GREENING AND SAFETY ASSURANCE OF FUTURE MODULAR ROAD VEHICLES (WORKSHOP HVTT-13)

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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

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Longer and heavier vehicles (LHVs) allow combinations of existing loading units (multiples), with the potential for reducing cost and environmental impact per unit load, complying with hub & spoke logistic concepts where vehicle systems can be split and loading units can be delivered separately into city areas.
The requirements for new (longer and heavier, and definitely more flexible) vehicle concepts provide a guideline for further investigations:

- Need for smart, clean and profitable transport
- Leading to a transport system with an efficient combination of logistic and transport concepts
- Legalisation 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 analyze the impact of allowing more multiples of loading units, a selection of vehicle combinations is made to be compared 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, existing LHVs and some reference vehicles. The selection is based on common loading unit lengths, with all LHVs complying with 60 ton GVW (Gross Vehicle Weight). 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 (stability, dynamic performance, powertrain and maneuverability) and standards to guarantee that no extra infrastructure damage will result from the use of the specific vehicle combination compared to already accepted ones. PBS has been used successfully in countries such as Canada and Australia, with an expected potential in other countries Modifications have been proposed 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. These analyses 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 the 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, steerable axles are required to meet the maneuverability limits as set by the 96/53/EC regulation.
Regarding the impact 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 63% lower. Replacement by different loading units results in a potential improvement of 4 to 10%.
In a similar way, a comparison is made on the total cost of ownership (TCO), 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 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 further to match European conditions.

This paper is presented at the HVTT-13 conference in San Luis in the form of a workshop, with three separate presentations. These presentations will follow the approach as described in this summary, and focus on:

- Megatrends in transport & logistics and proposal for a PBS legal framework
- Validation of smart transport: PBS on safety and infrastructure
- Validation of sustainable and efficient transport and proposal for new smart, green and profitable vehicle concepts.

1. Environment and legal framework

In this section, the consequences of megatrends on logistic and transport concepts are set against the current and upcoming legal framework.
The major megatrends which have an influence on transport are indicated as follows:

- 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 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, aiming at reducing the problems of road congestion, environment and safety. 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 a concept that allows combinations of existing loading units (multiples) on vehicles and is shown to be in conformity with all defined megatrends. EMS results in longer and sometimes heavier vehicle combinations. 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.

To cope with the future megatrends a vision for an efficient logistic system which combines the above logistic concepts is described, and which is illustrated in figure 1. This figure distinguishes between different types of transport (urban, interurban) and segments (city,

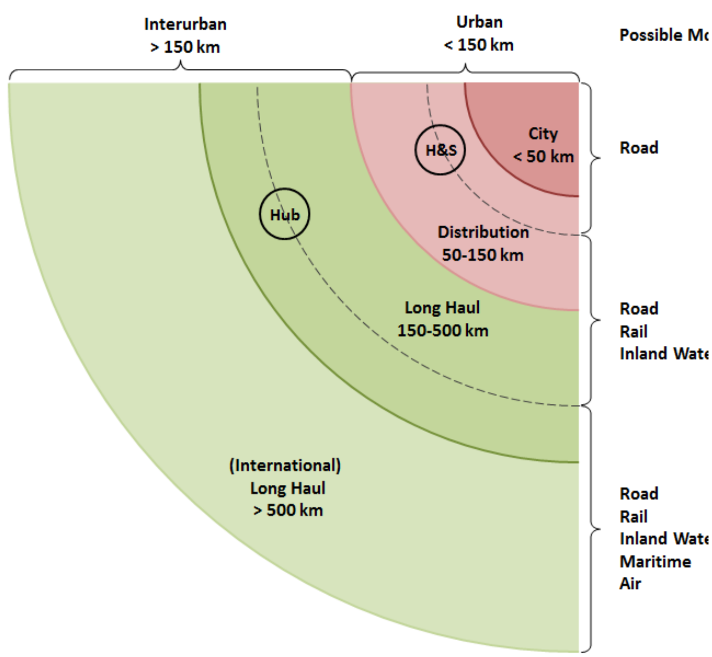

Figure 1.: Vision of logistic concepts (principle)

distribution, long-haul), with hub and spoke systems connecting these segments.
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 is of importance because they are needed for switching loading units between modes.

Transport concepts
With respect to transport concepts the megatrends issue in the need for multiples, accounting for pallets and loading units (swap bodies, containers, semi-trailer).
The above vision requires multiples of current loading units, improving the transport efficiency, and serving the logistic concepts. The requirement of making a complete turn or roundabout according to the 96/53/EC regulation limits the total vehicle length to approximately 33 m.

Infrastructure and vehicle regulations
There is an EU-wide agreement on infrastructure for certain roads, and there exist 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 agreed on the use of 25.25 m long and 60t trucks. 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.

Two directions to solve this conflict are treated in this paper:

- 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.

2. Vehicle combinations and new legal framework

We have analysed 14 different vehicle combinations with respect to safety, infrastructure impact, CO_2 and TCO. That includes standard vehicle combinations, existing LHVs and reference vehicles. In the existing LHV's, three combinations longer than 25.25 m have been considered, representing the current trend for LHV for the near future. These combinations still need to comply to 60t maximum GCW. The different groups were selected based on their combination of loading units, GCW and length, to permit a good comparison when the performance of the different groups is assessed. There are different stakeholders with interest in smart, clean and profitable vehicle combinations. Clean (CO_2 per unit load) means less impact on the environment. The customer requires efficient transport concepts. The lawmakers require smart concepts that are safe and suitable in their circumstances, and a new legal framework can be of help. The combinations considered are shown in table 1. The load units correspond to containers (20, 40, 45 ft), swap bodies (C782), and semitrailers.

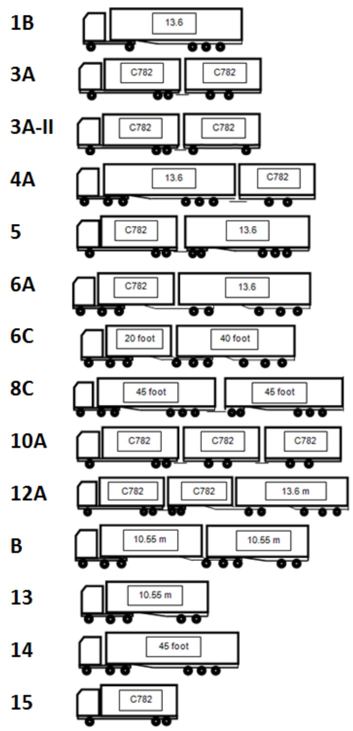

Table 1.: Vehicle combinations

To draw up a proposal for a new legal framework, regulations outside Europe have been studied. A number of countries (Australia, Canada and New Zealand) has a performance-based legal framework. Practice shows that this legal framework, verifying vehicle combinations against Performance-Based Standards (PBS), can be used for all vehicle combinations and has positive effects on safety and CO_2 emission compared with a conventional legal framework, which is the motivation to base a new legal framework on PBS.

The proposal is split into two subjects: road classes (with possibly different performance requirements) 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. Detailed characteristics still need to be defined by the road authorities.

The PBS are split up into safety standards (stability, dynamic performance, powertrain and manoeuvrability) and infrastructure standards. We use the Australian PBS as our starting point, but newly developed standards have been added. For each PBS the source, requirements from the European regulation, a short description and the load conditions has been defined.

standard	Source	EU-requirement	Description
Static roll-over threshold	Australian PBS	None	The steady state level of lateral acceleration that a vehicle can sustain without rolling over during turning.
Directional stability under braking	Australian PBS	UNECE agreement	The ability to maintain directional stability under braking
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

Table 2.: Stability standards

standard	Source	EU-requirement	Description
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
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 3.: Dynamic performance standards

standard	Source	EU-requirement	Description
Startability	Australian PBS	Directive 97/27/EC, point 7.9	The ability to commence forward motion on a specified upgrade
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 4.: Powertrain standards

standard	Source	EU-requirement	Description
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.
Frontal swing	Australian PBS	Directive 96/53/EC, point 7.6.2	The maximum width of the frontal swing swept path in a prescribed 90° low-speed turn.
Tail swing	Australian PBS	Directive 96/53/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	The smallest radius a vehicle combination can make in a 360° turn. The minimum radius that the turn needs to be depends on the road class.

Table 5.: Manoeuvrability standards

The performance value per European road class still requires further research. A short outline of the (EU-modified) PBS on safety and manoeuvrability is give in table 2 - 5. The infrastructure standards do not consist of groups. The four different PBS have to do with damage on roads and bridges. More research is required to define performance values per road class. The infrastructure standards are shown in table 6.

standard	Source	EU-requirement	Description
Pavement vertical loading	Australian PBS	Directive 96/53/EC	Limit the stress on the pavement layers below the surface of the road.
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.

Table 6.: Infrastructure standards

3. Validation of smart, clean and profitable transport

The assessment of the smart, clean and profitability properties of the selected vehicle combinations has been carried out in the following way:

- *Validation on smart transport*
  For validation on smart transport a simulation tool has been developed by the Eindhoven University of technology and the HAN University of Applied Sciences, analysing each combination against stability standards, dynamic performance standards, powertrain standards and manoeuvrability standards. 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 . 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. The vehicle models have been extensively validated on the basis of three sets of LHV test sessions, and a large number of field- and validation tests on conventional 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. A realistic 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.

- *Validation of 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.

3.1. Validation of smart (safe, with limited damage to the infrastructure) transport

The PBS were simulated with use of the software tool, both fully loaded and empty, where the worst case has been used for performance assessment. Based on the simulation results the combinations are assessed regarding their general safety and their suitability for the European infrastructure.

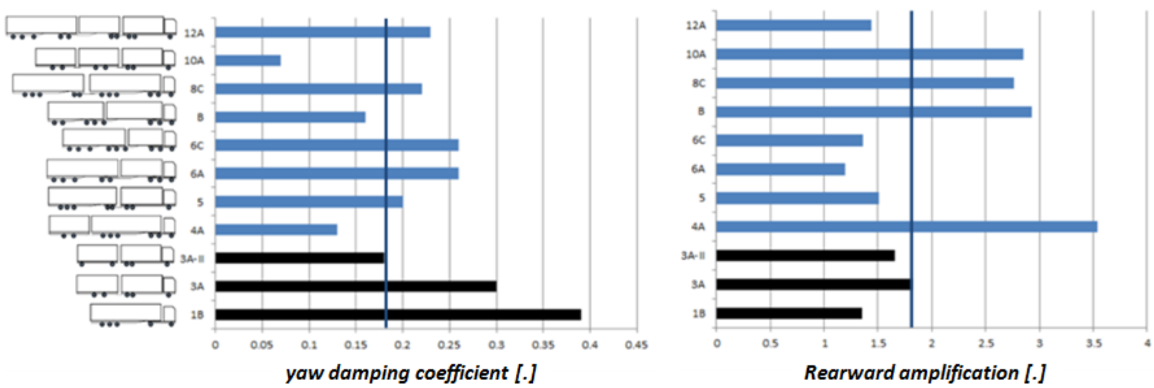

Figure 2.: Performance results for yaw damping and rearward amplification

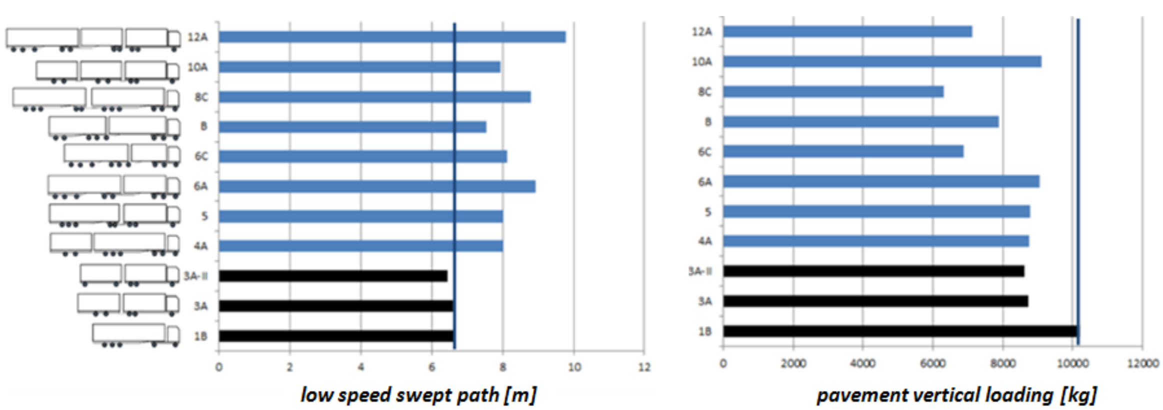

Figure 3.: Performance results for swept path and vertical pavement loading

The simulations are based on the Performance-Based Standard Scheme of the National Transport Commission of Australia.[1] 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.
We have shown some of the results in figures 2 (yaw damping, rearward amplification) and 3 (swept path and vertical pavement loading).
Observe that some combinations are not in the range of the standard vehicles (indicated in black, the lowest three combinations). For the damping coefficient, this is due to the number of articulations and the distance between kingpin and axle groups. Technological improvement related to air-suspension, roll-coupled modules and increasing the roll height will compensate that. Many combinations are in the range of the standard vehicles with respect to rearward amplification (RA). The vehicles with the last coupling being realised as a drawbar module results in the higher RA. The same technological improvement as mentioned above can reduce the rearward amplification. Low speed manoeuvring is worse than for the standard vehicles, due to the larger length and the number of unsteered axles.

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
Engine torque							↑	↑	↑										
Number of driven axles							↑	↑	↑										
Position of king pin and 5th wheel plate							↑	↑	↑										
Number of axles	↑		↑	↑	↑	↑													↑
Air suspension	x		x	x	x	x													x
Braking technologies		x																	
Distance between axles	↑				↑					↓				↓					↑
Number of articulation points					↓					↑									↓
Active and passive steering axles			↑	↑						x		x	x	↓					
Roll-coupled modules	x		x	x		x													
Increasing roll-centre height	x		x	x		x													
Distance from axles to rear end of trailer												↓							
Towing bar length			↑	↑	↑														
Distance from steered axle to front of cabin			↑	↑	↑						↓								
Distance from king pin to axle centre	↑									↓				↓					

Table 7.: The effect on the defined PBS of changing technical characteristics or adding technological improvements to a vehicle combination (×: positive influence, ↑: Increase characteristic for positive influence, ↓: decrease characteristic for positive influence)

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

This low-speed swept path can easily be improved by using active and passive axle steering systems. The pavement loading results reveal that the LHVs, in many cases, yield an even lower damage to the road compared to standard vehicles, which is due to the lower axle loads. 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 feasible technological improvements or changes in technical characteristics are necessary. In table 7, the effects on the different PBS of changes in technical characteristics or addition of technological improvements to a vehicle combination are summarised. In this table a cross means that the change has a positive influence. An arrow in upward or downward position means that raising or reducing the value for the characteristic has a positive effect on the PBS.

3.2. Clean vehicle combination validation

Clean transport is considered as CO_2-efficient transport. CO_2 emission is directly proportional to the fuel consumption. First, to obtain the CO_2 emission results the fuel consumption per vehicle combination is calculated. 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 figure 4. 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.

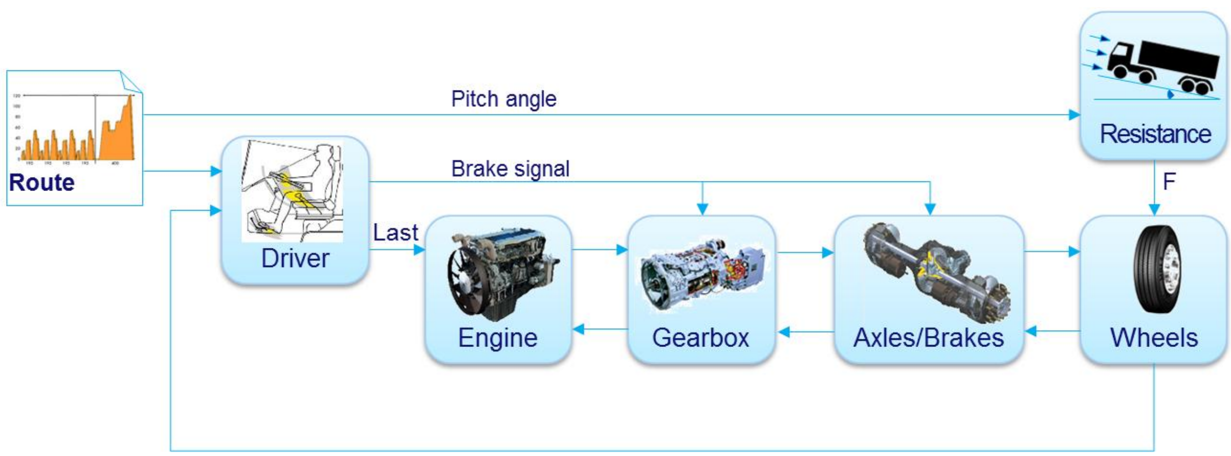

Fig. 4.: Schematic of fuel consumption tool

For the calculations, the following assumptions have been made:

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.[4] This value is valid only for the standard vehicle combinations.
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.[5] 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.

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 is determined. With the 86% to 14% split between articulated vehicles and road trains the value of 2.1 m^3 of freight per m^2 of container area is determined.

3.2.1 Simulation results

The **results** are shown in terms of both weight and volume. These results are shown in Table 8 . The average fuel consumption and CO_2 emission are the same for weight-related and volume related transport. 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.[6]
Based on the payload calculations the weight-related emission is expressed in grams CO_2 per tonne payload per km travelled (left part of table 7). Almost all LHVs appear to have a better tonne per km performance. Combinations 6C and B exceed the range of the standard vehicle combinations, 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 (right part of table 7). Almost all LHVs have a better m^3 per km performance, except for combinations 6C and B (due to the lower volume of the loading units).

[4] Akerman, I., & Jonsson, R. (2007). *European Modular System for road freight transport - experiences and possibilities.* Stockholm: TFG.
[5] Based on MAN sale volumes for long haul
[6] DIN EN 16258:2013-03

Combination	Average fuel consum-ption	CO_2 emission	Payload	Gram CO_2 per tonne payload per km travelled	Volume of freight	Gram CO_2 per m^3 freight per km travelled
	[l/100km]	[g/km]	[ton]	[g/tkm]	[l/100km]	[g/km]
Standard vehicle combinations						
1B	29.76	794.50	14.92	53.24	71.32	11.14
3A	34.06	909.31	16.19	56.18	80.46	11.30
LHVs						
4A	41.86	1117.58	22.39	49.92	111.29	10.04
5	42.50	1134.79	22.39	50.69	111.29	10.20
6A	43.74	1167.86	22.39	52.16	111.29	10.49
6C	42.16	1125.67	17.52	64.26	87.07	12.93
B	44.41	1185.85	17.84	66.46	88.69	13.37
8C	51.82	1383.67	27.83	49.72	138.34	10.00
10A	46.12	1231.48	24.28	50.72	120.69	10.20
12A	53.62	1431.77	29.31	48.85	151.52	9.45

Table 8.: Weight-related and volume-related fuel consumption and CO_2 emissions

3.2.2 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 9.

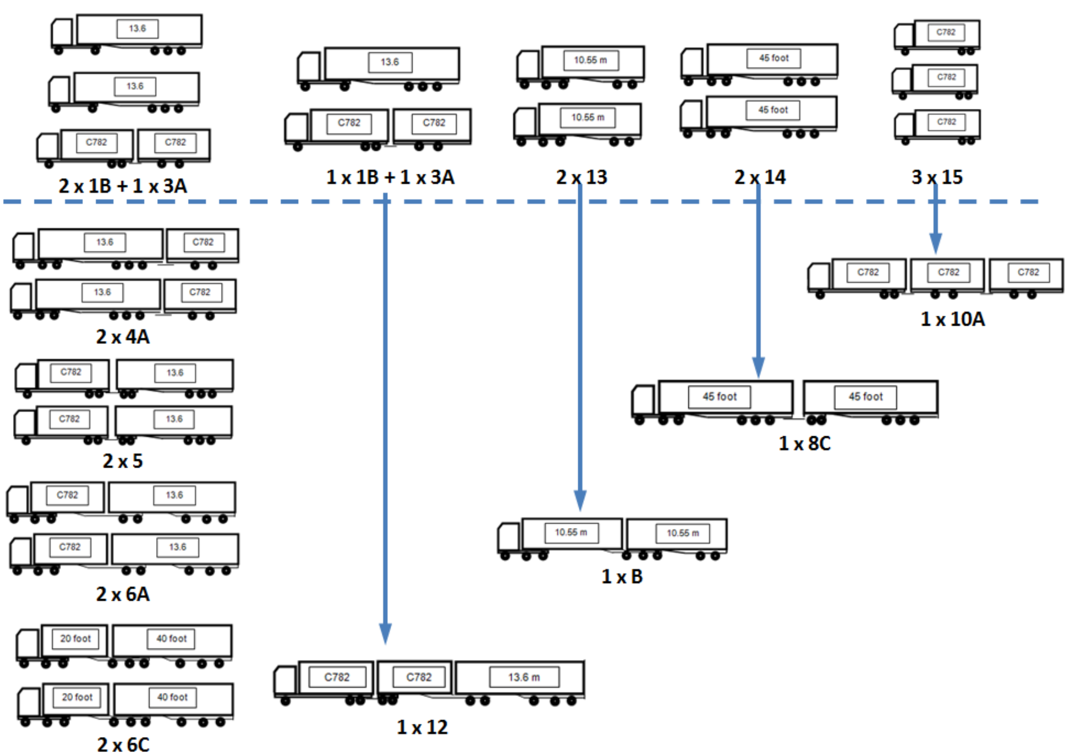

Table 9.: Replacement of standard vehicles by LHVs

Based on the comparison of these "use cases" CO_2 emission is again expressed in terms of mass and volume. The results of these calculations are shown in Table 10 .

Use case	Fuel consum-ption	CO_2 emission	Payload	Gram CO_2 per tonne payload per km travelled	Potential	Volume of freight	Gram CO_2 per m^3 of freight per km travelled	Potential
	[l/100km]	[g/km]	[ton]	[g/tkm]	[%]	[m^3]	[g/m^3km]	[%]
2×1B+1×3A	**95.57**	**2498.31**	**46.04**	**54.27**		**223.10**	**11.20**	
2×4A	83.71	2235.16	44.78	49.92	8.02	222.57	10.04	10.32
2×5	85.00	2269.16	44.78	50.69	6.60	222.57	10.20	8.94
2×6A	87.48	2335.72	44.78	52.16	3.88	222.57	10.49	6.29
2×6C	84.32	2251.34	35.03	64.26	-18.41	174.15	12.93	-15.45
1×1B+1×3A	**63.81**	**1703.81**	**31.11**	**54.77**		**151.78**	**11.23**	
1×12A	53.62	1431.77	29.31	48.85	10.79	151.52	9.45	15.82
2×13	**59.51**	**1589.00**	**8.92**	**178.14**		**44.35**	**35.83**	
1×B	44.41	1185.85	17.84	66.46	62.29	88.69	13.37	62.68
2×14	**68.60**	**1831.70**	**27.83**	**65.82**		**138.34**	**13.24**	
1×8C	51.82	1383.67	27.83	49.72	24.46	138.34	10.00	24.46
3×15	**74.20**	**1981.15**	**24.28**	**81.60**		**117.94**	**16.80**	
1×10A	46.12	1231.48	24.28	50.72	37.84	120.69	10.20	39.26

Table 10.:CO_2 emissions per use case, weight-related and volume-related.

For the weight-related comparison table 9 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 63%. For replacement with different loading units the potential is between 4 and 10%.

For the volume-related comparison, the CO_2 emission is also 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 63%. For replacement with different loading units this potential is between 6 and 16%.

3.3. Profitable vehicle combination validation

In this section, 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."[8] As such it gives an overview not only of the initial costs but also of all aspects of usage.

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

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.

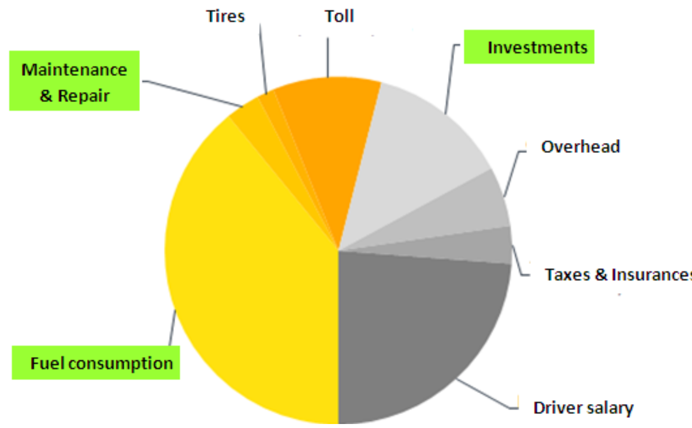

Fig. 5.: Exemplary Total Cost of Ownership composition of a heavy duty vehicle

3.3.1. 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 these 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.

3.3.2. Results, comparison of vehicle combinations

The Total Costs of Ownership are shown in 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. See table 11 for results, both related to weight and to volume.

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.

Combination	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^3km]
1B	154,876.53	1.147	14.924	57.0	7.687	71.321	82.0	1.609
3A	164,761.61	1.220	16.187	78.1	7.542	80.459	83.9	1.517
4A	190,718.66	1.413	22.388	58.5	6.311	111.287	82.5	1.269
5	192,995.38	1.430	22.388	58.8	6.390	111.287	82.5	1.284
6A	195,747.53	1.450	22.388	62.9	6.478	111.287	82.5	1.303
6C	195,027.73	1.450	17.517	52.0	8.245	87.074	88.1	1.659
8C	217,508.71	1.611	27.830	95.1	5.787	138.337	82.1	1.164
10A	197,588.54	1.464	24.280	69.6	6.029	120.688	83.9	1.213
12A	220,966.42	1.637	29.307	100.0	5.585	151.516	82.9	1.080
B	202,366.46	1.499	17.843	59.0	8.403	88.691	78.6	1.691

Table 11.:Total cost of ownership, weight- and volume-related.

Use case	Payload	TCO per tonne payload, per km travelled	Potential	Volume of freight	TCO per m^3 freight, per km travelled	Potential
	[ton]	[Ct/tkm]	[%]	[m^3]	[Ct/m^3km]	[%]
2×1B+1×3A	**46.04**	**7.635**		**223.10**	**1.575**	
2×4A	44.78	6.311	17.34	222.57	1.269	19.44
2×5	44.78	6.390	16.31	222.57	1.284	18.48
2×6A	44.78	6.478	15.16	222.57	1.303	17.32
2×6C	35.03	8.245	-7.99	174.15	1.659	-5.30
1×1B+1×3A	**31.11**	**8.719**		**151.78**	**1.560**	
1×12A	29.31	5.585	26.61	151.52	1.080	30.78
2×13	**8.92**	**13.688**		**44.35**	**2.751**	
1×B	17.84	8.403	38.52	88.69	1.691	38.52
2×14	**27.83**	**9.111**		**138.34**	**1.832**	
1×8C	27.83	5.787	36.48	138.34	1.164	36.45
3×15	**24.28**	**12.877**		**117.94**	**2.650**	
1×10A	24.28	6.029	53.18	120.69	1.213	53.23

Table 12.:TCO per use case, weight- and volume-related.

3.3.3. Results, 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 as shown in Table 9 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 12.

For the weight-related comparison table 12 shows that the TCO improved 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 25%. 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 50% is possible, as here only one combination is needed instead of three vehicles.

Also for the volume-related comparison 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 15 to 20%. 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%.

4. Proposal for new vehicle concepts being smart, clean and profitable.

In the preceding sections, the requirements from a logistics and environmental point of view have been analysed. A large number of existing vehicle combinations, operating in various areas of the world, 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 section to prescribe "the" exact future truck combination, as a PBS-based framework allows innovation and many alternative solutions are possible.

4.1. General trends.

Generally speaking, the future vehicle concepts should evolve from the current longer and heavier vehicle combinations which were discussed in previous sections. 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 the loading units which will be 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 mounted on any vehicle; this will lead to optimisation of the logistic process.

This will clearly result in elongation of the vehicles, a trend that is already present in the commercial-vehicle sector. However, longer mono-volume vehicles are still restricted by legislation; they are simply easier to maintain and operate at distribution hubs than multiples of smaller units with equal capacity.
Beside this, especially the towed vehicles should be limited in the number of active elements, as their introduction to the market might be very difficult due to the price for the fleet owners.
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 was to specify the future concepts for both tractors and rigid trucks in accordance with the matrix below:

	Tractor	Rigid truck
60 foot container	1 × 60 foot semi-trailer	
45 foot container	2 × 45 foot loading units	45 foot rigid truck with 45 foot loading unit
C745 Swap body	-	C745 rigid truck with 2 × C745 loading unit(s)

Table 13.: Loading unit vs. towing vehicle

Last but not least 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 - 1.25m in length at the back of the last vehicle. It opens only at high velocity and hence, does not influence the low-speed maneuverability and the tail swing.

Longer Cabin – it can be proved that forward elongation of the cabin will, provided that the radius is appropriate, not influence the frontal swing of the vehicle. Hence, an elongation of 1 m can, without affecting the performance, be used to substantially reduce the frontal air drag of the vehicle.

4.2. 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.

Concept I – Swap-body Combo

Since use of the C-series swap-body is predicted to increase in the future 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 (D-Tec) 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 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, see figure 6.

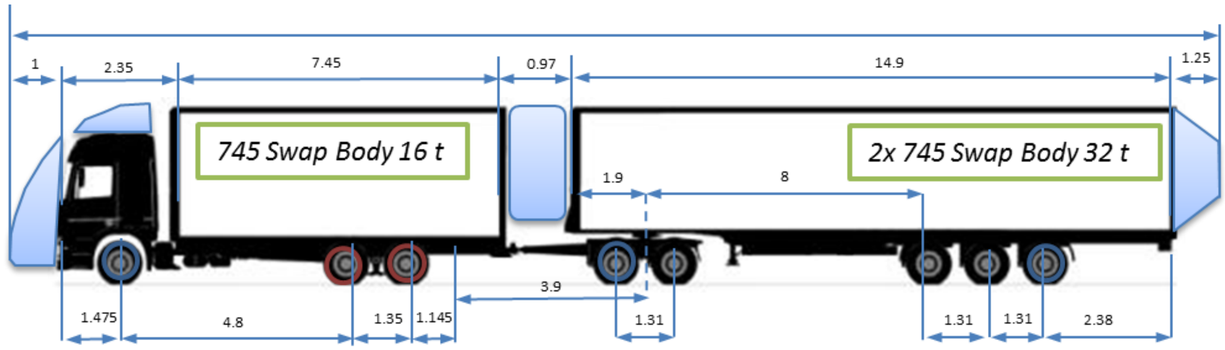

Fig. 6.: Future Vehicle concept I

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 14.

	Truck			Dolly		Semi-trailer		
Axle number	I.	II.	III.	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

Table 14.: Vertical axle loads when fully loaded, concept I

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), as the investment costs for fleet owners are lower. Combination 4A, however, has the worst performance, and hence the above combination is preferred.

Concept II.: Combination with two semi-trailers

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, see figure 7. The semi-trailers are linked 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 above that of the comparable combination 8C, which is always unlocked. This feature will transform the combination into a very long B-Double.

At low speed the lock is released, and so the maneuverability performances are guaranteed thanks to the steerable dolly and extra articulation point. The smart 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.

Vertical axle loads for fully loaded GVW are listed in table 15.

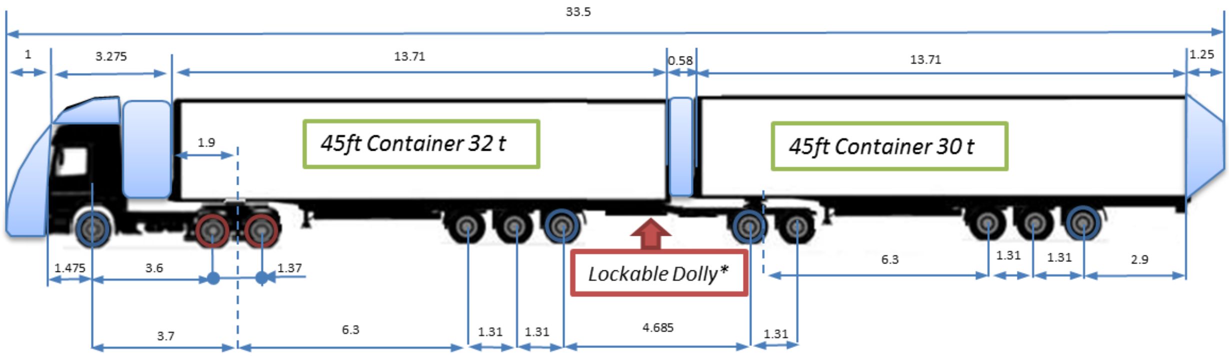

Fig. 7.: Future Vehicle concept II

	Truck			B-Unit					Semi-trailer		
Axle number	I.	II.	III.	I.	II.	III.	IV.	V.	I.	II.	III.
Axle type	Steerable	Driven	Driven	Steerable	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

Table 15.: Vertical axle loads when fully loaded, concept II

Concept III - Transport Bus

The third concept can be understood as a transport bus which is able to accommodate 45 ft 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 45 ft container. The combination is very stable during high speed and provides sufficient traction force for startability and gradeability. Low-speed manoeuverability 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 figure 8, and axle loads are shown in Table 16.

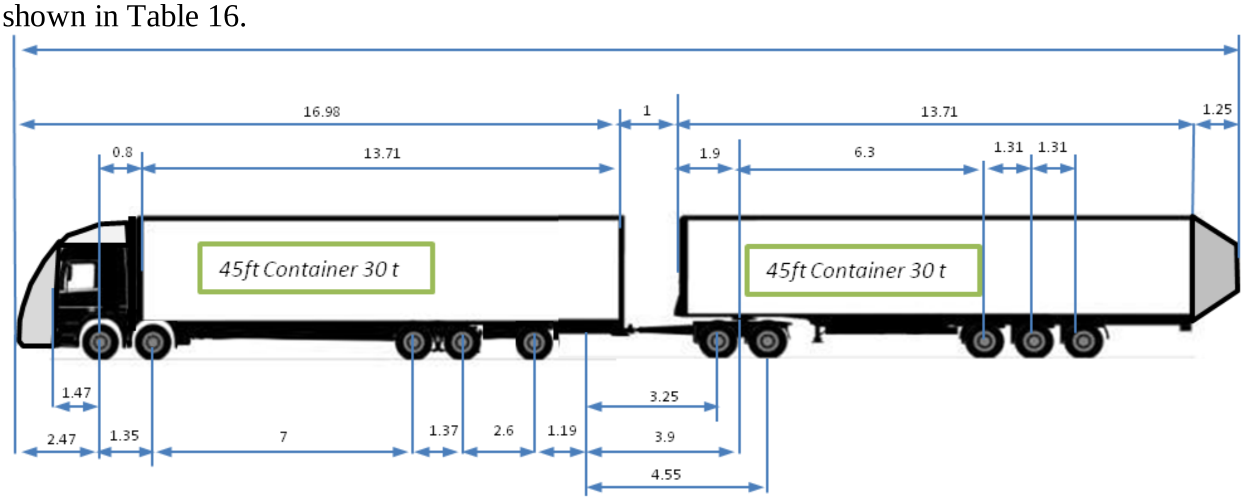

Fig. 8.: Future Vehicle concept III

	Truck					Dolly		Semi-trailer		
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

Table 16.: Vertical axle loads when fully loaded, concept III

4.3. Validation on smart, clean and profitable 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 identically simulated as in previous sections, and 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 and the worst-performing current LHV combination.

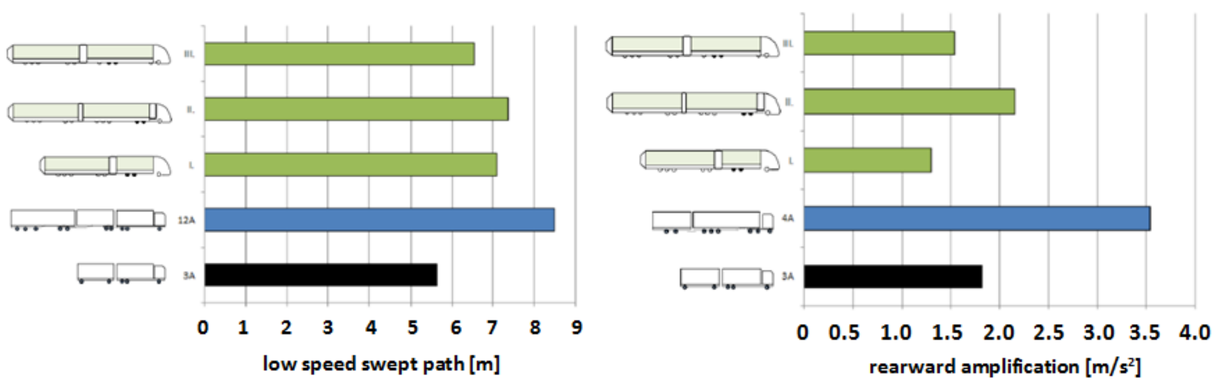

Figure 9.: Performance results for swept path and rearward amplification of future vehicle concepts

All of these future concept combinations satisfy the 7.2 m swept path width or are very close to that, and they are able to negotiate an entire circle of 12.5 m. Their static roll-over limit is found to be similar to those for standard vehicles. Lateral dynamic stability appears to be similar or even better, due to the proper distance between axle groups and kingpins, and all combinations satisfy the EU limits on startability of 12 %. See figure 9 where results for swept path and rearward amplification are shown.

For validation on **clean transport** again the fuel consumptions and the CO_2 emissions have been calculated. The same assumptions on route and average loading (weight and volume-related) were applied. For the average loading the weight and volume utilization is shown in Table 17.

	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

Table 17.: Weight and volume utilization of future concepts

The results shown in Table 18 are weight and volume-related. Based on the payload calculations the weight-related and volume-related emission are expressed in grams CO_2 per tonne payload per km travelled, and grams CO_2 per m^3 freight per km travelled, respectively.

	Average fuel consumption	CO2 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]	[m3]	[g/tkm]	[g/m3km]
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

Table 18.: Fuel consumption and CO_2 emission results

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 standard tractor - semitrailers (combination 14) is possible. In this way the use cases have been defined as indicated in Table 19.

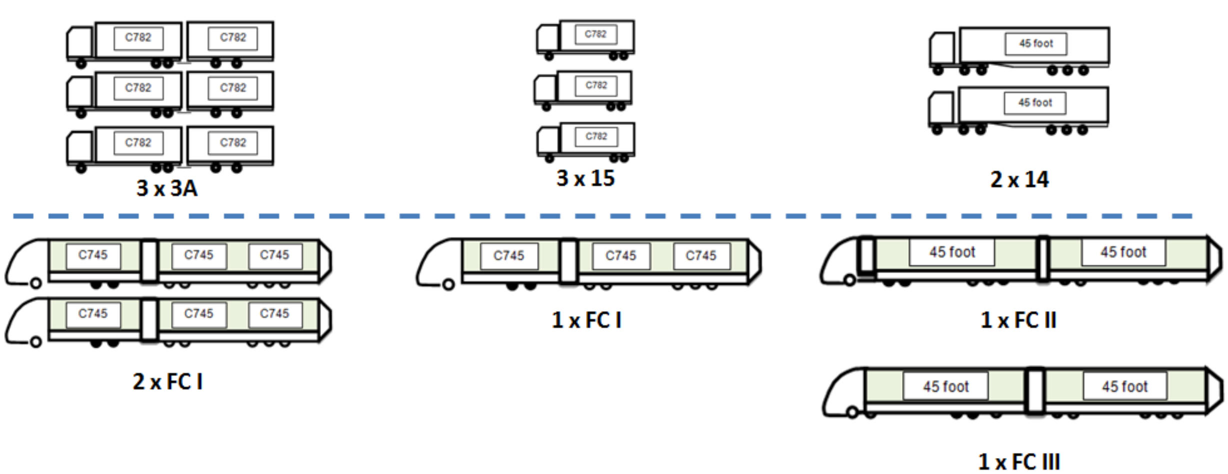

Table 19.: Replacement of standard vehicles by Future Concepts

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 20.

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

Use case	Fuel consum-ption	CO_2 emission	Payload	Gram CO_2 per tonne payload per km travelled	Potential	Volume of freight	Gram CO_2 per m^3 of freight per km travelled	Potential
	[l/100km]	[g/km]	[ton]	[g/tkm]	[%]	[m^3]	[g/m^3km]	[%]
3×3A	**102.17**	**2727.93**	**48,56**	**56.18**		**241.38**	**11.30**	
2×FC-I	89.12	2379.40	46.22	51.48	8.36	229.75	10.36	8.36
3×15	**74.20**	**1981.15**	**24.28**	**81.60**		**117.94**	**16.80**	
1×FC-I	44.56	1189.70	23.11	51.48	36.91	114.87	10.36	38.35
2×14	**68.60**	**1831.70**	**27.83**	**65.82**		**138.34**	**13.24**	
1×FC-II	51.60	1377.83	27.83	49.51	24.78	138.34	9.96	24.78
1×FC-III	51.29	1369.44	27.83	49.21	25.24	138.34	9.90	25.24

Table 20.: CO_2 emission results per use case, weight- en volume-related, of Future Concepts

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 21. 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.

	TCO per year	TCO per km	Payload	Average utilisation	TCO per tonne payload per km travelled	Volume of freight	Average utilisation	TCO per m3 freight per km travelled
	[€/year]	[€/km]	[ton]	[%]	[Ct/tkm]	[m^3]	[%]	[Ct/m^3km]
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

Table 21.: Total Cost of Ownership for de Future Concepts.

A proper comparison will again consider use cases. The same comparison as for the fuel consumption has been used, see Table 22. 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.

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%

Table 22.: Total Cost of Ownership per use case, of the Future Concepts.

We close this section with some remarks:

1. For comparing and choosing a vehicle combination it is essential to take a detailed look at smartness, cleanness and profitability. Concepts need thereby to fit inside the current infrastructure and should be safe at any speed. This is a task for the regulatory authorities, who will 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.

2. Although the future concepts may offer substantial improvements in terms of productivity and transport efficiency, there are still issues which need 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.

5. Conclusions and Outlook.

5.1. Conclusions

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.

5.2. 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. 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 is essential for successful implementation of a new legal framework based on PBS.