REPORT

Energy demand impacts of Long Heavy Duty Vehicles - Analysis of possible ways to introduce the effects of long vehicles into the GAINS model

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Report Summary

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Title and subtitle of the report

Energy demand impacts of Long Heavy Duty vehicles - Analysis of possible ways to introduce the effects of long vehicles category into the GAINS model

Summary

The objective of this study was to explore possible approaches to explicitly include the use of long heavy duty vehicles (vehicles with a total weight over 40 ton and a total length over 18.75 meter) as an energy efficiency measure in the GAINS model, to assess their efficiency in terms of transport work (ton-kilometres) and traffic work (vehicle-kilometres), and to provide a basis for the analysis of the emission mitigation potential with respect to this vehicle category, currently not distinguished in the model. Potential substitution of long heavy duty vehicles with conventional European vehicles for goods transportation in Sweden was modelled and analysed. Calculation results indicated that one conventional European vehicle would consume 22 per cent less fuel per traffic work but 30 per cent more fuel per transport work than one long heavy duty vehicle. As a net effect, the total fuel consumption of heavy duty trucks would increase by 24 per cent if long heavy duty vehicles were withdrawn. For the Swedish conditions represented in this analysis, the use of long heavy duty vehicles appears to be more fuel efficient than to use conventional EU vehicles. The main conclusions of this study is that it is possible to develop an integrated assessment model method for presenting long heavy duty vehicles as a fuel efficiency option in the transport sector, but that the benefit of the option is dependent on assumptions in the input data. Improved system understanding, statistical data, and scenarios would be needed for representation of long heavy duty vehicles as a general fuel efficiency option in future analyses.

Keyword

The GAINS model, heavy duty vehicles, fuel efficiency

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Summary

Road freight by heavy duty trucks with a total weight over 3.5 ton makes a significant input into the total European greenhouse gas emissions. The current European regulations for cross-border transport limit the trucks' total weight to 40 tons and their length to 18.75 meters. Within the member states even heavier and longer trucks – mega-trucks, also called long heavy duty vehicles – are allowed for use. The Netherlands, Germany, and especially the Scandinavian countries have practical experience of goods transportation with mega-trucks. A number of studies indicate that long heavy duty vehicles are more efficient in terms of fuel use per ton of transported goods than conventional European vehicles. The discussion is on-going whether long heavy duty vehicles should be permitted for cross-border transport throughout Europe.

The GAINS model, developed by the International Institute for Applied System Analysis (IIASA), currently operates with one heavy duty vehicle category including all vehicles with a total weight over 3.5 ton. Potential effects of differences in fuel efficiency between long heavy duty vehicles and conventional European vehicles are currently not possible to explicitly model in GAINS.

The objective of this study was to explore possible approaches to explicitly include long heavy duty vehicles in the GAINS model, to assess their fuel efficiency and to provide a basis for the analysis of emission mitigation potential with respect to this vehicle category.

A range of parameters were developed to characterize goods transportation, in addition to the parameters currently used in GAINS. Potential substitution of long heavy duty vehicles with conventional European vehicles for goods transportation in Sweden was modelled and analysed. Calculation results indicate that a conventional European vehicle would consume 22 per cent less fuel per traffic work (megajoule/vehicle-kilometre) but 30 per cent more fuel per transport work (megajoule/ton-kilometre) than a long heavy duty vehicle. The total fuel consumption by heavy duty trucks would increase by 24 per cent if long heavy duty vehicles were withdrawn. For the Swedish conditions represented in this analysis, the use of long heavy duty vehicles appear to be more fuel efficient than to use conventional European vehicles.

The main conclusions of this study is that it is possible to develop an integrated assessment model method for presenting long heavy duty vehicles as a fuel efficiency option in the transport sector in the GAINS model, but that this method requires data that is currently not available. Numerical assumptions were used in the analysis, but the results of the analysis varied greatly as a result of changes in the assumptions. Improved system understanding, statistical data, and scenarios would be needed for representation of long heavy duty vehicles as a general fuel efficiency option in future analyses.

The study was conducted within the Swedish Clean Air Research Program - SCARP (http://www.scarp.se/).

Foreword

This report presents the results from one of the research activities aimed at enhancing the Integrated Assessment Modelling capacity within the Swedish Clean Air Research Programme (SCARP). Within this programme one of the key research areas has been Integrated Assessment Modelling and development of a Swedish version of the GAINS model. The project group would like to thank the following organisations and experts for assistance and review of the project results.

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Contents

Abbreviations

C	Conventional vehicle technology
I	Improved vehicle technology
A	Advanced vehicle technology
EU	European Union
EU≤34 t	Conventional EU vehicles with a total weight up to 34 t (vehicle category)
EU>34 t	Conventional EU vehicles with a total weight over 34 t (vehicle category)
FC	Fuel consumption, PJ
FTcE	Fuel traffic efficiency, MJ/veh-km
FTtE	Fuel transport efficiency, MJ/t-km
GAINS	The Greenhouse gas – Air Pollution Interactions and Synergies model (http://gains.iiasa.ac.at)
HBEFA	The Handbook Emission Factors for Road Transport, road traffic emission model (http://www.hbefa.net)
HDT	Vehicle category Heavy duty trucks (a GAINS model sector)
IIASA	International Institute for Applied System Analysis
LCU	Load capacity utilization, shares
LV	Long vehicles: heavy trucks with a total weight over 40 t (vehicle category)
RT	Rigid trucks
SEK	Swedish Crowns
TRANS-TOOLS	TOOLS for TRansport Forecasting ANd Scenario testing, European transport network model (http://energy.jrc.ec.europa.eu/TRANS-TOOLS)
TT/AT	Truck trailers and articulated trucks
vtg	Share of post-2010 (new, non-vintage) vehicles
tkm	Transport work, Mt-km
vehkm	Traffic work, Gveh-km

1 Introduction

Road freight transport in the EU makes a significant input into the member states' emissions of CO_2 and air pollutants. Around 75 per cent of all freight in Europe is delivered by heavy trucks with a total weight over 3.5 tonnes (t), which accounts for 6 per cent of total EU greenhouse gas emissions (Transport and Environment, 2012). The current European standards for international lorry transport, set in the Directive 96/53/EC, declare the length limit of 18.75 meters (m) and the total weight limit of 40 t. This only applies to cross-border truck use; member states are allowed to deviate from these limitations within their borders.

The Directive 96/53/EC currently undergoes a revision, which is supposed to provide input into the European Commission's strategy to reduce CO_2 emissions from heavy duty vehicles. One of the most disputable issues during the revision process is whether international use of so called "mega-trucks" with a length over 18.75 m and a weight over 40 t should be permitted Europe-wide. The supporters of mega-truck use for cross-border transport claim the following advantages of these vehicles compared to currently allowed trucks:

- Lower total fuel consumption resulting in lower emissions of air pollutants and greenhouse gases;
- Lower transport cost expressed in Euro per t-km and hence higher cost-efficiency;
- Better road safety;
- Lower noise levels;
- Decreased road wear and increased road longevity.

The opponents of Europe-wide transport with mega-trucks bring up the potential disadvantages:

- Induced transport due to lower prices causing increased transport demand;
- Possible modal shift from rail and ship traffic to road traffic resulting in higher total fuel consumption and in increase of CO_2 emissions;
- Limited area of use: mainly motorways only;
- Need for adjustments in the road infrastructure.

A number of scientific studies, involving both transport models and study cases, have been conducted with the purpose to investigate economic, environmental and social effects of non-conventional trucks. There is a possibility to explore the real effects taking place in those of the EU member states using their rights to widen the allowed vehicle weights and dimensions within the country borders. Several countries have set the maximum total weight of trucks at 44 t, while vehicles with a total weight up to 50 t are allowed in the Netherlands. In Germany mega-trucks are used in trials. The Scandinavian countries have the richest practical experience of goods transportation with long and heavy trucks. Finland is one of two countries setting the limit for vehicle length at 25.25 m. In Sweden, truck modules with a length of 18.75 to 25.25 m and a weight between 40 and 60 t have been used for decades. In 2010, they accounted for 74 per cent of the weight transported by road traffic within the country, which corresponds to 90 per cent of the related transport work expressed in ton-kilometers (t-km) (Löfberg and Hallberg, 2011).

In this study, we use the term "long vehicles" when describing heavy duty vehicles with a length over 18.75 m and a weight over 40 t, and distinguish them from "conventional EU vehicles", by which we mean either the whole range of vehicles with a total weight under 40 t, or a part of this category that is most likely to be substituted with long vehicles in a hypothetical case, where the latter would become authorized in Europe as a whole.

As one group of scientists investigates environmental, social and economic effects of long vehicles, another group is equally interested in the possible implementation of these effects into various models. The GAINS model, developed by the International Institute for Applied System Analysis (IIASA), is designed to calculate emissions of air pollutants and greenhouse gases, environmental and health impacts as well as costs of emission abatement (Amann, 2012). Potentials and costs for emission mitigation in different sectors are analysed in a number of IIASA reports, and the transport sector is specifically described in Borken-Kleefeld & Ntziachristos, 2012 and Borken-Kleefeld et al., 2009. In the model, all heavy duty trucks – trucks with a total weight over 3.5 t – are defined as the category HDT. In the countries where long vehicles are allowed, total fuel consumption by this category implicitly accounts for the difference between fuel efficiency of long vehicles and fuel efficiency of conventional EU vehicles. Long vehicles consume more fuel per km than conventional EU vehicles, but due to their ability to transport more weight per vehicle, fuel efficiency expressed as fuel consumption per transport work (MJ/t-km) is often lower for long vehicles, which makes them more fuel efficient than conventional EU vehicles. This type of effect is currently not possible to model explicitly in GAINS, where heavy duty trucks are not split into sub-categories, and where no parameters describing transported weight or transport work are used at the moment.

The main objective of this study is to explore possible approaches to explicitly include long vehicles in the GAINS model, to assess their efficiency, and to provide a basis for the analysis of emission mitigation potential with respect to this vehicle category. This is done by developing a range of parameters characterizing goods transportation and by analysing the resulting total fuel consumption calculated in the new parameter systems for the Swedish heavy duty vehicle fleet. Special attention in this process is paid to the impact of necessary assumptions on the calculation results determining the efficiency of long vehicles.

Following this introduction, Chapter 2 presents the methods used, including a description of the suggested model parameterization system, background data, general assumptions and parameter calculations. Chapter 3 presents the results of the parameter calculations, analysis of the underlying assumptions, and discussion of the efficiency of long vehicles with respect to a range of aspects not specifically included in this study. The conclusions in Chapter 4 summarize the main findings of the study.

2 Method

In this study, a modelling approach was developed enabling analysis of effects of the use or non-use of long vehicles for goods transport. Such an analysis required further disaggregation of the heavy duty truck (HDT) vehicle sector currently available in the GAINS model. In this study, the HDT sector was therefore further disaggregated into three categories:

1. Category EU≤34 t (conventional EU vehicles with a total weight 3.5 – 34 t, length up to 18.75 m);
2. Category EU>34 t (conventional EU vehicles with a total weight 34 – 40 t, length up to 18.75 m);
3. Category LV (long vehicles, total weight 40 – 60 t, length 18.75 – 25.25 m).

To model total energy demand of the heavy duty trucks, the methodology developed by IIASA to calculate carbon dioxide (CO_2) emission abatement in the transport sector was used. The IIASA methodology is based on the division of the category HDT into three propulsion technologies – conventional (c), improved (i) and advanced (a) – each defined by specific fuel efficiency (MJ/veh-km) and certain technological improvements compared to the "reference vehicle" in the year 2005 (Borken-Kleefeld et al., 2009). The methodology takes into consideration the effects of vehicle age on mileage and fuel efficiency by employing such parameters as mileage deflator, mileage inflator and share of post-2010 vehicles (post-2010 vehicles are considered as "new vehicles", whereas pre-2010 vehicles are considered as "old vehicles"). The structural tree of heavy duty vehicles in accordance with Borken-Kleefeld et al., 2009 is presented in Table 1. All parameters used in the analysis are described in detail in Chapter 2.1.

The IIASA methodology provides a well-grounded basis for further modelling; however, in order to analyse changes in the total fuel demand caused by introduction or withdrawal of long vehicles, certain additional parameters were needed. In this study a range of new parameters were introduced, mainly characterising transport of goods, see parameter list in Appendix 1 and explanations in Chapter 2.1

Table 1: Structural tree of heavy duty vehicles as represented in this report

HDT																	
EU≤34 t						EU>34 t						LV					
conventional		improved		advanced		conventional		improved		advanced		conventional		improved		advanced	
new	old	new	old	new	old	new	old	new	old	new	old	new	old	new	old	new	old

After the analytical system was developed, and relevant parameters were identified and assigned numerical values, the possible effects of presence or absence of long vehicles in the Swedish heavy duty vehicle fleet in 2010 and in 2020 were analysed. The analysis was performed for four different cases of the chosen analytical system. First, values were calculated for all necessary parameters (including parameters already used in the GAINS model as well as suggested in this study) based on available statistical and modelling data. These data were used to analyse the total energy demand of the three suggested heavy duty vehicle categories. This calculation and chosen parameter values described the current situation in Sweden, where long vehicles are authorized and commonly used (System 3A, in Figure 1). Then, the case where the category LV would be fully substituted by the category EU>34 t was analysed (illustrating the potential situation if EU rules on maximum allowable weights and dimensions for heavy duty truck would be enforced in Sweden). The analysis demanded adjustments in the parameter values and the effects on the total fuel demand (System 3B in Figure 1). This case is hereinafter in this report referred to as "the (category) substitution" case or "the (category) shift" case. Finally, both of these cases were represented as systems where all the categories were combined into one sector, as done in the GAINS model (System 1A & 1B in Figure 1).

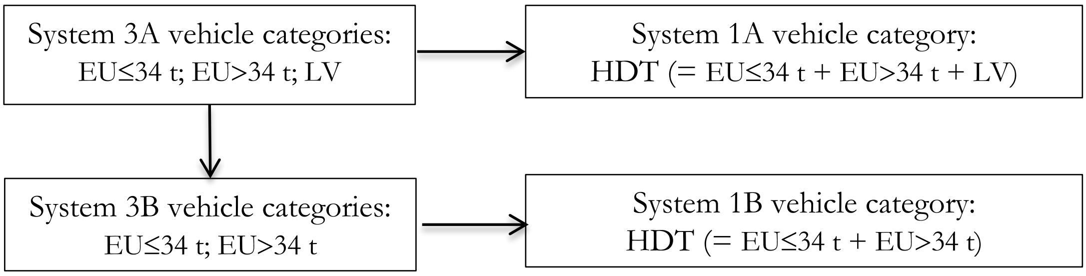

Figure 1: Parameter calculation systems and comprised heavy duty vehicle categories

It is important to note that the suggested split of heavy duty vehicle categories was determined by several important factors. The 34 t as a total weight limit value was chosen partly because it is consistent with the classification by Vierth et al. (2008), which to a certain extent allowed for comparison of results. More importantly, the same or at least a very similar categorization is used in the available statistical and modelling data on traffic work and transport work performed by Swedish heavy duty vehicles. As follows from the analysis below, suitable categorization of the input data (in particular data on transport work and traffic work) was important for the results to be correct. A total weight limit value other than 34 t could be used if it would better suit the available input data. However, the limit value should be chosen with respect to the reality so that the whole category with a total weight between the limit value and 40 t is most likely to substitute long vehicles in a case where they would no longer be authorized. To replace the goods transport performed by 60 t vehicles with 16 t vehicles is not credible.

2.1 Parameters needed for the analysis

All parameters used for calculations and analysis (see Appendix 1) can be divided into those already used in the current version of the GAINS model (either explicitly or in an implicit form) and those new suggested in this report. Some of the new parameter values are available from other models and statistical data as well as from the literature and were therefore considered as background data in this analysis (see Chapter 2.2), whereas other parameters needed to be calculated. Depending on the level of application, all parameters could be classified as either specific for a certain vehicle category (category-specific),

specific for a certain propulsion technology (technology-specific), or general (applied to both categories and technologies in the analysis). The category-specific parameters could in some cases be applicable to technologies as well, but in this particular analysis they were only applied to categories and thus considered as category-specific.

2.1.1 Vehicle category-specific parameters

Average mileage represents the number of kilometres one vehicle performs during a year and characterizes vehicles. *Average transport distance* characterizes transported goods and represents the distance one ton of goods is transported in average by a certain vehicle category. Both *average mileage* and *average transport distance* are expressed in kilometres but it is important to distinguish between them.

Vintage (vtg), or share of post-2010 vehicles, is used to model differences in fuel consumption between old (vintage) and new vehicles. In Borken-Kleefeld et al., 2009, *vtg* is expressed in shares of total vehicle number. In this analysis, shares by veh-km was used instead of vehicle number because of the availability of background data (see Chapter 2.2). The equations where *vtg* was used were adjusted accordingly.

Mileage deflator and *mileage inflator* were used to adjust the *average mileage* depending on the vehicle age. Compared to the average mileage of a whole category, old vehicles make fewer kilometres per year whereas new vehicles run more. The relative change in the average mileage of new and old vehicles expressed in shares of the average mileage of a whole vehicle category is called *mileage inflato*r and *mileage deflator*, respectively.

Load max is a technical characteristic of a vehicle used to assess how much load one vehicle can potentially transport. *Load capacity utilization (LCU) max* indicates what share *of load max* can be utilised in practice, which depends on the commodity being transported. *Load real-world* and *LCU real-world* parameters are used to indicate how much load is being transported by a vehicle, and what share of *LCU max* is being utilized in each of the chosen calculation cases describing real-world conditions.

Number of EU>34 t vehicles needed to substitute one LV vehicle was needed for recalculation of vehicle number in the case where long vehicles were substituted with conventional EU vehicles.

2.1.2 Vehicle technology-specific parameters

Fuel efficiency was the most important technology-specific parameter. In the study, we distinguished *fuel traffic efficiency* expressed in the unit MJ/veh-km and *fuel transport efficiency* expressed in the unit MJ/t-km. *Fuel traffic efficiency* was used as a technology defining parameter in Borken-Kleefeld et al. (2009), and was constant over time and characterised fuel consumption per traffic work. *Fuel transport efficiency* characterized fuel consumption per transport work and could be used as a technology defining parameter as well, but only under certain circumstances as described in Chapter 2.4.1. This parameter is not used in the GAINS model methodology at present.

Technology-to-category share by *veh-km* is used in the GAINS model methodology to show how much input each of the technologies makes into the traffic work performed by the total

HDT category. In this analysis, the *technology-to-category share* by *t* and by *t-km* was used to express the distribution of transported weight and transport work per vehicle technology for each of the three vehicle categories.

The parameters *share by veh-km, share by t* and *share by t-km* were different from *technology-to category-share* and characterized the relative distribution of the technologies of the total traffic work, transported weight and transport work, respectively, performed by all three vehicle categories.

2.1.3 General parameters

Traffic work is expressed in the unit Giga vehicle-kilometre (Gveh-km), while *transport work* is expressed in the unit Megaton-kilometre (Mt-km) performed by a vehicle category or a specific vehicle technology class. *Traffic work* is a function of *average mileage* and *vehicle number*, whereas transport work is a function of *transported weight* and *average transport distance.*

Transported weight per vehicle indicates how much goods one vehicle transports in a year. In this study, the numerical values of the parameter were based on data for the year 2010. The parameter was used for calculating transport work and transported weight by categories in future years, since there were no projected numbers for this year on the category level.

Total fuel consumption is a parameter indicating total fuel demand by heavy duty vehicles expressed in petajoule (PJ). Changes in the value of this parameter characterizes the efficiency of the substitution between the categories EU>34 t and LV. The value of the parameter available as exogenous background data should be consistent with the value calculated via the other system parameters.

Total fuel consumption can be calculated either via the conventional equation used by IIASA (see Borken-Kleefeld et al. (2009), where the equation is adjusted with respect to the unit chosen for expressing *vtg*) and includes the parameter *fuel traffic efficiency* (Equation 1) or via the alternative equation developed in this analysis which includes *fuel transport efficiency* (Equation 2).

Equation 1

$$FC = FC_{old} + FC_{new} = = \sum_t vehkm_t * FTcE_{t,old} * (1 - vtg_{vehkm}) + \sum_t vehkm_t * FTcE_{t,new} * vtg_{vehkm}$$

Equation 2

$$FC = FC_{old} + FC_{new} = \sum_t tkm_t * FTtE_{t,old} * (1 - vtg_{tkm}) + \sum_t tkm_t * FTtE_{t,new} * vtg_{tkm}$$

Where:

FC	= total fuel consumption by heavy duty trucks [PJ]
FC_{new}	= fuel consumption by new vehicles [PJ]
FC_{old}	= fuel consumption by old vehicles [PJ]
t	= propulsion technology classes: conventional (c); improved (i); advanced (a)
$vehkm_t$	= traffic work performed by technology t [Gveh-km]
$FTcE_{t, old}$	= fuel traffic efficiency of old vehicles using technology t [MJ/veh-km]
$FTcE_{t, new}$	= fuel traffic efficiency of new vehicles using technology t [MJ/veh-km]
vtg_{vehkm}	= shares of new vehicles by traffic work [share]
tkm_t	= transport work performed by technology t [Gt-km]
$FTtE_{t, old}$	= fuel transport efficiency of old vehicles using technology t [MJ/t-km]
$FTtE_{t, new}$	= fuel transport efficiency of new vehicles using technology t [MJ/t-km]
vtg_{tkm}	= shares of new vehicles by transport work [share]

2.2 Background data

The three vehicle categories system, an initial system for further recalculations and analysis describing the current situation, was built based on Swedish national data to the extent possible. In particular, the road traffic emission model HBEFA3.1A and the official Swedish national statistics on transport by heavy duty trucks were used as main national data sources. Where national data was missing, estimates made by IIASA were used. These estimates were developed for the GAINS model scenario BL_WEO_09 (Borken-Kleefeld, J., personal communication, 2012).

The sources of the background data used as a starting point for parameter calculations are presented in Table 2.

Table 2: Types and sources of the background data for parameter calculations

Source of data	Type of data	Available for years
HBEFA3.1A	Maximum and average fuel traffic efficiency for the categories EU≤34 t, EU>34 t, LV and by old and new vehicles	2010, 2020
	Traffic work, average mileage, number of vehicles and fuel consumption for the categories EU≤34 t, EU>34 t, LV	2010, 2020
	Share of post-2010 (new) vehicles by category	2010, 2020
Löfberg and Hallberg, 2011	Transport work by category	2010
	Transported weight by category	2010

Source of data	Type of data	Available for years
J. Borken-Kleefeld, 2012	Mileage deflator, mileage inflator	2010, 2020
GAINS scenario BL_WEO_09, 2012	Technology-to-category shares by veh-km	2010, 2020
	Fuel traffic efficiency ratio between conventional, improved and advanced technologies within a category	-
Vierth et al., 2008	Number of EU>34 t vehicles needed to substitute one LV vehicle = 1.37	-
	Load max, LCU max for categories EU>34 t, LV	-

The value of the parameter *number of EU>34 t vehicles needed to substitute one LV vehicl*e deserves special consideration. A detailed analysis performed to derive this number is described in Vierth et al. (2008). The number 1.37 is a weighted average over 12 commodity groups, for which both volume and weight limitations are taken into consideration.

2.3 General assumptions during parameter calculations

A range of assumptions were made in the parameter calculations. This chapter summarizes general assumptions valid for all the steps of the analysis.

One of the main assumptions was constant values of fuel traffic efficiency as vehicle technology defining characteristics. Fuel traffic efficiency data was obtained from the HBEFA model, which provides higher numbers for 2010 than for 2020. This can be explained by the increasing implementation of new, more fuel efficient technologies – a factor not included in the HBEFA model explicitly. However, such an implementation is taken into consideration in this analysis by operating with conventional (*c*), improved (*i*), and advanced (*a*) propulsion technology packages within each category. It was therefore assumed that in this analysis fuel traffic efficiency values for 2010 could be used as fuel traffic efficiency values characterizing conventional vehicle technology class in both 2010 and 2020. For improved and advanced vehicle technologies, fuel traffic efficiency numbers should be adjusted. As the shares of improved and advanced technologies increase, weighted average fuel traffic efficiency in 2020 would be lower than in 2010, in consistency with the data presented in HBEFA3.1A.

Fuel traffic efficiency of improved and advanced vehicles was calculated with an assumption of the same ratio between conventional, improved and advanced propulsion technologies as in the GAINS model scenario BL_WEO_09, see Table 3.

Table 3: GAINS scenario fuel traffic efficiency ratios (improved and advanced vehicles vs. conventional vehicles) and fuel traffic efficiency used in the GAINS scenario BL_WEO_09 and in this analysis

Technology	Fuel traffic efficiency in the GAINS scenario BL_WEO_09, MJ/veh-km	Ratio (c/c; i/c; a/c)	Derived fuel traffic efficiency in HBEFA, MJ/veh-km, new vehicles adjusted for efficiency improvements available in the GAINS model scenario BL_WEO_09		
	HDT		EU≤34 t	EU>34 t	LV
Conventional (*c*)	10.50	1	8.18	10.80	14.35
Improved (*i*)	8.93	0.85	6.96 =8.18*0.85	9.19 =10.80*0.85	12.20 =14.35*0.85
Advanced (*a*)	7.88	0.75	6.14 =8.18*0.75	8.11 =10.80*0.75	10.77 =14.35*0.75

The categories in modelling and statistical data were not fully consistent with the categorization used in this analysis. In particular, HBEFA operates with certain size classes of heavy duty trucks (see Bäckström and Jerksjö, 2010, Eichlseder et al., 2009), which in this analysis were combined into three categories as shown in Table 4. The HBEFA vehicle size class RT >32 t includes both vehicles with a total weight under 34 t and vehicles with a total weight over 34 t. However, according to Eichlseder et al., 2009, average gross weight of vehicles in this category is 35.5 t. Therefore, for simplicity, it was in this analysis assumed that all vehicles in this size class belonged to the category EU>34 t.

Table 4: Vehicle size classes in HBEFA3.1A vs. vehicle categorization in this analysis; nomenclature is based on total weight

Size classes in HBEFA3.1A		Categories in this analysis
Nomenclature	**Description**	
RT[a] ≤7.5 t	Small lorry / truck	EU≤34 t
RT 7.5 – 12 t		
RT 12 – 14 t	Large lorry / truck	
RT 14 – 20 t		
RT 20 – 26 t	Medium lorry / truck	
RT 26 – 28 t		
RT 28 – 32 t	Tractor + "city-trailer"	
TT/AT [b] 20 – 28 t	Lorry / truck + trailer	
TT/AT 28 – 34 t		EU>34 t
RT >32 t		
TT/AT 40 – 50 t	Tractor + MEGA-trailer	LV
TT/AT 50 – 60 t	Lorry / truck + semi-trailer	

[a] – rigid trucks;

[b] – truck trailers and articulated trucks.

Vehicle categories used in the official goods transportation statistics (Löfberg and Hallberg, 2011) are presented in Table 5. Here, the vehicle category 32 – 39.9 t is also inconsistent with the categorization in this analysis, but since more detailed division is not available, the statistical data category 32 – 39.9 t was in this analysis classified as the category EU>34 t. The implication of this latter assumption was that in our analysis vehicles in this larger category perform more transport work and transport more weight than they do according to statistical data.

Table 5: Vehicle categories in official goods transportation statistics (Löfberg and Hallberg, 2011) vs. vehicle categorization in the analysis

Categories in official goods transportation statistics, total weight	**Categories in the analysis**
3.5 – 5.9 t	EU≤34 t
6 – 7.9 t	
8 – 9.9 t	
10 – 11.9 t	
12 – 17.9 t	
18 – 23.9 t	
24 – 31.9 t	
32 – 39.9 t	EU>34 t
40 – 43.9 t	LV
44 – 49.9 t	
50 – 54.9 t	
≥ 55 t	

The merging of the GAINS model scenario data with the HBEFA data allowed for a more detailed analysis of vehicle fuel efficiency. It is however important to stress that the adaptation required assumptions on both data sets, since the GAINS model does not specify HDT vehicles with respect to weight classes, while HBEFA does not specify HDT vehicles with respect to propulsion technology classes.

In principle, vehicles with a total weight over 55 t can be even longer and heavier than long vehicles defined by the categorization in this analysis. In the Swedish forestry industry, vehicles with a total weight up to 90 t are used; their efficiency compared to the "usual" long vehicles with a total weight between 60 and 90 t is analysed in Löfroth and Svenson, 2010. In this analysis these types of vehicles were not taken into consideration and it was thereby assumed that their input into the total traffic work and transport work was negligible.

When modelling the substitution of long vehicles with conventional EU vehicles, it was assumed that the total transport work and the total transported weight remained constant; in other words, possible induced traffic and modal shift effects were not considered.

In this analysis, *technology-to-category shares* available from GAINS Europe model scenario BL_WEO_09 were used. These are shares by veh-km, which characterise the vehicles technologies' share of a vehicle category's *traffic work*. Data on *technology-to-category shares* characterizing vehicle technologies' share of a vehicle category's *transport work* and *transported weight* is not available. In this analysis it was therefore assumed that the relative distribution of each vehicle technology of a vehicle category's transport (transport work and transported weight) was identical to the relative distribution of the vehicle category's traffic work. The same assumption was made concerning the relative share of old and new vehicles of a category's transport. Due to these assumptions it was possible to apply the parameter *vtg* in Equation 2 as a share of new vehicles by transport work.

In this analysis, only the part of the Swedish heavy duty trucks fuelled by diesel was analysed; gasoline-fuelled heavy duty trucks were not considered. These vehicles are almost non-existent in the Swedish fleet.

2.4 System-specific assumptions and order of the parameter calculations

In this chapter, the order of parameter calculations and specific assumptions made in the calculations in the four parameter calculation systems (see Figure 1 above) are described in detail. In this analysis, the initial step was to analyse the situation when load capacity utilization (LCU) was used at the maximum level (trucks only drive fully loaded). In the following step, the parameters were re-calculated for the real-world situation with respect to LCU real-world values. Following this 'calibration', an analysis of a hypothetical situation where LV would be substituted by conventional EU vehicles could be analysed.

2.4.1 The potential to define vehicle technology by fuel transport efficiency (MJ/t-km) instead of fuel traffic efficiency (MJ/veh-km)

One of the initial intentions during the project was to define vehicle technologies by fuel transport efficiency (fuel consumption per transport work) instead of the vehicle technology fuel traffic efficiency in MJ/veh-km currently used in the GAINS model. This redefinition would be necessary in order to express the potential reduction in the total fuel demand associated with the use of long vehicles. However, during the calculations it was clear that this parameter could only be robust and used as a constant parameter in the case where load capacity utilization of the vehicles in a certain vehicle category remained constant, which was not a realistic assumption as follows from the description below. Moreover, even fuel traffic efficiency depended on the load capacity utilization and thus would change as well. So this problem was shared by both units available to define vehicle technology.

It was however possible to analyse the situation when load capacity utilization was assigned its maximum value and was constant for each vehicle technology. Such a situation would imply that all trucks always run as fully loaded as possible. In this case, fuel transport efficiency could be used as a technology defining parameter together with fuel traffic efficiency.

The detailed method of calculation with comments, used data sources and underlying assumptions are presented in Appendix 2. In brief, the calculations followed the steps described below:

1. Numbers for load max and LCU max for the categories EU>34 t and LV were taken directly from Vierth et al., 2008;
2. Fuel transport efficiency was calculated via fuel traffic efficiency (in this case – maximum values assuming fully loaded transport), load max and LCU max.

The results are given in Table 6 below.

Table 6: Fuel traffic efficiency and fuel transport efficiency as technology defining parameters in the "fully loaded rides only" case, categories EU>34 t and LV

Parameter	Unit	EU>34 t			LV		
		c	i	a	c	i	a
Load max	t/vehicle	24			40		
LCU max	shares	1.00			0.85		
FTcE*	MJ/veh-km	13.73	11.67	10.30	18.57	15.79	13.93
FTtE	MJ/t-km	0.572	0.486	0.429	0.546	0.464	0.410
Load real-world	t/vehicle	24			34		

*Vehicles with maximum load (HBEFA3.1A), weighted average over new and old vehicles for 2010.

Table 6 gives a good overview of comparative efficiency of the categories EU>34 t and LV in the "fully loaded rides only" case. If the same transport work was to be done by either one or the other category, it would be more efficient to use long vehicles. As follows from Equation 2, in this case the total fuel consumption was lower irrespective of the amount of transported goods or the transport distance.

How much lower the total fuel consumption by long vehicles would become was in this study determined by the ratio of the LV fuel traffic efficiency to the conventional EU vehicle traffic efficiency. In this case, the ratio was 18.57/13.73 = 15.79/11.68 = 13.93/10.30 = 1.35.

A critical value of the fuel traffic efficiency ratio can be obtained via the following equation describing identical fuel transport efficiency. A fuel traffic efficiency ratio value above the critical value would imply that conventional EU vehicles would be more efficient than long vehicles:

Equation 3

$$\frac{FTcE(LV)}{load\max(LV) * LCU\max(LV)} = \frac{FTcE(EU \succ 34t)}{load\max(EU \succ 34t) * LCU\max(EU \succ 34t)}$$

Where:

FTcE (LV or EU>34 t) = fuel traffic efficiency (maximum values) of LV or conventional EU vehicles [MJ/veh-km]
Load max (LV or EU>34 t) = maximum load [t]
LCU max (LV or EU>34 t) = maximum load capacity utilization [shares]

The solution of the Equation 3 is: $\frac{FTcE(LV)}{FTcE(EU \succ 34t)} = \frac{40t*0.85}{24t*1} = 1.42$

A ratio over 1.42 would mean that the lower fuel traffic efficiency of long vehicles compared to the fuel traffic efficiency of conventional EU vehicles would not be compensated for by the higher load capacity of long vehicles. In other words, if the ratio would be over 1.42 the use of long vehicles would imply higher total fuel demand of the goods transport system.

The critical value of the fuel traffic efficiency ratio depends on the vehicle categorization. With lower total weight limit values for each vehicle category (see above), the allowed maximum load would be lowered, and the critical value of the fuel traffic efficiency ratio would be higher. This imply that even though smaller trucks use less fuel per kilometre, as long as the ratio is lower than the critical value, long vehicles would remain more efficient compared to conventional EU vehicles in terms of fuel transport efficiency in the "fully loaded rides only" case.

The ratio 1.42 also describes the ratio of loads in the "fully loaded rides only" case, which follows from Equation 3 considering that load in this case is calculated as load max * LCU max. Load can also be calculated as transport work divided by traffic work. Thus, fully loaded conventional EU vehicles produce 1.42 times more traffic work compared to long vehicles per same unit of transport work.

Although the described case is most often hypothetical, the results of the calculations can be used for comparisons with results reflecting a real situation. The further away the real values of LCU and fuel transport efficiency are from their "fully loaded rides only" case values, the more unnecessary traffic work would be made per unit of transport work.

2.4.2 Parameter calculations, system 3A

System 3A was an initial calculation system built on the basis of the available national statistical and modelling data. This system was comprised of three heavy duty vehicle categories (EU≤34 t, EU>34 t and LV) and described the real-world situation in Sweden in 2010 as well as the projected situation in 2020.

Many of the parameter values were available from the literature, HBEFA and GAINS. Some parameters, however, needed to be calculated.

The detailed method of calculations with comments, used data sources and underlying assumption are presented in Appendix 3. In brief, the calculations followed the steps described below:

1. Numbers on total fuel consumption, vehicle number, *vtg*, traffic work and average mileage in 2010, 2020 by category and in total were taken directly from HBEFA3.1A;
2. Numbers on fuel traffic efficiency (average values) by category and by old and new vehicles were taken directly from HBEFA3.1A (same values assumed for 2020 as

for 2010). Fuel traffic efficiencies (average values) by technology were calculated using the assumption illustrated in Table 3 above;

3. Numbers on transport work and transported weight in 2010 by category and in total were taken directly from Löfberg and Hallberg (2011). Transported weight per vehicle and average transport distance in 2010 by category were calculated via transported weight, vehicle number and transport work. The same values were assumed for 2020. Transport work and transported weight in 2020 were calculated via transported weight per vehicle, vehicle number and average transport distance in 2020;
4. Vehicle number, traffic work and average mileage of old and new vehicles by category were calculated via vtg, average mileage of a category and mileage deflator (the original value of the mileage deflator was given from personal communication with J. Borken-Kleefeld). The mileage inflator was calibrated so that traffic work performed by a category equalled the sum of the traffic work performed by new and old vehicles within this category, irrespective of the way of calculation (traffic work can be calculated via average mileage and vehicle number of old/new vehicles or via average mileage of a category, mileage deflator and mileage inflator);
5. Real-world average load by category was calculated via transport work and traffic work. Load capacity utilization by category was then calculated via average load and maximum load.
6. Shares by traffic work, transport work and transported weight of different technologies (in relation to the total numbers for all heavy duty vehicles) were calculated via technology-to-category shares taken from the GAINS scenario BL_WEO_09 and total traffic work, transport work and transported weight. Based on these shares, traffic work, transport work and transported weight by technology were calculated;
7. Fuel consumption by technology and by old/new vehicles as well as in total was calculated by Equation 1. Value of the total fuel consumption should be the same as the value taken directly from HBEFA3.1A; different values mean that shares of technology implementation (technology-to-category shares) assumed in the GAINS scenario BL_WEO_09 should be further adjusted. In this case, the adjustment was made and steps 5 and 6 were repeated until the calculated total fuel consumption was the same as in the input data from HBEFA3.1A;
8. Fuel transport efficiency by technology was calculated via fuel consumption and transport work by technology;
9. Total average fuel traffic efficiency and fuel transport efficiency were calculated via total fuel consumption, total traffic work and total transport work.

The results of the parameter calculations in the system 3A are presented in Appendix 3 and summarized in Chapter 3.

2.4.3 Parameter calculations, system 3B

System 3B described a situation when all long vehicles would be substituted with conventional EU vehicles (the category EU>34 t). Comparison of the results obtained in the system 3B and in the system 3A is important for the analysis of the efficiency of long vehicles in real-world conditions.

One of the assumptions during the category substitution (from 3A to 3B) was that both total transport work and total transported weight would be constant. In other words, in the system 3B it was investigated how the parameters would change if the same goods transport demand would be fulfilled by EU≤34 t and EU>34 t category vehicles only. The results of a similar study are presented in Vierth et al. (2008), although different input data were used in this analysis.

It is very important to make reasonable assumptions during re-calculation of parameters illustrating the vehicle category shift. Vierth et al. (2008) suggested the unchanged average mileage of the categories EU>34 t and LV as a reasonable assumption.
Another possible assumption would be unchanged load capacity utilization of the conventional EU vehicles – that is, EU-sized vehicles substituting long vehicles would load as much as other EU-sized vehicles do. This assumption would mean that fuel traffic efficiency and fuel transport efficiency of the EU vehicles do not change after the shift, but it would also mean that either more EU vehicles than assumed in this analysis (1.37 per LV) would be needed, or these vehicles would have to perform more traffic work to perform the same transport work. As a result, mileage, traffic work and total fuel consumption would more than double, which is why this assumption could be considered unrealistic.
Assuming that the average mileage of long vehicles would be identical to the average mileage of the EU vehicles in the case of a vehicle category shift would be more reasonable, but it would also imply a change in the load capacity utilization, which again highlights the fact that the 1.37 ratio would not be directly applicable to the situation.

Considering the above mentioned reasons, the following key assumption was chosen when calculating the impact of a vehicle category shift: In this analysis it was assumed that the part of the conventional EU vehicles substituting long vehicles had the same load capacity utilization as the substituted long vehicles. This implied that EU vehicles after the substitution could be divided into two sub-categories: EU>34 t already in use (with the same average load and load capacity utilization as before the substitution) and EU>34 t substituting long vehicles. Vehicles in the latter sub-category had increased load capacity compared to the vehicles already in use. Their fuel traffic efficiency would therefore increase as well. This assumption made it possible to use 1.37 as the number of EU vehicles substituting one long vehicle.

Furthermore, it was assumed that EU vehicles substituting long vehicles had the same age distribution (value of parameter *vtg*) as the long vehicles substituted.

The detailed method of calculations with comments, used data sources and underlying assumptions are presented in Appendix 4. In brief, the calculations followed the steps described below:

1. For the categories EU<34 t and EU>34 t already in use, vtg was the same as in the system 3A. For the category EU>34 t substituting LV, vtg was the same as for LV category in the system 3A;

2. For the categories EU<34 t and EU>34 t already in use, (real-world) LCU was the same as in the system 3A. For the category EU>34 t substituting LV, LCU was the same as for LV category in the system 3A;
3. For the categories EU<34 t and EU>34 t already in use, numbers on fuel traffic efficiency by technology were the same as in the system 3A. For the category EU>34 t substituting LV, fuel traffic efficiency was increased in direct proportion to the increase of real-world LCU in relation to maximum LCU (see Table 7 below);
4. For the categories EU<34 t and EU>34 t already in use, real-world load was the same as in the system 3A. For the category EU>34 t substituting LV, real-world load was calculated via real-world LCU and maximum load;
5. For the categories EU<34 t and EU>34 t already in use, vehicle number was the same as in the system 3A. For the category EU>34 t substituting LV, vehicle number was calculated as the number of LV vehicles before the shift multiplied by 1.37;
6. For the categories EU<34 t and EU>34 t already in use, numbers for transport work and transported weight were the same as in the system 3A. For the category EU>34 t substituting LV, numbers for transport work and transported weight were the same as for LV category in the system 3A;
7. Traffic work by category was calculated via transport work and real-world load. Average mileage by category was calculated via traffic work and vehicle number;
8. Shares of different technologies of traffic work, transport work and transported weight (in relation to the total numbers for all heavy duty vehicles) were calculated via technology-to-category shares and total traffic work, transport work and transported weight. Based on these shares, traffic work, transport work and transported weight by technology were calculated;
9. Vehicle number, traffic work and average mileage of old and new vehicles by category were calculated via vtg, average mileage of a category and mileage deflator (the same as in the system 3A). Mileage inflator was calibrated in the same way as in the system 3A.
10. Fuel consumption by technology and by old/new vehicles as well as in total was calculated by Equation 1;
11. Fuel transport efficiency by technology was calculated via fuel consumption and transport work by technology;
12. Total average fuel traffic efficiency and fuel transport efficiency were calculated via total fuel consumption, total traffic work and total transport work.

Table 7: Adjustment of fuel traffic efficiency (weighted average over old and new vehicles) depending on the LCU, vehicle category EU>34 t substituting LV, year 2010

Parameter	Unit	Before shift (EU>34 t already in use)	After shift (EU>34 t substituting LV)	Max load
FTcE	MJ/veh-km	11.04	X	13.73
LCU real-world	shares	0.08	0.23	1.00
$X = 11.04 + \frac{(0.23-0.08)*(13.73-11.04)}{(1-0.08)} = 11.48$ MJ/veh-km				

The results of the parameter calculations in the system 3B are presented in Appendix 4 and summarized in Chapter 3.

2.4.4 Parameter calculations, systems 1A and 1B

Systems 1A and 1B aggregated all considered vehicle categories into one category HDT, identical to the HDT category in the GAINS model where the categories EU≤34 t, EU>34 t and LV are implicitly included but not distinguished. Both of the three-category systems 3A and 3B could be represented as a one category system: system 1A (combining EU≤34 t, EU>34 t and LV) and system 1B (combining EU≤34 t, and EU>34 already in use, and EU>34 t substituting LV), respectively. Values of the additive parameters (e.g., total vehicle number, total transport work, total traffic work, total fuel consumption) presented in a one category system and in the corresponding system 3A or 3B should be the same, since it simply was a different level of aggregation of the same real-world situation in a model.

The detailed method of parameter calculations with comments, used data sources and underlying assumption are presented in Appendix 5. In brief, the calculations followed the steps described below:

1. Transport work, traffic work, transported weight, vehicle number by technology and in total were calculated as sums by category;
2. Transported weight per vehicle was calculated via transported weight and vehicle number. Real-world load was calculated via transport work and traffic work;
3. Average transport distance and average mileage were the same as in the corresponding three categories system;
4. Shares by traffic work, transport work and transported weight of different technologies (in relation to the total numbers for all heavy duty vehicles) were in this case the same as technology-to-category shares;
5. Fuel traffic efficiency by technology was calculated as an average value over fuel traffic efficiencies by category weighted with the traffic work;
6. Traffic work and vehicle number of old and new vehicles were calculated as a sum by category. Average mileage of old and new vehicles was calculated via traffic work and vehicle number. Vtg was calculated as a share of traffic work performed

by new vehicles. Mileage inflator was calibrated in the same way as in the systems 3A and 3B;

7. Fuel consumption by technologies and by old/new vehicles as well as in total was calculated with Equation 1;
8. Fuel transport efficiency by technology was calculated via fuel consumption and transport work by technology.

The results of the parameter calculations in the systems 1A and 1B are presented in Appendix 5 and summarized in Chapter 3.

After the results in all four systems were calculated, it was necessary to adjust values of mileage inflator and deflator. The original values of these parameters, provided by J. Borken-Kleefeld (2012), were not consistent with the available modelling and statistical data, which made certain adjustments necessary. Adjustments were made by changing mileage deflator; mileage inflator was recalculated automatically. Mileage deflator and inflator were adjusted based on the following principles applicable to all four calculation systems (1A, 1B, 3A, 3B):

- Both deflator and inflator were close to the original values (provided by J. Borken-Kleefeld (2012));
- Both deflator and inflator could differ for vehicle categories but not much;
- Average annual mileage of new vehicles were higher and average annual mileage of old vehicles were lower than average mileage of a vehicle category;
- Deflator values were increasing and inflator values were decreasing over the years.

Adjustments of the values of mileage inflator and deflator did not affect the total results such as total fuel consumption or total traffic work. However, the adjustments did affect the distribution of traffic work and vehicle number between new and old vehicles, as well as the deviations of their average mileage from the average mileage of a category.

3 Calculation results and discussion: efficiency of long vehicles

3.1 Main calculation results

The aggregated results of the parameter calculations are summarized in Tables 8 and 9, where values of the most important parameters in the systems 3A and 3B are compared. More detailed results for each of the parameter calculation systems are available in Appendixes:

- Appendix 3: System 3A;
- Appendix 4: System 3B;
- Appendix 5: Systems 1A and 1B

Table 8: Aggregated results of the parameter calculations: system 3A (long vehicles present) vs. system 3B (long vehicles substituted), 2010

Parameter, unit		**3A (long vehicles)**	**3B (no long vehicles)**
Average mileage, km/veh-year	EU≤34 t	19 991	19 991
	EU>34 t already used	48 509	48 509
	LV / EU>34 t substituting LV	543 230	660 864
LCU real-world, shares	EU>34 t already used	0.08	0.08
	LV / EU>34 t substituting LV	0.23	0.23
Fuel traffic efficiency of new conventional vehicles, MJ/veh-km	EU≤34 t	8.18	8.18
	EU>34 t already used	10.80	10.80
	LV / EU>34 t substituting LV	14.35	11.21
Fuel transport efficiency of new conventional vehicles, MJ/t-km	EU≤34 t	3.72	3.72
	EU>34 t already used	5.72	5.72
	LV / EU>34 t substituting LV	1.59	2.06
Total vehicle number, thousands of vehicles		77.2	79.4
Total traffic work, Gveh-km		4.81	6.97
Fuel consumption by LV and EU>34 t, PJ		50.17	64.47
Total fuel consumption, PJ		60.77	75.08

Tables 8 and 9 illustrate in a concise way how the main parameters characterising fuel efficiency of a vehicle category (fuel traffic efficiency, fuel transport efficiency, total fuel consumption) and some other related parameters would change if long vehicles were substituted with conventional EU vehicles.

Table 9: Aggregated results of the parameter calculations: system 3A (long vehicles present) vs. system 3B (long vehicles substituted), 2020

Parameter, unit		**3A (long vehicles)**	**3B (no long vehicles)**
Average mileage, km/veh-year	EU≤34 t	19 560	19 560
	EU>34 t already used	41 664	41 664
	LV / EU>34 t substituting LV	528 744	643 240
Load capacity utilization, shares	EU>34 t already used	0.09	0.09
	LV / EU>34 t substituting LV	0.23	0.23
Fuel traffic efficiency of new conventional vehicles, MJ/veh-km	EU≤34 t	8.18	8.18
	EU>34 t already used	10.80	10.80
	LV / EU>34 t substituting LV	14.35	11.21
Fuel transport efficiency of new conventional vehicles, MJ/t-km	EU≤34 t	3.64	3.64
	EU>34 t already used	4.91	4.91
	LV / EU>34 t substituting LV	1.54	2.01
Total vehicle number, thousands of vehicles		92.9	95.8
Total traffic work, Gveh-km		5.96	8.69
Fuel consumption by LV and EU>34 t, PJ		62.23	79.83
Total fuel consumption, PJ		74.16	91.77

The calculation results for 2020 showed that a hypothetical substitution of long vehicles with conventional EU vehicles would increase total fuel consumption by 24 per cent. Considering only vehicles with the total weight over 34 t, total fuel consumption would increase by 30 per cent. Following one of the main assumptions in the calculations, the transport work would be constant. But the total traffic work would however increase by 46 per cent due to fewer tons being loaded per vehicle. Total vehicle number would increase by three per cent in order for the substituting EU vehicles to perform the same transport work as long vehicles but with the lower maximum allowable load. The average mileage of the EU vehicles substituting long vehicles would be about 1.2 times higher than the average mileage of the substituted long vehicle.

In Vierth et al. (2008), the results of a similar study on vehicles substitution indicated a 6.4 per cent increase in fuel consumption by heavy trucks due to the shift, 24 per cent increase in the related traffic work, and 35-50 per cent increase in the number of vehicles. The results, however, are not directly comparable because of the different underlying assumptions: Vierth et al. (2008) assumed a constant average mileage during the shift, whereas in this study load capacity utilization was chosen as a constant parameter.

As regards fuel efficiency, a conventional new EU vehicle substituting a LV vehicle would consume 22 per cent less fuel per traffic work (MJ/veh-km) but 30 per cent more fuel per transport work (MJ/t-km) than a new LV vehicle. Fuel traffic efficiency would however be higher for the substituting EU vehicles than for vehicles already being in use because of the former's higher load capacity utilization. Numbers for fuel transport efficiency of both long vehicles and substituting EU vehicles would be much lower than for EU>34 t vehicles already in use.

For 2010, very similar results were obtained regarding the effects of the shift on the relative increase in total traffic work, total fuel consumption, number of vehicles, and fuel efficiency ratios.

According to the calculation results summarized in Tables 8 and 9, for the Swedish conditions represented in this analysis, long vehicles appear as more efficient than conventional EU vehicles.

3.2 Analysis of the underlying assumptions and input data

It is important to note that the results in this study were obtained based on the available statistical and modelling data and on a range of assumptions. There are several issues related to the assumptions that deserve additional discussion.

The vehicle category specific fuel traffic efficiency estimates taken from the HBEFA model were used as an average value for all types of driving conditions. In reality though, the long vehicles in use today are mostly trafficking motorways. This indicates that the fuel traffic efficiency estimates in HBEFA might be somewhat misrepresentative for the objectives of this study.

For simplicity, and due to lack of data, the vintage (*vtg* = the share of the post-2010 vehicles by veh-km) of the vehicles was considered as constant during recalculations from the 3A system into the 3B system. In practise, this parameter would most probably increase together with the increase in vehicle number (substituting vehicles would probably be new). The impact on the resulting total fuel demand is unclear.

The analysis was grounded on the assumption of the constant load capacity utilization during the vehicle category shift. In the ideal "full rides only" case, the ratio of maximum load capacity utilization numbers of LV and EU>34 t vehicle categories, as well as the ratio of their fuel traffic efficiencies, are critical for the assessment of the efficiency of long vehicles compared to conventional EU vehicles. In the cases describing real-world conditions, LCU numbers affect the resulting traffic work increase or decrease from the shift and, in turn, the fuel transport efficiency and the resulting change in the total fuel consumption. However, the numbers for maximum load capacity utilization used in the study – 1 for the category EU>34 t (implying 24 t of load) and 0.85 for the category LV (implying 34 t of load) – might be overestimated.

In almost all calculations it was assumed that the number of conventional EU vehicles needed to substitute one long vehicle was 1.37, meaning that long vehicles have 37 per cent more transport capacity. This number, calculated in Vierth et al. (2008), is based on the choice of certain commodity groups and on the assumptions on the maximum load factor (load capacity utilization), the maximum load weight and the maximum load volume (which, in turn, depends on the maximum length) of vehicles in different categories. For the maximum load factor, the limiting factor is either volume or weight, which depends on the commodity group (e.g., oil products and timber are "weight cargo" and high-value products are "volume-cargo"). The prevalence and composition of certain commodities is quite country-specific; so the ratio 1.37 should be re-assessed for other countries. For instance, in one of the studies focused on the effects of long vehicles with the purpose to provide advice to the European Commission on the optimal weights and dimensions of heavy duty vehicles (De Ceuster et al., 2008), different load factors were used, and it was assumed that long vehicles have 50 per cent more capacity in terms of both volume and weight than vehicles with a total weight up to 40 t. Another study (Doll et al., 2008) suggested 26 t as maximum load of the conventional vehicles instead of 24 t used in Vierth et al. (2008) and in this analysis. All in all it appears as if also the vehicle weight classification needs national specific considerations.

3.3 Other possible effects of long vehicles

In this study, possible ways to include long vehicles in integrated assessment models, and in the GAINS model in particular, have been analysed. During the analysis, the efficiency of the substitution of long vehicles with conventional EU vehicles was assessed based on the fuel efficiency and on the total fuel demand of the Swedish heavy duty vehicle fleet. There was, however, a range of possible effects of long vehicles that were not considered. Many of them are actively discussed within the debate on the potential authorization of long vehicles in the EU as a whole. Several studies have been conducted to investigate economic, social and environmental aspects of long vehicle implementation in Europe (e.g., Doll et al., 2008, De Ceuster et al., 2008), or their substitution with conventional EU vehicles in the countries where long vehicles already are implemented (e.g., Vierth et al., 2008).

Transportation costs are analysed, inter alia, in Vierth et al. (2008). The increase in average transport cost (consisting of personnel costs, fuel costs and other costs (maintenance etc.)) due to substitution of long vehicles with conventional EU vehicles is estimated to 24 per cent. Doll et al. (2008) suggest 18 to 25 per cent cost savings in the case of long vehicle implementation in Europe.

One of the main concerns is that reduced transportation costs for long vehicles would result in *modal shift* from railway traffic to road traffic. Vierth et al. (2008) take model shift into consideration by developing two relevant scenarios for Sweden, both implying modal shift and additional investments into the Swedish railway transport, but one with the long vehicles allowed whereas the other with long vehicles prohibited. The results of these scenarios are compared to the results of the relevant scenarios without modal shift. The results indicate that additional investments into railway transport together with the existing Swedish norms for heavy duty traffic (long vehicles allowed) would reduce road transport work by 2 per cent compared to a case without modal shift. If the additional investment is taking place simultaneously with the shift to conventional EU vehicles, road transport work would decrease by 12 per cent. The study thus indicates larger transport work shift from road to rail traffic in case of the present EU legislation for trucks than in case of if long vehicles are permitted, but both cases imply a certain level of investment into the Swedish railway transport system. Different results are presented by De Ceuster et al. (2008), which suggest a very small increase in European road transport work due to the modal shift –

about 1 per cent. Doll et al. (2008) refer to research results suggesting that 10 to 30 per cent of long distance rail container shipments are most likely to be shifted to road as a result of cross-border long vehicle transportation. It is also noted that modal shift will be the same in case the higher limit for a total weight of 60 t (as in the case of Swedish trucks) or 50 t (another considered alternative) was introduced. Doll et al. (2008) explain relatively low modal shifts from railway to road traffic in Sweden, Germany and the Netherlands given the fact that long vehicles are restricted to motorways and mostly permitted as national traffic only.

Apart from modal shift, transportation by road in the case of long vehicle implementation can potentially increase due to i*nduced (generated) traffic* driven by transport price effects – the effect when lower transportation costs result in higher transport demand. The results obtained in the TRANS-TOOLS model for Europe (De Ceuster et al., 2008) show almost no generation effect as a consequence of price decrease.

The *Safety* aspect is analysed in Vierth et al. (2008). Long vehicles are heavier and larger than conventional EU trucks and have poorer breaking ability, which is why accidents with long vehicles are expected to have more serious consequences. Nevertheless, the study results indicate an increase in number of deaths (plus 12 persons per year) if long vehicles would be substituted with conventional EU trucks. This can be explained by the increased traffic work even though individual long vehicles are less safe than conventional EU vehicles.

The *Road infrastructure* is expected to be affected by introduction of long vehicles as well. In particular, Doll et al. (2008) note that the life expectancy of bridges would decrease and the need for maintenance would increase as well as certain infrastructural elements (such as small roundabouts) would become insufficient. At the same time, De Ceuster et al. (2008) suggest that additional investments into road infrastructure are lower than savings due to better safety and lower emissions.

The increased number of heavy duty trucks on the roads would likely cause *time delays* for other types of vehicles in certain circumstances, e.g., on two-lane roads with a width of 5.5 – 11.5 meters. Estimates presented in Vierth et al. (2008) indicate that due to a higher number of vehicles, in the case of a shift from long vehicles to conventional EU vehicles, delays would actually increase by 331 360 hours per year in Sweden, valued at 49.7 million SEK per year.

Exhaust emissions are not analysed explicitly but in the GAINS model they are calculated in direct proportion to fuel consumption, which is one of the most important parameters in this analysis. If long vehicles are more fuel efficient than conventional EU vehicles it also implies that they emit less in total, even if the impact on emissions is not to be considered as directly linear since the different driving pattern of long vehicles will cause different emission factors per vehicle kilometre.

Non-exhaust emissions might be affected by long vehicle presence or absence as well: emission of particles from *tire* and *road wear* can increase together with the higher pressure caused by heavier loads. Road pressure depends on the number of axles – an aspect not specifically considered in this analysis. However, possible increase in non-exhaust emissions applies to individual vehicles, whereas in total these emissions might decline with the long vehicle authorization due to fewer veh-km driven.

It is important to realize that the results of the studies cannot be automatically applied to conditions other than these that the studies were considering. In particular, findings presented in Vierth et al. (2008) are not necessarily valid for other European countries since the study was based on national data and variations between countries can be suspected to be large.

The factors mentioned above were not specifically considered in this analysis due to the complexity of their quantification and the proper description of interconnections between the different factors. This makes inclusion of these factors into integrated assessment modelling a difficult and time-consuming task.

However, these factors are important in a comprehensive analysis of the environmental effects of different transport policy options, especially if such an analysis is supposed to support important strategic decisions such as whether cross-border transportation with long vehicles should or should not be authorized by EU legislation.

4 Conclusions

In this report, an analysis of possible ways to include of Swedish heavy duty trucks with a total weight of 40 to 60 t and a length of 18.75 to 25.25 m (also called "mega-trucks", here called "long vehicles") in the GAINS model as an option to reduce emissions is presented. The system of parameters currently used in the GAINS model was supplemented with a range of parameters characterizing goods transportation (transport work, transported weight, etc.) so as to enable a calculation on the impact of long vehicles and fuel consumption and emissions. The effects of long vehicles on the total fuel consumption of the Swedish heavy duty vehicle fleet were analysed based on parameter calculations in four alternative systems describing two possible situations in Sweden: when long vehicles are authorized for national transport (the current situation), and when long vehicles are prohibited and substituted by conventional EU vehicles.

Fuel efficiency of long vehicles compared to fuel efficiency of conventional EU vehicles can be estimated at two different levels. At the disaggregated level of vehicles representation, fuel transport efficiency and fuel traffic efficiency could be used as fuel efficiency indicators, implying the same transport work to be done. At this level, the results show that long vehicles are usually more efficient than conventional EU vehicles (even though they consumed more fuel per km) because they would need fewer veh-km for each ton of transported goods. A more significant impact is visible on aggregated fuel efficiency, at the level of the total heavy duty vehicle fleet, measured by total fuel consumption – a parameter serving as a basis for making conclusions about long vehicle efficiency. In this analysis, the use of long vehicles decreased the total heavy duty vehicle number by 3 per cent, total traffic work by 31 per cent, and total fuel consumption by 19 per cent.

The results were affected by complex combinations of assumptions, such as on the number of conventional EU vehicles needed to substitute one long vehicle, on distribution of available input data over categories, on degree of implementation of different vehicle technologies, on constant or flexible values of certain parameters (transport work, load factor, average transport distance, etc.) over the years and during the category shift. Also, available input data can differ between countries, which can be a very important factor for the results as well. In particular, small changes in data on traffic fuel efficiency, in traffic work, or in transport work performed by different vehicle categories, can be a reason for long vehicles to become more or less fuel-efficient than conventional EU vehicles. With respect to all this, interpretation of the calculation results presented in the report or making similar calculations based on different background data should not be done without consideration of the underlying assumptions and important factors – subject to analysis in a separate chapter in this report.

Fuel efficiency of long vehicles alone is seldom considered as a basis for important strategic decisions concerning authorization of prohibition of this type of trucks. Studies conducted to provide information for revision of the Directive 96/53/EC, regulating transport by trucks in the EU, comprise a range of economic, social and environmental aspects of long vehicles. The most important of these aspects are possible modal shift from railway and shipping to road, induced traffic due to lower transport costs and the resulting increase in fuel consumption and CO_2 emissions. The analysis presented in this report focuses on the aspects directly concerning integrated assessment modelling and does not take all possible effects of long vehicles into account; however, a brief description of the effects is included in the report to provide a comprehensive overview of the issue. It needs to be noted that statistical data obtained from Sweden and other countries where long vehicles are actively used, should not be generalised: certain positive and negative effects of long vehicles can be determined by local conditions, including, for instance, restrictions and regulations that can be changed over time.

The main findings of this study were that it is possible to develop an integrated assessment model method for presenting long vehicles as a fuel efficiency option in the transport sector, but that this method requires data that is currently not available. This lack of data motivates the use of numerical assumptions in the analysis, but the results of the analysis vary from positive to negative as a result of minor changes in the assumptions, rendering the method too dependent on assumptions. Improved system understanding, statistical data, and scenarios would be needed for representation of long heavy duty vehicles as a modelled fuel efficiency option in future analysis.

Continued analysis on effects of long vehicles and ways to include them into integrated assessment models is encouraged. Cost-efficiency aspects, data on vehicle load utilisation and vehicle shift characteristics, modal shift from railway and shipping to road transport, and generation of additional transport need as a result of decreasing transport costs, could be topics for further research in this direction. As a complement to analysis on cost efficient road transport solutions it is also important to continue environmental analysis of other modes of transport and modal shifts.

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Appendix 1. Analytical system parameters

Parameter	Unit	Applied to	Used in GAINS at present	Available as background data or calculated
Fuel traffic efficiency	MJ/veh-km	Technology	Yes	Background data
Fuel transport efficiency	MJ/t-km	Technology	No	Calculated
Load max	t/vehicle	Category	No	Background data
Load capacity utilization (LCU) max	share	Category	No	Background data
Load real-world	t/vehicle	Category	No	Calculated
Load capacity utilization (LCU) real-world	share	Category	No	Calculated
Fuel consumption	PJ, MJ	Technology or category	Yes	Both background data and calculated (same value)
Traffic work	Gveh-km	Technology or category	Yes	Background data
Transport work	Mt-km	Technology or category	No	Background data for 2010 Calculated for 2020
Transported weight	Mt	Technology or category	No	
Vtg = share of post-2010 (new) vehicles	share by veh-km	Category	Yes	Background data
Vehicle number	thousands	Technology or category	Yes	Background data
Average mileage	km/veh-year	Category	Yes	Background data
Average transport distance	km	Category	No	Calculated
Mileage deflator	-	Category	Yes	Background data, further adjusted during calculations
Mileage inflator	-	Category	Yes	
Transported weight per vehicle	t/veh-year	Technology or category	No	Calculated
Technology-to-category share	% by veh-km, t and t-km	Technology	Yes	Background data, further adjusted during calculations
Share by veh-km	% by veh-km	Technology	No	Calculated
Share by t	% by t	Technology	No	Calculated
Share by t-km	% by t-km	Technology	No	Calculated
Number of EU>34 t vehicles needed to substitute one LV vehicle	-	Category	No	Background data

Appendix 2. Fuel traffic efficiency and fuel transport efficiency as technology defining parameters in the "fully loaded rides only" case, categories EU>34 t and LV

Calculation: method and sources

<table>
<tr><th colspan="4">2. Fuel traffic efficiency and fuel transport efficiency as technology defining parameter in the "fully loaded rides only" case, categories EU>34 t and LV</th></tr>
<tr><th colspan="2">Parameter, unit</th><th>Source or method of calculation</th><th>Assumptions, comments</th></tr>
<tr><td rowspan="2">Fuel traffic efficiency, MJ/veh-km</td><td>c</td><td>HBEFA3.1A, values for 2010 (maximum).</td><td rowspan="2">Fuel traffic efficiency was assumed to be constant over the years; here values for 2010 were used as technology characteristics of conventional vehicles.</td></tr>
<tr><td>a, i</td><td>Fuel traffic efficiency ratio of GAINS technologies (c, i, a) applied to fuel traffic efficiency values for conventional vehicles in HBEFA3.1A.
i /c = 0.85
a/c = 0.75</td></tr>
<tr><td colspan="2">Load max, t/vehicle</td><td>Vierth et al., 2008.</td><td>-</td></tr>
<tr><td colspan="2">LCU max, shares</td><td>Vierth et al., 2008.</td><td>-</td></tr>
<tr><td colspan="2">Load real-world, t/vehicle</td><td>Load real-world = transport work (Mt-km) / traffic work (Gveh-km) = load max * LCU max</td><td>Maximum possible LCU: fully loaded rides only, no empty or partly loaded rides.
In this case, parameter depends only on load max and LCU max</td></tr>
<tr><td colspan="2">Fuel transport efficiency, MJ/t-km</td><td>Fuel transport efficiency (MJ/t-km) = fuel traffic efficiency (MJ/veh-km) * traffic work (Gveh-km) / transport work (Mt-km) =
= fuel traffic efficiency (MJ/veh-km) / load real-world (t/vehicle)
= fuel traffic efficiency (MJ/veh-km) / (load max * LCU max).</td><td>Maximum possible LCU: fully loaded rides only, no empty or partly loaded rides.
In this case:
traffic work =
= transport work / load max * LCU max
Parameter is technology-specific and can be used as a technology defining characteristic similar to fuel traffic efficiency.
Parameter does not depend on traffic work or transport work.</td></tr>
</table>

Appendix 3: Parameter calculations, system 3A (EU<34 t, EU>34 t, LV)

Calculation: method and sources

3. Parameter calculations, system 3A (including long vehicles) (EU<34 t, EU>34 t, LV)		
Parameter, unit	**Source or method of calculation**	**Assumptions, comments**
Vtg = share of post-2010 (new) vehicles by veh-km	HBEFA3.1A.	In Borken-Kleefeld et al. (2009), by vtg is meant share by number of vehicles. In this analysis, vtg is share by veh-km because of the availability of the required input data. Equations employing vtg in the present study were adjusted accordingly.
Vehicle number, thousands	By category: HBEFA3.1A. Number of old vehicles = traffic work performed by old vehicles / average mileage of old vehicles. Number of new vehicles = difference between numbers of total and old vehicles.	-
Average mileage, km/veh-year	By category: HBEFA3.1A. New vehicles: Average mileage = traffic work performed by new vehicles / number of new vehicles. Old vehicles: Average mileage = average mileage by category * (1-mileage deflator).	Mileage is different between categories and for old/new vehicles but same for technologies within a category.
Mileage inflator	Personal communication with J. Borken-Kleefeld. Mileage inflator was derived using the following equation system: Average mileage of new vehicles = traffic work performed by new vehicles / number of new vehicles, Average mileage of new vehicles = average mileage by category * (1+ mileage inflator).	Same mileage inflator for technologies within a category. Different mileage inflator for categories. Calculated mileage inflator was further adjusted together with mileage deflator, see below. Original mileage inflator (J. Borken-Kleefeld): 2010 – 0.45, 2020 – 0.1.
Mileage deflator	Personal communication with J. Borken-Kleefeld. Original mileage deflator was further adjusted together with mileage inflator so that in all calculation systems: -both deflator and inflator were	Same mileage deflator for technologies within a category. Different mileage deflator for categories. Original mileage deflator (J. Borken-Kleefeld): 2010 – 0.05,

3. Parameter calculations, system 3A (including long vehicles) (EU<34 t, EU>34 t, LV)		
Parameter, unit	**Source or method of calculation**	**Assumptions, comments**
	close to the original numbers; -deflator and inflator could differ for vehicle categories but not much; -average mileage of new vehicles was higher and average mileage of old vehicles was lower than average mileage of a category; -deflator was increasing and inflator was decreasing over the years.	2020 – 0.4.
Traffic work, Gveh-km	By category: HBEFA3.1A, traffic work = average mileage * vehicle number. For new and old vehicles: Traffic work = traffic work of a category adjusted with vtg. By technology: Traffic work = total traffic work * share of technology by veh-km.	-
Share by veh-km, %	Category share = traffic work of a category * 100% / traffic work total. Technology share = category share * technology-to-category share= = traffic work of a category * technology-to-category share * *100%/traffic work total.	Same proportion between shares of technologies of each category (technology-to-category shares). Starting point was technology-to-category shares in the GAINS-scenario, adjusted later so that calculated total fuel consumption per category was consistent with HBEFA3.1A value. For 2020, ratio between improved and advanced technologies was assumed to be the same as for the original GAINS scenario data. Year when improved vehicles appear: 2010. Year when advanced vehicles appear: 2015. Original shares: 2010: 100(c)-0(i)-0(a) 2020: 73(c)-20(i)-7(a) Adjusted shares: 2010: 98.1(c)-1.9(i)-0(a) 2020: 88.6(c)-8.4(i)-3.0(a)
Transported weight per vehicle, t/vehicle-year	Transported weight per vehicle = transported weight / vehicle number.	Same transported weight per vehicle per year in 2020 as in 2010.

3. Parameter calculations, system 3A (including long vehicles) (EU<34 t, EU>34 t, LV)		
Parameter, unit	**Source or method of calculation**	**Assumptions, comments**
Average transport distance, km	Löfberg and Hallberg, 2011: Average transport distance = transport work / transported weight.	Same average transport distance in 2020 as in 2010.
Transported weight, Mt	By category: Löfberg and Hallberg, 2011. For 2020 by category: transported weight = vehicle number * transported weight per vehicle. By technology: Transported weight = share by t * total transported weight.	Weight transported by category 32-40 t in Löfberg and Hallberg (2011) was assumed to be transported by category EU>34 t.
Transport work, Mt-km	By category: Löfberg and Hallberg, 2011. For 2020 by category: transport work = transported weight * average transport distance. By technology: Transport work = share by t-km * total transport work.	Transport work by category 32-40 t in Löfberg and Hallberg (2011) was assumed to be performed by category EU>34 t.
Share by t, %	Category share = Mt by category *100% / Mt total. Technology share = category share * technology-to-category share.	Technology-to-category shares are the same as for veh-km (adjusted to total fuel consumption).
Share by t-km, %	Category share = Mt-km by category * 100% / Mt-km total. Technology share = category share * technology-to-category share.	Technology-to-category shares are the same as for veh-km (adjusted to total fuel consumption).
Load max, t/vehicle	Vierth et al., 2008.	-
Load real-world, t/vehicle	Load real-world = transport work/ traffic work.	Same parameter value for technologies within a category. Unavailable for EU<34 t because of the lack of data on load max.
LCU real-world, shares	LCU real-world = load real-world / load max	Same parameter value for technologies within a category.
Fuel consumption, PJ	HBEFA3.1A, recalculation from t/year. Same value should be obtained by applying the following equations and summarizing numbers over all technologies: New vehicles: Fuel consumption = traffic work by technology * fuel traffic	Diesel characteristics (Swedish Petroleum and Biofuel Institute): density = 0.81 kg/l, calorific value = 35.28 MJ/l.

3. Parameter calculations, system 3A (including long vehicles) (EU<34 t, EU>34 t, LV)			
Parameter, unit		**Source or method of calculation**	**Assumptions, comments**
		efficiency (MJ/veh-km) * vtg. Old vehicles: Fuel consumption = traffic work by technology * fuel traffic efficiency (MJ/veh-km) * (1-vtg).	
Fuel traffic efficiency, MJ/veh-km	By category	HBEFA3.1A, numbers for 2010 (average)	Fuel traffic efficiency differed for new and old vehicles but was a considered to be a constant parameter defining technologies within categories, in particular, in Borken-Kleefeld et al. (2009). In this study, HBEFA3.1A numbers for 2010 were used for both 2010 and 2020.
	Average	HBEFA3.1A; By technology: average fuel traffic efficiency = sum of fuel traffic efficiencies of old and new vehicles weighted with (1-vtg) and vtg, respectively. Total average fuel traffic efficiency = total fuel consumption / total traffic work.	
Fuel transport efficiency, MJ/t-km		Fuel transport efficiency (MJ/t-km) = fuel consumption / transport work.	-

Results: 2010

3. Parameters in system 3A (including long vehicles) (EU<34 t, EU>34 t, LV), 2010											
Parameter	**Unit**	**Age**	**EU<34 t**			**EU>34 t**			**LV**		
			c	**i**	**a**	**c**	**i**	**a**	**c**	**i**	**a**
Vtg	share	-	0.18			0.27			0.23		
Fuel traffic efficiency	MJ/veh-km	new	8.18	6.95	6.14	10.80	9.19	8.11	14.35	12.20	10.77
		old	7.98	6.79	5.99	11.13	9.46	8.35	14.81	12.60	11.12
		av	8.02	6.82	6.02	11.04	9.39	8.28	14.71	12.51	11.04
		total av	12.64								
Fuel transport efficiency	MJ/t-km	new	3.72	3.16	0.00	5.72	4.87	0.00	1.59	1.35	0.00
		old	3.63	3.09	0.00	5.89	5.01	0.00	1.64	1.39	0.00
		av	3.65	3.10	0.00	5.85	4.97	0.00	1.62	1.38	0.00
		total av	1.86								
Transport work	Mt-km	-	2862	55	0	434	8	0	28819	558	0
		total	32736								
Transported weight	Mt	-	64.9	1.3	0.0	15.3	0.3	0.0	229.4	4.4	0.0
		total	315.6								
Average transport distance	km	-	44			28			126		
		total av	104								
Vehicle number	thousands	new	8.3			1.1			1.1		
		old	58.1			3.7			4.9		
		total	77.2								
Transported weight per vehicle	t/veh-year	-	997			3224			39146		
Average mileage	km/veh-year	new	28417			58402			694123		
		old	18792			45598			510637		
		av	19991			48509			543230		
		total av	62282								
Mileage deflator	-	-	0.06			0.06			0.06		
Mileage inflator	-	-	0.42			0.20			0.28		
Traffic	Gveh-	-	1.30	0.03	0.00	0.23	0.004	0.00	3.18	0.06	0.00

3. Parameters in system 3A (including long vehicles) (EU<34 t, EU>34 t, LV), 2010											
Parameter	**Unit**	**Age**	**EU<34 t**			**EU>34 t**			**LV**		
			c	**i**	**a**	**c**	**i**	**a**	**c**	**i**	**a**
work	km	new	0.24			0.06			0.74		
		old	1.09			0.17			2.51		
		total	4.81								
Load real-world	t/vehicle	-	2.2			1.9			9.1		
LCU real-world	shares	-	unknown			0.08			0.23		
Fuel consumption	PJ	new	1.9	0.03	0.0	0.7	0.01	0.0	10.4	0.2	0.0
		old	8.5	0.1	0.0	1.9	0.03	0.0	36.5	0.6	0.0
		total	10.4	0.2	0.0	2.5	0.04	0.0	46.8	0.8	0.0
		total	60.77								

Results: 2020

3. Parameters in system 3A (EU<34 t, EU>34 t, LV), 2020											
Parameter	**Unit**	**Age**	**EU<34 t**			**EU>34 t**			**LV**		
			c	**i**	**a**	**c**	**i**	**a**	**c**	**i**	**a**
Vtg	share	-	0.80			0.80			0.62		
Fuel traffic efficiency	MJ/veh-km	new	8.18	6.95	6.14	10.80	9.19	8.11	14.35	12.20	10.77
		old	7.98	6.79	5.99	11.13	9.47	8.35	14.81	12.60	11.11
		av	8.14	6.92	6.11	10.86	9.24	8.15	14.53	12.35	10.90
		total av	12.45								
Fuel transport efficiency	MJ/t-km	new	3.64	3.09	2.73	4.91	4.18	3.69	1.54	1.31	1.16
		old	3.55	3.02	2.67	5.06	4.31	3.80	1.59	1.35	1.20
		av	3.62	3.08	2.72	4.94	4.20	3.71	1.56	1.33	1.17
		total av	1.75								
Transport work	Mt-km	-	2978	284	99	705	67	24	33790	3220	1127
		total	42294								
Transported weight	Mt	-	67.6	6.4	2.3	24.8	2.4	0.8	269.0	25.6	9.0
		total	407.9								
Average transport distance	km	-	44			28			126		
		total av	104								
Vehicle number	thousands	new	46.5			6.0			3.8		
		old	30.0			2.6			4.0		
		total	92.9								
Transported weight per vehicle	t/veh-year	-	997			3224			39146		
Average mileage	km/veh-year	new	25857			48040			667733		
		old	9780			27082			396558		
		av	19560			41664			528744		
		total av	64124								
Mileage deflator	-	-	0.50			0.35			0.25		
Mileage inflator	-	-	0.32			0.15			0.26		
Traffic	Gveh-	-	1.33	0.13	0.04	0.32	0.03	0.01	3.63	0.35	0.12

3. Parameters in system 3A (EU<34 t, EU>34 t, LV), 2020											
Parameter	**Unit**	**Age**	**EU<34 t**			**EU>34 t**			**LV**		
			c	**i**	**a**	**c**	**i**	**a**	**c**	**i**	**a**
work	km	new	1.20			0.29			2.52		
		old	0.29			0.07			1.58		
		total	5.96								
Load real-world	t/vehicle	-	2.2			2.2			9.3		
LCU real-world	shares	-	unknown			0.09			0.23		
Fuel consumption	PJ	new	8.7	0.7	0.2	2.8	0.2	0.1	32.1	2.6	0.8
		old	2.1	0.2	0.1	0.7	0.1	0.02	20.7	1.7	0.5
		total	10.8	0.9	0.3	3.5	0.3	0.1	52.8	4.3	1.3
		total	74.16								

Appendix 4. Parameter calculations, system 3B (EU<34 t, EU>34 t already in use, EU>34 t substituting LV)

Calculation: method and sources

4. Parameter calculations, system 3B (no long vehicles) (EU<34 t, EU>34 t already in use, EU>34 t substituting LV)		
Parameter, unit	**Source or method of calculation**	**Assumptions, comments**
Vtg = share of post-2010 (new) vehicles by veh-km	For EU<34t and for EU>34t already in use: Same as in the system 3A. For EU>34t substituting LV: Same as vtg for LV in the system 3A.	It was assumed that substituting EU vehicles had the same age distribution as LV vehicles they substituted.
Vehicle number, thousands	Total for EU<34t and for EU>34t already in use: Same as in the system 3A. Total for EU>34t substituting LV: LV vehicle number in the system 3A * 1.37. Number of old vehicles = traffic work performed by old vehicles / average mileage of old vehicles. Number of new vehicles = difference between number of total and old vehicles.	Vierth et al., 2008: 1.37 conventional EU vehicles are needed to substitute one long vehicle.
Average mileage, km/veh-year	By category: Average mileage = traffic work / vehicle number. New vehicles: Average mileage = traffic work performed by new vehicles / number of new vehicles. Old vehicles: Average mileage = average mileage of a category * (1-mileage deflator).	Mileage is different between categories and for old/new vehicles but same for technologies within a category.
Mileage inflator	Mileage inflator was derived using the following equation system: Average mileage of new vehicles = traffic work performed by new vehicles / number of new vehicles, Average mileage of new vehicles = average mileage by category * (1+ mileage inflator).	Same mileage inflator for technologies within a category. Different mileage inflator for categories. Due to the assumption on the same age distribution of the substituting EU vehicles and for LV vehicles before the shift, mileage inflator was the same as in the system 3A.

4. Parameter calculations, system 3B (no long vehicles) (EU<34 t, EU>34 t already in use, EU>34 t substituting LV)		
Parameter, unit	**Source or method of calculation**	**Assumptions, comments**
Mileage deflator	Personal communication with J. Borken-Kleefeld. Same as in the system 3A.	Same mileage deflator for technologies within a category. Different mileage deflator for categories.
Traffic work, Gveh-km	By category: Traffic work = transport work / load real-world. For new and old vehicles: Traffic work = traffic work of a category adjusted with vtg. By technology: Traffic work = total traffic work * share of technology by veh-km.	Same (real-world) LCU of the category EU>34 t substituting LV as LCU of LV in the system 3A.
Share by veh-km, %	Category share = traffic work of a category * 100% / traffic work total. Technology share = category share * technology-to-category share= = traffic work of a category * technology-to-category share * *100%/traffic work total.	Technology-to-category shares are the same as in the system 3A.
Transported weight per vehicle, t/vehicle-year	Transported weight per vehicle = transported weight / vehicle number.	-
Average transport distance, km	Average transport distance = transport work / transported weight.	-
Transported weight, Mt	For EU<34t and for EU>34t already in use: Same as in the system 3A. For EU>34t substituting LV: Same as transported weight by LV in the system 3A. By technology: Transported weight = share by t * total transported weight.	Total transported weight is the same as in the system 3A.
Transport work, Mt-km	For EU<34t and for EU>34t already in use: Same as in the system 3A. For EU>34t substituting LV: Same as transport work by LV in the system 3A. By technology: Transport work = share by t-km * total transport work.	Total transport work is the same as in the system 3A.

4. Parameter calculations, system 3B (no long vehicles) (EU<34 t, EU>34 t already in use, EU>34 t substituting LV)

Parameter, unit		Source or method of calculation	Assumptions, comments
Share by t, %		Category share = Mt by category *100% / Mt total. Technology share = category share * technology-to-category share.	Technology-to-category shares are the same as in the system 3A.
Share by t-km, %		Category share = Mt-km by category * 100% / Mt-km total. Technology share = category share * technology-to-category share.	Technology-to-category shares are the same as in the system 3A.
Load max, t/vehicle		Vierth et al., 2008.	-
Load real-world, t/veh		Load real-world = LCU real-world * load max	Unavailable for EU<34 t because of the lack of data on load max.
LCU real-world, shares		For EU<34 t and EU>34 t already in use: Same as in the system 3A. For EU>34 t substituting LV: Same as (real-world) LCU of LV in the system 3A.	It was assumed that during the shift LV vehicles were substituted with EU vehicles with higher real-world LCU than EU vehicles already being used. The latter were most probably used for transportation of different sorts of goods than LV vehicles.
Fuel consumption, PJ		New vehicles: Fuel consumption = traffic work by technology * fuel traffic efficiency (MJ/veh-km) * vtg. Old vehicles: Fuel consumption = traffic work by technology * fuel traffic efficiency (MJ/veh-km) * (1-vtg).	-
Fuel traffic efficiency, MJ/veh-km	By category	For EU<34 t and EU>34 t already in use: Same as in the system 3A. For EU>34 t substituting LV: Fuel traffic efficiency was adjusted (increased) proportionally to the increase of LCU.	It was assumed that fuel traffic efficiency increases in direct proportion to the increase of real-world LCU. At the same time, proportion between fuel consumption of new and old vehicles was left the same for EU>34 t already in use and substituting LV. For 2020, the same numbers were used for EU>34 t substituting LV as for 2010, because of the very similar increase in real-world LCU and assumption on the constant fuel traffic efficiency values for other categories in 2010 and 2020.
	Average	Average fuel traffic efficiency = total fuel consumption / total traffic work.	
Fuel transport efficiency, MJ/t-km		Fuel transport efficiency (MJ/t-km) = fuel consumption / transport work.	-

Results: 2010

4. Parameters in the system 3B (no long vehicles) (EU<34 t, EU>34 t already in use, EU>34 t substituting LV), 2010											
Parameter	**Unit**	**Age**	**EU<34 t**			**EU>34 t already in use**			**EU>34 t substituting LV**		
			c	**i**	**a**	**c**	**i**	**a**	**c**	**i**	**a**
Vtg	share	-	0.18			0.27			0.23		
Fuel traffic efficiency	MJ/veh-km	new	8.18	6.95	6.14	10.80	9.19	8.11	11.21	9.54	8.42
		old	7.98	6.79	5.99	11.13	9.46	8.35	11.55	9.83	8.67
		av	8.02	6.82	6.02	11.04	9.39	8.28	11.48	9.76	8.61
		total av	10.78								
Fuel transport efficiency	MJ/t-km	new	3.72	3.16	0.00	5.72	4.87	0.00	2.07	1.76	0.00
		old	3.63	3.09	0.00	5.89	5.01	0.00	2.13	1.81	0.00
		av	3.65	3.10	0.00	5.85	4.97	0.00	2.12	1.80	0.00
		total av	2.30								
Transport work	Mt-km	-	2862	55	0	434	8	0	28819	558	0
		total	32736								
Transported weight	Mt	-	64.9	1.3	0.0	15.3	0.3	0.0	229.4	4.4	0.0
		total	315.6								
Average transport distance	km	-	44			28			126		
		total av	104								
Vehicle number	thousands	new	8.3			1.1			1.5		
		old	58.1			3.7			6.7		
		total	79.4								
Transported weight per vehicle	t/veh-year	-	997			3224			28573		
Average mileage	km/veh-year	new	28417			58402			844435		
		old	18792			45598			621212		
		av	19991			48509			660864		
		total av	87803								
Mileage deflator	-	-	0.06			0.06			0.06		
Mileage	-	-	0.42			0.20			0.28		

4. Parameters in the system 3B (no long vehicles) (EU<34 t, EU>34 t already in use, EU>34 t substituting LV), 2010											
Parameter	**Unit**	**Age**	**EU<34 t**			**EU>34 t already in use**			**EU>34 t substituting LV**		
			c	**i**	**a**	**c**	**i**	**a**	**c**	**i**	**a**
inflator											
Traffic work	Gveh-km	-	1.30	0.03	0.00	0.23	0.004	0.00	5.31	0.10	0.00
		new	0.24			0.06			1.23		
		old	1.09			0.17			4.18		
		total	6.97								
Load real-world	t/vehicle	-	2.2			1.9			5.4		
LCU real-world	shares	-	unknown			0.08			0.23		
Fuel consumption	PJ	new	1.9	0.03	0.0	0.7	0.01	0.0	13.5	0.2	0.0
		old	8.5	0.1	0.0	1.9	0.03	0.0	47.4	0.8	0.0
		total	10.4	0.2	0.0	2.5	0.04	0.0	60.9	1.0	0.0
		total	75.08								

Results: 2020

4. Parameters in the system 3B (no long vehicles) (EU<34 t, EU>34 t already in use, EU>34 t substituting LV), 2020											
Parameter	**Unit**	**Age**	**EU<34 t**			**EU>34 t already in use**			**EU>34 t substituting LV**		
			c	**i**	**a**	**c**	**i**	**a**	**c**	**i**	**a**
Vtg	share	-	0.80			0.80			0.62		
Fuel traffic efficiency	MJ/veh-km	new	8.18	6.95	6.14	10.80	9.19	8.11	11.21	9.54	8.42
		old	7.98	6.79	5.99	11.13	9.47	8.35	11.55	9.83	8.67
		av	8.14	6.92	6.11	10.86	9.24	8.15	11.34	9.65	8.51
		total av	10.56								
Fuel transport efficiency	MJ/t-km	new	3.64	3.09	2.73	4.91	4.18	3.69	2.01	1.71	1.51
		old	3.55	3.02	2.67	5.06	4.31	3.80	2.07	1.76	1.55
		av	3.62	3.08	2.72	4.94	4.20	3.71	2.03	1.73	1.53
		total av	2.17								
Transport work	Mt-km	-	2978	284	99	705	67	24	33790	3220	1127
		total	42294								
Transported weight	Mt	-	67.6	6.4	2.3	24.8	2.4	0.8	269.0	25.6	9.0
		total	407.9								
Average transport distance	km	-	44			28			126		
		total av	104								
Vehicle number	thousands	new	46.5			6.0			5.2		
		old	30.0			2.6			5.4		
		total	95.8								
Transported weight per vehicle	t/veh-year	-	997			3224			28573		
Average mileage	km/veh-year	new	25857			48040			812327		
		old	9780			27082			482430		
		av	19560			41664			643240		
		total av	90742								
Mileage deflator	-	-	0.50			0.35			0.25		
Mileage inflator	-	-	0.32			0.15			0.26		

4. Parameters in the system 3B (no long vehicles) (EU<34 t, EU>34 t already in use, EU>34 t substituting LV), 2020											
Parameter	**Unit**	**Age**	**EU<34 t**			**EU>34 t already in use**			**EU>34 t substituting LV**		
			c	**i**	**a**	**c**	**i**	**a**	**c**	**i**	**a**
Traffic work	Gveh-km	-	1.33	0.13	0.04	0.32	0.03	0.01	6.06	0.58	0.20
		new	1.20			0.29			4.21		
		old	0.29			0.07			2.63		
		total	8.69								
Load real-world	t/vehicle	-	2.2			2.2			5.6		
LCU real-world	shares	-	unknown			0.09			0.23		
Fuel consumption	PJ	new	8.7	0.7	0.2	2.8	0.2	0.1	41.8	3.4	1.0
		old	2.1	0.2	0.1	0.7	0.1	0.02	26.9	2.2	0.7
		total	10.8	0.9	0.3	3.5	0.3	0.1	68.7	5.6	1.7
		total	91.77								

Appendix 5. Parameter calculations, systems 1A (EU<34 t + EU>34 t + LV) and 1B (EU<34 t + EU>34 t already in use + EU>34 t substituting LV)

Calculation: method and sources

5. Parameter calculations in the systems 1A (EU<34 t + EU>34 t + LV) and 1B (EU<34 t + EU>34 t already in use + EU>34 t substituting LV)	
Parameter, unit	**Source or method of calculation**
Vtg = share of post-2010 (new) vehicles by veh-km	Vtg = sum of traffic work by all new vehicles / traffic work total.
Vehicle number, thousands	Sum of vehicle number by category and for old and new vehicles separately.
Average mileage, km/veh-year	Average mileage = traffic work / vehicle number.
Mileage inflator	Mileage inflator = average mileage of new vehicles / average mileage for category - 1
Mileage deflator	Mileage deflator = average mileage for category / average mileage of old vehicles - 1
Traffic work, Gveh-km	Sum of traffic work by category and for old and new vehicles separately.
Share by veh-km, %	Technology share = technology-to-category share, same as in the three or two categories system.
Transported weight per vehicle, t/vehicle-year	Transported weight per vehicle = transported weight / vehicle number.
Average transport distance, km	Average transport distance = transport work / transported weight.
Transported weight, Mt	Sum of transported weight by category.
Transport work, Mt-km	Sum of transport work by category.
Share by t, %	Technology share = technology-to-category share, same as in the systems 3A and 3B.
Share by t-km, %	Technology share = technology-to-category share, same as in the systems 3A and 3B.
Load real-world, t/veh	Load real-world = transport work/ traffic work.
Fuel consumption, PJ	<u>New vehicles</u>: Fuel consumption = traffic work by technology * fuel traffic efficiency * vtg. <u>Old vehicles:</u> Fuel consumption = traffic work by technology * fuel traffic efficiency * (1-vtg).
Fuel traffic efficiency*, c-i-a	For each technology, fuel traffic efficiecny is a sum of fuel traffic efficiencies by categories weighted with shares of their actual traffic

5. Parameter calculations in the systems 1A (EU<34 t + EU>34 t + LV) and 1B (EU<34 t + EU>34 t already in use + EU>34 t substituting LV)		
Parameter, unit		**Source or method of calculation**
MJ/veh-km		work. Values for old and new vehicles were calculated separately.
	Average	Fuel traffic efficiency = total fuel consumption / total traffic work.
Fuel transport efficiency, MJ/t-km		Fuel transport efficiency = fuel consumption / transport work.

*Fuel traffic efficiency in a one category system cannot be the same as in the three or two categories system because they define different categories: one category system combines all heavy duty vehicle categories into the one HDT category.

Fuel traffic efficiency differs depending on whether one category system includes long vehicles or not (whether it is the system A or the system B).

Results, systems 1A and 1B: 2010

5. Parameters in systems 1A (EU<34 t + EU>34 t + LV) and 1B (EU<34 t + EU>34 t already in use + EU>34 t substituting LV), 2010								
Parameter	**Unit**	**Age**	**1A= EU<34 t + EU>34 t + LV**			**1B = EU<34 t + EU>34 t already in use + EU>34 t substituting LV**		
			c	**i**	**a**	**c**	**i**	**a**
Vtg	share	-	0.22			0.22		
Fuel traffic efficiency	MJ/veh-km	new	12.73	10.83	9.55	10.73	9.13	8.05
		old	12.67	10.77	9.51	10.82	9.20	8.12
		av	12.68	10.78	9.52	10.80	9.19	8.11
		total av	12.64			10.77		
Fuel transport efficiency	MJ/t-km	new	1.87	1.59	0.00	2.28	1.94	0.00
		old	1.86	1.58	0.00	2.30	1.96	0.00
		av	1.86	1.58	0.00	2.30	1.96	0.00
		total av	1.86			2.29		
Transport work	Mt-km	-	32114	622	0	32114	622	0
		total	32736			32736		
Transported weight	Mt	-	309.6	6.0	0.0	309.6	6.0	0.0
		total	315.6			315.6		
Average transport distance	km	-	104			104		
Vehicle number	thousands	new	11.1			11.9		
		old	66.0			67.4		
		total	77.2			79.4		
Transported weight per vehicle	t/veh-year	-	4090			3976		
Average mileage	km/veh-year	new	99307			141081		
		old	56496			79393		
		av	62282			87803		
Mileage deflator	-	-	0.10			0.11		
Mileage inflator	-	-	0.59			0.61		
Traffic work	Gveh-km	-	4.71	0.09	0.00	6.84	0.13	0.00
		new	1.04			1.53		

5. Parameters in systems 1A (EU<34 t + EU>34 t + LV) and 1B (EU<34 t + EU>34 t already in use + EU>34 t substituting LV), 2010								
Parameter	**Unit**	**Age**	**1A= EU<34 t + EU>34 t + LV**			**1B = EU<34 t + EU>34 t already in use + EU>34 t substituting LV**		
			c	**i**	**a**	**c**	**i**	**a**
		old	3.77			5.44		
		total	4.81			6.97		
Load real-world	t/vehicle	-	6.8			4.7		
Fuel consumption	PJ	new	12.9	0.2	0.0	16.1	0.3	0.0
		old	46.9	0.8	0.0	57.8	1.0	0.0
		total	59.8	1.0	0.0	73.9	1.2	0.0
		total	60.77			75.08		

Results, systems 1A and 1B: 2020

5. Parameters in systems 1A (EU<34 t + EU>34 t + LV) and 1B (EU<34 t + EU>34 t already in use + EU>34 t substituting LV), 2020								
Parameter	**Unit**	**Age**	**1A= EU<34 t + EU>34 t + LV**			**1B = EU<34 t + EU>34 t already in use + EU>34 t substituting LV**		
			c	**i**	**a**	**c**	**i**	**a**
Vtg	share	-	0.67			0.66		
Fuel traffic efficiency	MJ/veh-km	new	12.24	10.41	9.19	10.55	8.97	7.92
		old	13.64	11.60	10.24	11.19	9.52	8.40
		av	12.70	10.80	9.53	10.77	9.16	8.08
		total av	12.45			10.56		
Fuel transport efficiency	MJ/t-km	new	1.73	1.47	1.29	2.17	1.84	1.63
		old	1.92	1.63	1.44	2.30	1.96	1.73
		av	1.79	1.52	1.34	2.21	1.88	1.66
		total av	1.75			2.17		
Transport work	Mt-km	-	37473	3572	1250	37473	3572	1250
		total	42294			42294		
Transported weight	Mt	-	361.4	34.4	12.1	361.4	34.4	12.1
		total	407.9			407.9		
Average transport distance	km	-	104			104		
Vehicle number	thousands	new	56.3			57.7		
		old	36.6			38.0		
		total	92.9			95.8		
Transported weight per vehicle	t/veh-year	-	4389			4258		
Average mileage	km/veh-year	new	71300			98714		
		old	53068			78639		
		av	64124			90742		
Mileage deflator	-	-	0.21			0.15		
Mileage inflator	-	-	0.11			0.09		
Traffic work	Gveh-km	-	5.28	0.50	0.18	7.70	0.73	0.26
		new	4.02			5.70		

5. Parameters in systems 1A (EU<34 t + EU>34 t + LV) and 1B (EU<34 t + EU>34 t already in use + EU>34 t substituting LV), 2020								
Parameter	**Unit**	**Age**	**1A= EU<34 t + EU>34 t + LV**			**1B = EU<34 t + EU>34 t already in use + EU>34 t substituting LV**		
			c	**i**	**a**	**c**	**i**	**a**
		old	1.94			2.99		
		total	5.96			8.69		
Load real-world	t/vehicle	-	7.1			4.9		
Fuel consumption	PJ	new	43.6	3.5	1.1	53.3	4.3	1.3
		old	23.5	1.9	0.6	29.7	2.4	0.7
		total	67.0	5.4	1.7	83.0	6.7	2.1
		total	74.16			91.77		