2727.93**	**48.56**	**56.18**	
2 x FC-I	89.12	2379.40	46.22	51.48	8.36%
3x 15	**74.20**	**1981.15**	**24.28**	**81.60**	
1 x FC-I	44.56	1189.70	23.11	51.48	36.91%
2 x 14	**68.60**	**1831.70**	**27.83**	**65.82**	
1x FC-II	51.60	1377.83	27.83	49.51	24.78%
1x FC-III	51.29	1369.44	27.83	49.21	25.24%

Table 9-9 CO_2 emission results per use case – volume-related.

Concept combination	Fuel consumption	CO_2 emission	Volume of freight	Gram CO2 per m^3 of freight per km travelled	Potential
	[l/100km]	[g/km]	[m^3]	[g/m^3km]	
3x 3A	**102.17**	**2727.93**	**241.38**	**11.30**	
2 x FC-I	89.12	2379.40	229.75	10.36	8.36%
3x 15	**74.20**	**1981.15**	**117.94**	**16.80**	
1 x FC-I	44.56	1189.70	114.87	10.36	38.35%
2 x 14	**68.60**	**1831.70**	**138.34**	**13.24**	
1x FC-II	51.60	1377.83	138.34	9.96	24.78%
1x FC-III	51.29	1369.44	138.34	9.90	25.24%

As already seen with the existing LHVs, for the future concepts too there is a saving potential of about one quarter for both weight-related and volume-related loading. For weight-related transport in some use cases even a saving potential of about 35% is possible if replacement of three standard vehicles by one future concept is feasible. For this use case, however, one must keep in mind that a higher mileage will be required to distribute the loading units if the fleet owner has only one instead of three trucks available; the mileage will rise in conjunction with a decrease in the total fuel savings, which will lead to a shrinking potential.

With volume-related transport too high saving potentials are possible. For some use cases, however, the potential is very low due to the relatively higher tare weights combined with a constant maximum loading volume.

Validation on profitable transport

Fuel consumption is again not the only relevant factor for the fleet owner: a look at the Total Cost of Ownership is necessary. Therefore the TCO has been calculated on the same assumptions as for the standard and existing LHVs, see Table 9-10. It can be seen that due to their higher utilisation rate in terms of both weight and volume their costs per kilometer and payload of freight are lower.

Table 9-10 Total Cost of Ownership.

	TCO per year	TCO per km	Payload	Average utilisation	TCO per tonne payload per km travelled	Volume of freight	Average utilisation	TCO per m^3 freight per km travelled
	[€/year]	[€/km]	[ton]	[%]	[Ct/tkm]	[m^3]	[%]	[Ct/m^{3}km]
FC-I	198,709.02	1.472	23.11	69.5	6.368	136.90	83.9	1.282
FC-II	219,228.78	1.624	27.83	98.4	5.836	168.54	82.1	1.174
FC-III	220,236.21	1.631	27.83	96.2	5.859	168.54	82.1	1.179

A proper comparison will again consider use cases. The same comparison as for the fuel consumption has been used. The results are listed in Table 9-11.

Table 9-11 Total Cost of Ownership per use case.

Use case	Payload	TCO per tonne payload per km travelled	Potential weight-related	Volume of freight	TCO per m3 freight per km travelled	Potential volume-related
	[ton]	[Ct/tkm]		[m3]	[Ct/m^{3}km]	
3x 3A	**48.560**	**7.542**		**241.38**	**1.517**	
2x FC-I	46.220	6.368	15.56%	229.75	1.282	15.53%
3x 15	**24.280**	**12.877**		**117.94**	**2.650**	
1x FC-I	23.110	6.368	50.55%	114.87	1.282	51.64%
2x 14	**27.830**	**9.111**		**138.34**	**1.832**	
1x FC-II	27.830	5.836	35.95%	138.34	1.174	35.95%
1x FC-III	27.830	5.859	35.95%	138.34	1.179	35.65%

The comparison shows potential savings of 15% for replacement of one standard articulated vehicle or even about 50% for replacement of a single truck. For future concepts II and III savings of about 36% compared to the existing vehicles are possible. There are no great differences in the TCO between future concepts II and III, as the only difference is in the layout of the combination with tractor unit or rigid truck with nearly the same tare weights and payloads.

Overall performance – smart, clean and profitable

For comparing and choosing a vehicle combination it is essential to take a detailed look not only at smartness but also at cleanness and profitability. First of all a concept needs to fit inside the current infrastructure and should be safe at any speed. This is a task for the regulatory authorities, who will thereby enable the manufacturers to design a variety of vehicle combinations. For efficient transport the responsibility rests with the fleet owner, who has to make a very careful and detailed analysis of his business before switching to a new vehicle combination.

9.4 Technical challenges

Although the future concepts may offer substantial improvements in terms productivity and transport efficiency, there are still issues which needs to be resolved before the concepts can be introduced in real-life operation. Clearly one of these is supporting the driver during reversing, which might be beyond his/her capabilities if the vehicle combination has two or three articulation points. Another challenge is linked with combining sufficient high-speed stability and good low-speed manoeuvrability, which might be realised through the appropriate active steering. One can also imagine that active safety programs (e.g. ESP) for such vehicles need to be modified to achieve optimal performance.

Conclusion and Outlook

Conclusion

In order to approach the topic “Greening and Safety Assurance of Future Modular Vehicles” a trend analysis was implemented. The analysis of future logistic and transport concepts reveals an incompatibility with the existing infrastructure regulation and with the (upcoming) vehicle regulation.

To resolve this conflict two solutions were derived. First there is a need for vehicle combinations which can handle multiples within the existing infrastructure. These vehicle combinations must meet the requirements of smart, clean and profitable transport. This means they should not negatively affect transport in terms of safety, environmental performance or cost-efficiency compared with today’s standard vehicles. The second solution aims at resolving the conflict between the upcoming developments and the existing regulations and is a proposal for a new EU-wide legal framework. The proposal is based on the approach of performance-based standards and allows the use of multiples within the existing infrastructure by assessing the vehicle performance.

To validate the approach of new vehicle combinations and a new legal framework, investigations in terms of smart, clean and profitable transport were made. For this tools had to be developed and used. For validation on smart transport in particular a new simulation tool was developed on the basis of the performance-based standards used in Australia and some current regulations in the EU. The investigations on smart, clean and profitable transport permitted a comparison of standard vehicles with existing LHVs in terms of use cases, and requirements for future concepts were derived from this.

The verifications show that there is no “right vehicle combination” for all transport tasks. There is a need to differentiate between weight-related and volume-related transport tasks as well as to choose the right loading units to suit transport tasks and use of different modes. With this knowledge it is possible to define the most efficient and most effective transport concept for achieving high productivity. The efficiency is determined by choice of the right vehicle concept. The vehicle concept should meet all requirements for smart, clean and profitable transport within its transport task. This means that it needs to be safe for the driver, infrastructure and its environment as well as fuel-efficient and environmentally friendly, and last but not least profitable for the fleet owner. The effectiveness is determined by choice of the right application. The application is determined by the logistic concept, intermodality and market segments. This means choosing the right loading units for the transport task by using the appropriate modes and focusing on the right market segments. Only the combination of efficient vehicle concepts and effective applications results in high productivity.

In-depth knowledge and further advice and consulting based on expert knowledge are therefore required to ensure that the right choice for achieving the predicted savings and productivity is made.

Outlook

In view of the results and conclusions outlined in the previous sections further research in two main fields is needed in order to achieve the target of smart, clean and profitable transport.

First a detailed look at how transport works and at the associated correlations which determine the design of the vehicles is necessary.

Many studies have been carried out on the impact of longer and heavier vehicles on emissions, safety, TCO, transport efficiency, all against a certain logistic framework. There is, however, a lack of information on real transport conditions, where goods are transported from one location to another with various mode transitions and transfers between city, regional, national and international levels, all with specific use conditions. Longer and heavier vehicles are part of an overall logistic framework, and certain benefits may be linked to other effects or even counteract them.

In addition to various transport conditions the performance of the vehicle combinations was derived by experimental and/or simulation analysis in which certain aspects of the design were changed. There appear to be clear and interpretable correlations between the different performance measurements which are determined by underlying factors. These factors allow improved design strategies contributing to safety, a lower environmental impact and profitability, all in a balanced way.

A set of transport scenarios with different stakeholders therefore needs to be chosen and analysed to obtain a better understanding of real logistic scenarios and to develop the correlations between the performance measurements.

The second main field for further exploration is the proposal for a new European legal framework based on PBS and the follow-up on this proposal.

The assessment of performance (safety, profitability, sustainability) requires a set of rules/procedures as well as criteria against which vehicles are assessed. Such criteria have been established or are under consideration in non-European countries such as Australia, Canada, USA etc. The challenge in Europe is the variation in infrastructure and transport conditions on the one hand, whereas on the other hand a consensus exists regarding our European objectives for greener, safer and more profitable transport. A legislative basis must also reflect the opinion of all stakeholders, including forwarders, consignors, different modes of transport, infrastructure owners and road authorities. That raises the questions as to what extent these specific different conditions can be taken into account in a PBS framework to guarantee good performance and how this can be used to find a common ground for requirements for LHVs.

Examination of the pros and cons as well as possible alternatives for the suggested framework are therefore necessary if a new legislative basis for LHVs is to be derived. The cooperation, support and commitment of organisations such as ACEA too is essential for successful implementation of a new legal framework based on PBS.

Appendix

Glossary

CO_2	-	Carbon Dioxide
ACEA	-	European Automotive Manufacturers' Association
EMS	-	European Modular System
EU	-	European Union
GCW	-	Gross Combined Weight
GDP	-	Gross Domestic Product
GHG	-	Green House Gas
ISO	-	International Organization for Standardization
LHV	-	Longer Heavier Vehicles
HDV	-	Heavy Duty Vehicle
HP	-	Horse Power
PBS	-	Performance Based Standards
SAG	-	Scientific Advisory Group
TCO	-	Total Cost of Ownership
TU/e	-	Eindhoven University of Technology
UNECE	-	United Nations Economic Commission for Europe
VKT	-	Vehicle Kilometres Travelled

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World Urbanization Prospects, the 2011 Revision. (n.d.). Retrieved 11 7, 2013, from United Nations, Department of Economic and Social Affairs: http://esa.un.org/unup/Documentation/Definition-Problems_1.htm

Appendix A

This appendix describes different sorts of transferring technologies and strategies from road transport to rail, road or water transport and vice versa. One of the targets of the HTAS EMS project is to make the vehicle combinations more interesting for combined transport with rail and water by using specific loading units. To optimise this not only the loading units have to be intermodal: well-developed transferring systems and strategies are also a must for improving the productivity of combined transport.

There are currently six main types of transferring technologies. These are described below.

Transhipment equipment as an element of the means of transport itself
This concept is based on the idea that the transporters are equipped with special systems which enable them to transfer the loading units from one to another. The main purpose of this is to eliminate the need for any special handling by cranes at terminals. Thus, the higher the numbers of transfers, the lower the costs and the total lead time needed. Examples of such devices are ACTS (Roll-on/roll-off Container Transport System), Bimodal Technique, Mercedes Benz Kombi Lifter, semi-trailer with side loader, U.L.S. ("Umschlagfahrzeug" Lässig / Schwanhausser) and self-unloading ship(s).[124]

Transhipment devices
This technology concept is based on cranes at terminals which transfer the loading units. These cranes lift the loading unit off the trailer transferring it to its destination. Innovative projects which work with this concept are the Fast Transfer Technicatome commuter handling device and the Krupp Fast Handling device.[125]

Transhipment and internal transport devices
This form of transferring is done by automated robots or a single-person-operated vehicle that moves around in a terminal transferring and moving the loading units and containers. Concepts which operate according to this approach are the Terminal Truck with Lifting Devices for Swap Bodies and the Self-Loading AGV Robot.[126]

Internal transport equipment
Here internal transport in the terminals is optimised by all kinds of devices to reduce the lead time of the supply chain. This concept focuses on a certain form of loading unit, container or packaging which is handled, transported and transferred in different ways. The following concepts work according to this process: Shuttle Wagon (Navette), Multi Trailer System (MIS), Skid/Pallet (Longitudinal conveyor), Moving Train, Skid/Pallet (Cross Conveyor), Bi-directional Rail-mounted Shuttle "B+" and Train Transfer and Positioning Devices.[127]

Stacking devices
Here use is made primarily of shelves and racks where the loading units are stored until their next step in the supply chain. This form of storing ensures the freedom of picking the relevant loading unit without handling other loading units first because the loading units are freely accessible without moving other loading units. This form of transferring technology is ideal for the Transfer Optimised Approach. Concepts that work according to this system are the Portal Crane for Stacking, One-Arm Crane (Stack Lifter), High-Rack Handling Device and Mechanical Storage.[128]

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[124] Peterlini, E. (2001). *Innovative Technologies for Intermodal transfer Points.* Page 6-28.

[125] Peterlini, E. (2001). *Innovative Technologies for Intermodal transfer Points.* Page 29-30.

[126] Peterlini, E. (2001). *Innovative Technologies for Intermodal transfer Points.* Page 32.

[127] Peterlini, E. (2001). *Innovative Technologies for Intermodal transfer Points.* Page 33 - 41.

[128] Peterlini, E. (2001). *Innovative Technologies for Intermodal transfer Points.* Page 43 - 46.

Technical and organisational concepts

The last group of concepts consists of those which not only transfer the loading units but also organise the transferring. These are especially interesting for the Timed Transfer Approach, which is based on simultaneous arrival of the transporters. Concepts following this principle are the 'Technicatome commutor Concept, Krupp Fast Handling System, Automated Guided Vehicle System and Automated Stacking Cane, Cargo 2000 Concept, NOELL Fast Transshipment System'[129] and the CargoBeamer.[130]

A closer look at the intermodal transfer technologies which are set up nowadays shows that these are used are mainly between road, rail and water. They also have to be flexible enough to ensure that different sorts of loading units can be transhipped between the modes of transport.

With the above-mentioned types of intermodal transfer technologies there are two main transfer strategies. These are the "timed transfer approach" and the "transfer optimisation approach".

Timed Transfer Approach

'A timed transfer approach is a strategy to develop a transport network in which transport units arrive simultaneously at transferring places to offer coordinated transfers in all directions. The basic idea of the timed transfer system is the pulsing of headways so that transporting units from different transport modes meet at the same time. Accordingly, for this type of coordination, the pulse headway is one of the critical decision variables. Using an appropriate pulse headway common to all routes, transporting units from different routes can be synchronised so that they arrive and possibly depart at the same time. Transfer delay is inserted into schedules in order to account for the variability of transporting vehicle arrivals. There have been several studies addressing the optimisation of the pulse headway and the slack time for successful timed transfer systems'[131] In the case of logistics this is a simultaneous arrival of the loading units at the right place for their transfer. Here the main target is the shortest possible total transfer and lead time.

Transfer Optimisation Approach

'Unlike the timed transfer approach system, the transfer optimisation approach does not require that transporting units simultaneously meet at a transferring place. This approach plans the departure times at a transferring place so as to minimise some functions that indicate the overall disutility of the transfer.'[132] This strategy is chosen mainly to combine the lowest costs with the highest effectiveness. Here the loading units can be stored, mainly in the form of stacking, when they arrive at a transferring area. Other loading units can then be taken along, as there is no need for the transporters to meet simultaneously. This rules out exact planning but entails the possibility of reducing the number of empty runs.

[129] Peterlini, E. (2001). *Innovative Technologies for Intermodal transfer Points. Page 47 - 63.*

[130] CargoBeamer. (2013). *Fact Sheet CargoBeamer AG.* Leipzig: CargoBeamer AG.

[131] Chung, E.-H. (2009). *Transfer Coordination Model and Real-Time strategy for Inter-Modal Transit Services.* Toronto: University of Toronto. Page 5.

[132] Chung, E.-H. (2009). *Transfer Coordination Model and Real-Time strategy for Inter-Modal Transit Services.* Toronto: University of Toronto. Page 8.

Appendix B

This appendix gives information about the European regulations and country-specific regulations with respect to infrastructure.

European regulations

The United Nations Economic and Social Council has set the road parameters described in Table B-1 in the European agreement on main international traffic arteries.

Table B-1 minimum road parameters dependent on road design speed.[133]

Design speed [km/h]		60	80	100	120	140
Minimum radii in plane (corresponding to maximum superelevation 7%)		120	240	450	650	1000
Maximum gradient (percentage not to be exceeded)[a]		8	7	6	5	4
Maximum longitudinal gradient in new tunnels[b]		5	5	5	5	5
Minimum radii at the highest point of the vertical alignment [m]	**One-way**	1500	3000	6000	10000	18000
	Two- way	1600	4500	10000	-	-
Minimum radii at the lowest point of the vertical alignment [m]		1500	2000	3000	4200	6000

[a] The maximum gradient should be decreased by 1% in the case of express roads and motorways. When the maximum gradient is applied, an additional lane for slow-moving vehicles should be envisaged.

[b] Unless no other solution is geographically possible. In tunnels with gradients higher than 3%, additional and/or reinforced measures should be taken to enhance safety on the basis of a risk analysis.

Country-specific regulations

Belgium [134]

'For a single one-way lane, the width of it has to be between 3.0 and 4.0 m. On average the suggested width should be 3.5 m.'

Netherlands[135]

A vehicle has to reach 75% of the maximum speed for the designated road. An extra point here is that the acceleration lane mostly starts from a higher point and descends towards the main road. This ensures that the driver reaches 75% of the maximum speed for that road.

The deceleration lane is dependent on a formula. The length of the lane must be such that it will not be necessary to decelerate on the main road. This ensures higher safety and fewer accidents. Whereas the acceleration lanes in the Netherlands mostly descend towards the main road, deceleration lanes often rise in order to increase deceleration of the vehicle, which reduces the total length needed for this lane.

[133] United Nations Economic and Social Council . (2008). *European agreement on main international traffic arteries.* Page 35.

[134] VMSW. (2009). *Infrastructuuraanleg voor sociale woonprojecten.* Brussel.

[135] Rijkswaterstaat. (2007). *NOA - Nieuwe Ontwerprichtlijn Autosnelwegen.* Nijkerk: Drukkerij Van de Ridder bv.

Italy[136] [137]

Italy has three sorts of roundabouts which differ in their outer circle radius:

- 40 to 50 m outer radius
- 25 to 40 m outer radius
- 14 to 25 m outer radius

Road parameters are described in Table B-2. Lane width regulations are described in Table B-3.

Table B-2 Road parameters.

Design Velocity	[km/h]	30	40	50	60	70	80
Minimum radius	**[m]**	25	45	75	120	180	250
Max slope up	**[%]**	10	7.0		5.0		
Max slope down	**[%]**	10	8.0		6.0		
Radius of convex bump	**[m]**	500	1,000	1,500	2,000	2,800	4,000
Radius of concave bump	**[m]**	250	500	750	1,000	1,400	2,000
Visibility distance	**[m]**	25	35	50	70	90	115

Table B-3 Lane width regulations Italy.

Modular element	Outer city		City	
Lane for crossing	**Road class**	**Width**	**Road class**	**Width**
Lane for exit	C	3.5 m	E	3.0 m
	F	3.25 m	F	2.75 m
Extra lane in centre for turning	C	3.25 m	E	3.0 m
	F	3.0 m	F	2.75 m

C: Single carriageway with at least one lane for each direction.
E: Single carriageway with at least two lanes for each direction.
F: Inner-city streets, not yet exactly classified.

Switzerland[138] [139]

Lane parameters for normal roads, tunnels and bridges are given in Tables B-4 to B-6 respectively.

Table B-4 Swiss lane parameters.

Number of lanes	Speed [km/h]	Minimum street width incl. striping	Space for separation element	Guardrail / crash barrier	Total width
2	60	6 m		0.3 m	6.6 m
2 + 2	80	2x 5.5 m	0.5	0.3 m	12.1 m
3 + 1	(80)	5.5 m + 3 (2.5) + 3.5	0.5	0.3 m	9.6 (9.1) + 3.8 m
2 + 2	120	2x 7.75 (7.5)	1.5 + 2.5	4.0 (2.0)	27.5 m (25.0)
3 + 3	120	2x 3.75 + 7.0 or 7.0 +3.25	0.5 + 2.5	3.5 m or 2,0 m	31.0 m or 28.5 m
3 + 3 with work lanes	(120)	2x 10.2 m or 9.3 m	0.5	1.2 + 0.8 m or 1.2 + 0.75 m	31.0 m or 28.5 m
4 + 4	120	2x 3.75 + 10.5 m 2x 3.75 + 10.5 m 2x 10.5 + 3.25 m	0.5 + 2.5 0.5 + 2.5 0.5 + 2.5	5.0 + 3.5 m 3.5 m 2.0 m	43.0 m 38.0 m 35.5 m

[136] Ministero Delle Infrastrutture e Dei Trasporti. (2001). *Norme fuzionali e geometrische per la construzione delle strade.* Italy

[137] Ministre Delle Infrastrutture e Dei Transporti. (2006). *Norme funzionali e geometriche per la costruzione delle intersezioni stradali.* Italy.

[138] Bundesamt für Strassen. (2002). *Normalprofile, Rastplätze und Raststätten der Nationalstrassen.* Bern: Bundesamt für Strassen.

[139] Bundesamt für Strasse. (2002). *Berücksichtigung des Unterhalts bei der Projektierung und beim Bau der Nationalstrassen.* Bern.

Table B-5 Lane parameters for tunnels.

Number of lanes	Minimum street width incl. striping	Safety space on both sides	Total width
2 + 2	7.75 m	1.0 m	9.75 m
3 + 3	10.75 m	1.0 m	12.75 m

Table B-6 Lane parameters for bridges.

Number of lanes	Minimum street width incl. striping	Safety separation length	Min. distance between two roads	Min. distance between crash barriers of two roads	Total min. width
2 + 2	7.75 or 7.5	2.5 + 0.6 or 0.9	4.0	1.6	25.8
3 + 3	2x 3.75 +7.0 or 2x 7.0 + 3.25	2.5 + 0.5 + 0.95	3.5	1.6	31.0 or 30.0
4 + 4	2x 3.75 + 10.5	2.5 + 0.5 + 0.95	3.5	1.6	38.0 or 37.0

There is a minimum transverse slope of 3.0% on Swiss highways.

France[140] [141]

Basic road parameters for highways are described in Table B-7. Below the table other aspects are described. Table B-8 describes road parameters for roads other than highways. The last part describes lane widths.

Table B-7 Highway road parameters.

Category	L1 (130 km/h)	L2 (110 km/h)
Minimum radius	600 m	400 m
Min. radius without transverse slope	1,000 m	650 m
Maximum slope	5%	6%
Min. radius in salient angle	12,500 m	6,000 m
Min. radius in a returning angle	4,200 m	3,000 m

The normal transverse slope (banking) on a highway is 2.5% (1.4°), meaning that the left side of the road from the driving direction is always somewhat higher than the right side to allow rainwater to run off. The transverse slope must not exceed 7% (4°). The exit lanes have a minimum radius of 240 m if the speed there is 90 km/h.

Table B-8 Parameters for roads other than highways.

Category	50 km/h (speed limit)	70 km/h	90 km/h
Minimal radius	50 m	120 m	230 m
Min. radius without transverse slope	70 m	180 m	360 m

The steepest slope in France is 7.5% (4.3°).

Lane width:

- For motorways each carriageway has 2 to 4 lanes with a width of 3.5 m for each lane.
- For highways (inner or outer city) the lane width is between 3.0 m and 3.5 m.
- For small roads, if the total width is less than 5.2 m for the two lanes, there is no indication of the division between the two traffic directions.

[140] Ministère de l´Equipment et des Transport : ICTAAL

[141] Ministère de l´Equipment et des Transport : SETRA

Germany[142] [143] [144]

For Germany different infrastructure parameters are described. Table B-9 shows the parameters for different kinds of roads. The lane widths for normal roads, bridges, tunnels and two-lane roads are described in Tables B-10, B-11, B-12 and B-13 respectively. Urban infrastructure parameters and roundabout parameters are given in Tables B-14 and B-15 respectively. Next, in Table B-16, the minimum distances between crossings are shown for different speeds and road categories. Last, facts about the radius in a curve and slopes are described.

Table B-9 Parameters for different kinds of roads.

Designation	Long-distance motorway	Inter-regional motorway	Motorway-like road	Urban motorway
Advised permissible speed	130 km/h	120 km/h	100 km/h	≤ 100 km/h
Recommended distance between junctions	> 8,000 m	> 5,000 m	> 5,000 m	None
Traffic management around construction works on four-lane roads	4+0 generally necessary*		4+0 not absolutely necessary	

*'4+0' indicates the lane configuration during reconstruction. The '4' indicates that four lanes (two in each direction) will be accommodated on the one carriageway and the '0' indicates that there will be no traffic on the other carriageway while it is being reconstructed.

Table B-10 Lane widths for normal roads.

Number of lanes	**Minimal street with incl. striping**	**Space for separation element**	**Guardrail / crash barrier**	**Total width**
2 + 2	2x 7.5	2x 3.0 + 0.75 m	4.0 + 2x 0.5 + 2x 1.5 m	31.0 m
	2x 7.0	2x 2.5 + 0.5 m	4.0 + 2x 0.75 + 2x 1.5 m	28.0 m
	2x 3.5 + 3.25 m	2x 2.0 + 0.5 m	2.5 + 2x 0.5 + 2x 1.5 m	25.0 m
3 + 3	2x 3.75 + 6.0 m	2x 0.5 + 2.5 m	4.0 + 2x 0.75+ 2x 1.5 m	36.0 m
	2x 3.5 + 6.5 m	2x 2.0 + 0.5 m	2.5 + 2x 0.5 + 2x 1.5 m	31.5 m
4 + 4	2x 7.5 m + 2x 7.0 m	2x 0.5 + 2.5 m	4.0 + 2x 0.75 + 2x 1.5 m	43.5 m
	2x 7.0 + 2x 6.5 m	2x 2.0 + 0.5 m	2.5 + 2x 0.5 + 2x 1.5 m	38.5 m

Table B-11 Lane widths for bridges.

Number of lanes	**Minimal street width incl. striping**	**Space for separation element**	**Guardrail / crash barrier**	**Total width**
2 + 2	2x 7.5 m	2x 3.0 + 0.75 m	4.0 + 2x 0.75 + 2x 2.0 m	32.0 m
	2x 7.0 m	2x 2.5 + 0.5 m	4.0 + 2x 0.5 + 2x 2.0 m	29.0 m
3 + 3	2x 3.75 + 7.0 m	2x 2.5 + 0.5 m	4.0 + 2x 0.75 + 2x 2.0 m	37.0 m
4 + 4	2x 7.5 + 7.0 m	2x 2.5 + 0.5 m	4.0 + 2x 0.75 + 2x 2.0 m	44.5 m

Table B-12 Lane widths for tunnels.

Number of lanes	**Minimal street width incl. striping**	**Space for separation element**	**Guardrail / crash barrier**	**Total width**
2 + 2	2x 3.5 + 3.25 m	2x 2.0 + 0.5 m	2.5 + 2x 0.5 + 2.0 m	26.0 m
3 + 3	2x 3.5 + 6.5 m	2x 2.0 + 0.5 m	2.5 + 2x 0.5 + 2.0 m	32.5 m
4 + 4	2x 7.0 + 6.5 m	2x 2.0 + 0.5 m	2.5 + 2x 0.5 + 2.0 m	39.5 m

For the tunnels there are other different sizes but these are the main ones.

[142] Road and Transport Reasearch Association. (2006). *Directives for the Design of Urban Roads.*

[143] RAA – Guidelines for the Design of Motorways.

[144] Bayerische Staatsbauverwaltung. (2012). *Kostenbewusstes Planen unde Bauen.*

Table B-13 Standard lane width of a two-lane road.

Application	Width
Standard case	6.5 m
Low frequency of bus or truck traffic	6.0 m (5.5 m in constrained space situations)
Bus or truck traffic predominant	7.0 m (only where permanent side-by-side driving is to be accommodated)

Table B-14 Urban infrastructure parameters.

Application	Carriageway width, main arterial roads	Carriageway width, access roads
Standard case	6.5 m	4.5 m – 5.5 m
With scheduled bus traffic	6.5 m	6.5 m
Light scheduled bus traffic with a low use requirement	6.0 m	6.0 m
Low frequency of HGV traffic meeting	5.5 m (at reduced speed)	-
High frequency of bus or HGV traffic coming together	7.0 m	-
Advisory lane for cyclists	7.5 m with 1.5 m advisory lane on both sides 1.0 m with a 1.25 m advisory lane on both sides in confined situations	

Table B-15 Roundabout parameters.

Element	Mini-roundabout		Small roundabout			
	Min.	Max.	Min.	Standard		Max.
Outer diameter	13 m	22 m	26 m	30 m	35 m	≥ 40 m
Carriageway width	4.0 m – 5.0 m		9.0 m	8.0 m	7.0 m	6.5 m
Approach width	3.25 m – 3.75 m					
Exit width	3.5 m – 4.0 m					
Approach radius	8 m – 10 m			10 m – 14 m		
Exit radius	8 m – 10 m			12 m – 16 m		

Table B-16 Minimum distance between crossings for different speeds and road categories.

Road categories	V_{limit}	Longitudinal gradients				
		-8%	-4%	0%	+4%	+8%
Local streets, built-up main roads	30 km/h	-	-	22 m	-	-
	40 km/h	-	-	33 m	-	-
	50 km/h	-	-	47 m	-	-
Open main roads	50 km/h	54 m	50 m	47 m	44 m	42 m
	60 km/h	73 m	67 m	63 m	59 m	56 m
	70 km/h	94 m	86 m	80 m	75 m	71 m

Minimum radius of a curve is 8.0 m and the maximum lateral slope in curves is 2.5%.

The maximum uphill gradient of a motorway in Germany is 6% (3.43°) and the maximum downhill gradient is 7% (4.0°).

Appendix C

The European regulations regarding allowed axle loads are shown in Table C-1. In this table *d* represents the distance between the axles.

Table C-1 European regulations regarding axle loads.[145]

Vehicle combination	Allowed weight [t]
Two-axle trailer	18
Three-axle trailer	24
Road trains with 5 or 6 axles Two-axle motor vehicle with three-axle trailer Three-axle motor vehicle with two or three-axle trailer	 40 40
Articulated vehicles with 5 or 6 axles Two-axle motor vehicle with three-axle semi-trailer Three-axle motor vehicle with two or three-axle semi-trailer Three-axle motor vehicle with two or three-axle semi-trailer carrying a 40-foot ISO container as a combined transport operation	 40 40 44
Road trains with four axles consisting of a two-axle motor vehicle and a two-axle trailer	36
Articulated vehicles with four axles consisting of a two-axle motor vehicle and a two-axle semi-trailer, if the distance between the axles of the semi-trailer: is 1.3m or greater but not more than 1.8m is greater than 1.8m	 36 36 (+2)
Two-axle motor vehicles	18
Three-axle motor vehicles	25 (26)
Four-axle motor vehicles with two steering axles	32
Three-axle articulated buses	28
Single axles, non-driven	10
Tandem axles of trailers and semi-trailers. The sum of the axle weight per tandem axle must not exceed. if the distance (d) between the axles is: less than 1m (d<1..0) between 1.0m and less than 1.3m (1.0≤d<1.3) between 1.3m and less than 1.8m (1.3≤d<1.8) 1.8m or more (1.8>d)	 11 16 18 20
Tri-axles of trailers and semi-trailers. The sum of the axle weight per tri-axle must not exceed. if the distance (d) between the axles is: 1.3m or less (d≤1.3) over 1.3m and up to 1.4m (1.3<d≤1.4)	 21 24
Driving axle of the vehicles less than 1m (d<1.0)	11,5
1.0m or greater but less than 1.3m (1.0≤d<1.3)	16
1.3m or greater but less than 1.8m (1.3≤d<1.8)	18 (19)
Load on the driven axles	At least 25% (20% in Netherlands)

[145] European Commision. (1996). *Directive 96/53/EC.* Page 12 – 14.

Appendix D

Canadian PBS

The different PBS for Canada are divided into stability and control measures and off-tracking measures, see Tables D-1 and D-2 respectively.

Table D-1 Stability and control measures, Canadian PBS.[146]

Stability and control measures	
Name	**Summary statement**
Static Rollover Threshold	Maximum severity of steady turn which a vehicle can tolerate without rolling over.
Dynamic Load Transfer Ratio	The extent to which a vehicle approaches the rollover condition in a dynamic steering manoeuvre such as in avoiding an obstacle in the roadway.
Friction Demand in Tight Turns	Resistance of multiple, non-steered axles to travelling around a tight-radius turn, such as at an intersection.
Braking Efficiency	The percentage of available tyre/road friction limit that can be utilised in achieving an emergency stop without incurring wheel lockup.

Table D-2 Off-tracking measures Canadian PBS.[147]

Off-tracking measures	
Name	**Summary statement**
Low Speed Off-tracking	The extent of inboard off-tracking which occurs in a turn.
High Speed Off-tracking	Extent of outboard off-tracking of the last axle of the truck combination in a moderate steady turn of 0.2 g's lateral acceleration.
Transient High Speed Off-tracking	The peak overshoot in the lateral position of the rearmost trailer axle, following the severe lane-change-type manoeuvre.

Australian PBS

The complete list of the Australian safety PBS with short explanations is shown in Table D-3. Note that standard Nr. 6 and 15 have not yet been incorporated in the scheme as the performance limits are not yet specified. Table D-4 shows the Australian PBS with respect to infrastructure. A short explanation is given below this table.

Table D-3 Safety-related PBS used in Australia.[148]*.*

Safety-related performance-based standards		
Nr.	**Name**	**Summary statement**
1	Startability	The ability to commence forward motion on specified upgrade.
2	Gradeability	
	a) Maintain Motion	The ability to maintain forward motion on specified upgrade.
	b) Maintain Speed	The ability to maintain a minimum speed on a specified upgrade.
3	Acceleration Capability	The ability to accelerate either from rest or to increase speed on a road with no grade.

[146] Woodrooffe, J. (2012). *Performance-Based Standards and Indicators for Sustainable Commercial Vehicle Transport.* Michigan: Michigan Transportation Research Institute. Page 5-7.

[147] Woodrooffe, J. (2012). *Performance-Based Standards and Indicators for Sustainable Commercial Vehicle Transport.* Michigan: Michigan Transportation Research Institute. Page 5-7.

[148] National Transport Commission Australia. (2008). *Performance based standards scheme. The standards and vehicle assesment rules.*

4	Overtaking Provision	Specifies the length of the envelope which is occupied by the vehicle.
5	Tracking Ability on a Straight Path	The total swept width while travelling on a straight path, including the influence of variations due to cross fall, road surface unevenness and driver steering activity.
6	Ride Quality	Comfort experienced by driver while driving over defined road profile.
7	Low-speed swept path	The maximum width of the swept path in a prescribed 90° low speed turn.
8	Frontal Swing	
	a) Trucks	The maximum width of the frontal swing swept path in a prescribed 90° low-speed turn.
	b) Semi-trailers: Maximum difference	The maximum difference between the frontal swing-out distances between adjacent vehicle units in a prescribed 90° low speed turn.
	c) Semi-trailers: Difference of maxima	The difference between the maximum frontal swing-out distances between adjacent vehicle units in a prescribed 90° low speed turn.
9	Tail Swing	The maximum outward lateral displacement of the outer rearmost point on a vehicle unit during the initial and final stages of a prescribed 90° low speed turn.
10	Steer-Tyre Friction Demand	The maximum friction level demanded of the steer tyres of the hauling unit in a prescribed 90° low speed turn.
11	Static Rollover Threshold	The steady state level of lateral acceleration that a vehicle can sustain without rolling over during turning.
12	Rearward Amplification	The degree to which the trailing unit(s) amplify the lateral acceleration of the hauling unit.
13	High-Speed Transient Off-tracking	The lateral distance that the last-axle on the rearmost trailer tracks outside the path of the steer axle in a sudden evasive manoeuvre.
14	Yaw Damping	The rate at which “sway” or yaw oscillations decoy after a short duration of steer input at the hauling unit.
15	Handling Quality	Oversteer/Understeer vehicle handling behaviour at certain levels of lateral accelerations.
16	Directional Stability Under Braking	The ability to maintain directional stability under braking.

Table D-4 Infrastructure related PBS used in Australia.[149]

Infrastructure related performance based standards		
Nr.	**Name**	**Summary statement**
17	Pavement Vertical Loading	State to which each individual axle group vertical loads the road
18	Pavement Horizontal Loading	State to which each individual axle group horizontally loads the road during low speed turn, acceleration and uphill grades.
19	Tyre Contact Pressure Distribution	Patterns of the pressure distribution measured between road and tyre in the contact patch.
20	Bridge Loading	The rate at which the bridge is loaded by axle groups' normal forces.

Each standard has four levels reflecting the performance. Depending on the performance level, the vehicle is allowed to access on dedicated parts of the road network. For example Level 1 has general access on any part of the road network (including cities), whereas Level 4 can operate only in remote areas with sufficient lanes for overtaking.

[149] National Transport Commission Australia. (2008). *Performance based standards scheme. The standards and vehicle assesment rules.*