RICARDO-AEA

Light weighting as a means of improving Heavy Duty Vehicles' energy efficiency and overall CO2 emissions

Heavy Duty Vehicles Framework Contract – Service Request 2

Report for DG Climate Action

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Executive summary

Introduction and scope

Ricardo-AEA, together with our partners Ricardo, Millbrook, TRT and TEPR, was commissioned to provide technical support to work evaluating the potential of light-weighting as a means of improving heavy-duty vehicles' energy efficiency and overall CO_2 emissions.

The objective of the work was to provide a comprehensive survey and analysis of the potential contribution of HDV light-weighting to improving future fuel consumption and reducing GHG emissions in the EU. This final report provides a summary of the work carried out on project tasks.

HDV lightweighting options

The objective of the first task for the project was to identify options for lightweighting of different types of HDVs, and also gather information on their likely costs. The work involved carrying out a review of available literature, developing draft estimates for HDV lightweighting options and their potential, and consulting with relevant stakeholders to seek feedback on/help refine these estimates into a final list.

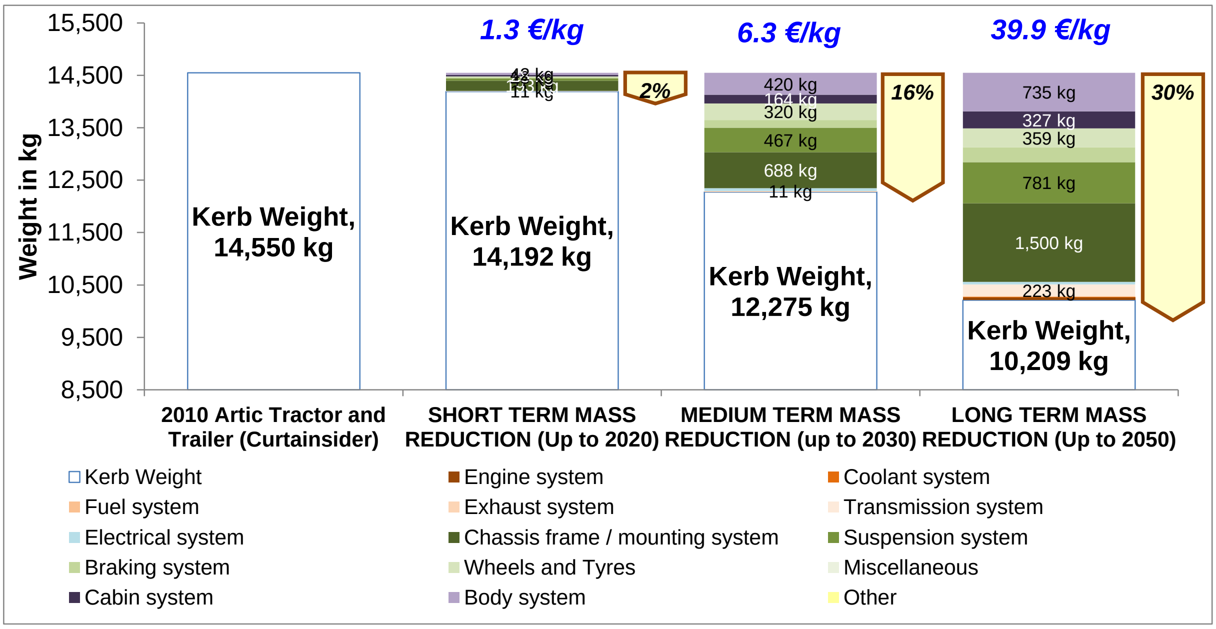
A key sub-task included the development of a 'virtual tear-down' of a set of five representative HDV types, using Ricardo's internal expertise and publically available data sources to provide a breakdown of the vehicle's mass and materials by system and sub-system. The five HDV types identified included:

1. Heavy van (5t GVW)
2. Rigid truck (12t GVW)
3. Artic truck (40t GVW)
4. City bus (12t GVW)
5. Coach (19t GVW)

Very little information was identified in the available in public information sources on individual lightweighting measures, nor the overall weight reduction potential of HDVs. Therefore Ricardo used their internal engineering expertise to develop an indicative bottom-up list of options for weight reduction and their costs and effectiveness for the five different representative HDV types. The results of this assessment were also sense-checked in the stakeholder consultation process to further refine them.

An example of the final results is presented in the following Figure ES1 below, providing a summary of the estimated weight reduction potential for an articulated truck.

Figure ES1: Estimated mass reduction potential by system and costs for an articulated truck



Source: Study analysis by Ricardo-AEA and Ricardo UK.

Notes: Estimates are based on current costs for weight reduction measures.

As part of this study we also carried out a review of publically available information sources to develop indicative estimates of the additional weight of alternative fuel and/or powertrain systems. The results of this review suggest that that for fully electric vehicles at least, the 1 tonne additional weight allowance proposed for the amendment of the EC Directive covering the weights and dimensions of HDVs may not be sufficient to balance the additional weight due to batteries for larger vehicles. Though clearly this depends on a number of factors including the efficiency/electric range of the vehicle and improvements to battery energy density in the coming years (which is anticipated to potentially halve by 2020).

Impact of lightweighting on fuel consumption and CO_2 emissions

The previous task provided a comprehensive assessment of the options and technical developments for light-weighting. It generated a list of potential weight savings for the different light-weighting options and technical developments. The important linked question is: *"What levels of energy and CO_2 savings might this light-weighting produce?"*

This second task compiled the results of three different sources in order to estimate the potential energy and CO_2 savings resulting from HDV lightweighting:

1. Literature sources
2. HDV simulations (using the VECTO model)
3. Pervious HDV testing (from dynamometer tests and test track driving with PEMS[1])

The analysis of the data from these sources confirmed the linear relationship of weight reduction and fuel consumption/CO_2 emissions for a series of different HDV types and duty cycles. The principal output from this task was the development of a series of linear equations for the relationship between the vehicle's weight and its CO_2 emissions (per km) for different HDV type and duty cycle combinations, i.e.:

$$CO_2 \text{ (g/km)} = \text{Gradient x vehicle weight + constant.}$$

The values of these gradients and constants are listed in Table 3.17 of the report for different vehicle categories, and different drive cycles.

An additional output from this task was the development of low and high estimates of the average share of km that are weight limited, for different HDV types and duty cycles.

Marginal abatement cost-curve analysis of HDV lightweighting

The aim of the third and fourth tasks were to produce vehicle-level marginal abatement cost (MAC) curves, and hence estimates for the cost-effective lightweighting potential of different HDV types, which were then used as a basis for estimating overall EU HDV consumption/CO_2 emissions in Task 5. As part of this work Ricardo-AEA adapted/built upon the framework from the previously developed MACC model previously developed by CE Delft for DG Climate Action[2]. The new HDV Lightweighting MACC Model was populated with information/outputs from the previous project tasks, plus additional information to help characterise the development of the future performance of HDVs to 2050 and the costs of the identified lightweighting options.

The developed model was designed to output results for a series of 17 different vehicle combinations of HDV weight classes and duty cycles for a series of different time periods from 2015 to 2050. An example of one the MAC curve generated for a 16-32 tonne construction truck for the 2030 time-period is presented in the following Figure ES2 below.

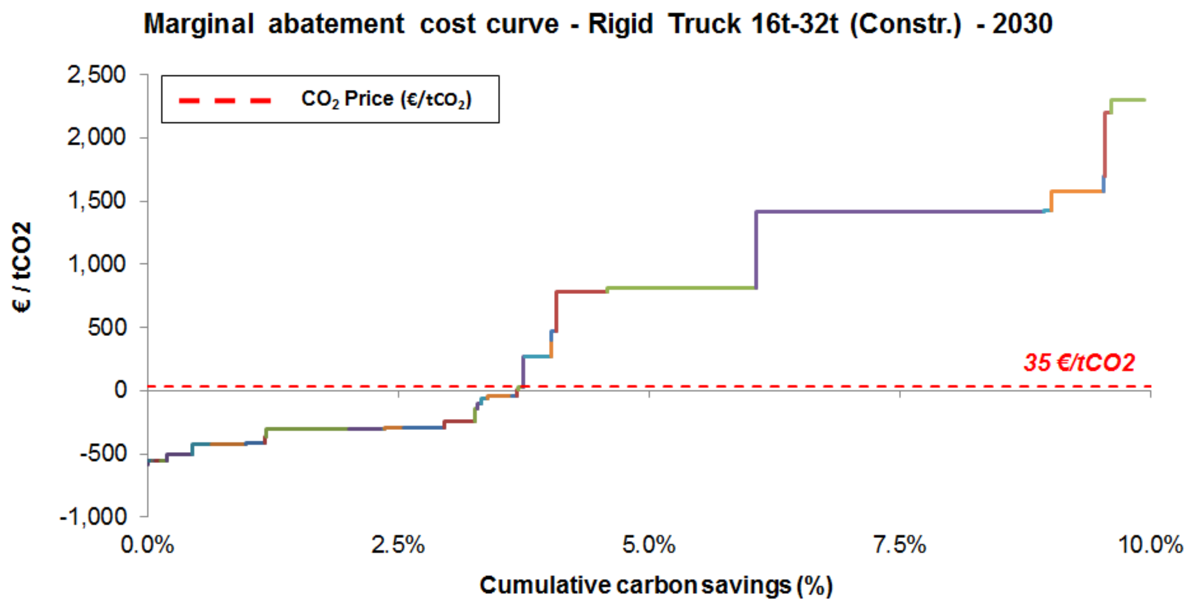
The developed model was then used to provide a series of summary outputs on the overall cost-effective weight/CO_2 reduction potential for HDVs, and also the exploration of a range of sensitivities on this. Table ES1 and Table ES2, provide a summary of the results for the overall average cost-effective weight reduction potential and CO_2 savings for different HDV duty cycles under the default/core set of assumptions.

[1] PEMS = Portable Emissions Measuring System
[2] CE Delft. (2012). 'Marginal abatement cost curves for Heavy Duty Vehicles'. Final report for DG Climate Action. European Commission. http://www.cedelft.eu/publicatie/marginal_abatement_cost_curves_for_heavy_duty_vehicles_/1318?PHPSESSID=fd472a7cb3cf9d7ca910579edf80e4b4.

The results show that when looking across all HDV modes, all trucks other than utility trucks are expected to be able to achieve at least a 7% reduction in weight cost-effectively by 2025, under the defined social perspective and payback over the lifetime of the vehicle. By 2050, construction trucks have the most cost-effective light-weighting potential, expected to be able to reduce their weight cost effectively by over 13%.

At the other end, utility trucks appear to have least potential for cost-effective lightweighting with only around 4-5% weight reduction estimated to be attainable throughout all time period.

Figure ES2: Marginal abatement cost curve for 16-32 tonne construction truck for 2030



The situation is also similar with respect to CO_2 savings: construction trucks have the greatest cost-effective potential of all truck duty cycles. Almost 3.7% cost-effective weight reduction may be achievable by 2030 and 5% by 2050. These figures are substantially greater than those of the other truck duty cycles; one of the principal factors contributing to this is their greater levels of weight-limited operation.

Of all HDVs, buses have the highest cost-effective weight reduction potential, with over 20% cost-effective lightweighting estimated to be possible by 2050. This equates to around 17% reduction in CO_2, due to the highly transient nature of bus duty cycles, with frequent stops. In contrast, coaches are anticipated to have some of the lowest levels of cost-effective weight reduction potential.

Table ES1: Calculated cost-effective weight reduction potential (%) versus 2015 baseline vehicle

Vehicle type	2020	2025	2030	2040	2050
Average Truck	**4.1%**	**7.4%**	**8.6%**	**9.8%**	**10.2%**
Urban	4.4%	8.4%	10.3%	11.5%	11.8%
Utility	3.7%	4.0%	4.6%	4.6%	4.6%
Regional	4.9%	8.6%	9.9%	10.1%	10.2%
Construction	3.8%	8.2%	9.9%	12.0%	13.5%
Long Haul	4.1%	7.6%	8.0%	10.1%	10.6%
Average Bus	**2.8%**	**4.2%**	**5.4%**	**5.1%**	**10.5%**
Bus	3.5%	7.1%	8.0%	8.0%	20.5%
Coach	2.3%	2.4%	3.8%	3.3%	4.2%

Table ES2: Calculated CO_2 savings potential (%) versus baseline vehicle for model year for cost-effective weight-reduction

Vehicle type	2020	2025	2030	2040	2050
Average Truck	**1.06%**	**1.91%**	**2.24%**	**2.56%**	**2.68%**
Urban	1.17%	2.14%	2.67%	2.97%	3.03%
Utility	1.48%	1.57%	1.78%	1.78%	1.80%
Regional	1.12%	1.94%	2.28%	2.34%	2.36%
Construction	1.40%	3.05%	3.67%	4.38%	4.94%
Long Haul	0.85%	1.58%	1.66%	2.13%	2.23%
Average Bus	**1.58%**	**2.78%**	**3.38%**	**3.28%**	**7.54%**
Bus	2.76%	5.81%	6.56%	6.56%	17.12%
Coach	0.85%	0.89%	1.40%	1.24%	1.57%

A range of sensitivities were also explored using the MACC model, in order to estimate the potential impacts of different assumptions/outcomes for key parameters, including fuel prices, capital costs of lightweighting, annual mileage, share of weight-limited operations, capital payback period, social vs end-user perspectives, etc.

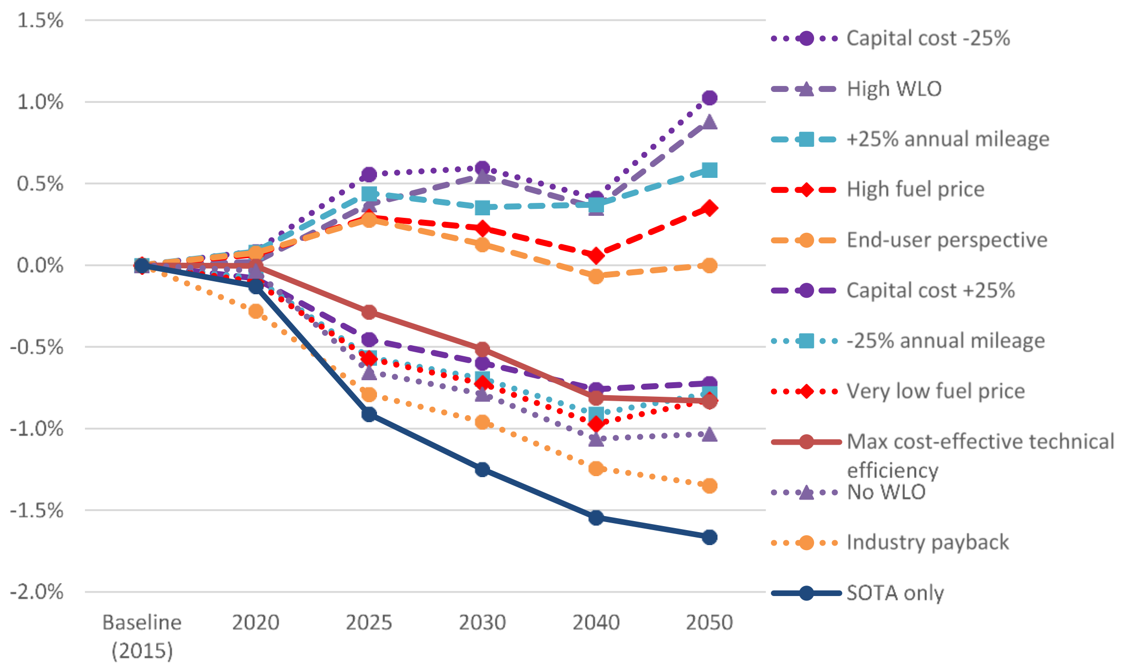
For trucks, it was found that the assumption of a 25% reduction in the cost of lightweighting measures has the greatest impact in terms of making more lightweighting measures cost-effective and thereby increasing fuel savings (Figure ES4). The assumption of higher weight limited operation has the second most significant positive impact on fuel savings due to the application of cost-effective lightweighting. The assumption of 25% increase in annual mileage per vehicle has a similarly high impact in most years. High fuel prices and taking into account the end-user perspective also slightly increase the level of cost-effective lightweighting.

The assumed unavailability of future lightweighting technologies, short industry payback requirements and the assumption of no weight limited operations to benefit from reduced trip numbers have the greatest impact in terms of reducing the cost-effectiveness of lightweighting, leading to increases in fuel consumption over the default scenario. Annual mileage reduction, low fuel prices, high costs of lightweighting measures and maximum uptake of alternative fuel savings technologies also make lightweighting less financially attractive.

Almost all sensitivities have rather low impact in the short term time horizon up to 2020.

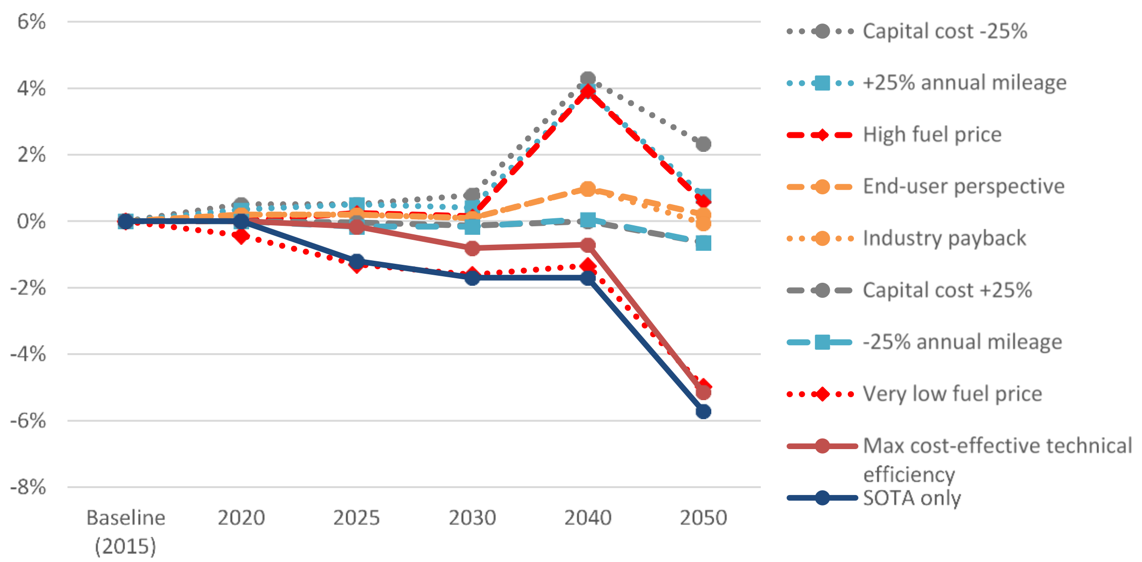
In the case of buses/coaches (Figure ES5) where cost-effective weight reduction potentials lead to significantly greater fuel savings compared to trucks, the assumption of 25% lower capital cost for lightweighting measures has the single greatest positive impact on fuel savings. In second place, 25% annual mileage increase, high fuel prices, end-user perspective and industry payback all have similar, slightly positive consequences for cost-effective lightweighting and fuel savings. Notably, fuel savings are drastically lower under the SOTA assumptions (no future lightweighting measures available). Especially in 2050, maximum uptake of alternative fuel savings technologies and very low fuel prices also greatly reduces fuel savings and levels of lightweighting.

Figure ES3: Summary: impact of altered assumptions on truck fuel/CO_2 savings relative to the default lightweighting scenario



Notes: WLO = weight limited operation; SOTA = state-of-the-art technologies

Figure ES4: Summary: impact of altered assumptions on bus/coach fuel/CO_2 savings relative to the default lightweighting scenario



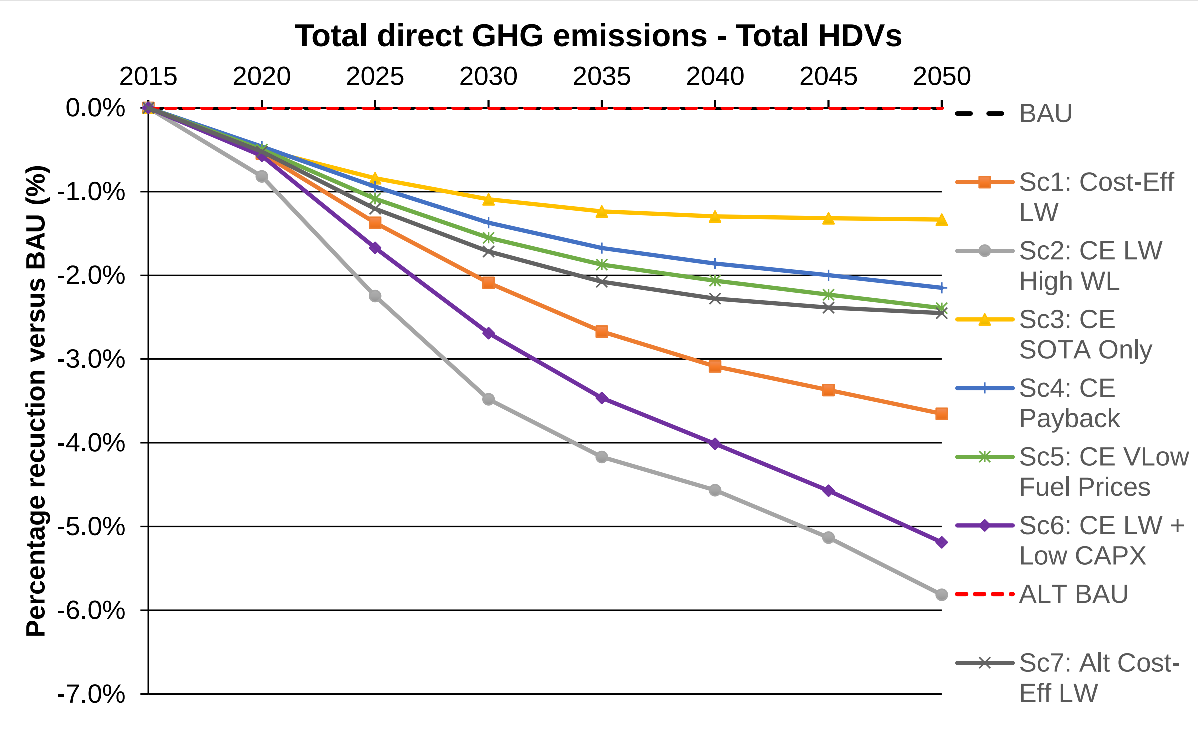
Notes: WLO = weight limited operation; SOTA = state-of-the-art technologies

Potential impacts of light-weighting for the EU HDV fleet

The final task in this project involved the estimation of the potential impacts for take-up of cost-effective lightweighting on overall fuel consumption and CO_2 emissions from the European HDV fleet. Outputs from the previous MACC modelling analysis were used within an adapted version of the SULTAN model previously developed by Ricardo-AEA for DG Climate Action[3], in order to estimate these impacts.

The following Figure ES5 and Table ES3 provide a summary of the overall results of the European HDV fleet modelling in terms of the estimated changes in overall direct CO_2 emissions for different HDV lightweighting scenarios. In the core/baseline lightweighting scenario (#1, Cost-Eff LW), it is estimated that the application of cost-effective lightweighting could reduce emissions from the European HVD fleet by around 2.1% by 2030 and almost 3.7% by 2050. A range of sensitivities were also explored on the levels of weight limited operations, assumptions on industry payback requirements, fuel prices and capital costs and on the impacts of including other cost-effective HDV CO_2 reduction technologies. These are also presented in the table and figure, and show that as a consequence, emission reductions could be as little as half of those in the core/baseline scenario (#1), or up to almost double the size.

Figure ES5: Summary of the change in projected direct CO_2 emissions from all HDVs due to cost-effective uptake of lightweighting in the EU fleet for different scenarios vs the relevant BAU scenario



Note: * For the Alt BAU and Alt Cost-Eff LW, % reduction is calculated vs the Alt BAU scenario.

Table ES3: Total HDV direct CO_2 emissions by scenario, Mtonnes CO_2

#	*Scenario*	*2015*	*2020*	*2025*	*2030*	*2035*	*2040*	*2045*	*2050*
	BAU	*288.3*	*293.3*	*304.5*	*316.1*	*320.5*	*327.7*	*331.6*	*336.0*
1	Cost-Eff LW	288.3	291.7	300.3	309.5	312.0	317.6	320.4	323.7
2	CE LW High WL	288.3	290.9	297.6	305.1	307.2	312.8	314.6	316.5
3	CE SOTA Only	288.3	291.8	301.9	312.6	316.6	323.5	327.2	331.5
4	CE Payback	288.3	291.9	301.6	311.7	315.2	321.6	325.0	328.8

[3] AEA et al. (2012). Developing a better understanding of the secondary impacts and key sensitivities for the decarbonisation of the EU's transport sector by 2050 - Final Project Report. A report by AEA, TNO, CE Delft and TEPR for the European Commission, DG Climate Action. Retrieved from http://www.eutransportghg2050.eu/cms/reports/

#	Scenario	2015	2020	2025	2030	2035	2040	2045	2050
5	CE V Low Fuel Prices	288.3	291.8	301.2	311.2	314.5	320.9	324.2	328.0
6	CE LW + Low CAPX	288.3	291.6	299.4	307.6	309.4	314.6	316.4	318.6
	Alt BAU	*288.3*	287.0	282.5	267.4	246.0	232.6	220.0	207.2
7	Alt Cost-Eff LW	288.3	285.5	279.1	262.8	240.9	227.3	214.8	202.2

Table of contents

Appendices

Table of figures

Table of tables

1 Introduction

Ricardo-AEA, together with our partners Ricardo, Millbrook, TRT and TEPR, was commissioned to provide technical support to work evaluating the potential of light-weighting as a means of improving heavy-duty vehicles' energy efficiency and overall CO_2 emissions.

This final report provides a summary of the work carried out on project tasks, and has been structured to provide the following elements:

- Summary of the context and foundation of the work to be undertaken (this Section 1);
- A summary of the technical work undertaken and key project findings/outputs by task (Sections 2 to 6);
    - Task 1: Assessment of options and technical developments (Section 2);
    - Task 2: Energy and CO2 benefits of identified light-weighting options (Section 3);
    - Task 3: Cost benefit analysis of identified lightweighting options (Section 4);
    - Task 4: An assessment of the cost-effective lightweighting potential (Section 5);
    - Task 5: Potential impacts of light-weighting for the EU HDV fleet (Section 6);
- A summary of the overall project findings and key conclusions from the analysis (Section 7);
- Additional technical material provided in the Appendices.

1.1 General context

Heavy duty vehicles account for just under 20% of EU total transport sector GHG emissions and over 27% of road transport GHG emissions. As a result, in the last few years there has been a significant amount of research conducted to understand and develop approaches to more effectively measure CO_2 emissions from HDVs, and on the options that are available to improve HDV efficiency and reduce emissions.

There are currently no fuel efficiency or CO_2 targets for heavy duty vehicles (HDVs), and HDVs are typically used in a much wider variety of applications and configurations than light duty vehicles (LDVs). Nevertheless, there are strong drivers to reduce fuel consumption and hence CO_2 emissions in the heavy duty vehicle market because:

- Fuel costs are a major part of overall operating costs for purchasers of these vehicles.
- Reduced vehicle weights can improve fuel efficiency in volume-limited operations and allow for increased payloads and reduced numbers of journeys to be made in weight limited operations, improving system efficiency.

As a result of these factors, all heavy duty vehicle manufacturers offer light-weighting options as part of their model line-ups in many vehicle categories. However, there are a number of considerations which can act as barriers to HDV light-weighting, such as: cost, reliability, durability, flexibility and safety. Therefore, while some sectors of the HDV market will still maintain a strong market pull for reducing vehicle weights, as a result of these barriers in many other sectors there may not be sufficient demand for vehicle manufacturers to prioritise weight reduction measures over other vehicle characteristics.

Previous studies carried out for the Commission have identified only high-level potential for lightweighting in heavy duty vehicles. There is therefore a need to better qualify and understand in more detail the overall potential for lightweighting to contribute to reductions in GHG emissions from the HDV sector and its likely cost-effectiveness. In the context of the above, the Commission has contracted this project entitled *"Light-weighting as a means of improving Heavy-Duty Vehicles' (HDVs) energy efficiency and overall CO_2 emissions"*, which complements work Ricardo-AEA has carried out on downweighting of light duty vehicles for DG CLIMA.

1.2 Objectives of the study

The objective of the work was to provide a comprehensive survey and analysis of the potential contribution of HDV light-weighting to improving future fuel consumption and reducing GHG emissions in the EU. Specifically the objectives of this study, set out at the start of the project, were as follows:

1. To produce a comprehensive list of the options and technologies which may be deployed to achieve weight reduction in HDVs, considering both current state-of-the art as well as potential options that might be deployed further in the future.
2. For each option, to assess the likely energy savings and CO_2 emissions reductions which may be achieved both:
    a. individually - as discrete individual changes
    b. cumulatively - working in combination with other light-weighting technologies

    [Note: These potential benefits were assessed against an agreed list of each of the main categories of HDVs.]
3. To undertake cost benefit analysis for each option, assessing the likely costs of applying the option versus the likely benefits due to reduced fuel consumption, with these costs and benefits being used to produce marginal abatement cost curves (MACC). This should factor in both running weight reduction and load efficiency impacts.
4. Based on the developed MACCs, carry out an assessment of the cost-effective potential for different categories of HDVs based on existing state-of-the-art technologies, and also consider likely future developments (i.e. in technologies, production methods and costs).
5. To make an overall assessment of the potential of light-weighting to achieve cost effective fuel consumption and CO_2 emissions reductions for the agreed main categories of HDVs across the whole EU fleet. This assessment should be based on the existing state-of-the-art technologies, but should also consider likely future developments as well as factoring in both running weight reduction and/or load efficiency impacts (e.g. via increased average payload).

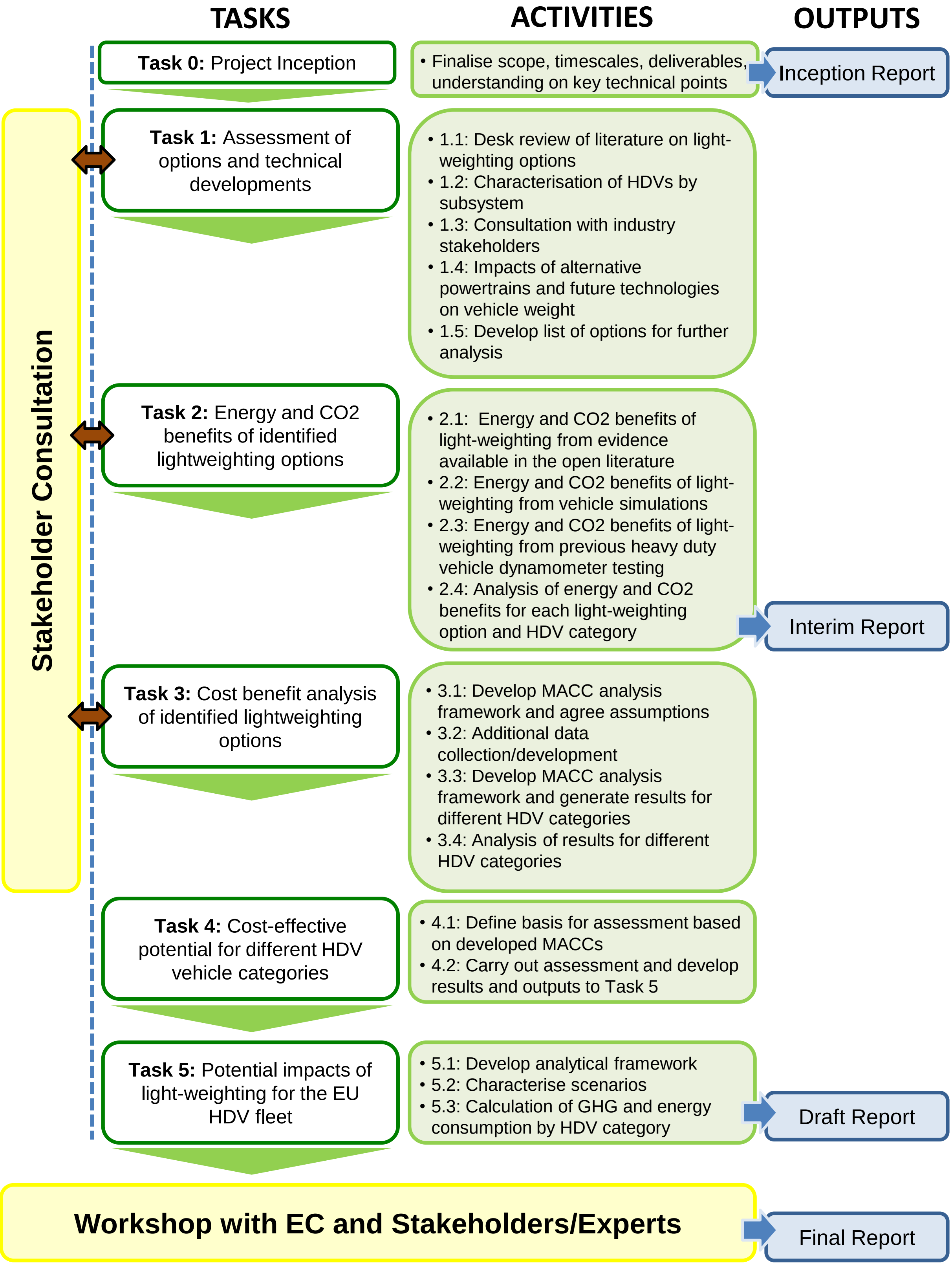
The resulting report (this document) addresses these objectives in a comprehensive and detailed manner, thereby providing guidance for policy formulation.

This final report presents a detailed summary of the work completed and draft findings on the project.

1.3 Methodology overview

The following sections provide progress on the methodology for delivering this project, covering each of the technical tasks (1 to 5) specified in the Commission's Terms of Reference. An overview of the whole project methodology is summarised overleaf in Figure 1.1.

Figure 1.1: Overview of methodology



2 Task 1: Assessment of options and technical developments

Box 1: Key points for Task 1

Objectives:

- **Produce and assess a comprehensive list of potential options and technologies for light-weighting of HDVs**

Key tasks:

- **Literature review**
- **Component / sub-system level weight saving assessments for different HDV categories**
- **Stakeholder consultation**

Outputs:

- **Condensed list of options for further analysis**
- **Indicative costs for individual options**

2.1 Overview of Task 1

The aim of this first task was be to produce a comprehensive list of options and technologies which could be employed to achieve light-weighting of heavy duty vehicles, ensuring all the significant options have been identified and considered. The original plan for this work was for this to be done through a combination of desk based literature research together with stakeholder engagement. However, some revisions to this approach were necessary, as the information on HDV light-weighting available from the literature review sources identified (discussed further in sections 2.2 and 2.3) was found to be very limited. In the end a consolidated list of options and indicative costs was put together by experts at Ricardo. The stakeholder engagement included a review of the initial findings from this analysis so that a final amended/prioritised list of options could be generated to take forward for further analysis in later tasks.

It was necessary to agree priorities for vehicle types and usage patterns in which lightweighting is likely to be of the greatest benefit. This prioritisation was informed by a combination of current estimates for the relative importance (in terms of overall energy consumption and GHG emissions), likely potential for cost-effective lightweighting and other considerations (such as potential to influence greater uptake of lightweighting through policy action). The initial proposal agreed with the Commission for this disaggregation and prioritisation is presented in the following Table 2.1.

Table 2.1: Proposed maximum level of disaggregation and prioritisation of duty cycles and body types to be taken forward in the analysis

Vehicle Group	Vehicle Category	Drive Cycles		Body Types[2]		
		Cycle	Priority	Type	Notes	Priority
Rigids	<7.5t truck	Urban Delivery	High	Box	Urban only	High
		Utility	Low	Sweeper/other	Utility only	Low
		Construction	Medium	Tipper	Construction only	Medium
	7.5t-<16t truck	Urban Delivery	High	Box/Curtain	Excl. utility	High
		Utility	Low	RCV	Utility only	Low
		Regional Delivery	High	Refrigerated	Excl. utility	Medium
	16t-32t truck	Urban Delivery	Medium	Box/Curtain	Excl. utility/ const'n	High
		Utility	Low	Refrigerated	Excl. utility/ const'n	Medium
		Regional Delivery	High	Flat	Excl. utility	Medium
		Long-Haul	High	RCV	Utility only	Low
		Construction	High	Tipper	Construction only	High

Vehicle Group	Vehicle Category	Drive Cycles		Body Types[2]		
		Cycle	Priority	Type	Notes	Priority
	>32t truck [1]	Long-Haul	Medium	Box/Curtain	N/A	High
Artics	16t-<32t artic	Regional Delivery	Medium[3]	Box/Curtain	Excl. construction	High
		Long-Haul	Low	Tanker	Excl. construction	Low
		Construction	Low	Tipper	Construction only	Low
	>32t artic	Regional Delivery	High	Box/Curtain	Excl. construction	High
		Long-Haul	High	Tanker	Excl. construction	Medium
		Construction	High	Tipper	Construction only	High
Bus/coach	Urban bus	Urban	High	Urban bus	N/A	High
		Heavy Urban	Medium			
	Inter-urban bus	Inter-urban	Medium	Inter-urban bus	N/A	Medium
	Coach	Coach	High	Coach	N/A	High

Notes: (1) >32t truck is a road train = truck+trailer combo, (2) Listed options are only relevant to some duty cycles. (3) In the UK at least there is significant use of smaller 'urban artics' for deliveries into city centres, however it is unclear whether use is significant in other countries and overall numbers versus larger artics is relatively low.

Definitions of duty cycles / mission profiles were required. For this project, we have used existing definitions established under the previous European Commission HDV GHG LOT 1 /LOT 2 studies (AEA/Ricardo, 2011) / (TU Graz et al, 2012).

The following sections provide a summary of the work completed in this task.

2.2 Task 1.1: Literature review

The first part of this task involved a comprehensive review of literature identified in the public domain on lightweighting options available for heavy duty vehicles. Material was identified through a combination of previously identified sources from Ricardo's library of information, web searches, and conversations with key stakeholders. Summary tables of the reports and other information sources initially reviewed are provided in Appendix 1. Over the course of the stakeholder consultation and the review of the quantitative analysis more literature was identified. The insights from all literature reviewed are summarised in the following sections.

Unlike light duty vehicles, where a significant amount of comprehensive analysis has recently been carried out on weight reduction options, we found there was far less readily identifiable and relevant/useful information on heavy duty vehicles. Most of the information on HDV sub-systems and scenarios for lightweighting these (Task 1.2) was therefore provided by Ricardo's vehicle experts, and discussed and verified with stakeholders during the consultation (Task 1.3).

2.2.1 Weight trends in heavy duty vehicles

2.2.1.1 Articulated trucks

Over the past 20 years, the average weight for tractors (of articulated trucks) appears to have increased to a small degree. Stakeholders have attributed this to the increasing stringency of Euro emission standards, increased safety requirements and increased comfort demand (e.g. through greater use of soundproofing materials).

Comparing the tractor kerb weight of a 20-25 year old Scania R-series cab Euro I tractor with 11 litre engine (7,340 kg) (Eurotransport, Scania: Drei Lkw-Generationen im Vergleich. By Michael Kern., 2013) to the weights of five typical Euro VI trucks with 13l engines (7,325 – 7,465 kg) (Eurotransport, 1000-Punkte-Test: Euro-6-Zugmaschinen im Vergleich. By Frank Zeitzen., 2014) suggests that weight has not increased dramatically. However, the five Euro VI trucks were all equipped with aluminium wheels and had no spare wheel included (potentially to offset increases in weight in other areas – discussed below). Steel wheels and a spare wheel may add some 200 kg to a current standard tractor. Thus, a typical Euro VI tractor can be expected to be some 200 – 350 kg (or 2.5 – 5%) heavier than a typical Euro I tractor with equivalent specification in this area.

Various factors have driven this weight increase. Stakeholders have attributed increased safety requirements (such as updated ECE R29 cab structure requirements), increased comfort (Eurotransport

(2013) illustrates progress made in terms of space, equipment and noise levels inside the cab between a Euro I and a Euro VI tractor) as well as increased emissions performance requirements. The latter has led to a significant increase in weight in the transition from Euro V to Euro VI, of which there has been some discussion in the literature. According to Commercial Motor (Commercial Motor, 2013), a Euro VI aftertreatment box (including oxidation catalyst, diesel particulate filter, AdBlue injection, two parallel SCR catalysts and ammonia slip catalysts to prevent excess ammonia emissions) weighs around 125-150 kg for a typical 13 litre engine. AdBlue has a density of around 1.1kg/litre, so a full AdBlue tank with a capacity of 60-80 litres may add over 100 kg weight, including the weight of the tank itself. Cooled exhaust gas recirculation systems which are used on many engines add 40 kg to engine weight (Ibid.). Manufacturers have generally tried to compensate for the weight increases associated with Euro VI emissions control equipment by applying weight reduction measures. Suppliers therefore often refer to Euro VI to advertise compensating weight reductions from their lightweighted truck components and systems. Consequently, TruckScience (2013) finds that weight increases on artic tractors from the transition from Euro V to Euro VI have been quite variable between manufacturers; ranging from 0 kg to 200 kg. Volvo's FM truck even appears to have become some 75 kg lighter in its Euro VI version compared to the Euro V version by reducing weight in various components including the front axle leaf springs (Trucker, 2013).

2.2.1.2 Rigid trucks

Less information on weight trends for rigid trucks was available. However, given the modularised structure of truck models, the cab and powertrain options of the heavier variants will also tend to be available for rigid truck chassis variants. For example, Scania's three cab variants, the P, G and R series, are available for both articulated and rigid trucks.

The situation is slightly different for lighter rigid trucks (typically within the 7.5 t to 18 t GVW classes). These tend to have a range of smaller cabs and powertrains (e.g. Iveco Eurocargo). No figures on weight increases in this class of vehicles were identified from the literature but a stakeholder indicated that "payload for a given weight has certainly gone down over the years". This is due to better noise encapsulation, air suspension (replacing leaf spring suspension), fully suspended cabs, more sophisticated brakes and other factors.

The transition from Euro V to Euro VI has increased weight by a similar extent as in artic tractors so the proportionate impact on payload is usually greater. One operator interviewed quoted a 150 kg kerb weight increase for Euro VI compared to Euro V on his 7.5 t trucks. Additionally, a manufacturer quoted weight penalties ranging from 150 kg to 250 kg for Euro VI vehicles applying equally to rigid and articulated trucks.

2.2.1.3 Buses and coaches

As for trucks, little information was available in the public domain. IRU estimate that increases in comfort, safety and environmental equipment have led to increases of some 1.4 t in coaches, with 300 kg attributable to the transition from Euro V to Euro VI (Table 2.2).

Table 2.2: Weight increases in coach components (IRU)

Embedded materials (safety/environment/comfort)	Situation - end-90's (in kg)	Current situation (in kg)	Additional weight (in kg)
Noise reduction	15	100	85
Retarder and brake systems: ABS, ESP, ACC, AEBS, LDWS	70	220	150
Strength of the body (UN R 66)	110	200	90
Safety belts and anchorages	80	200	120
Double glazing	200	220	20
Air-conditioning system + Toilets + Water tank + Kitchen	300	450	150
On-board equipment: Camera & Mirrors + Multimedia + ITS systems	30	70	40

Embedded materials (safety/environment/comfort)	**Situation - end-90's (in kg)**	**Current situation (in kg)**	**Additional weight (in kg)**
Lighting: *glazing + Directional Headlamps*	15	65	50
Engine (Euro III to Euro V)	260	700	440
Engine Euro VI: 2014		1000	300
Total additional weight			**1,445**

During our stakeholder consultation, a coach manufacturer stated that his coaches had become around 500-600 kg heavier over the past 20 years. Weight increases due to additional comfort, safety and environmental equipment were in part compensated through lighter body parts.

City buses have also increased in weight: the standard Mercedes-Benz 12 m low-floor bus O405N from the early 1990s was available with kerb weights from around 10.4 t (Traditionsbus, Technische Daten - MB EN 90, 91, 92, 95, 97 (Mercedes-Benz O405N). By Ulf Bergmann., 2011) while the high floor variants were around 600 kg lighter (Traditionsbus, Technische Daten - DB E 85, 86, 88 (Mercedes-Benz O405). By Ulf Bergmann., 2011a). The latest Euro VI Mercedes-Benz Citaro 12 m bus weighs 11.4 t (Bus-Fahrt, 2014).

2.2.2 The role of weight savings in heavy duty vehicles

2.2.2.1 Articulated trucks

For trucks, weight saving mainly plays a role in the context of increasing payload for weight restricted operations. Suppliers indicate that, as a rule of thumb, manufacturers are willing to spend up to €10 per kg saved for lightweighting measures if the product is used for weight-restricted operations (SAE, 2012). Similarly, MAN claims that for Silo and tanker operations, annual cost savings due to lightweighting will be around €10/kg (MAN Truck International, 2014). Cost implications will be examined in more detail and modelled in Task 2.

OEM brochures sometimes specify the weight impacts of different engines, gearboxes, cab sizes and optional equipment. This information indicates that lightweighted tractor variants can be made approx. up to 1,000 kg lighter than a standard long-distance tractor. While a typical Euro VI tractor weighs around 7,500 kg (steel wheels, no spare wheel and 400 litres of fuel) (Eurotransport, 1000-Punkte-Test: Euro-6-Zugmaschinen im Vergleich. By Frank Zeitzen., 2014) a lightweight Euro V tractor could be specified to be as light as 6,100 kg (including fuel) (Scania, P 360 and P 400 Euro 5 added to range: Scania P-series available with bigger engines. , 2009) – a lightweight Euro VI vehicle can be expected to be some 100-200 kg heavier than its Euro V equivalent. Options to reduce weight includes aluminium wheels, choice of lower cab class, size and equipment levels (short day cab instead of sleeper cab), smaller tank size (Scania, Specification: R/G 410 LA4x2MNA Euro 6, 2013), as well as variations to chassis frame thickness. For example, Scania offers frame profile thickness from 7mm to 17.5 mm with weights ranging from 21kg/m to 54kg/m, respectively (Scania, The Scania chassis frame range, 2009a).

Significant weight reduction options are also available for semi-trailers. Whereas standard curtainsider trailers weigh around 6 t to 7 t (see the online truck marketplace TruckScout24[4] for typical curtainsider weights) several manufactures offer lightweight curtainsiders: Schmitz-Cargobull offers lightweight trailers at 5.4 t (Schmitz-Cargobull, 2011), Schwarzmüller and Kögel offer lightweight trailers at around 5.2 t while Fliegl offer trailers at 5 t (Fliegl) and Berger Ecotrail at 4.7 t (Berger).

For box vans and reefers, weight depends to a large extent on the panel materials used. Plywood panels for side walls weigh around 16 kg/m^2 whereas polypropylene panels weigh around 5 kg/m2 (Don-Bur, Don-Bur Blade Panel Brochure).

Lightweighting and use of aluminium in tipper trailers appears to be wide-spread and manufacturers are increasingly introducing lightweight constructions into the market (Eurotransport, Kippaufbauten: Die Pfunde purzeln weiter. By Markus Braun., 2012). As tipper operation is often weight limited there is a wide range of tipper designs and weights to accommodate different needs. Four 24m^3 half-pipe steel tippers tested by Eurotransport had kerb weights between 5.6 t and 6.3 t (Eurotransport, Vier Stahl-Halbrundmulden im Vergleich: Einer für Alles. By Markus Braun., 2013a). Schmitz Cargobull's

[4] http://www.truckscout24.com/semi-trailers/used/flatbed-tarpaulin

lightweight steel tipper weighs around 5 t. Weight is further reduced to 4.5 t when using an aluminium box body (Schmitz-Cargobull, Press Release: Tipper trailer with tare weight of less than 5 tonnes., 2010). Steel tends to be more robust and therefore more suitable for frequent tipping while aluminium tippers are more suitable for longer distance operations (Schmitz-Cargobull, 8 Tough Questions To Ask Your Tipper Semitrailer Manufacturer.).

Lightweight silo/tanker semi-trailers are also available both with tanks made of steel or aluminium. Aluminium chassis are also used; manufacturers include Feldbinder and Kässbohrer. Most tanker trailers for sale on the online marketplace TruckScout24 tend to have kerb weights from around 5.5 t to 7 t. In subsequent analysis we will assume 6.5 as baseline weight.

2.2.2.2 Rigid trucks

For heavier rigid trucks, the situation tends to be similar to articulated trucks: lightweighting is particularly relevant with respect to silo and tipper bodies where maximum payload is easily exceeded in daily use.

With regard to lighter rigid trucks, payload restrictions tend to be particularly relevant in the 7.5 t GVW category. These trucks tend to be popular with operators as car driving licences issued up to the late 1990s permit driving trucks up to 7.5 t GVW in several European Member States. Consequently, manufacturers advertise low kerb weight (MAN Truck International, 2014) and offer lightweight packages which can save several hundred kg through lighter chassis, smaller wheels and lighter axles (Eurotransport, Iveco Eurocargo 120E25 im Test, 2011).

In Germany, lightweight, high volume trucks with 12 t gross train weight are in widespread use as trucks up to 12 t are exempt from motorway tolls. These trucks are mostly used in the so-called 'Jumbo' sector specialising in the transportation of low-density, high volume goods such as packaging or insulation materials. An ultra-light Jumbo can carry volumes of up to 120 m^3, thus exceeding the volume of standard 40 t GVW curtainsider trucks (which have volumes of around 90 m^3). A rigid 7.5 t GVW truck with a kerb weight from around 4.5 t is combined with a one axle aluminium trailer weighing around 1.5-2.5 t. Thus payloads of 5-6 t are achieved (Verkehrsrundschau, Leichte Muse. By Johannes Reichel and Gregor Soller., 2004) (L.I.T. Spedition). Similarly, lightweight articulated trucks with 12 t GVW are available. The semi-trailer has the standard 13.6 m length and uses an aluminium chassis with a single axle, weighing 3 t (2.4 t without tail-lift and spare wheel). The tractor weighs around 4.2 t, thus enabling payloads of over 5 t if required at load volumes of around 70 m^3 (Verkehrsrundschau, Kleine Kombi für große Touren. By Johannes Reichel and Gregor Soller., 2005).

2.2.2.3 Buses and Coaches

Gross vehicle weight and axle load restrictions also tend to drive lightweighting efforts in coaches. Two-axle coaches are restricted to 18 t GVW in most EU Member States. France, Belgium, the Netherlands, Luxembourg, Portugal and Spain already allow coaches with GVW in the range 19 t to 20 t (RDA Internationaler Bustouristik Verband, 2011). Legislation for an EU-wide increase of GVW to 19 t or 19.5 t for two-axle coaches is currently being developed (European Parliament, 2014), as advocated by industry associations such as the IRU (EurActiv, 2013). The Commission's impact assessment on the amendments to maximum authorised weights finds that "the growing weight of vehicle safety and comfort equipment, and of passengers, are forcing coach operators to reduce the number of passengers per coach" (European Commission, 2013).

For city buses, the effects of weight savings on fuel consumption will tend to be greater. For example, the VDL Citea LLE, which is around 20% lighter than a standard city bus, provides around 20% fuel saving according to an operator (VDL Groep, 2014). In an interview, the manufacturer estimated typical fuel savings to be around 15%. However, the uptake of lightweight buses has been greater in some markets than in others. 12 m buses in continental Europe tend to typically weigh between 11 t and 12 t (Bus-Fahrt, 2014) while in the UK lightweight buses body are more common (Transport Engineer, 2013). For example, the 12 m version of the Alexander Dennis Enviro, a popular UK bus platform, has a kerb weight of 8.6 t (Alexander Dennis, 2013). Lightweight buses also tend to be fairly common in the Netherlands where over 1,000 Berkhof Ambassador buses, and its successor, the VDL Citea LLE, are in operation (Wikipedia, 2014). Its kerb weight is around 8.5 t-9 t.

2.2.3 Weight saving options for specific HDV systems or components

Aside from gathering general information about the weight trends in HDV and the role of lightweighting in the industry, one of the main aims of the literature review was to gather information on the weight, weight reduction potential and costs of reducing weight in individual HDV components and systems, in order to provide a 'virtual teardown' of different representative categories of HDV and identify lightweight potentials and costs in each system. The component data found within the general literature proved to be insufficient for either the virtual teardown or the lightweighting analysis. It is summarised in Table 2.3 below.

To complete the exercise, missing data and analysis were instead sourced from Ricardo UK using their sources, knowledge and engineering experience, as summarised in section 2.3.

Table 2.3: Weight-saving HDV systems or components identified in the literature

Component/system description	Weight of component	% weight reduction	Absolute weight reduction	Source
Tractor/Rigid truck: Wabco single cylinder brake compressor weighs 20% less than a two-cylinder compressor	not known	20%	-	(Wabco, Maufacturer information: h-comp High Output Compressor)
Tractor/Rigid truck: Heavy Duty disc brakes, lightweight design Trailer: disc brakes, lightweight design	39 kg, versus 47 kg for predecessor 32 kg, versus 36 kg for predecessor	17% 11%	8 kg 4 kg	(Wabco, Wabco MAXX Air Disk Brakes brochure, 2013)
Tractor/Rigid truck: Cabin Body-in-White	380-420 kg is standard weight quoted for BIW, 320 kg is the weight of the light-weighted cab design	15-24%	60-100 kg	(EDAG, 2013)
Tractor/Rigid truck: Lightweight modular cab design	'Savings potential up to 150 kg' - Fibre-reinforced composites allow for weight reduction in the roof module of around 30% taking into account the need for reinforced roof elements for crash safety requirements according to ECE R29-3	not known	150 kg for total cab	(Engineering Centre Steyr, 2013)
Tractor: Fifth wheel	from 94 kg, versus 130 kg for standard fifth wheel	28%	36 kg	(SAF-Holland)
Tractor: Lightweight monocoque chassis frame design	595 kg, vs. 850 kg for standard frame	30%	255 kg	(Engineering Centre Steyr, 2013)
Tractor/Rigid truck: Four-point link -- tractor rear axle suspension part	46 kg	30%	20 kg (over conventional V-link plus stabiliser suspension)	(SAE, 2012)

Component/system description	Weight of component	% weight reduction	Absolute weight reduction	Source
Tractor/Rigid truck: Four-point link made of glass fibre reinforced plastic-- tractor rear axle suspension part	35 kg	50%	11 kg (over standard 4-point link) -- should save around 35 kg in total	(SAE, 2012)
Tractor/Rigid truck: Front axle independent suspension	550 kg	7%	40 kg over rigid axle solution	(ZF)
Tractor/Rigid truck: Glass fibre leaf spring for front axle	17 kg instead of 66 kg. One leaf spring for each front wheel, thus savings of approx. 100kg per truck	74%	50 kg per wheel - 100 kg per truck	(Schroeter, 2011)
Trailer or rigid truck body: Lightweight body panels	Normal plywood panel weighs 16 kg per m^2, polypropylene panel weighs 5 kg per m^2. Thus potentially over 1 t savings on a semi-trailer box van using 100 m^2 of panels	not known	1 t for box-van semi-trailer	(Don-Bur, Don-Bur Blade Panel Brochure, 2014)
Trailer: Air suspension module with axle and running gear components made of GFRP	320 kg instead of 400 kg for lightest standard air suspension module	20%	80 kg per trailer axle -- 240 kg per trailer	(BPW, 2012)

Component/system description	Weight of component	% weight reduction	Absolute weight reduction	Source
Weight reductions from aluminium structures and components Tractors and rigid trucks, various components: • cabin & doors: 200 kg • chassis: 350 kg • power train parts: 125 kg • suspension parts: 110 kg • fifth wheel: 33 kg Trailer: weight reductions from aluminium, sub-structures: • chassis: 13.5 m: 700 kg • chassis: 6 m: 300 kg • chassis+floor: 13.5 m: 1100 kg • legs: 35kg Trailer/rigid truck superstructures: • rigid body: 90 m^2: 800 kg • tipping body: 800 to 2000 kg • ADR fuel tank: 43000 litres: 1100 kg Trailer/rigid truck body components: • curtain rails: 2x13.5 m: 100 kg • front wall: 85kg • rear door: 85kg • side boards: 600 mm: 240 kg • stanchions: 10x600 mm: 50 kg Safety parts and accessories: • front bumpers: 15 kg • rear bumpers: 15 kg • side bumpers: 20 kg • air pressure vessels: • 6x60 litres: 54 kg • diesel tank: 600 litres: 35 kg • toolbox: 15 kg • tail lift: 150 kg • wheels: 14 rims: 300 kg	Not indicated	Not indicated	See description	(European Aluminium Association, 2014)
Wheels: Comparing general catalogue weight of aluminium wheels with that of steel wheels suggests weight savings of around 15kg per wheel	For 385/65 tyre size: Aluminium: 29 kg Steel: 44 kg	34%	6 x 15 kg	(MWS Chevron, 2012), (MWS Xlite, 2012)
Wheels: Comparing the weight of aluminium wheels with that of steel wheels according to data from ACOA suggests weight savings of around 18.4 kg per wheel	For 385/65 tyre size: Aluminium: 23.6 kg Steel: 42 kg	44%	6 x 18.4 kg	(ALCOA, 2015)
Tyres: Bridgestone Ecopia trailer tyre claims 1.5 kg of weight savings over other tyres	not known	not known	1.5 kg	(Bridgestone)

While not providing sufficient data for the lightweighting analysis, the literature review helped us identify interviewees from organisations specialised in lightweighting. Interviews with Engineering Centre Steyr, Stuttgart University Institute for Aircraft Design, TTT and VDL were held based on public information on their HDV lightweighting products or expertise.

2.2.4 Summary of information on materials

This section provides a summary of the standard materials used on HDV, and of materials with the potential for wider usage on light-weighted HDV.

2.2.4.1 Steels

Conventional mild steel tends to be the dominant material in the manufacture of HDVs and their components (Transport Engineer, 2012). Compared to other materials of similar strength and durability, steel is a relatively inexpensive material with favourable properties for processing; a range of relatively simple and well-understood techniques for forming and joining are available. A wide variety of different steels with different characteristics are available and there is a tendency towards increased uptake of high strength steels (HSS) and advanced (or ultra) high strength steels (AHSS/UHSS) in the industry. HSS is generally used to describe steels with yield strengths in the range 210 MPa to 550 MPa and tensile strengths in the range 270 MPa to 700 MPa. Steels with strengths beyond that range count as AHSS or UHSS. The shift from conventional steels to AHSS allows weight reductions of up to 30% (US DoE, 2013). In HDV, high strength steels are used in the cabin-in-white to meet crash requirements (Volvo Trucks). Higher grade steels also help reduce weight on truck chassis frames (Transport Engineer, 2012). Lightweight trailers also typically rely on higher grade steels in the chassis for weight reduction (ArcelorMittal, 2011).

2.2.4.2 Aluminium

Aluminium alloys have approximately one third of the density of steel and iron and therefore allow for significant weight savings over steel in various structures and components (US DoE, 2013). Aluminium wheels, for example, can provide over 40% weight savings compared to steel (expert interviews). Aluminium is used for some bodies and chassis on weight-sensitive operations, in particular for silo and tipper trucks (European Aluminium Association, 2014). Manufacturers for semi-trailers with chassis and bodies from aluminium alloys include Feldbinder and Kässbohrer. Some bus bodies also use aluminium. For example, the ADL Enviro 300 uses an extruded aluminium body frame and exterior body panels from aluminium sheets (Alexander Dennis, 2013). The Mercedes Econic truck cab for urban applications uses an aluminium “space-cage” cabin-in-white structure (Mercedes-Benz, 2008). The main barriers to greater uptake identified by US DoE (2013) include inadequate joining techniques for connecting aluminium to other materials as well as issues with predictive modelling of its properties.

2.2.4.3 Plastics and fibre-reinforced materials

There is an emerging trend for non-structural parts on HDVs to be made of plastics. For example, plastic oil sumps, which are 30-50% lighter than their aluminium equivalents are beginning to be fitted to new vehicles in Europe (Automobil-Industrie, 2012). Other plastic HDV components, some of which have replaced metals, include roof fairings, mirror casings, side deflectors, bumper corners, mudguards, steps, front underrun protection, instrument panel elements, storage boxes and bed structures (expert interviews). Components that play a structural role tend to be reinforced with fibres.

Composite materials, such as glass-fibre reinforced plastics (GFRP) are increasingly used in HDVs, mostly as panelling materials. GFRP is used in reefer and box bodies as well as buses and coaches, often as part of a sandwich-structured composite (e.g. with a honeycomb or polystyrene core) for floors, roofs and side walls, as well as for some cab body parts on trucks (high roof cabin, air deflectors). Air tanks made of GFRP are also available (BPW). Its use in HDVs is likely to increase with leaf springs and axles made of GFRP expected to become widely available within the coming five years. US DoE (2013) estimates weight reduction potentials of 25-35% from GFRP. Weight savings on selected applications can be larger; for example, GFRP leaf springs for artic trucks provide 75% weight savings over steel.

Carbon fibre can be combined with suitable polymer matrix materials to create CFRP. It features very high specific strength and stiffness while providing high weight savings over steel. Therefore, it has the potential to be used for structural elements such as chassis and body systems in HDV where it could provide radical weight savings. US DoE estimate weight savings of 50-70%. A stakeholder involved with designing and manufacturing prototype CFRP components for HDV suggested that weight savings achieved in practice tend to be around 30-40%.

The most significant barriers to widespread adaptation of CFRP identified by US DoE (2013) include a lack of low-cost precursors and energy efficient production processes for the fibres, a lack of high volume manufacturing methods allowing for short cycle times as well as a lack of experience with good CFRP design and predictive modelling. Some stakeholders have indicated that longer cycle times might be less of an issue in HDV manufacturing compared to automotive manufacturing due to its lower production volumes. However, at present, CFRP has no significant application in HDV, and this is likely to be due to high costs. Some prototype vehicles with body and chassis made out of CFRP exist, as do prototypes of individual components from CFRP. The Kögel Phoenixx trailer with rear doors, front walls and neck floor section made from CFRP (Kögel) went into production in 2008 but was discontinued after a few years.

2.3 Task 1.2: Characterisation of HDV by sub-system

The objective of this sub-task was to characterise the major types of heavy duty vehicles in terms of their mass, and as far as possible, materials breakdown to inform the later analysis on the degree of future lightweighting that might be feasible with different technical options.

2.3.1 Current situation

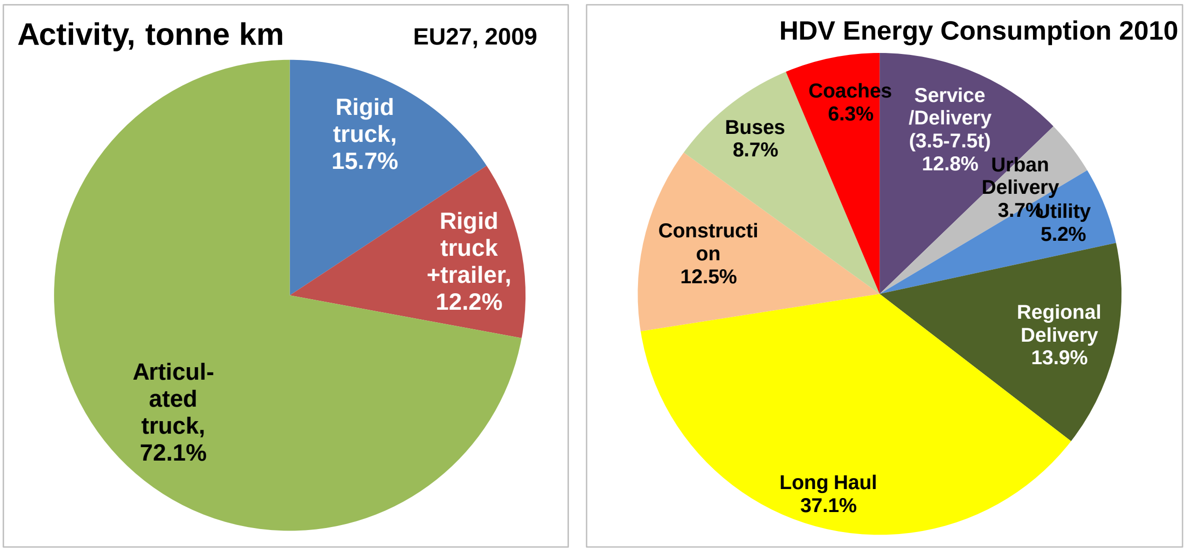
HDVs tend to be tailored to their specific duties. Common European truck types can also be distinguished by a variety of criteria:

- Chassis type:
  - Articulated versus rigid trucks (with and without trailer)
  - GVW classes (7.5 t, 12 t, 18 t etc.), typically indicative of the size of the chassis
  - Variations typically available within each GVW class
- Cab type:
  - Sleeper/day cab/double cab/Low-entry cab (e.g. Mercedes Econic)
  - Cab size/comfort class (e.g. Scania P, G, R-Series)
  - Cab height/width
- Body/trailer type:
  - Curtain-sider / Box van / reefer / tanker / silo / tipper / moving floor / container / flatbed / low-loader / refuse etc.

Covering all of these vehicle types was not possible within the time and resources available for this project. However, particular types of vehicle tend to have a high market share, e.g. although articulated trucks account for around a quarter of all European trucks, they account for over 70% of total tonne-km activity. Most tractors will tend to be high comfort class sleeper cab tractors[5] and almost 70% of trailers are curtain-siders, box vans or reefers (refrigerated) (AEA/Ricardo, 2011), which tend to be structurally similar – see Figure 2.2. Tanker and tipper trailers each also account for around 18% in total. Such considerations informed the decision-making in prioritising certain vehicle types for more detailed evaluation in 2.3.2.

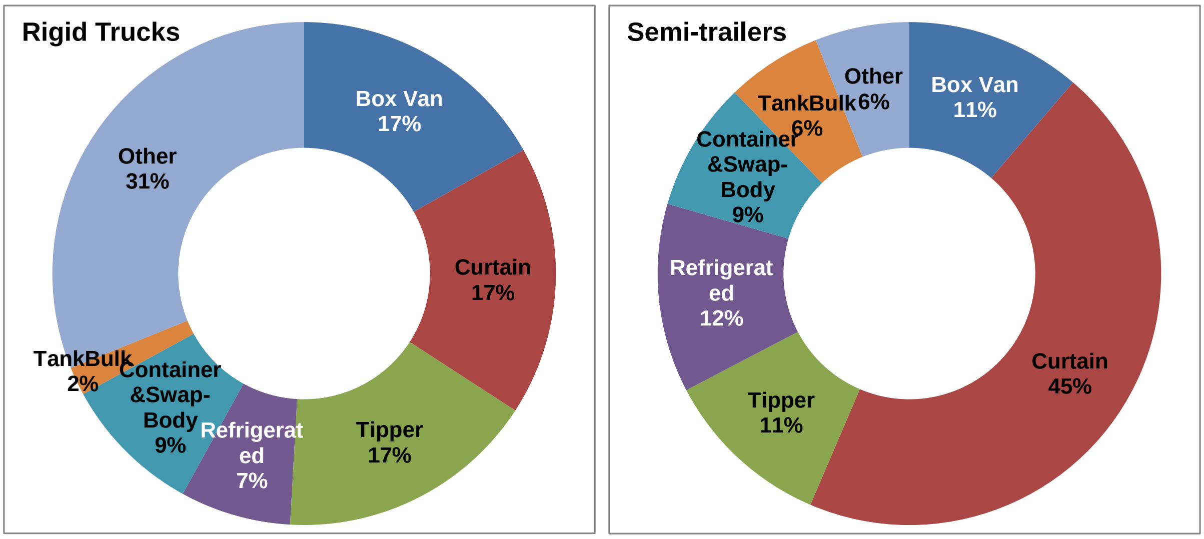
[5] For example, amongst Scania's long distance vehicles the CR19 Highline and Topline cab variants each account for some 30% of sales in Germany; the slightly lower-mounted and more modestly equipped CG19 Highline accounts for some 20% of German sales. All of these models feature sleeper cabs **Invalid source specified.**.

Figure 2.1: Estimated EU share of activity and energy consumption from different HDV types duty cycles



Source: AEA/Ricardo (2011)

Figure 2.2: Estimated breakdown of the EU vehicle parc by body type for rigid and articulated vehicles



Rigid trucks **Semi-trailers for articulated trucks**

Source: AEA/Ricardo (2011)

2.3.2 Characterisation of current/baseline HDVs

The original objective of the work was to simply provide a 'virtual teardown' of a representative set of HDV categories to aid further analysis, which included: van, rigid truck, artic truck, city bus and coach. These were selected as broadly representing the major categories of HDV in order to manage the complexity of the task in the available resources.

Given that the data from the literature review was insufficient to be able to fully determine this breakdown, instead Ricardo UK provided indicative estimates for certain sub-systems using the experience of their engineers. This analysis focused on five representative categories of HDV which were to be used as a basis for initial analysis/characterisation of HDV weights and options for weight reduction. These include the following vehicle types, with the gross vehicle weight (GVW) of the version assessed provided in brackets. It is assumed that the results for vehicles with different GVW will scale approximately directly up/down from these base types:

1. **Heavy van (5t GVW):** 5 tonne GVW, similar to standard 3.5t GVW van, but with reinforced chassis and suspension to allow for higher payload.
2. **City bus (12t GVW):** Some detailed weight data was already available on an aluminium body midibus, which has been used as a baseline for the study. Lightweight buses are most common in the UK and in the Netherlands.
3. **Coach (19t GVW):** standard 12.3m 4x2 coach, with a GVW of around 18 tonnes (e.g. Volvo 9700 12.3m RHD 4x2 Euro 5).
4. **Rigid truck (12t GVW):** 12 tonne GVW with a box body and tail lift.
5. **Artic truck (40t GVW)**: heavy long-haul tractor with 40 tonne curtain-sider trailer.

More information on these vehicles is also provided in the following section.

As part of the general consultation and interviews carried out with stakeholders as part of this project, we also asked for feedback on the virtual teardown assumptions made. This is further discussed under Task 1.3, in later section 2.4.

2.3.2.1 Summary of methodology and key assumptions

In order to support the evaluation of light-weighting technologies for heavy duty vehicles, a representative sample of vehicles was identified for characterisation and mass breakdown. The vehicles were selected in order to suitably cover the differing industry sectors (road haulage, passenger transport), gross vehicle weight range, vehicle size and construction and material type. For each vehicle selected, a mass breakdown by major system and/or module was created. Where possible, a material breakdown for each system was also noted. A number of sources were used to generate the vehicle mass breakdown which are described below. The unladen and fully laden weights were validated using web based information from the vehicle OEMs. A complete physical teardown of the sample vehicles was not possible within the resources available for this study. The following vehicles were selected and characterised:

- **"Large Van":** Examples include VW Crafter, Mercedes Sprinter and Ford Transit. The unladen weight for this category of vehicle is typically 1.8 tonne with up to a 2.0 tonne payload capacity with a Gross Vehicle Weight (GVW) of 3.5 tonnes, but there are also larger versions available with much higher GVW (e.g. VW Crafter comes in GVW of up to 7 tonnes (Volkswagen, 2014)). The mass breakdown was assembled using knowledge from Ricardo's Vehicle Engineering System Specialists and web source information.
- **"Rigid Truck":** Vehicles in this category typically consist of a steel cab structure mounted on a steel ladder frame, with rigid or semi-rigid axles. Vehicles are typically supplied by the OEM in "flatbed" condition, with coachbuilders providing unique upper structures to contain the payload, typically flatbed for vehicle transportation or box type structure for general goods transportation, although there are many variants used for other purposes (e.g. utility vehicles, construction vehicles, and other vocational applications). The upper box structures are typically welded steel or aluminium box section in construction, can be curtain-sided or rigid fibre-reinforced panel mouldings. Rigid trucks can range from 3.5 tonne to 26 tonne gross vehicle weight (i.e. generally using a draw-bar trailer for configurations above this weight). Typically the vehicles are used for urban and inter-urban goods distribution, although they are also sometimes used in longer-haul operations (e.g. also with additional draw-bar trailers). Example vehicles from this category include Isuzu Grafter and Forward, Fuso Canter, Nissan Cabstar and Volvo FL Series. For the purpose of this evaluation, a 12 tonne (GVW) rigid truck was selected, incorporating a rigid aluminium upper box structure. Background knowledge from Ricardo's Vehicle Engineering System Specialists was used to assemble the mass inventory.
- **"City bus":** Typically 8-12 tonne kerb weight and 12-18 tonne GVW in single-deck, single-axle configurations (with inter-urban bus variants usually being on the heavier end of this scale). Vehicles from this category include the Optare Tempo (Optare, 2014) and Wrightbus StreetLite (Wrightbus, 2014). Generally, the vehicles have capacity for urban transportation of between 60 and 90 passengers (combined seating and standing). The vehicle structure typically comprises a heavy duty box frame structure in steel or aluminium with aluminium or Fibre Reinforced Plastic (FRP) exterior panels.
- **"Coach".** Example vehicles from this classification include the Plaxton Panther (Alexander Dennis, 2014), accommodating up to 65 seated passengers for long distance passenger

transportation. The vehicle structure is typically similar to the urban and inter-urban buses, however the unladen/kerb weight for typical single-deck variants can be up to 13.5 tonne (and 18-19 tonnes GVW) due to higher greater interior mass for comfort seats and equipment and volume/space. Higher weight configurations with multiple axles or even double-deck configurations are also available.

- **"Articulated truck tractor unit".** A Scania R420 E5 (2008) was selected as the reference vehicle, primarily as a thorough mass breakdown is available on the a2mac1 vehicle benchmarking service (A2mac1, 2014). The powertrain mass was updated to incorporate the expected increase from Euro V to Euro VI level (primarily exhaust after-treatment). Also, the transmission was deemed to be unusually heavy and not representative for a typical tractor unit in the category, therefore the mass was revised down, based on background knowledge from Ricardo's transmission systems specialists. Other examples of trucks in this category include the Daimler Actros and Volvo FH.
- **"Articulated truck trailer".** A diverse range of articulated trailers are used to transport a wide range of goods, generally over longer distances. A detailed mass breakdown of trailers was very difficult to obtain, therefore an approach was developed where a common "lower structure" mass breakdown was estimated for all trailers which was then combined with a unique upper structure mass estimation for the trailers below. The common lower trailer structure was assumed to consist of basic drawbar ladder frame construction, supporting bed, undercarriage, twin rear axles, brakes and electrics. The following trailers were selected for the study:
    - ***Box trailer:*** Typically used for "volume" type transportation such as packages, parcels, domestic and food goods. The upper structure consists of a steel or aluminium box frame structure with aluminium or Fibre Reinforced Plastic side and roof panels. (Schmitz Cargobull , 2014a)
    - ***Curtainsider:*** Similar to box trailer but with fabric type sides in order to facilitate the easier loading and unloading of goods. (Schmitz Cargobull, 2014b)
    - **Flatbed trailer:** Most "basic" type of articulated trailer (no upper structure), used for transporting of industrial goods and products (i.e. steel coils, large vehicles, building materials and containers). (Schmitz Cargobull, 2014c)
    - **Reefer trailer:** Similar to box trailers but with insulated panels and refrigeration units (of typically around 850 kg weight); these are used in the transport of temperature controlled goods (i.e. typically foodstuffs). Due to the additional weight of the insulation and refrigeration equipment they typically have lower available weight for payload. (Schmitz Cargobull, 2014d)
    - ***Tipper trailer:*** Primarily for the transportation of aggregate and grain/cereal type goods. These trailers typically operate close to maximum GVW and feature a steel or aluminium open tipper and tailgate and hydraulic rams to enable tipping. (Schmitz Cargobull, 2014e), (Freuhauf, 2014)
    - ***Tanker trailer:*** For transporting liquid goods such as oils/petroleum. As per the tipper trailer, these tend to operate close to maximum GVW

The articulated tractor unit was combined with the six different trailer units to create five unique tractor-trailer vehicle combinations. The resulting vehicle mass characterisations for the different sample heavy duty vehicles is provided in the next report section.

2.3.2.2 Summary of results from the baseline vehicle characterisation

As outlined in the previous subsection, based on a combination of literature reviews and estimates from Ricardo engineers we have developed a **base case** (2010 model year vehicle, Euro V) reflecting an estimate of the current split of the kerb weight by component and material for each of the five vehicle categories.

The following tables (Table 2.4 to Table 2.5) and figures (Figure 2.3 and Figure 2.5) provide a summary of the results of the baseline vehicle analysis in terms of (a) the breakdown by vehicle system, and (b) breakdown by material type (a more complete selection of results by subsystem is also provided in an Excel file accompanying this report).

In addition, the overall mass comparisons for an expanded list of important heavy duty vehicle body types and weight categories is provided in Figure 2.4, which have been extrapolated based on the base vehicle types and information from the literature.

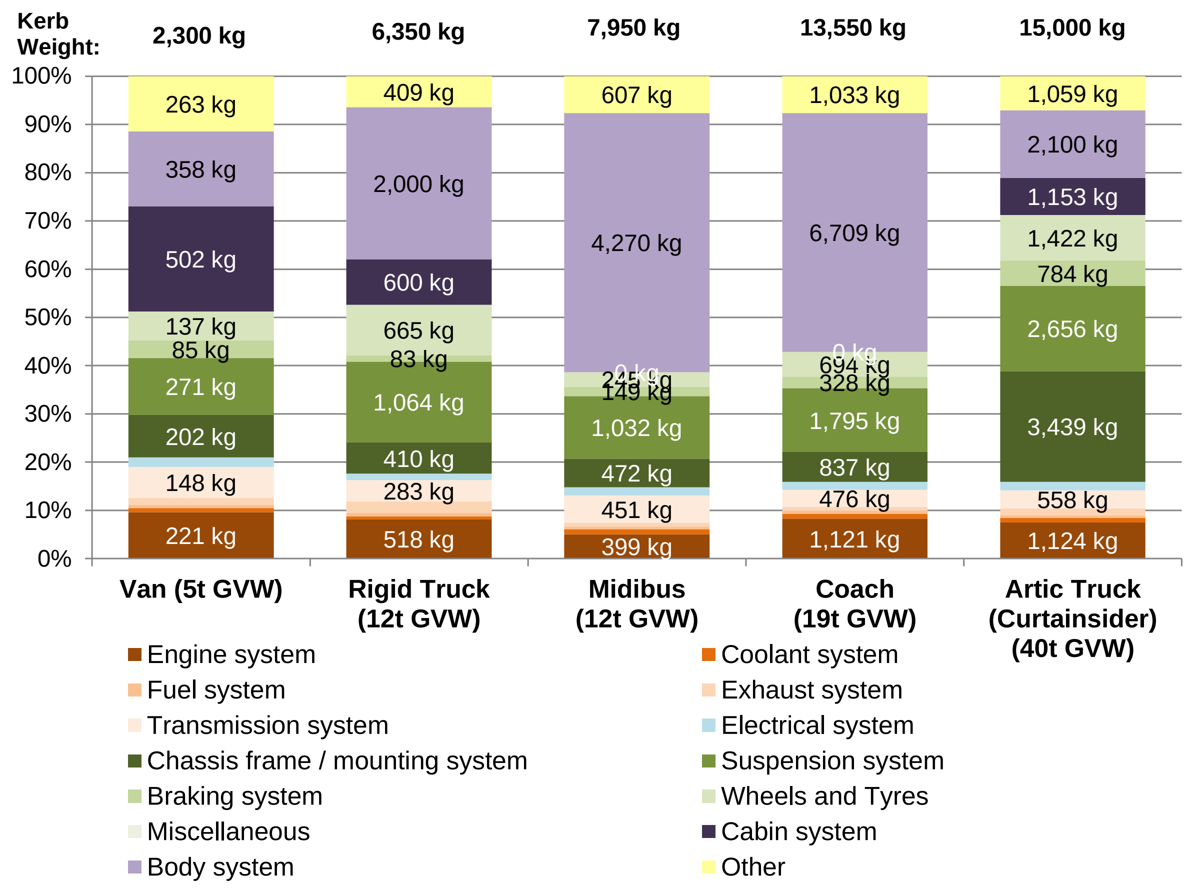
Because of the relatively low amount of data available/identified in the literature review, we expanded this task to further identify and develop initial estimates for HDV lightweighting options and their respective indicative costs. More information is provided on this work in Section 2.3.3.

Table 2.4: Summary of vehicle system and subsystem weights

System	Subsystem	Subsystem weight (kilograms)				
		Van (5t GVW)	Rigid Truck (12t GVW)	Midibus (12t GVW)	Coach (19t GVW)	Artic Truck (Curtainsider) (40t GVW)
Powertrain system	Engine system	221	518	399	1,121	1,124
	Coolant system	20	37	84	140	140
	Fuel system	17	47	46	80	80
	Exhaust system	32	150	60	118	220
	Transmission system	148	283	451	476	558
Electrical system	Electrical system	46	83	135	220	265
Chassis system	Chassis frame / mounting system	202	410	472	837	3,439
	Suspension system	271	1,064	1,032	1,795	2,656
	Braking system	85	83	149	328	784
	Wheels and Tyres	137	665	245	694	1,422
Cabin /body system	Cabin system	0	0	0	0	0
	Body system	502	600	0	0	1,153
Other	Other	358	2,000	4,270	6,709	2,100
Total	**Total Kerb Weight**	**2,300**	**6,350**	**7,950**	**13,550**	**15,000**
Payload	*Max Payload*	*2,700*	*5,650*	*4,050*	*5,450*	*25,000*

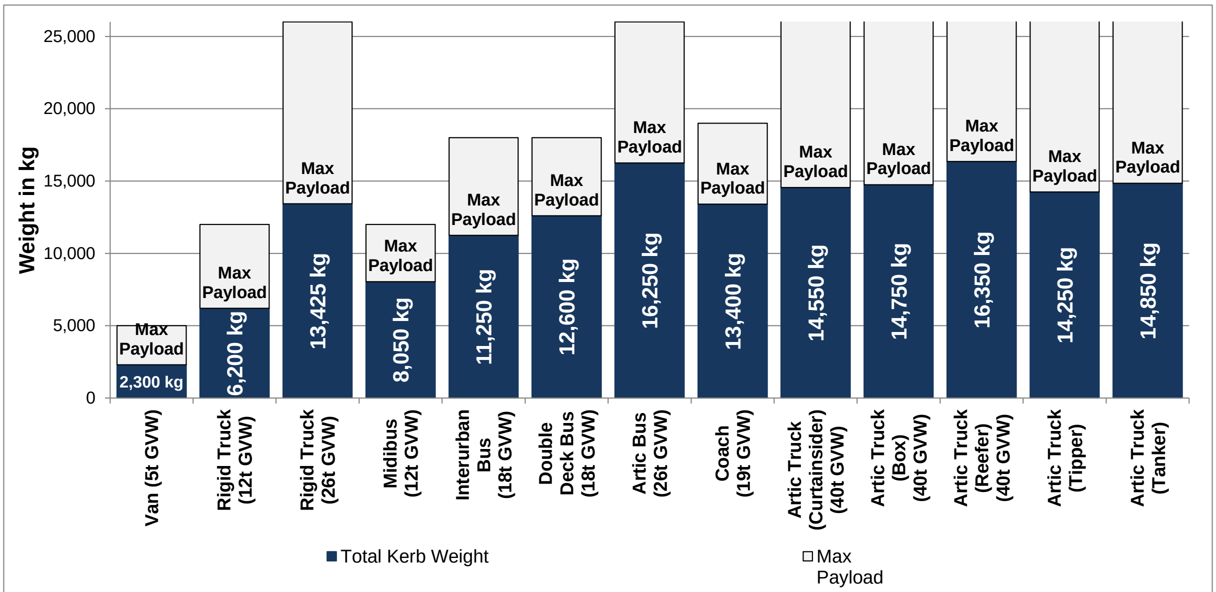
Source: Study analysis by Ricardo-AEA and Ricardo UK.

Figure 2.3: Summary of vehicle system and subsystem weights



Source: Study analysis by Ricardo-AEA and Ricardo UK.

Figure 2.4: Summary of overall vehicle weights for a wider range of vehicle weights and body types



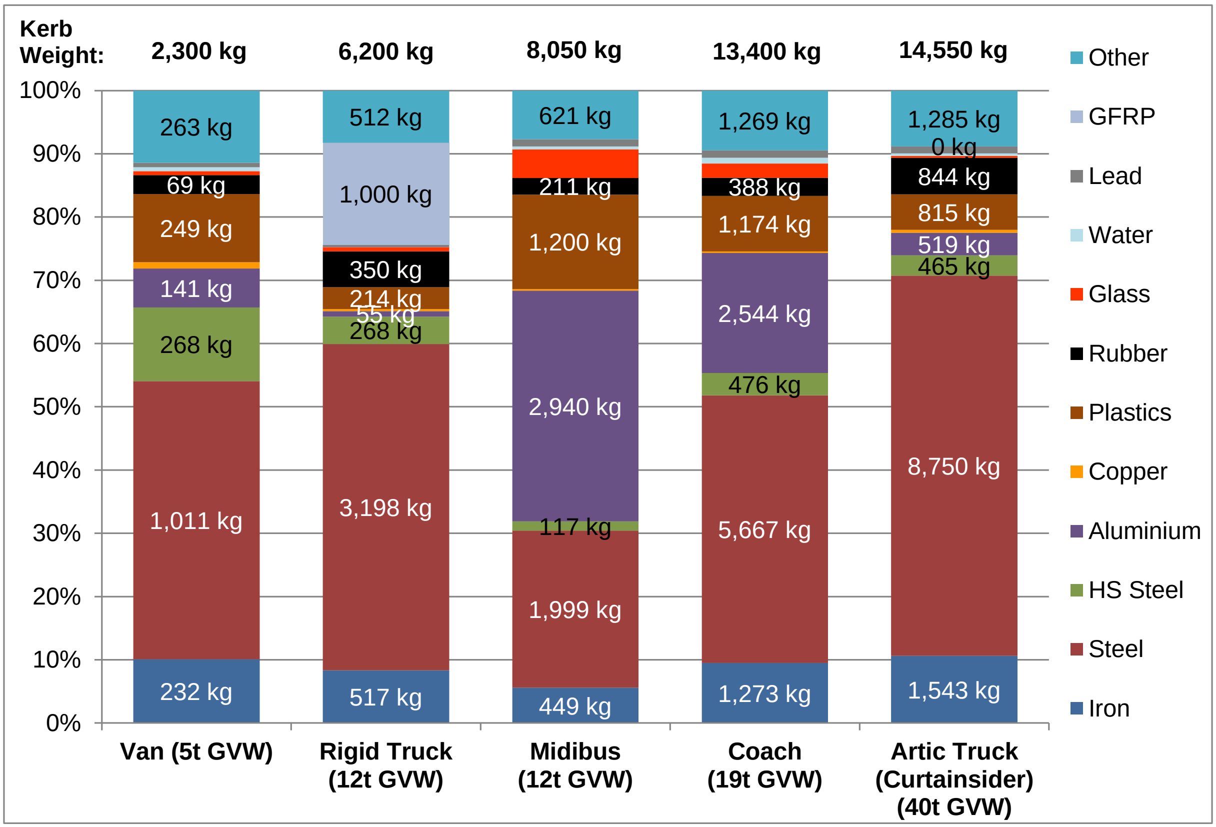
Source: Study analysis by Ricardo-AEA and Ricardo UK.

Table 2.5: Breakdown of vehicle composition by material type

Material	Total weight of material (kilograms)				
	Van (5t GVW)	Rigid Truck (12t GVW)	Midibus (12t GVW)	Coach (19t GVW)	Artic Truck (Curtainsider) (40t GVW)
Iron	232	517	449	1,273	1,543
Steel	1,011	3,198	1,999	5,667	8,750
HS Steel	268	268	117	476	465
Aluminium	141	55	2,940	2,544	519
Copper	23	20	20	34	70
Plastics	249	214	1,200	1,174	815
Rubber	69	350	211	388	844
Glass	14	41	367	300	43
Water	15	0	36	120	60
Lead	16	25	90	156	156
GFRP	0	1,000	0	0	0
Other	263	512	621	1,269	1,285
Payload	*2,700*	*5,800*	*3,950*	*5,600*	*25,450*
TOTAL	**2,300**	**6,200**	**8,050**	**13,400**	**14,550**

Source: Study analysis by Ricardo-AEA and Ricardo UK.

Figure 2.5: Breakdown of vehicle composition by material type



Source: Study analysis by Ricardo-AEA and Ricardo UK.

2.3.3 Future technical options for HDV lightweighting

Because of the relatively limited amount of data available/identified in the initial literature review, we agreed with the Commission to adjust the originally intended work programme. Instead of simply relying on the limited data available, Ricardo UK prepared a set of indicative lightweighting options by system/subsystem/component which were envisaged to be most applicable to three generalised time horizons (applicable by 2020, by 2020-2030 or in the 2030-2050 time horizon) for each of the five vehicle categories. It was anticipated that at least some of the options identified against the later generalised time horizons might also be applicable / taken up at least in lower volume/niche applications at an earlier date. However, this will be factored into the later MACC analysis to be carried out in Task 3 (see section 4).

The Ricardo analysis provided an assessment of the percentage weight reduction at the sub-system level, and used standardised costs per kg of weight reduced for particular types of common measure (e.g. weight reduction by switching to different material types). This indicative analysis was prepared prior to the stakeholder interviews in order to give the stakeholders the opportunity to indicate what they think might be plausible without being expected to necessarily share detailed or confidential/sensitive information.

After establishing the base case values, further analysis has also been performed to develop an initial estimate on the potential lightweighting opportunities and their costs. The objective was to test and further refine these figures though discussions and feedback from stakeholders (discussed further in section 2.4). We have made estimates for the technical potential for lightweighting for technological options that are assessed to be widely available / applicable at three different time horizons:

A. *Technologies that could be applied for mass-deployment in the short-term (up to 2020):* The current 'state-of-the art' options available here mainly include smaller design changes to components intended to reduce weight, as well as an increased use of higher grade steels on the chassis, the body and the suspension. Some of these measures may have already been taken up or will be applied to compensate for weight increases from Euro VI powertrains or on optional weight-reduced variants of standard trucks.
B. *Technologies that could be applied for mass-deployment in the medium-term (up to 2030):* The options available here include stronger lightweighting, mainly through material substitution of iron and steel by advanced high-strength steel and aluminium/magnesium for various components, as well as additional use of some composite materials. This scenario reflects a combination of (i) state-of-the-art measures which currently have seen some uptake on specialist vehicles such as lightweight city buses and lightweight tipper/tanker trucks, and (ii) those that are not yet applied but are expected to be ready for mass-deployment before 2030.
C. *Technologies that could be applied for mass-deployment in the long-term (up to 2050):* The options available here primarily include much greater levels of material substitution with fibre composites replacing metals for structural elements, the body and smaller components. At present, the measures presented in this scenario have only been applied to HDVs at a prototype stage.

The time horizons and costs chosen for each of the scenarios reflect the assumption of an increasing extent of lightweighting being possible over time due to technical progress, time horizons for planning and implementation in new vehicle designs, and changing market conditions. Other key assumptions for the light-weighting and costings include the following:

- Cost estimates are for lightweighting measures only, i.e. exclude other technology costs.
- Costs are based on current estimates at 2014 prices. No account for future price changes has been made at this stage (this is covered in Task 3). The effects of inflation were also not included.
- Cost estimates were based on Ricardo experience from vehicle light-weighting programmes and published technical articles and papers. In some specific cases, the costs have been benchmarked using a specific cost estimation tool ("Design Advisor" from World Auto Steel) (WorldAutoSteel, 2014a).

The following two subsections provide first a short summary of the approach and key assumptions utilised by Ricardo in developing the initial estimates and, second, a summary of the final results – as adjusted according to feedback from the stakeholder interviews.

2.3.3.1 Estimates of future options for lightweighting and their costs

Potential light-weighting technologies were categorised according to the appropriate or expected introduction timescales (near-term, medium-term and long-term) and the heavy duty vehicle type. Light-weighting technologies and cost estimates were generated based on a system level review across the sample heavy duty vehicle fleet, as the technologies would likely be applied across a vehicle system (i.e. to engine or chassis components). A number of sources of information were used to compile the light-weighting technology forecast; Ricardo's knowledge database on light-weighting consists of published technical articles and journals from academic institutions, vehicle OEMs and component and system suppliers, internet searches from known suppliers, information gathered by Ricardo through exposure to other lightweighting projects and attendance at conferences and exhibitions, e.g. the Superlight Car Project (SuperLIGHT-CAR, 2014) and Future Steel Vehicle Project (WorldAutoSteel, 2014b). Information was also gathered based on the supplier consultations and interviews conducted as part of this project. Consideration was also given for the application of known light-weighting technologies from other vehicle sectors (i.e. passenger car, off highway vehicles).

With a large number of vehicle systems and components to evaluate, different heavy duty vehicle types and three timescale categories to consider, it was not possible to generate specific technology cost estimates for each light-weighting technology proposed within the scope of this project – the costs for lightweight components typically comprise design, engineering, testing and development costs, raw material and material processing cost and transport/logistics costs. A simple approach was therefore adopted, where lightweight component costs were estimated based on a cost per kilogram reduced (€/kg). The light-weighting cost estimates varied between €3/kg weight reduction for more conventional technologies such as Advanced High Strength Steels and up to around €46/kg weight reduction (based on €42-100/kg material at 50% weight reduction over steel based on (McKinsey, 2012) and interviews with expert stakeholders), for more advanced materials such as Carbon Fibre/CFRP (Carbon Fibre Reinforced Plastic).

In some cases, costs were estimated as €0/kg where light-weighting was achieved as part of on-going component design and development. Cost estimates were based on 2014 material prices and economics. Subsequent studies in this project will attempt to forecast the actual lightweight technology cost changes for the short, medium and long term timeframes. Occasionally, more detailed cost estimates were made to validate the simplistic €/kg approach. The "Design Advisor" tool as provided by World Auto Steel (World Auto Steel, 2014) enables a basic cost calculation and comparison of lightweight technologies. Whilst the tool is generally targeted at the passenger and light commercial vehicle market, the parameter inputs can be adjusted to suit the heavy duty vehicle market conditions of typically lower production volumes. The €/kg estimates were updated where significant discrepancies to the Design Advisor calculations were identified.

2.3.3.2 Larger mass items

The following narrative provides a broad overview of the light-weighting technologies identified for heavy duty vehicles and the considerations in the selection for the larger mass items in the vehicles:

Powertrain: Engine: Ricardo's Heavy Duty Engines experts were consulted for this study. Heavy duty engine design, technology and development is generally driven by the legislative emissions targets. These drivers have historically increased engine mass through the implementation of technologies such as Selective Catalyst Reduction (SCR). Engine reliability and durability are also identified as key requirements for this market sector and OEMs are generally averse to compromising this attribute to achieve mass reduction. Engine size and the subsequent mass is generally proportional to the power and torque outputs which are matched to the expected demands of the vehicle. Engine light-weighting could therefore be achieved by reducing the power and torque demands of the vehicle where appropriate. An example of the potential for engine light-weighting would be a reduction in aerodynamic loads for buses and coaches or volume goods vehicles which would subsequently reduce the tractive effort requirements. Engine light-weighting opportunities would be limited for vehicles operating close to GVW due to the limited potential reduction in tractive effort requirements. The mass estimates and changes for heavy duty engines are therefore predicted to be relatively conservative when compared to other vehicle systems. In the short term, some engine mass increase (up to 3%) is expected in order to achieve emissions requirements. In the medium and long term, some engine mass reduction could be achieved for bus and coaches where light-weighting spiral/secondary effects, lower rolling resistance tyres and aerodynamic improvements could reduce the tractive effort requirements on the engine. For weight limited carriers (rigid truck and HDV tractor unit), the medium and long term mass reduction potential is forecast to be very limited due to the maintained or higher power and torque demands of the vehicle.

Powertrain: transmission and driveline: Similarly, the transmission and driveline sizing and therefore weight is significantly influenced by the torque demands of the vehicle and output from the engine. This is especially true for the transmission internals (gears and shafts). The transmission and driveline mass trends and technologies are therefore forecast to follow a similar trend to the engine, with the exception for the potential for significant improvements in transmission casing through the application of more exotic material such as Carbon Fibre Reinforced Plastics (CFRP) in the long term.

Chassis: ladder frame, trailer draw bar: These components are sized according to the payload, stiffness requirements and operating conditions and are traditionally roll formed steel or extruded aluminium sectioned beams. Light-weighting opportunities therefore exist in the form of material changes to Advanced Higher Strength Steel (enabling gauge/thickness reduction), aluminium or composite/CFRP. Secondary or weight spiral effects may potentially enable the downsizing of ladder frame structures for bus and coach type vehicles. In the short term, conservative mass reductions (2% to 7%) are estimated through the application of higher grade steels and design optimisation. In the medium term, it is expected that steel structures will be replaced with aluminium subject to acceptable economics. Longer term, up to 2050, it is expected that composite materials such as CFRP could be viable for application and offer mass reductions in the region of 40-50%.

Chassis: axles, wheels, tyres, brakes, springs, dampers and steering systems: These components are typically manufactured by Tier 1 suppliers for multiple OEMs, therefore enabling higher production volumes and economies of scale. Heavy duty vehicle axles and suspension arms may transition from the traditional cast iron construction to aluminium in the medium term and possibly more disruptive metal matrix compounds in the longer term (similar technologies have been demonstrated on passenger cars). The uptake of alloy wheels is anticipated to increase in the medium term with the potential for composite/CFRP materials being used by 2050. Composite leaf-springs for heavy duty trucks have been demonstrated at concept level and have a good potential for introduction in the medium to long term (composite leaf springs are already used in production for some larger vans, such as the Volkswagen Crafter). Similar technologies are due to be launched on passenger cars (coil springs) in coming years. Brake system mass reduction could be achieved as a result of secondary/spiral effect as a result of GVW decrease. Also, aluminium could feature more prominently in the medium term with composite materials being adopted in the long term. Such technologies are already prevalent in high performance sports cars and aerospace industry.

Body structure, cabin, trailer upper structures: Heavy duty vehicle upper structure construction types and materials vary quite widely depending on the application, therefore these are discussed by heavy duty vehicle type:

- **Large van and truck cabin:** These body structures typically comprise welded monocoque steel construction. It is expected that the light-weighting trends for these structures would typically "lag" those expected for passenger cars by five to ten years. In the short term, relatively moderate weight savings could be achieved through the application of high strength steels. In the medium term, a transition to multi-materials (steel and aluminium) would provide further mass reduction, initially by application to less disruptive parts of the structure such as closures. Longer term, up to 2050, composite materials such as CFRP may become viable and offer significant mass reductions. With the introduction of multi-material monocoque structures, the joining technologies become more challenging and complex. Again, technologies being developed and applied in the passenger car industry are likely to penetrate this sector. Laser welding, structural adhesives, self-piercing rivets will potentially be introduced to overcome the challenges and enable stiffer, stronger structures.
- **Coach and bus upper structures:** Coach and bus upper structures are conventionally welded spaceframes manufactured from extruded steel or aluminium box sections. The outer body panels are made from steel, aluminium, sheet moulded compound (SMC) or thermoplastic. A high percentage of the structure consists of glazing. Future light-weighting trends are expected to demonstrate a shift to full aluminium structures and plastic panels in the medium term and CFRP structures in the longer term. Moderate reductions in conventional glazing thickness will provide mass reduction opportunities in the short to medium term. More advanced glazing technologies such as polycarbonates may provide greater opportunities in the medium to long term.

- **Trailer upper structures:** Likewise, trailer upper structures may follow a steel-aluminium-CFRP route for the short, medium and long term, subject to viable economics and material improvements. (In particularly weight sensitive operations and/or market segments, e.g. using tippers and tankers, use of light weight designs using HSS or aluminium are already in the marketplace and taken up, due to the overall economic benefits). The relatively lower volume production methods may enable more creative technologies and designs. Advances in joining technologies as described above will also benefit the light-weighting of trailer upper structures.

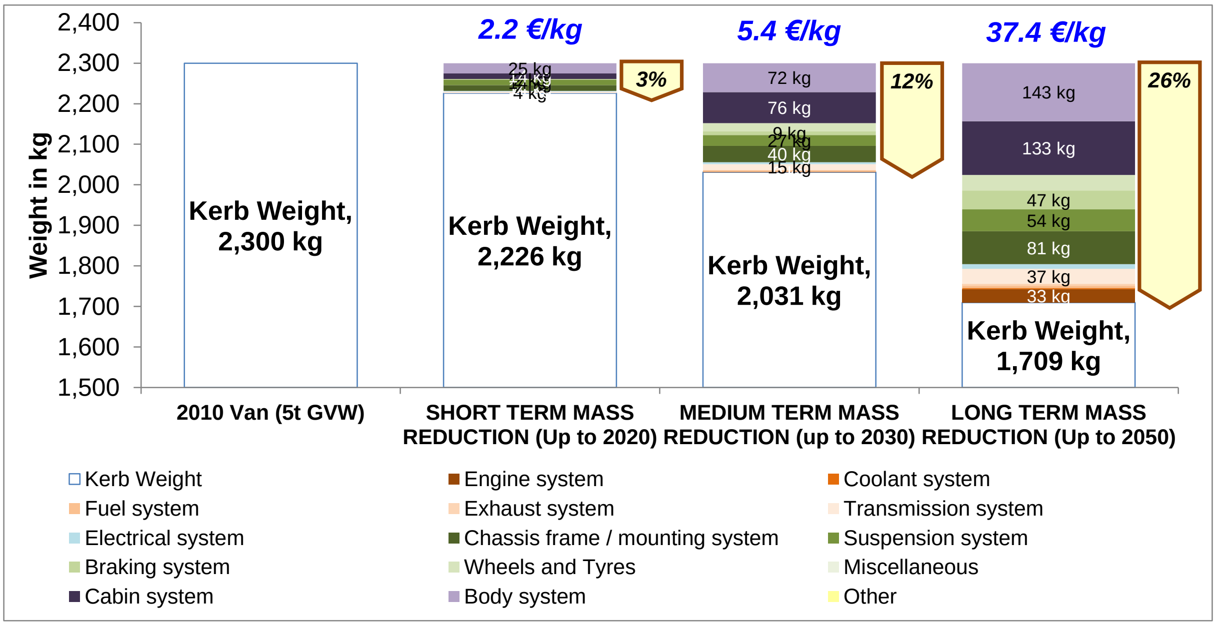
2.3.3.3 Summary of results for the analysis on future HDV lightweighting options

The following Figure 2.6 to Figure 2.14 provide a summary of the results of the indicative analysis on the future lightweighting potential from the five different HDV types investigated. These results include the amendments made to the core assumptions following feedback from the stakeholder consultation (Task 1.3), as discussed in the next section (2.4). The corresponding data tables are also provided in an Excel file accompanying this report. The savings presented are believed to be broadly representative for typical mainstream vehicles, although clearly there will be niche segments/applications where greater reductions might be achieved/cost-effective at an earlier date.

The results show that in the short term horizon, weight reductions of between 1% and 3% are anticipated to be achievable on average for a mainstream HDVs. The costs from these reductions are estimated to be around €1-2 per kg saved, relying mainly on slight improvements to component design, sometimes combined with a shift to a higher steel grade. In the mid-term scenario, weight reductions in the order of up to 11-15% are believed to be achievable for mainstream vehicles and on the artic trailer as much as 19%. Costs for such reductions range between €4 and €8 per kg saved (on current prices), driven by increased use aluminium and glass fibre composites. Overall costs for achieving similar levels of lightweighting are substantially higher on the city bus at €21 per kg saved. [The city bus analysed already has a lightweight aluminium body and lightweight steel chassis in the 2010 baseline.] Achieving weight reductions in the order of 15% therefore may require a composite body structure with some use of carbon fibre which is more expensive. In the long term horizon, CFRP chassis and body structures are potentially applicable in all vehicle types, and CFRP may also be used as standard material on various other vehicle components. Consequently, average lightweighting costs increase to €34-43 per kg saved. Around 25-30% weight savings are achieved on most vehicle types. On the curtainsider semi-trailer, where chassis and body components dominate vehicle weight, weight savings from the CFRP design are 35%.

The future costs of the different options were estimated as part of the analysis in later Task 3 (see section 4), for input into the developed MACC (marginal abatement cost curve) model.

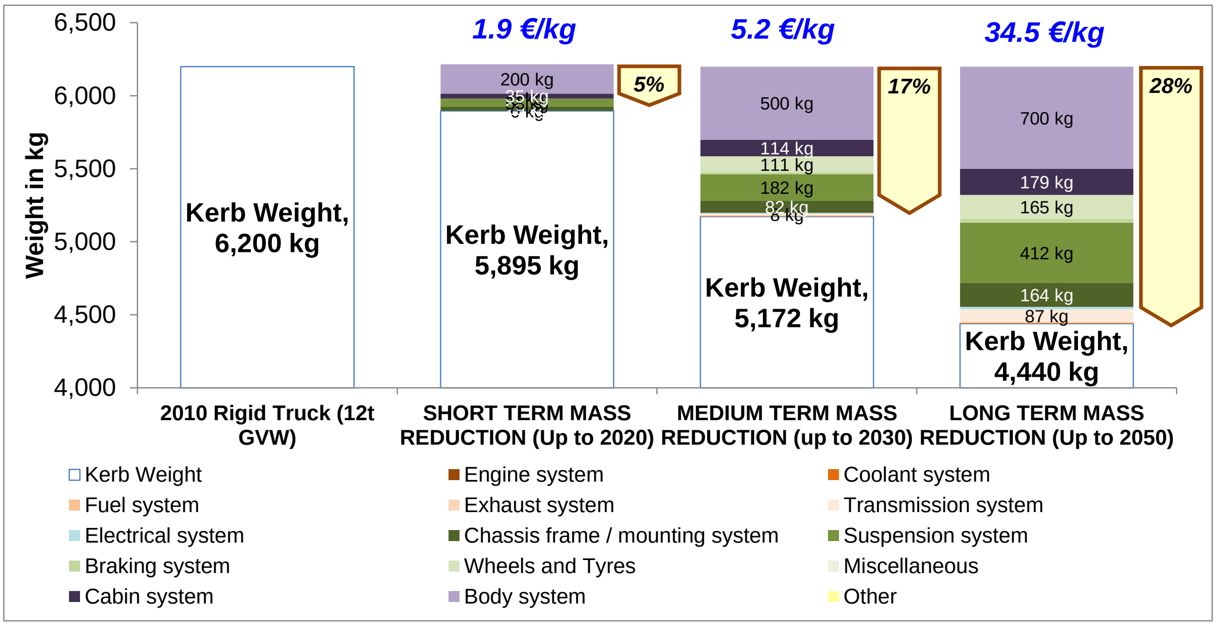
Figure 2.6: Estimated mass reduction potential by system and costs for large van



Source: Study analysis by Ricardo-AEA and Ricardo UK.

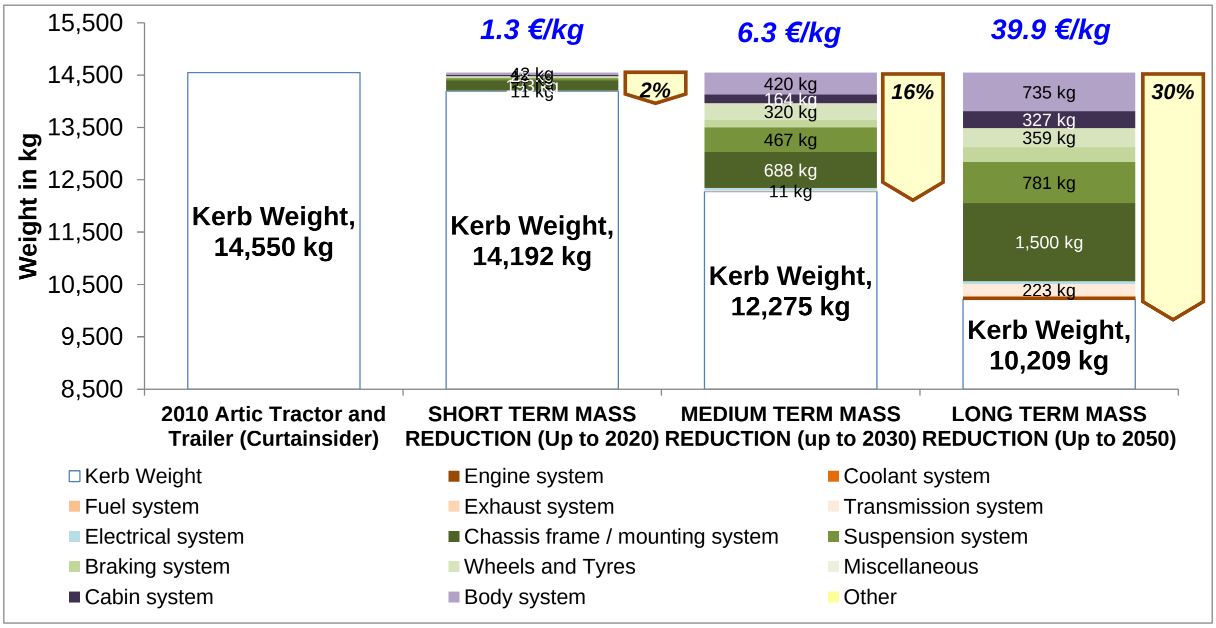
Notes: Estimates are based on current costs for weight reduction measures.

Figure 2.7: Estimated mass reduction potential by system and costs for a medium rigid truck



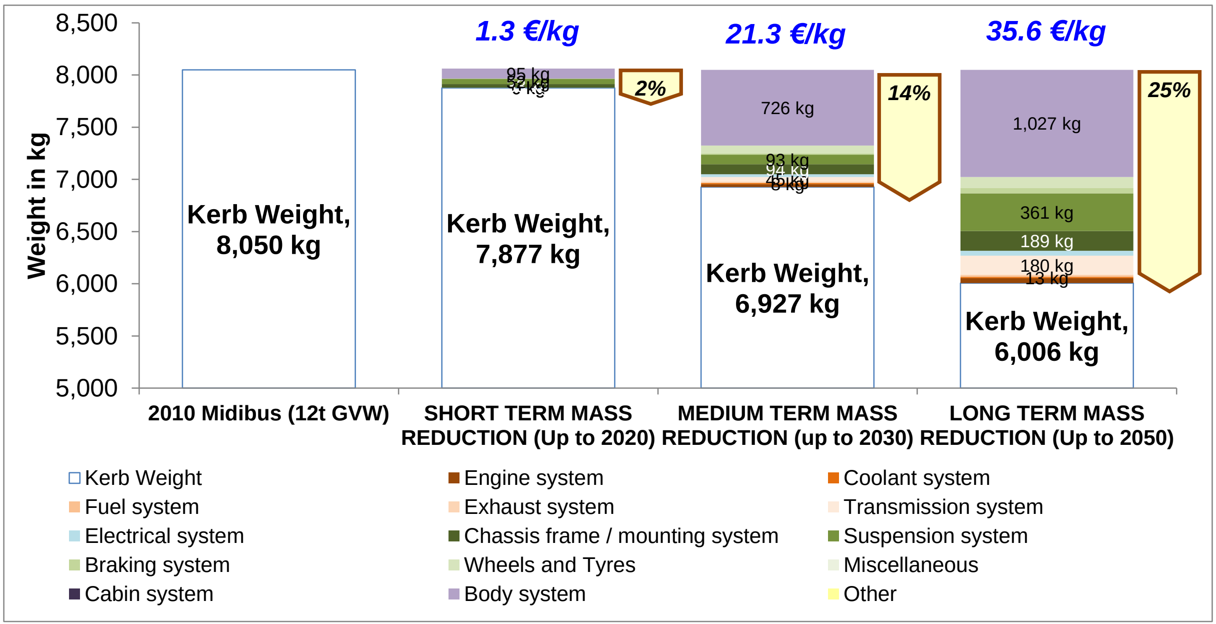
Source: Study analysis by Ricardo-AEA and Ricardo UK.
Notes: Estimates are based on current costs for weight reduction measures.

Figure 2.8: Estimated mass reduction potential by system and costs for an articulated truck



Source: Study analysis by Ricardo-AEA and Ricardo UK.
Notes: Estimates are based on current costs for weight reduction measures.

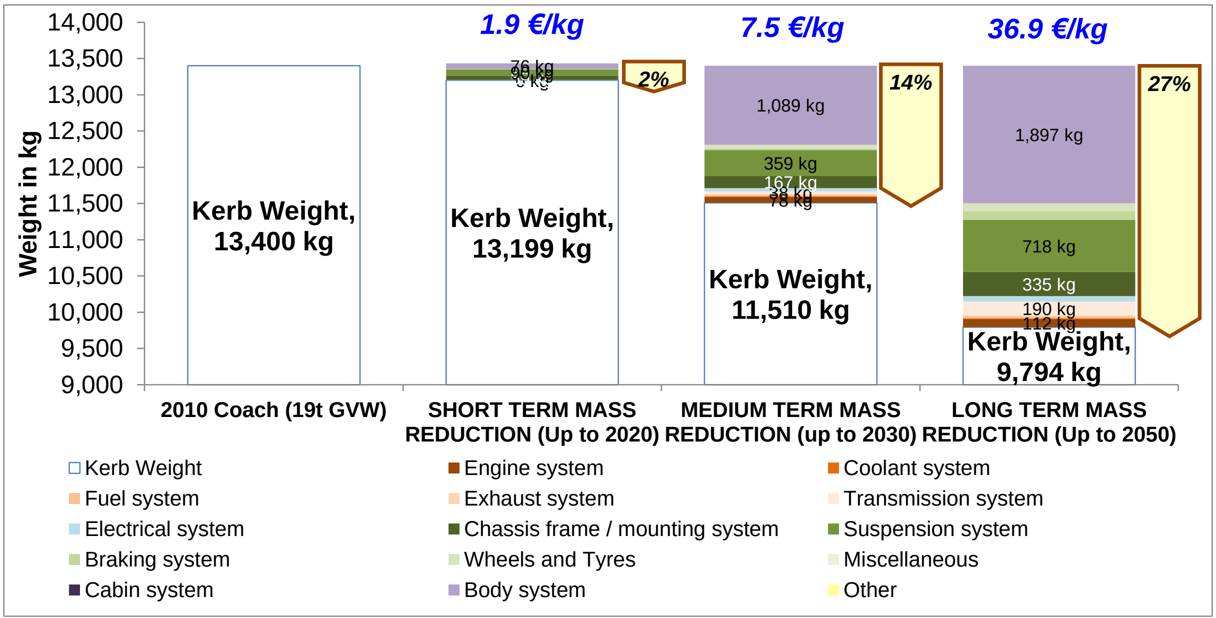
Figure 2.9: Estimated mass reduction potential by system and costs for a city bus



Source: Study analysis by Ricardo-AEA and Ricardo UK.

Notes: Estimates are based on current costs for weight reduction measures.

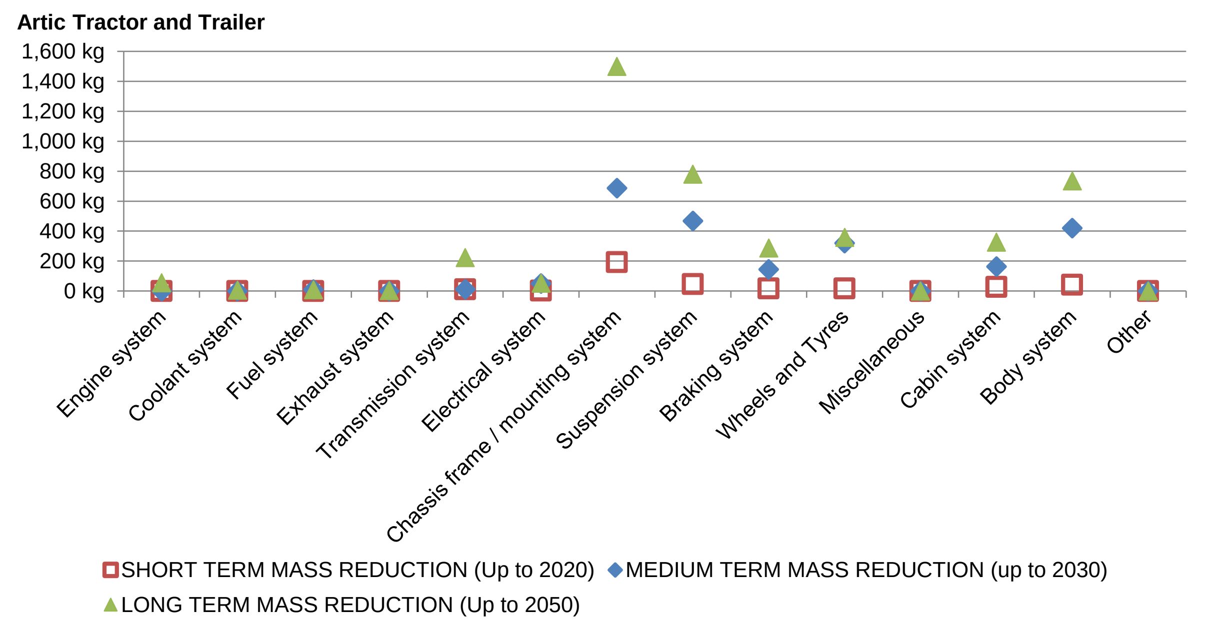
Figure 2.10: Estimated mass reduction potential by system and costs for a coach



Source: Study analysis by Ricardo-AEA and Ricardo UK.

Notes: Estimates are based on current costs for weight reduction measures.

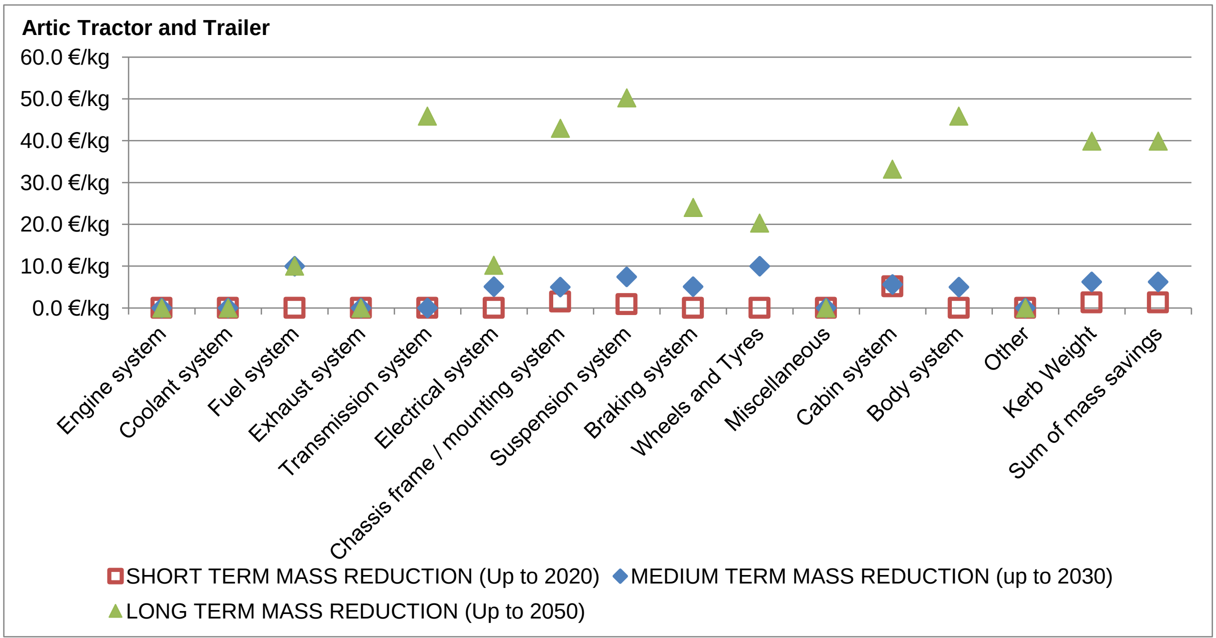
Figure 2.11: Summary of the extent of mass reduction by system in short, medium and long term scenarios for a 40t articulated truck



Source: Study analysis by Ricardo-AEA and Ricardo UK.

Notes: Estimates are based on current costs for weight reduction measures.

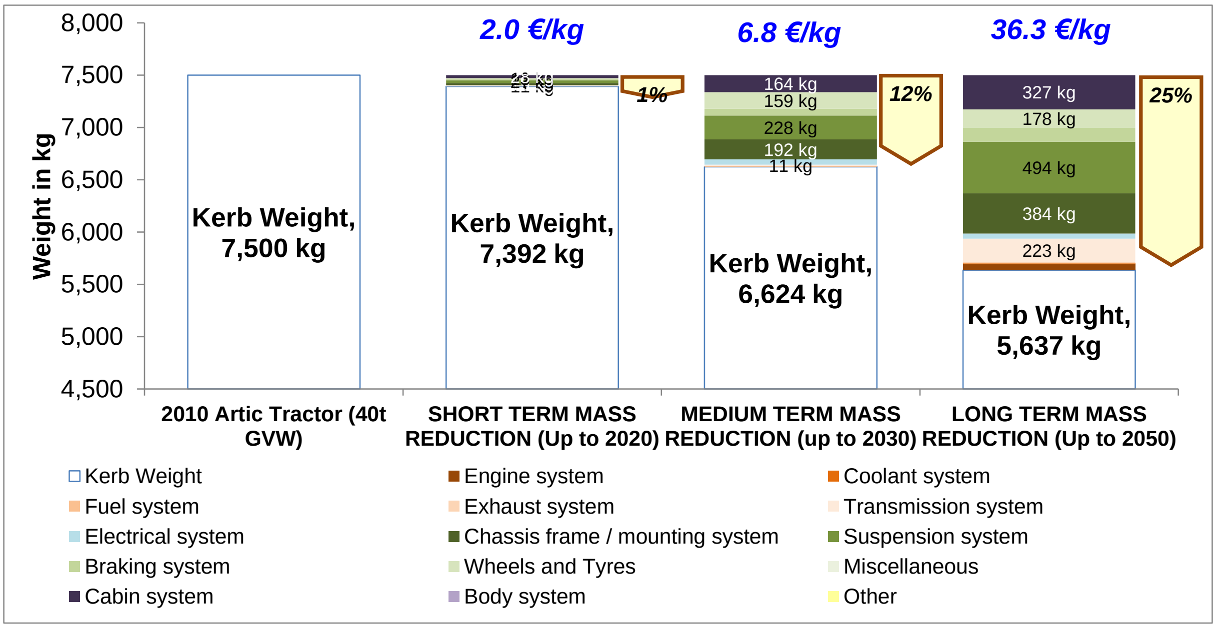
Figure 2.12: Summary of the extent of mass reduction by system in short, medium and long term scenarios for a 40t articulated truck (current costs for weight reduction measures)



Source: Study analysis by Ricardo-AEA and Ricardo UK.

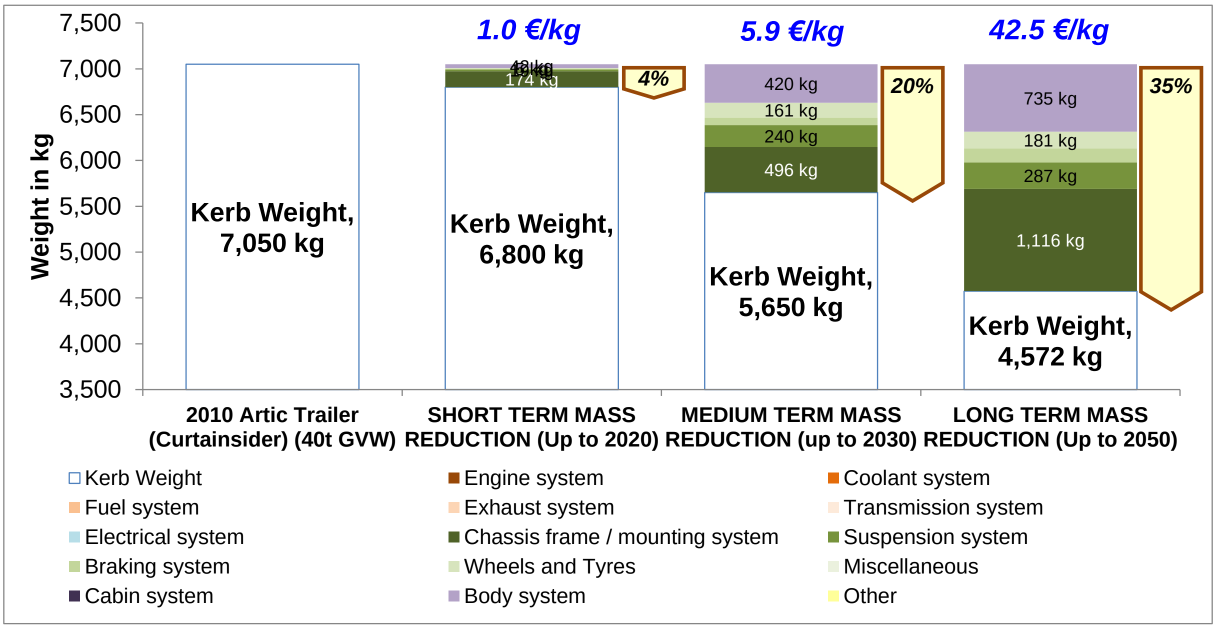
Notes: Estimates are based on current costs for weight reduction measures. For most systems, the unit costs per kg saved ramp up to high levels in order to achieve the long term weight reduction goals, hence there is a big difference in cost between medium term and long term costs in most cases.

Figure 2.13: Estimated mass reduction potential by system and costs for a road tractor for an artic tuck



Source: Study analysis by Ricardo-AEA and Ricardo UK.
Notes: Estimates are based on current costs for weight reduction measures.

Figure 2.14: Estimated mass reduction potential by system and costs for a semi-trailer for an artic truck



Source: Study analysis by Ricardo-AEA and Ricardo UK.
Notes: Estimates are based on current costs for weight reduction measures.

2.4 Task 1.3: Stakeholder Consultation

2.4.1 Methodology

As agreed with the Commission in the inception report, a list of potential interviewees based on the project partners' contacts in the field and contacts identified in the course of the literature review was developed. Contacts were then prioritised with the aim of securing a balanced number of responses from actors within different fields. The views of prioritised stakeholders were generally obtained through a request for an interview by telephone. In four cases, face-to-face interviews were possible. Views from other stakeholders were gathered via email or via telephone interview, if they preferred.

The objectives of the interviews were to gather more information on the costs and technical opportunities for lightweighting as well as the organisation's views and strategies on the issue. Many of the questions were general and put forward to most or all interviewees while others were tailored to the specific area of expertise of the interviewee. Specifically, questions addressed the following aspects:

- Overall company strategy (i.e. OEM, bodybuilder, supplier, etc.) with regards to light-weighting
- Cost and effectiveness of light-weighting
- Identification of barriers to light-weighting
- Customer (end-user) attitudes to light-weighting
- Relevance on different vehicle types, duty-cycles and weight versus volume-limited operations
- Importance as a strategy versus alternative CO_2 reducing technologies

The interviews were postponed until Ricardo UK had provided the virtual teardown and lightweighting scenarios. Stakeholders who indicated willingness to participate were then provided with a summary of the Ricardo analysis several days prior to the interview, along with the high-level interview questions, to give stakeholders the opportunity to indicate agreement or disagreement on weight and cost assumptions rather than asking outright for proprietary data which stakeholders might be unwilling to share. Table 2.6 indicates which stakeholders participated while Table 2.7 indicates other stakeholders contacted who did not participate. In addition, several suppliers, OEMs and trailer manufacturers were approached for brief, informal conversations on their views about lightweighting at the IAA 2014 commercial vehicle trade fair in Hanover.

Table 2.6: Stakeholders who participated

	Company	Type of enterprise
1	Magna Powertrain / ECS	HDV developer
2	DAF Leyland Trucks	HDV manufacturer
3	Daimler Commercial Vehicles	HDV manufacturer
4	Scania	HDV manufacturer
5	VDL	HDV manufacturer
6	Don-Bur	Trailer/Body manufacturer
7	Kögel	Trailer/Body manufacturer
8	TTT the team composites	Trailer/Body manufacturer
9	Alcoa Wheel Products Europe	Supplier
10	Celanese	Supplier
11	SABIC Innovative Plastics	Supplier
12	Stuttgart University, Institute for Aircraft Design	Academia
13	European Aluminium Association	interest group/NGO
14	European Express Association	interest group/NGO
15	ICCT (International Council on Clean Transportation)	interest group/NGO
16	IRU	interest group/NGO
17	Transport and Environment	interest group/NGO
18	WorldAutoSteel	interest group/NGO
19	ARCESE	End user
20	FERCAM (Italian based transport company with over 2000 trucks managed)	End user
21	Royal Mail Group	End user
22	Stobart Group	End user
23	TNT	End user
21	UPS	End user

Table 2.7: Stakeholder contacted who did not participate

	Company	Type of enterprise	Reason for non-participation
1	Alexander Dennis	HDV manufacturer	No response
2	IVECO	HDV manufacturer	TBC
3	MAN Truck and Bus	HDV manufacturer	Not available
4	Optare Busses	HDV manufacturer	No response
5	Volvo Group	HDV manufacturer	No response
6	Berger Ecotrail	Trailer/Body manufacturer	No response
7	Fliegl Fahrzeugbau	Trailer/Body manufacturer	No response
8	Krone	Trailer/Body manufacturer	No response
9	Schmitz Cargobull	Trailer/Body manufacturer	No response
10	Stas Trailers	Trailer/Body manufacturer	No response
11	Bosch	Supplier	Not available
12	Momentive	Supplier	Not available
13	Valeo	Supplier	No response
14	ACEA	interest group/NGO	Forwarded to group members
15	CLCCR / VDA	interest group/NGO	Forwarded to group members
16	CLEPA	interest group/NGO	Forwarded to group members
17	ERTRAC	interest group/NGO	Not available
18	PlasticsEurope	interest group/NGO	Forwarded to group members
19	DHL	End user	Not responded
20	Norbert Dentressangle	End user	Not available

2.4.2 Summary of results from the stakeholder consultation

2.4.2.1 Overall company views and strategy (i.e. OEM, bodybuilder, supplier, etc.) with regards to light-weighting

Artic tractors tend to be the most important type of HDV for truck manufacturers. In terms of vehicle weight, the main priority appears were to be to avoid significant weight increases when introducing new comfort, safety and environmental features. Thus, some lightweighting within various sub-systems has been undertaken to compensate the weight increases that occurred with the introduction of Euro VI. In doing so, manufacturers have tended to focus on reducing weight through redesigning chassis and suspension systems. One OEM interviewee stated that modifications to the tractor's rear air suspension and anti-roll bar saved some 100 kg and that further weight reductions are sought through use of higher strength steels on the chassis frame. Another OEM engineer interviewed stated that while the industry was slow in the uptake of lighter materials and techniques compared to the passenger car sector, due to lack of experience and cost, the marketing department is always keen to highlight weight-savings resulting from modifications to systems and components. A common observation is that in most cases the market is not willing to pay for weight reductions, or only to a limited extent. A supplier interviewed stated that OEMs are very keen on weight reduced components at equal cost while offering a weight reduced component at a higher price will tend to be a difficult sale. Weight increases are also sometimes accepted by customers/users given sufficient cost reductions.

Weight reductions are welcomed as many customers' operations are at least partly weight sensitive. However, it is generally not thought of as an effective strategy for saving fuel. Consequently, willingness to pay for weight savings is generally low and the industry tends to be very cautious about weight saving materials and techniques that have not been demonstrated to be as reliable as standard practice. (This was supported by an operator who stated that their main criteria for choosing a vehicle were previous experience, reliability and cost).

ACEA also indicated in their general comments that the main driver to reduce kerb weight is the possibility to take more payload. For volume limited transports (typically long haul operations) only smaller relative fuel savings are possible and therefore weight saving options are very seldom cost efficient for the customer. However, ACEA also noted that for weight limited applications (typically tanker/bulk, tipper and timber operations) the impact from weight reduction *is* very important for their customer's income. In these cases more weight saving options are cost-efficient, and market forces are consequently already influencing decision-making within this area.

Lightweighting on city buses can save fuel, thus providing a business case for lightweight buses. VDL's 20% lighter 12 m buses (including smaller engine) provide around 15% fuel saving (see also section 2.2.2). An interview with the manufacturer revealed increased interest from operators as lightweight buses are able to meet the tender specifications of hybrid buses in terms of fuel savings and passenger capacity. In contrast, the lightweight buses often cannot meet standard bus tender specifications as with 14.9 t GVW they are designed for a maximum capacity of around 80 passengers rather than the typical specification of 100 or more passengers. As the interviewee pointed out, in practice city buses run at less than 50% of capacity 90% of the time.

While lightweighting generally won't save as much fuel on coaches due to less urban driving, a coach manufacturer pointed out that lightweight design can provide a competitive edge due to the 18 t GVW restriction for two-axle coaches. The manufacturer's two-axle coaches provide for passenger capacities for which competitors require three-axle models.

Trailer manufacturers tend to have considerable interest in lightweight designs and materials and many offer lightweight versions of their standard trailers (see section 2.2.3). A trailer manufacturer who responded to the consultation viewed lightweighting as increasing in importance, both for allowing payload increases but also for fuel savings.

2.4.2.2 Identification of barriers to light-weighting

A trailer manufacturer that responded to the consultation and which manufactures both standard and lightweighted trailers stated that lightweight trailers tend to be slightly less durable; however there are models available of equivalent durability to steel according to (EAA, 2014). Another interviewee suggested that while lightweight trailers are usually made out of durable, high quality steel, the greater 'softness' of the structure means that standard components fitted to the chassis tend to wear more quickly and result in higher maintenance costs. An operator mentioned increased deformation and maintenance requirements with lightweight trailers, another mentioned that these issues mainly affected early lightweight models which have since substantially improved.

Overall, uncertain or reduced durability and reliability are identified by most stakeholders as a barrier to further lightweighting in the market. Various stakeholders described the market as 'conservative'. Operators welcome fuel savings and payload increases if relevant but only if it is fairly certain that these will outweigh any increase in purchase or repair costs and reductions to resale value. One OEM interview stated that the market situation makes operators 'put reliability before everything else' as 'a single breakdown could cost them the vehicle's profit for the whole year'. Another barrier to the uptake of lightweight designs and materials is the vehicle's second (and third) life: Unconventional designs or materials don't tend to sell well on the used vehicle market. This may be in part due to reliability concerns, but also due to reduced flexibility in future uses. Operators typically have resale value in mind when making purchasing decisions. For example, it may be attractive for an operator to order a truck with sleeper cab even if the sleeper cab is not needed, as it may sell better on the second hand market. One developer of HDVs suggested that given this situation there might be a role for public funding of more specialised lightweight solutions for defined uses to counter-act the market-pressures for a one-size-has-to-fit-all solution. One operator interviewed also mentioned there can potentially be a problem with one-size fits all solutions: suggesting that their trucks are over-engineered for what they need (e.g. they are designed for pulling 50 tonnes in other EU countries, whereas they never need to pull loads anywhere near as large as this). In this respect, the reason was the relatively small size of the truck market involved.

Increased cost of lightweight materials is a further barrier. According to a supplier, as a rule of thumb, OEMs and operators are looking for payback times of less than two years. Another general rule is that, if weight savings are sought, manufacturers are willing to pay up to €10 per kg weight saved (see also section 2.2.2). Stakeholders have pointed out that this rule applies to weight-sensitive applications such as tanker and tipper trucks and that willingness to pay across the industry is usually substantially less. On the other hand, aluminium wheels tend to cost substantially more up-front (although with pay-back time being variable depending on the actual fleet/usage – can be 2-3 years for weight limited operations). One supplier indicated costs of €15-17/kg saved, pointing out that aluminium wheels are not only purchased due to weight savings but also due to their 'cleaner' appearance which some operators value, especially when transporting food. A developer of lightweight trailers stated that for an operator every extra kg of payload on a tipper truck will increase revenue by around €5/year; and every extra kg on a silo truck will increase revenue by around €10/year. Therefore, a tanker operator could spend almost €20/kg saved and still achieve a payback period of two years.

While lightweight trailers tend to be more expensive than conventional trailers, the interviewed bus manufacturer pointed out that the purchase price for a lightweight bus tends to be around the same or less than for a conventional bus. This indicates that lightweighting measures are available that might be applied in a way that is cost-neutral for the capital costs, at least if concessions to other vehicle attributes are made, such as 20% reduced peak passenger capacity in the case of the lightweight bus.

2.4.2.3 Relevance of weight savings for different vehicle types

Most stakeholders found that lightweighting was mostly relevant for operators facing constraints on maximum payload, and generally only demanded by those who really need it. This includes tipper and silo operators, but also transporters of coils, beverages, etc. One trailer manufacturer emphasised that diesel is a key driver in total costs of ownership (TCO) and that lightweighting of trailers is therefore relevant for fuel savings, as long as additional investments in lightweighting can be recovered. However, other interviewees from truck and trailer manufacturers also found many operators to be too sensitive to purchase costs and that they insufficiently consider total costs of ownership (TCO). One interviewee found that companies' purchasing departments will tend to 'go for the cheapest they can find' unless they have a specific mandate to consider fuel cost implications, etc.

One manufacturer highlighted that internal tests as well as tests by truck magazines are typically carried out at laden weight and consequently do not capture the fuel savings from reduced kerb weight. Since fuel savings from lightweighting will tend to be greater in urban duty cycles than for long-haul inter-urban operations, one manufacturer of truck bodies suggested that a suitable certification procedure could help persuade operators or purchasers of these types of vehicle that lightweighting can be a worthwhile investment. However, delivery trucks with urban duty cycles tend to account for a small (and declining) share of the market.

As discussed above, weight savings tend to have a fairly large impact on the fuel consumption of city buses and the resulting operating cost and CO_2 reductions tend to be a key selling point for the interviewed bus manufacturer.

2.4.2.4 Importance as a strategy versus alternative CO_2 reducing technologies

In a typical long-distance truck, stakeholders did not find weight savings to be very important for reducing CO_2. One truck manufacturer found weight reduction on HDVs to be the least important of all CO_2 reduction options available. However, as also discussed above, there is significant interest from manufacturers to compensate weight increases from other CO_2 reducing technologies (hybrid equipment, aerodynamic improvements).

Other comments from operators highlighted the difference between weight-constrained and volume-constrained operators. Some of the operators interviewed indicated that weight reduction can be important for weight-constrained operators as a means of increasing the payload. For those that are volume-constrained, this seems to be less of an issue.

Others also mentioned that other strategies for fuel savings – e.g. driver training, installation of automatic roof deflectors – tend to be taken up first, as these can be dealt with in-house. Engagement with suppliers is needed for lightweighting.

2.4.2.5 Opinions of stakeholders on baseline weights and scenarios and implications for the analysis

Overall it appeared that often stakeholders did not study the weight by component in detail, possibly because they were not always aware of the weight of individual components. Only one stakeholder provided written comments on the assumptions for different sub-system weights and their future lightweighting potential. Stakeholders generally tended not to make/be able to provide specific comments on lightweighting costs. Several stakeholders found the costs estimated by Ricardo broadly plausible but found it hard to comment on likely future cost developments. Two stakeholders indicated that costs per kg saved for composite substitutions were quite optimistic. One OEM stated they saw different costs from ours but did not indicate in which direction or to what extent.

The short-term scenarios appeared plausible to most stakeholders, although some stakeholders felt that 2025 might be a more realistic time frame to achieve the weight reductions given that recently introduced products would still be on the market in 2020. One stakeholder found that short-term weight reductions could be greater, using the product they are currently seeking to introduce into the market.

Several stakeholders found it very difficult to comment on time horizons beyond 2020 or 2025. Those who did comment indicated that medium- and long-term lists of potential weight reduction options were fairly optimistic but technically conceivable. Depending on how prices for lightweighting technologies evolve achieving the scenarios might be costly. Whether the scenarios materialise would depend largely on the requirements set by policy.

The detailed comments made by stakeholders on the analysis are provided in Table 2.8 below.

Table 2.8: Stakeholder comments on lightweighting analysis

Stakeholder	Comments
Vehicle manufacturer	As a baseline weight, the artic truck should be at least 200 kg heavier; around 15.2 t rather than 14.9. This would be more representative of the market average.
	Baseline tractor should have higher aluminium content; aluminium wheels are widely used. High strength steels are also used more than suggested in Ricardo-AEA's analysis.
	Coach: empty weight is too optimistic. Should be closer to 14 t. Even for 2020 may be optimistic. Already invested 200-300 m Euro in latest generation of vehicles, so see is difficult to see much change by 2020.
	Costs from Ricardo-AEA Analysis are different to the ones the company sees.
Vehicle manufacturer	The medium term weight reduction potential (at 730kg) from use of aluminium on rigid truck looks quite ambitious. Current lightweighting project is looking at lower savings.
Vehicle manufacturer	Total weight appears broadly plausible. No equivalent weight decomposition of company's products available, so difficult to directly compare. Not sure about weight of coach body and chassis. Coach body appears slightly heavy while total weight is close to company's product.
	Mid- and long term scenarios appear very ambitious. Could happen with CFRP but hard to tell now. In the mid-term, unlikely everything will be aluminium. Possibilities for more composite use and sandwiched materials in various applications. Aluminium can only save some 10% of weight at equivalent stiffness: in buses main issue is stiffness, not stability.[6] Much will depend on part suppliers. There has been progress in recent years: ten years ago suppliers had little interest in making lightweight axles; this has changed.
Vehicle developer	No specific comments on the assumed costs. However, only those who really need it will pay for weight reduction (i.e. weight-limited operations).
	Baseline articulated truck around 1,000 kg too heavy. Especially tractor gearbox seems rather heavy while tractor cabin system seems rather light.
	Short term progress is too conservative. At least 250 kg could be saved on the artic tractor.
	Medium term: Overall plausible weight reduction level in artic tractor. Savings on suspension seem really high. Potential for downsizing of conventional drivetrain but need to consider the weight-increasing effects of alternative powertrains – we don't know how trucks will be powered in 20 or 40 years' time.
	Overall, the weight reductions in the mid-term scenario of 15-20% appear feasible, but the outlook shouldn't be confined to aluminium – similar reductions may be made through HSS designs. Which materials would actually end up being used on a 20% weight-reduced truck is uncertain.
	Long term scenario: weight reductions in suspension and cabin system extremely ambitious
Trailer manufacturer	Trailer weight in practice 3-5% heavier than according to initial assumption (of 6.3 t) (catalogue values versus actual value of vehicle configured to client needs)

[6] Opinions on weight-savings from aluminium differ the: European Aluminium Association (2014) claims 40% weight reductions at equal stillness from a 'double-T'-chassis beam is possible using aluminium alloys.

Stakeholder	Comments
Trailer manufacturer	UK single deck trailers generally 7 - 7.5 t, slightly heavier than trailers in mainland Europe. Around 1.2 t weight savings potential from options such as using PVC roof, rears and various aluminium components.
Supplier	Overall, figures are a good estimate, but a workshop might be helpful to elaborate under which conditions the cost and weight reduction and material assumptions made in the weight reduction scenarios might materialise. Uptake of new lightweight materials could either be driven by cost reductions in manufacturing or by legislation.
	A figure of €15/kg weight reduction in the long-term scenario sounds OK, but more as an average figure for all types of composites rather than exclusively carbon fibre. Replacing conventional parts with plastics will anyway generally result in a variety of fibre composites being used, rather than exclusively CFRP (see e.g. ZF four point link made of glass fibres).
	Slightly more conservative than the assumption of a 50% weight reduction through use of plastics. Maybe 'up to 50%'.
	Plastics content on artic tractor at 600 kg is broadly realistic but towards the low end.
Supplier	Trailer: around 20 kg weight savings from aluminium wheels at €15-17/kg. Comparison to best steel wheels: 142 kg vs. 255 kg total per trailer (i.e. for all wheels)
	Tractor: there are around 17 kg weight savings per wheel possible from aluminium: Comparison to best steel wheels: 141kg vs. 242kg total per tractor (i.e. for all wheels).
Research institute	Carbon fibre reinforced plastic costs up to around €100 per kg; glass fibre reinforced plastics cost around €20 or less.
	Up to 50% weight reduction in components is possible. Given the need to satisfy various conditions the weight reductions that could be achieved over steel in practice are around 30%. In principle, reducing total trailer weight by 30-40% should be possible and has already been achieved e.g. on the ALDI reefer. Whether this can be achieved at €15 per kg weight reduced, however, is impossible to tell now. 2050 is very far off, and development will tend to depend on the regulatory situation. Many composite elements may find their way into HDVs earlier than 2050. Material cost for carbon fibre at the moment is around €100/kg (not per kg saved!) and has changed little over the past 10 years. Costs of glass fibres have decreased substantially and tend to be around €20/kg. However, given its tensile, compressive and flexural properties, CFRP will tend to be the only composite fibre option for many structural parts. The material cost and the energy cost will probably increase in future while the manufacturing process costs may of course decrease with experience and scale.
NGO	On mass reduction measures: maybe look at different periods – 2020 is a bit close, so 2025 probably better.
	Assumptions slightly conservative. Perhaps earlier opportunities for downsizing or material substitution on individual engine parts?

As a result of these stakeholder comments, a number of adjustments were made to the virtual teardown and lightweighting scenario assumptions. These include:

- Adjustment of tractor gearbox weight
- Adjustment of weight saving on tractor suspension in mid- and long-term scenarios
- Adjustment of weight saving from aluminium wheels (to 40%-45%)
- Revision of trailer sub-system weights with input from a manufacturer
- Revision of weight savings in sub-systems in the long-term scenario
- Adjustment of lightweighting cost assumptions using CFRP
- Some adjustments to materials used in different sub-systems

2.5 Task 1.4: Impacts of alternative powertrains and future technologies on vehicle weight

The impact of alternative powertrains and other technologies on vehicle weight (and indeed volume), and therefore also their impact on available payload, is likely to become an increasingly important factor in the future. Such considerations therefore also have the potential to help facilitate uptake of lightweighting options into the marketplace to offset such increases and mitigate barriers to uptake.

This is also reflected within the proposal to amend the EC Directive covering the weights and dimensions of HDVs (EC, 2013a) and the impact assessment on the proposal's amendments (EC, 2013b) that *"maximum weights of HGVs imposed by the Directive are preventing the market uptake of electric/hybrid vehicles, being heavier than conventional vehicles, which consequently would have to reduce their payload."*. The current publically available proposal and definitions within it are limited to hybrid-electric systems and pure battery electric vehicles and do not currently also cover other types of hybrids (e.g. flywheel or hydraulic systems) or alternatively fuelled vehicles (e.g. gas-fuelled vehicles) that also incur an additional weight penalty.

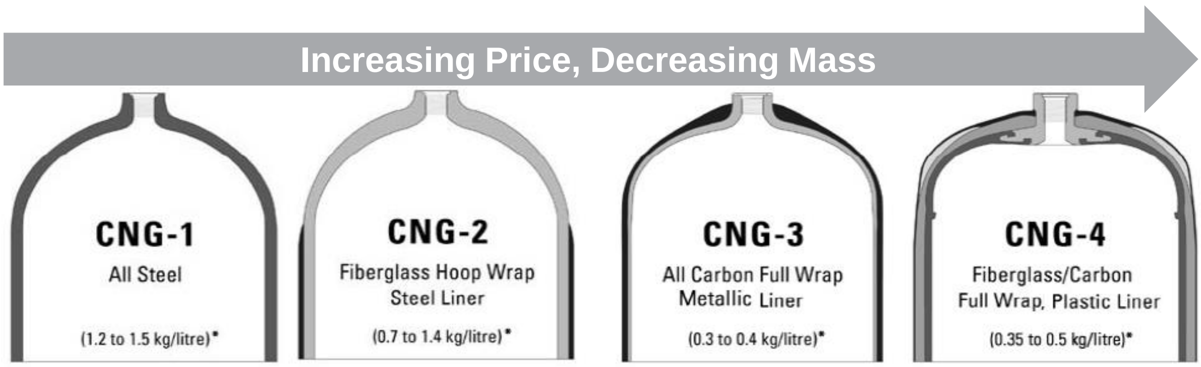
However, according to DG MOVE[7], the latest discussions in the Parliament and Council are likely to lead to an amended final proposal that will be extended to include other efficient or low carbon technologies including alternative fuel systems (e.g. hydrogen, CNG, LNG, etc.), mechanical energy storage systems (e.g. flywheel or hydraulic hybrid systems) and waste heat recovery systems. However, although there will be a maximum additional weight allowance of 1 tonne, there will be provisions in the Directive to limit the actual allowance for specific types of systems to what is actually needed (i.e. their additional weight). Determination of such allowances is likely to be developed only after the Directive amendment is in place (expected summer 2015).

These changes, whilst positive from the perspective of removing barriers to efficient powertrain technologies, may reduce the degree to which their market introduction also facilitates greater uptake of additional lightweighting options. Clearly the degree to which there is still some additional incentive to further lightweight alternative technology vehicles will be linked to the specific allowances developed in support of the amended Directive.

Ricardo UK has carried out a review of publically available information sources to develop indicative estimates of the additional weight of alternative fuel and/or powertrain systems. This is presented in the following Table 2.9. This suggests that for fully electric vehicles at least, the 1 tonne additional weight allowance may not be sufficient to balance the additional weight due to batteries for larger vehicles – though clearly this depends on a number of factors including the efficiency/electric range of the vehicle and improvements to battery energy density in the coming years (which may potentially halve by 2020).

With particular reference to CNG systems: CNG storage tanks are pressure vessels, available in various materials, see Figure 2.15. Different applications will favour different tank types, depending on a cost vs. mass trade-off. This will be heavily application dependent; where payload is crucial, lighter tanks may be cost effective.

Figure 2.15: Typical examples of on-vehicle storage systems for CNG, by classification type.



[7] Telephone conversation with Philippe Hamet (DG MOVE), 8th October 2014.

Table 2.9: Indicative vehicle weight increases due to alternative powertrain and/or fuel technologies

	Indicative additional weight added to vehicle, kg									
Technology	**Heavy Van (5 t GVW)**		**Rigid Truck (12 t GVW)**		**Midibus (12 t GVW)**		**Coach (19 t GVW)**		**Artic Truck (Box) (40 t GVW)**	
Baseline kerb weight	**2,305 kg**		**6,349 kg**		**7,962 kg**		**13,560 kg**		**15,057 kg**	
Additional weight of technologies	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Stop-start system	0 kg	20 kg								
Hybrid electric*	50 kg	100 kg	100 kg	150 kg	100 kg	150 kg	200 kg	300 kg	200 kg	400 kg
Flywheel hybrid	150 kg	200 kg	200 kg	300 kg	200 kg	300 kg	200 kg	300 kg	300 kg	400 kg
Dedicated gas or dual-fuel (gas/diesel) vehicle**	50 kg	150 kg	200 kg	300 kg	1,000 kg	1,500 kg	500 kg	1,000 kg	500 kg	1,000 kg
Plug-in hybrid electric vehicle	150 kg	250 kg								
Fully (battery) electric vehicle***	250 kg	400 kg			1,000 kg	1,500 kg				
Euro VI - additional aftertreatment	40 kg	90 kg	50 kg	100 kg	50 kg	100 kg	100 kg	300 kg	100 kg	200 kg

Notes:

Blank cells indicate that no data was available/identified.

* Depends on level of hybridisation (voltage, motor, battery pack)

** Assume CNG for Van, Rigid Truck and Midibus. Assume LNG for Coach and Artic Truck. Assume Type 2 tanks for Buses and Type 3 or Type 4 tans for Trucks (N.B. Type 2 tanks are cheaper, but heavier. Highly dependent on the amount of NG to be stored).

*** Highly dependent on the battery capacity.

Sources: Ricardo UK estimates based on a review of information on real alternative powertrain/fuel vehicles and comparable conventional equivalents from public sources. For coaches, the upper limit quoted is from (IRU), see earlier Table 2.2.

2.6 Task 1.5: Develop list of options for further analysis

Table 2.10 below provides a summary of the lightweighting options identified for each sub-system in the scenarios developed under Task 1.2, and for different vehicle types. From these options we can develop the shortlist of defined light-weighting options to be included in the more detailed analysis in later tasks. It might be necessary to further aggregate certain options identified below, depending on the further development of the MACC model in Task 3. This will be discussed and agreed with the Commission where relevant.

Level 1 options correspond to the options most likely to be taken up in the short-term scenario up to 2020, level 2 options correspond to the options mainly likely to be taken up in the mid-term 2020-2030 scenario, and level 3 options correspond to the options mostly likely to be taken up only in the long-term scenario beyond 2030. *'SOTA'* denotes an option is state-of-the-art, i.e. currently available in the market but potentially too expensive or unproven for widespread uptake at present moment. *'Future'* denotes that a particular technology option is assumed to be available on the market within the time horizon of the scenario. *'None'* denotes that an option is not taken up in the scenario on a particular vehicle category, *'N/A'* denotes that the measure is not applicable to the particular vehicle type.

Table 2.10: List of options taken up in scenarios

Sub-system	Level	Short ID	Option	Large Van	Rigid truck	Artic tractor	Bus	Coach	Artic trailer
Engine	1	Engine (1)	Engine mass increase due to performance and emission improvements	None	SOTA	None	SOTA	SOTA	N/A
	2	Engine (2)	Powertrain downsizing due to lower power requirements	None	None	None	SOTA	Future	N/A
	3	Engine (3a)	Powertrain downsizing, equal performance	SOTA	None	Future	None	None	N/A
	3	Engine (3b)	Further powertrain downsizing due to lower power requirements	None	None	None	Future	Future	N/A
Cooling system	1	N/A	None identified	-	-	-	-	-	-
	2	Cooling (2a)	Secondary reductions from engine downsizing and improvements	None	None	None	Future	Future	N/A
	2	Cooling (2b)	Coolant flow optimisation, higher flow pump	Future	Future	None	None	None	N/A
	3	Cooling (3a)	Further secondary reductions from engine downsizing and improvements	Future	None	Future	Future	Future	N/A
	3	Cooling (3b)	Further coolant flow optimisation, higher flow pump	None	Future	None	None	None	N/A
Fuel	1	N/A	None identified	-	-	-	-	-	-
	2	Fuel (2a)	Plastic fuel tank	SOTA	SOTA	Future	Future	Future	N/A
	2	Fuel (2b)	Reduced capacity due to lowered energy consumption	None	Future	Future	SOTA	Future	N/A
	3	Fuel (3a)	Plastic fuel tank	SOTA	SOTA	Future	Future	Future	N/A
	3	Fuel (3b)	Further reduced capacity due to lowered energy consumption	Future	Future	None	Future	Future	N/A

Sub-system	Level	Short ID	Option	Large Van	Rigid truck	Artic tractor	Bus	Coach	Artic trailer
Exhaust	1	N/A	None identified	-	-	-	-	-	-
	2	Exhaust (2)	Secondary reductions from engine downsizing and improvements	None	None	None	SOTA	Future	N/A
	3	Exhaust (3)	Further secondary reductions from engine downsizing and improvements	None	None	None	Future	Future	N/A
Transmission	1	Transmission (1)	Minor design improvements	SOTA	N/A	SOTA	N/A	N/A	N/A
	2	Transmission (2a)	Secondary reductions from engine downsizing	None	None	None	SOTA	Future	N/A
	2	Transmission (2b)	Further design/material improvements	Future	Future	Future	Future	Future	N/A
	3	Transmission (3)	FRP casing and use of metal matrix composites	Future	Future	Future	Future	Future	N/A
Electrical system	1	Electrical (1)	Small battery technology advances/electrical design improvements	SOTA	SOTA	SOTA	SOTA	SOTA	N/A
	2	Electrical (2)	Medium battery technology advances/electrical design improvements	Future	Future	Future	Future	Future	N/A
	3	Electrical (3)	Major battery technology advances/electrical design improvements	Future	Future	Future	Future	Future	N/A
Chassis	1	Chassis (1)	Steel grade and design improvements	SOTA	SOTA	SOTA	SOTA	SOTA	SOTA
	2	Chassis (2)	Aluminium frame (+Aluminium under-run and mounting brackets)	Future	Future	Future	Future	Future	SOTA
	3	Chassis (3)	CFRP frame	Future	Future	Future	Future	Future	Future
Suspension	1	Suspension (1)	design improvements + higher grade steels	SOTA	SOTA	SOTA	SOTA	SOTA	SOTA
	2	Suspension (2a)	Aluminium axles	Future	Future	Future	Future	Future	Future
	2	Suspension (2b)	Springs and Anti-roll bar made of HSS	None	Future	Future	None	None	None
	3	Suspension (3)	FRP (or metal matrix composites), e.g. axles, brackets, dampers springs	Future	Future	Future	Future	Future	Future
Braking	1	Braking (1)	design improvements	SOTA	SOTA	SOTA	SOTA	SOTA	SOTA
	2	Braking (2a)	Secondary reductions from vehicle downweighting	None	None	None	SOTA	Future	None
	2	Braking (2b)	Aluminium calipers and discs	Future	Future	Future	Future	Future	Future

Sub-system	Level	Short ID	Option	Large Van	Rigid truck	Artic tractor	Bus	Coach	Artic trailer
	2	Braking (2c)	Aluminium air tank	None	SOTA	SOTA	SOTA	SOTA	SOTA
	3	Braking (3a)	Carbon/ceramic brakes	Future	Future	Future	Future	Future	Future
	3	Braking (3b)	Metal matrix calipers	Future	Future	Future	Future	Future	Future
	3	Braking (3c)	FRP tank	None	SOTA	SOTA	SOTA	SOTA	SOTA
Wheels	1	Wheels (1)	Small design improvements	SOTA	SOTA	SOTA	SOTA	SOTA	SOTA
	2	Wheels (2)	Alloy wheels	SOTA	SOTA	SOTA	SOTA	SOTA	SOTA
	3	Wheels (3)	FRP wheels	Future	Future	Future	Future	Future	Future
Tyres	1	N/A	None identified	-	-	-	-	-	-
	2	Tyres (2)	Lightweight tyres	Future	Future	Future	Future	Future	Future
	3	Tyres (3)	Ultra-lightweight tyres	Future	Future	Future	Future	Future	Future
Cab-in-white and closures	1	Cab+ (1)	Advanced HSS and design optimisation	Future	Future	Future	N/A	N/A	N/A
	2	Cab+ (2)	Aluminium cab and doors	Future	SOTA	SOTA	N/A	N/A	N/A
	3	Cab+ (3)	CFRP cab and doors	Future	Future	Future	N/A	N/A	N/A
Glazing	1	Glazing (1)	Small thickness reduction	SOTA	SOTA	SOTA	SOTA	SOTA	N/A
	2	Glazing (2a)	Further thickness reduction	Future	Future	Future	Future	Future	N/A
	2	Glazing (2b)	Polymeric glazing	Future	Future	Future	Future	Future	N/A
	3	Glazing (3a)	Polymeric glazing	Future	Future	Future	Future	Future	N/A
	3	Glazing (3b)	Further material/plastic glazing technology improvements	Future	Future	Future	Future	Future	N/A
Instrument panel + interior trim	1	Instr.panel /trim (1)	Minor design improvements	SOTA	SOTA	SOTA	SOTA	SOTA	N/A
	2	Instr.panel /trim (2)	Natural fibres and design improvements	Future	Future	Future	Future	Future	N/A
	3	Instr.panel /trim (3)	Natural fibres and design improvements	Future	Future	Future	Future	Future	N/A
Driver/front seats	1	Front Seats (1)	Design improvements	SOTA	SOTA	SOTA	SOTA	SOTA	N/A
	2	Front Seats (2)	Magnesium frame	Future	Future	Future	Future	Future	N/A
	3	Front Seats (3)	FRP frame	Future	Future	Future	Future	Future	N/A
Passenger seats	1	Pax Seats (1)	Small design improvements	N/A	N/A	N/A	SOTA	SOTA	N/A

Sub-system	Level	Short ID	Option	Large Van	Rigid truck	Artic tractor	Bus	Coach	Artic trailer
	2	Pax Seats (2)	Lightweighting seating: Combination of alum and plastics	N/A	N/A	N/A	SOTA	SOTA	N/A
	3	Pax Seats (3)	FRP and advanced materials	N/A	N/A	N/A	Future	Future	N/A
Miscellaneous cab equipment (mirrors / wheel arch liners / other trim)	1	N/A	None identified	-	-	-	-	-	-
	2	Misc Cab (2)	Material improvements	Future	Future	Future	Future	Future	N/A
	3	Misc Cab (3)	Further material improvements	Future	Future	Future	Future	Future	N/A
Body structure/closures	1	Body+ (1)	Steel grade and design improvements	SOTA	SOTA	N/A	SOTA	SOTA	SOTA
	2	Body+ (2a)	FRP structure/elements	Future	Future	N/A	SOTA	SOTA	SOTA
	2	Body+ (2b)	Aluminium structure	Future	Future	N/A	SOTA	SOTA	SOTA
	3	Body+ (3)	FRP frame and panels	Future	Future	N/A	Future	Future	Future
Floor covering	1	N/A	None identified	-	-	-	-	-	-
	2	Floor cover (2)	PP/natural fibres	N/A	N/A	N/A	Future	Future	N/A
	3	Floor cover (3)	Material improvements	N/A	N/A	N/A	Future	Future	N/A
Toilet	1	N/A	None identified	-	-	-	-	-	-
	2	Toilet (2)	Plastics / fibre improvements	N/A	N/A	N/A	N/A	Future	N/A
	3	N/A	None identified	-	-	-	-	-	-
Air Conditioning Unit	1	N/A	None identified	-	-	-	-	-	-
	2	Aircon (2)	Downsizing due to improved solar reflection	N/A	N/A	N/A	N/A	Future	N/A
	3	Aircon (3)	FRP casing	N/A	N/A	N/A	N/A	Future	N/A

3 Task 2: Energy and CO_2 benefits of identified light-weighting options

Box 2: Key points for Task 2

Objectives:

- **To quantify the energy and CO_2 benefits of the identified light-weighting options from existing data and vehicle simulation tools**

Key tasks:

- **Energy and CO_2 benefits of light-weighting from evidence available in the open literature**
- **Energy and CO_2 benefits of light-weighting from vehicle simulations**
- **Energy and CO_2 benefits of light-weighting from previous dynamometer testing**
- **Analysis of energy and CO_2 benefits for each light-weighting option and HDV category using the evidence from the preceding three tasks**

Outputs:

- **Tables of the energy and CO_2 benefits of the identified light-weighting options for the different vehicle categories when operating both at constant payload, and under GVW conditions**

3.1 Overview of Task 2

The previous task provided a comprehensive assessment of the options and technical developments for light-weighting. It generated a list of potential weight savings for the different light-weighting options and technical developments. The important linked question is: "What levels of energy and CO_2 savings might this light-weighting produce?"

Reductions in the energy consumed and in CO_2 emissions are the same irrespective of where the light-weighting occurs, although there are exceptions to this generalisation for components that rotate, or move at a different speed to the vehicle as a whole. However, the energy and CO_2 emissions benefits of a reduction in vehicle weight differ dependent on the drive cycle used. This task quantifies these reductions using data from a number of different sources, namely:

- *Task 2.1: Energy and CO_2 benefits of light-weighting from evidence available in the open literature*: The premise for this subtask is that there is a range of stated energy and CO_2 benefits from light-weighting cited in the open literature.
- *Task 2.2: Energy and CO_2 benefits of light-weighting from vehicle simulations:* This subtask uses vehicle simulation tools to calculate the changes in energy and CO_2 emissions from combinations of different vehicle categories / weights / driving cycles.
- *Task 2.3: Energy and CO_2 benefits of light-weighting from previous heavy duty vehicle dynamometer testing*: The third way of assessing benefits of light weighting will be from real heavy duty vehicle chassis dynamometer tests, which will help to validate/cross-check the results from modelling/simulation based approaches in Task 2.2.

In the final sub-task (Task 2.4) the generic light-weighting lightweighting benefits generated using the three different information sources are compared and collated. These are then combined, and further analysed, to generate an estimate of the impacts of lightweighting for a wide range of vehicle categories when used over their standard driving cycles.

In addition, an assessment of the potential share of weight-limited operations for different HDV types in the EU is presented.

3.2 Task 2.1: Energy and CO_2 benefits of light-weighting from evidence available in the open literature

In the literature review and during the stakeholder consultations, various estimates for fuel savings from lightweighting in different vehicle types were obtained. As highlighted by Helms & Lambrecht (2005), as a general rule air resistance accounts for 60-65% of an articulated truck's fuel consumption at highway speeds. This means that weight accounts for some 35-40% of fuel consumption so a 10% weight reduction should yield a fuel consumption reduction of approximately 3.5-4% (excluding energy consumption from auxiliary systems and changes to engine thermal efficiency from load changes), translating into savings of 0.05 l/100km per 100 kg weight reduction on a 27t truck consuming 35l/100km. Subsequent modelling carried out using TU Graz's PHEM model confirms this value for typical highway driving (Ibid.) and truck manufacturers indicated similar values (Table 3.1). The literature indicates that the share of weight-dependent fuel consumption will tend to be higher for urban duty cycles (as intuitively expected).

For LDVs, similar figures are also available assuming no changes are made to the powertrain (i.e. the power-to-weight ratio increases, and hence performance actually improves). If performance is simply maintained at its previous levels by downpowering the engine at the same time as reducing weight to keep the power-to-weight ratio the same as the baseline vehicle, it is possible to reduce fuel consumption by around 6.5% for a 10% reduction in weight. However, most HDVs (with the possible exception of buses) need to be able maintain their performance when fully laden (i.e. at max GVW), so such opportunities for secondary mass reduction are extremely limited.

A summary of further estimates from the literature is provided in Table 3.1 below.

Table 3.1: Illustration of the information to be obtained from the literature

Vehicle category	Vehicle	Fuel savings	Reference
Articulated truck	average value	0.03-0.05l/100km per tonne saved in long-haul duty cycle.	Truck manufacturer interview
		1% fuel savings per 500 kg in long-haul	Truck manufacturer interview
		Flat highway: 0.3l/100km per tonne saved Urban: 1l/100km per tonne saved Average German mileage shares for traffic situations and gradients: 0.6l/100km per tonne saved	(Helms & Lambrecht, Energy savings by light-weighting for European articulated trucks. Report commissioned by European Aluminium Association., 2005)
Urban bus	VDL Citea LLE	≈15% over standard bus	Manufacturer interview
		20% over standard bus	Berlin bus operator (VDL Groep, 2014)
		Standard bus: 42l/100km VDL Citea LLE: 32l/100km	Düsseldorf bus operator (Rheinbahn, 2013)

In addition, K+P & hwh (2012) measured fuel consumption for the Berger Ecotrail and three different standard trailers on a total of 16 standardised 228 km trips with two tractor units (Renault Premium 460 EEV Optifuel and Volvo FH 16 750). The Berger Ecotrail trailer weighed 4.7t and was compared to other trailer models weighing 6.3t, 6.4t and 6.6t using a standard payload of 24t potting soil. It should be noted that Thuringia is a fairly hilly region and lightweight vehicles tend to have over-proportionate savings on hilly terrain (Helms & Lambrecht, The potential contribution of light-weighting to reduce transport energy consumption, 2006). The results are given in Table 3.2.

Table 3.2: Fuel consumption test results from K+P & hwh (2012)

Comparator trailer	Tractor	Train weight (kg)	Fuel consumption (l/100km)	Fuel savings per tonne (l/100km) using the Berger Ecotrail trailer
Berger	Volvo	37,070	33.39	N/A
Krone	Volvo	39,060	34.59	0.60
Schwarzmüller	Volvo	38,820	35.56	1.24
Schmitz	Volvo	38,720	35.55	1.31
Berger	Renault	36,070	32.58	N/A
Krone	Renault	38,340	34.41	0.81
Schwarzmüller	Renault	37,920	35.12	1.37
Schmitz	Renault	37,960	35.49	1.54
Berger (at max. load)	Renault	40,240	34.61	0.49

Finally, another example from the literature includes the following Table 3.3 from (IAI/EAA, 2010) which provides savings per 100 kg weight reduction for buses and trucks.

These different sources provide supporting corroborating evidence to the findings of this study's more detailed analysis of the impacts of lightweighting carried out in Task 2.2 and Task 2.3. This analysis is further outlined in the following report sections, with the subsequent conclusions / recommendations on the relationships to use for different vehicle types and weights are provided in Task 2.4 (section 3.5).

Table 3.3: Savings per 100 kg weight reduction for different vehicle categories and their drive cycles

Vehicle type	Weight (at full load for trucks)	Average diesel consumption (at full load for trucks)	Diesel consumption per 100 kg weight	Percentage air friction	Diesel savings per 100 kg weight savings	CO_2 savings per 100 kg weight savings*	Lifetime performance	Lifetime Diesel savings per 100 kg weight savings	Lifetime CO_2 savings per 100 kg weight savings*
	t	l/100 km	l/100 km	%	l/100 km	gCO_2/km	km	litres	Tonnes CO_2
City bus, few stops	15.0	40.5	0.27	45%	0.15	4.0	1 000 000	1 485	4.0
City bus, many stops	15.0	45.0	0.30	15%	0.26	6.9	1 000 000	2 550	6.8
Long distance bus, high speed	18.0	30.0	0.17	75%	0.04	1.1	1 200 000	500	1.3
Long distance bus, medium speed	18.0	35.0	0.19	50%	0.10	2.7	1 200 000	1 167	3.1
Truck/trailer, long distance, medium speed	40	59	0.15	50%	0.074	2.0	1 200 000	889	2.4
Truck/trailer, long distance, high speed	27	35	0.13	70%	0.039	1.0	1 200 000	467	1.2
Truck/trailer, long distance, medium speed	27	40	0.15	50%	0.074	2.0	1 200 000	889	2.4
Light-duty vehicle, average use	3.5	12	0.34	50%	0.171	4.5	375 000	643	1.7
Light-duty vehicle, urban commercial use	3.5	13.5	0.39	25%	0.289	7.7	450 000	1302	3.5
Light truck, average use	7.5	18	0.24	50%	0.120	3.2	300 000	360	1.0
Light truck, urban commercial use	7.5	20	0.27	25%	0.200	5.3	570 000	1140	3.0

Source: International Aluminium Institute (2010), "Improving Sustainability in the Transport Sector Through Weight Reduction and the Application of Aluminium"

Notes: * Calculated from diesel savings data by Ricardo-AEA.

3.3 Task 2.2: Energy and CO_2 benefits of light-weighting from vehicle simulations

The objective of this task was to use vehicle simulation to calculate the changes in energy and CO_2 emissions from different vehicle categories of different weights being driven over different driving cycles. The use of two possible tools/approaches was proposed:

- The VECTO tool, developed on behalf of the European Commission, and a key tool for this whole HDV framework contract;
- Ricardo simulation tools, e.g. "Heavy goods vehicle simulation tool", developed on behalf of the UK Department for Transport;

However, greater detail than expected was available from Millbrook test data. This has been augmented with data from the VECTO model, where a range of light-weighting rates and different loads have also been assessed. Analysis of these have provided sufficient data for input into the next project task (development of MAC curves). Therefore there has been no need to also use the Ricardo "Heavy goods vehicle simulation tool".

3.3.1 Simulations using the VECTO tool

As one of the central parts in the development of the CO_2 certification procedure the EC launched the development of a "Vehicle Energy Consumption calculation Tool" (VECTO). VECTO simulates CO_2 emissions and fuel consumption based on vehicle longitudinal dynamics using a driver model for backward simulation of target speed cycles. The required load to be delivered by the internal combustion engine is calculated based on the driving resistances, the power losses in the drivetrain system and the power consumption of the vehicle auxiliary units.

The overall method uses component data (e.g. the engine fuel/CO_2 map, drivetrain including the gear box, tyres) and combined these with fundamental engineering and physics principles. This approach has been has successfully validated for several truck configurations (a 12 tonne GVW rigid truck and a 40 tonne GVW articulated truck), and is at an advanced stage of development for a representative coach, through projects known as LOT 2 (TU Graz et al, 2012) and LOT 3 (TU Graz et al, 2014).

Rather than drive cycles defining the speed-time profile to be followed, the distances to be travelled and the target speeds are specified on a metre by metre basis. This provides a more accurate simulation for HDVs where the same vehicle can have very different loads which lead to different speed-time profiles. For example, when pulling on to a trunk road the driver may wish to accelerate to the vehicle's maximum speed as swiftly as possible, i.e. he applies full power. When fully laden the acceleration is slower than when lightly laden, the time taken to reach maximum speed will be longer, and the associated CO_2 emissions will be higher. VECTO simulates all of this over a "mission", a specified distance to be travelled and target speeds at points along the route.

VECTO uses component data, which includes the user input specification of the vehicle's characteristics. Two important parameters for this study are the vehicle's kerb weight and GVW. The methodology adopted in this task was to "modify" the kerb weight of the vehicle (upwards to simulate payload, and downwards to simulate reduced kerb weight due to lightweighting) and to investigate the impact this has on the CO_2 emissions.

At the end of the LOT 3 VECTO project, the time when this simulation of the impacts of light-weighting was performed, the vehicles defined within VECTO, and the drive cycles/missions configured for these vehicles were as summarised in Table 3.4. Since other vehicle types were not yet configured in VECTO it has not been possible to run simulations for them. However, certain extrapolations were possible using information on the other drive cycles defined in VECTO, that currently cannot be utilised directly because the vehicle models have yet to be generated (e.g. utility, construction, heavy urban city bus, urban city bus, interurban bus), which is discussed later in Section 3.3.2.

Table 3.4: Vehicle category-drive cycle combinations currently available for simulation runs in VECTO

Vehicle category	Drive cycles/missions			
	Urban delivery	Regional delivery	Long haul	Coach
12 t delivery truck	✓	✓	✓	
40 t long haul truck		✓	✓	
Coach				✓

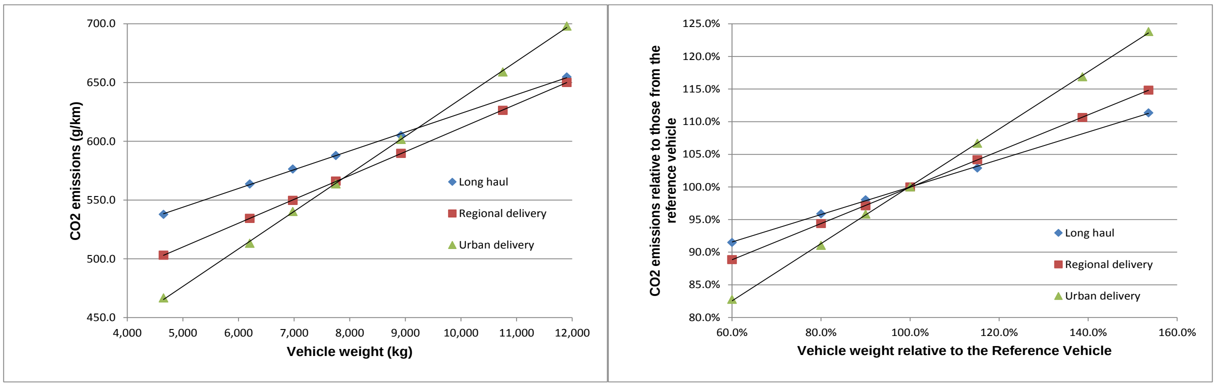
In terms of the variations in weight simulated, the aim was:

- to cover the realistically achievable range for the down-weighting options;
- to link to the vehicle dynamometer testing data in the next sub-task;
- to seek relationships between the light-weighting and CO_2 change, rather than an enormous matrix of results.

To be consistent with these overall aims, reductions of 10%, 20% and 40% were therefore simulated. In addition, to link with Task 2.3 (previous heavy duty dynamometer testing), where increases in weight (i.e. load) were investigated, increases of 20% and higher were also simulated in VECTO.

Figure 3.1 to Figure 3.3 show the data from the VECTO model for the 12 tonne rigid truck, 40 tonne articulated truck[8] and the coach, respectively. These are plotted as graphs of both the CO_2 emissions (g/km) against the vehicle weight (kg) (this is the figure on the left of each pair below), and the percentage change in vehicle weight, relative to the reference vehicle, against the percentage change in CO_2 emissions, relative to the reference vehicle (the figure on the right of each pair below). Further discussion on this is given in Section 3.5.

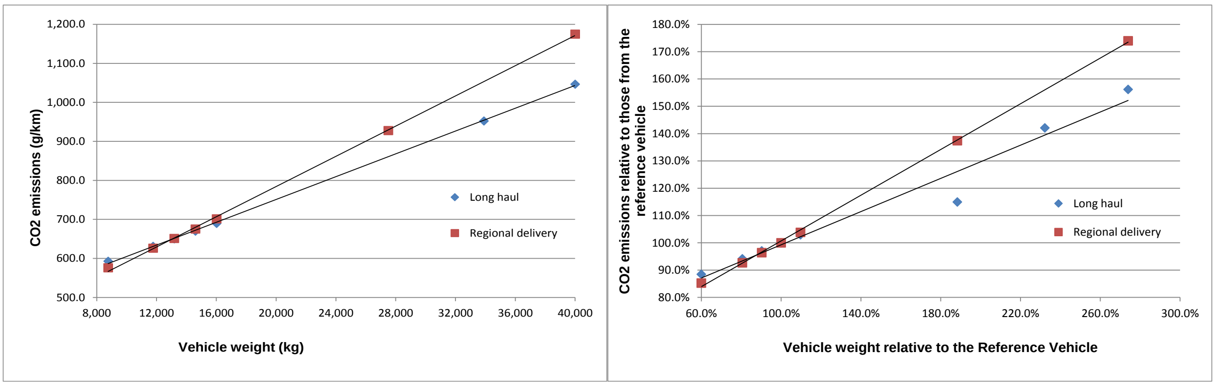
Figure 3.1: Simulated CO_2 emissions from a 12 t GVW rigid truck having various weights



Note: Reference weight (100% point) for the vehicle in VECTO was 7,750 kg.

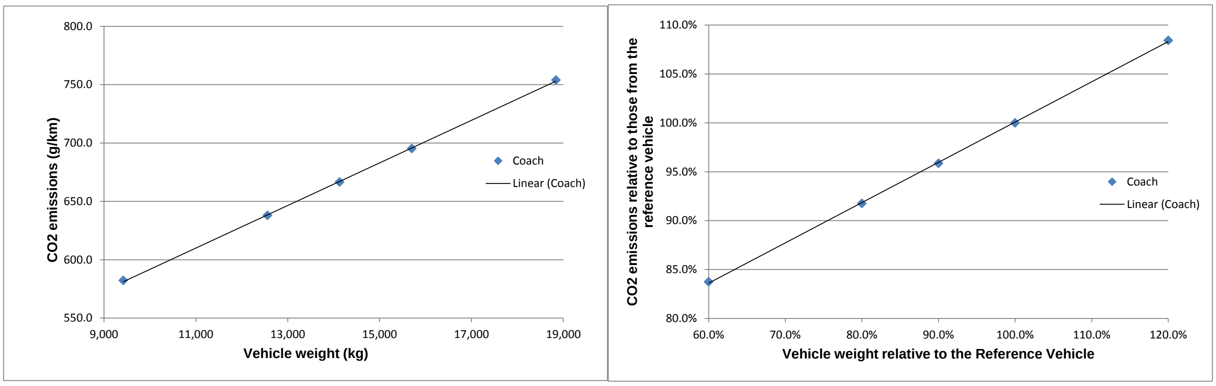
[8] For the 40 tonne articulated truck the reductions are relative to the empty tractor + trailer combination.

Figure 3.2: Simulated CO_2 emissions from a 40 t GVW articulated truck having various weights



Note: Reference weight (100% point) for the vehicle in VECTO was 14,600 kg.

Figure 3.3: Simulated CO_2 emissions from a coach having various weights



Note: Reference weight (100% point) for the vehicle in VECTO was 15,700 kg.

All three figures show a linear relationship between changes in emissions, relative to the reference vehicle, and changes in vehicle weight, relative to the reference vehicle, over the extended range. The figures also include the least squares regression fit to all the data for a given vehicle and drive cycle.

The VECTO model also calculates the CO_2 emissions per tonne km of goods carried for semi- or fully-loaded vehicles, by simple division. Whilst for a fully-loaded vehicle, lightweighting does not change the vehicle's overall CO_2 emissions (because the fully-loaded vehicle is always at the plated GVW) it does increase the maximum load that can be carried, and therefore reduces the CO_2 emissions per tonne carried. This is given in Table 3.5 for the two trucks with the three lightweighting scenarios and the analogous emissions for the reference truck.

Table 3.5: CO_2 emissions per tonne-km of payload for fully loaded vehicles for the reference vehicle and three levels of lightweighting.

		CO_2 emissions for fully laden vehicle g CO_2 /t.km			
Vehicle category	**Drive cycle**	**Reference vehicle**	**10% light-weighting**	**20% light-weighting**	**40% light-weighting**
12 t delivery truck	Long haul	157.8	132.9	114.9	90.3
12 t delivery truck	Regional delivery	156.7	132.0	114.1	89.7
12 t delivery truck	Urban delivery	168.2	141.7	122.5	96.3
40 t long haul truck	Long haul	41.2	39.0	37.1	33.5
40 t long haul truck	Regional delivery	46.3	43.8	41.6	37.6

These data are shown graphically in Figure 3.4. This shows how the CO_2 emissions per tonne.km are much lower for the larger vehicle. It also shows that for a given percentage of lightweighting, the CO_2 emissions reduction is greater for the smaller vehicle. This is true also when the change is expressed as a percentage of the original. For example, 40% lightweighting leads to around a 43% reduction in CO_2 emissions per tonne.km for the 12 t truck, and around a 19% reduction in CO_2 emissions per tonne.km for the 40 t articulated truck.

Figure 3.4: Impact of lightweighting on the CO_2 emissions of fully loaded trucks expressed per g CO_2 tonne.km

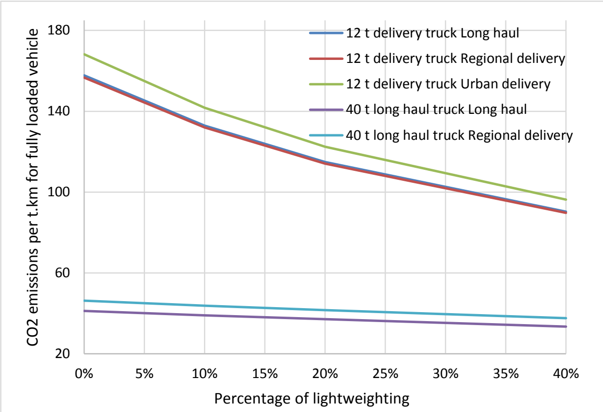


Table 3.7 tabulates the data from the linear regressions for the six vehicle type/drive cycle combinations shown in Table 3.4 and the figures above when the data are plotted as CO_2 emissions against vehicle weight. The table also contains the R^2 value for the regression. This is always equal to, or greater than, 0.9996, i.e. the correlations are all very close to linear

Table 3.6: Linear regression coefficients for the six vehicle category/drive cycle VECTO simulations from emissions vs vehicle weight graphs

		Linear regression values			
Vehicle category	**Drive cycle**	**Gradient**	**Constant**	**R^2 value**	**Average speed**
12 t delivery truck	Long haul	0.0160	464.1	0.9994	74.6 kph
12 t delivery truck	Regional delivery	0.0203	408.7	0.9999	58.4 kph
12 t delivery truck	Urban delivery	0.0319	317.0	0.9998	30.5 kph
40 t long haul truck	Long haul	0.0146	459.0	0.9996	74.8 kph
40 t long haul truck	Regional delivery	0.0194	397.2	0.9994	59.3 kph
Coach	Coach	0.0182	409.6	0.9998	64.9 kph

Table 3.7 tabulates the data from the linear regressions for the six vehicle type/drive cycle combinations shown in the figures above when the data are plotted as relative CO_2 emissions against relative vehicle weight. Again the R^2 values for the regression are always close to unity, demonstrating how each relationship is very close to linear.

Table 3.7: Linear regression coefficients for the six Vehicle category/Drive cycle VECTO simulations from relative emissions vs relative vehicle weight graphs

		Linear regression values			
Vehicle category	**Drive cycle**	**Gradient**	**Constant**	**R^2 value**	**Average speed**
12 t delivery truck	Long haul	0.211	0.789	0.9994	74.6 kph
12 t delivery truck	Regional delivery	0.278	0.722	1.0000	58.4 kph
12 t delivery truck	Urban delivery	0.439	0.562	0.9998	30.5 kph
40 t long haul truck	Long haul	0.304	0.689	0.964	74.8 kph

		Linear regression values			
Vehicle category	**Drive cycle**	**Gradient**	**Constant**	**R^2 value**	**Average speed**
40 t long haul truck	Regional delivery	0.419	0.588	0.9994	59.3 kph
Coach	Coach	0.412	0.589	0.9998	64.9 kph

The gradients in the table change in understandable ways, being larger for more transient cycles, and for heavier vehicles (see Box 5). For coaches a 20% lightweighting is calculated to lead to an 8% reduction in CO_2 emissions, whereas for the 12 tonne truck for the long haul delivery cycle it leads to a 4% reduction, and for the 40 tonne articulated truck it leads to a 6% reduction in CO_2 emissions. In essence this occurs because the same percentage of lightweighting leads to larger absolute weight reductions for heavier vehicles.

3.3.2 Use of the VECTO tool to define drive cycles for the different vehicle categories

Whilst VECTO currently only has a vehicle category/drive cycle (or mission) combination capability as summarised in Table 3.4, a number of other drive cycles have also been defined within VECTO. These are for:

- Utility;
- Construction;
- Urban city bus;
- Heavy urban city bus;
- Inter-urban bus.

To estimate the impacts of these different drive cycles on the overall fuel consumption and the impacts of lightweighting for different vehicle types it was necessary to develop an alternative, complementary approach. Section 3.5.2 provides a summary of the lightweighting characteristics tabulated for a range of different drive cycles (which include those above); in order to populate this table an understanding of the average speed for these additional cycles is an important input into estimating the impact of lightweighting.

For the vehicle and drive cycle combinations presented in Table 3.4, running the simulation in VECTO provides an average speed for the cycle, together with the CO_2 emissions (per kilometre) from the simulation. For the drive cycles for which vehicle simulations are *not* currently available, examination of the drive cycle provided the cycle characteristics that are summarised in Table 3.8: below. These figures were calculated by converting the respective .DRI VECTO file into a time-speed equivalent, and manipulating these data to calculate an average speed.

The use of this data to calculate the relevant emissions profiles for different vehicle types and levels of weight reduction is discussed further in Section 3.5.1.

Table 3.8: Characteristics of the drive cycles used in this analysis

Drive cycle	Total distance	Average speed	Stops (duration)	Average speed whilst driving
Urban delivery	27.8 km	30.5 kph[1]	27 (639 s)	37.9 kph
Regional delivery	25.8 km	58.8 kph[1]	6 (114 s)	63.4 kph
Long haul	108.2 km	74.8 kph[1]	6 (224 s)	78.3 kph
Utility	10.0 km	8.6 kph[2]	56 (3,188 s)	36.8 kph
Construction	21.2 km	38.5 kph[2]	21 (646 s)	57.2 kph
Urban city bus	39.6 km	20.9 kph[2]	119 (2,778 s)	35.2 kph

Drive cycle	Total distance	Average speed	Stops (duration)	Average speed whilst driving
Heavy urban city bus	30.5 km	14.9 kph[2]	153 (3,939 s)	31.9 kph
Inter-urban bus	123.6 km	39.6 kph[2]	87 (1,705 s)	46.7 kph
Coach	275.2 km	64.9 kph[1]	10 (400 s)	66.7 kph

Notes:

1 Average speed determined from a VECTO simulation and vehicle model

2 Average speed determined from analysis of VECTO drive cycle only.

3.4 Task 2.3: Energy and CO_2 benefits of light-weighting from previous heavy duty vehicle testing

In addition to the simulation of lightweighting, data has been collected from previous heavy duty **vehicle testing**. There are few heavy-duty dynamometer facilities available, and so the availability of data was expected to be limited, as we knew that only limited recent testing had occurred.

At the beginning of the project, the team at Millbrook Proving Ground reviewed the data potentially available. This can be categorised into the following three types:

1. Single vehicle heavy duty dynamometer tests;
2. Dynamometer tests where a vehicle's emissions were quantified for several different loads;
3. Real driving emissions, measured from test track driving using a portable emissions measuring system (PEMS).

The results from the analysis of these different datasets is summarised in the following subsections.

3.4.1 Single heavy duty vehicle dynamometer tests

23 single heavy duty vehicle dynamometer tests were identified from previous HDV testing, six for trucks and 17 for buses, for which five were for hybrid buses. However, in the context of there being data from categories 2 and 3 above, closer examination of this data indicated their value was somewhat limited. This is principally because too many parameters changed between data sets, and it is therefore difficult to uncouple changes in vehicle type and drive cycle from changes caused by variations in vehicle weight.

Notwithstanding this complication, it is important to this project that the impact of light-weighting for different vehicle segments, driven using different drive cycles, is evaluated. In particular, the truck (and coach) data simulated by VECTO, and the truck data reported below leave a gap regarding an assessment of the impact of light-weighting for buses.

Therefore the 12 bus emissions measurements were analysed. All were collected over the Millbrook London Transport Bus cycle (MLTB). This comprises two phases: an outer London phase of nominal distance 6.45 km, which takes 23 minutes, and which is conducted an average speed of 16.8 kph; and an inner London phase of nominal distance 2.47 km, which takes 901 seconds, and is conducted at an average speed of 9.87 kph[9]. The average speed of the overall cycle is 14.1 kph.

Figure 3.5 shows a graph of vehicle weight, in kg, against the CO_2 emissions, in gCO_2/km, and Table 3.9 gives the linear regression least squares fit to these data (for the two separate and the combined MLTB cycle).

[9] http://www.lowcvp.org.uk/ugc-1/1/2/0/vehicle_certification_requirements.pdf

Figure 3.5: CO_2 emissions data for dynamometer tests for various buses of different weights

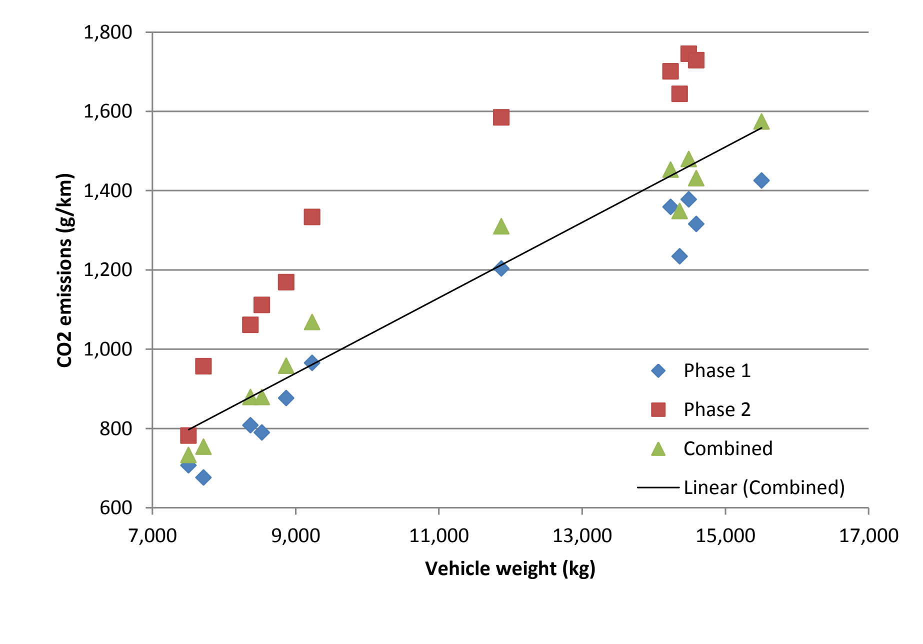


Table 3.9: Linear regression values for the Vehicle weight and CO_2 emissions data shown in Figure 3.5.

		Linear regression values			
Type of vehicle	**Drive cycle**	**Gradient**	**Constant**	**R^2 value**	**Average speed**
Diesel buses	MTLB Phase 1	0.0879	70.4	0.959	16.8 kph
Diesel buses	MTLB Phase 2	0.115	106.1	0.935	9.87 kph
Diesel buses	MTLB Overall	0.0952	83.1	0.959	14.1 kph

Splitting the data further into single and double deck buses did not provide further insights. The equations given above are generic, and do not involve selecting a reference vehicle.

Two "reference buses" are defined as having a kerb weight of 8,000 kg for a midibus[10], and a kerb weight of 11,500 kg for a 12 m single deck bus[11]. CO_2 emissions over the two phases and for the combined MLTB are calculated from the linear regressions summarised in Table 3.9, then the data can be expressed relative to these two assumed reference city buses, and the effective change in CO_2 resulting from a change in weight calculated as for the VECTO simulation data shown in Figure 3.1 to Figure 3.3. This approximation is made so that later analysis of X% lightweighting resulting in Y% change in CO_2 emissions can be undertaken for all vehicle categories in later Task 2.4. The linear regression coefficients are shown in Table 3.10.

Table 3.10: Linear regression coefficients for the Relative vehicle weight and relative CO_2 emissions data from dynamometer testing of buses

		Linear regression values			
Type of vehicle	**Drive cycle**	**Gradient**	**Constant**	**R^2 value**	**Average speed**
Reference Midi Bus	MTLB Phase 1	0.909	0.091	0.9590	16.8 kph
Reference Midi Bus	MTLB Phase 2	0.893	0.103	0.9354	9.87 kph
Reference Midi Bus	MTLB Overall	0.901	0.098	0.9594	14.1 kph
Reference 12 m bus	MTLB Phase 1	0.935	0.065	0.9590	16.8 kph

[10] In close agreement with the 7,962 kg figure from HDV Baseline Vehicle Weights analysis from Task 1.2
[11] Figure of 11,500 kg is based on the Task 1 analysis and is consistent with that of a MB Citaro 12 m bus

		Linear regression values			
Type of vehicle	**Drive cycle**	**Gradient**	**Constant**	**R^2 value**	**Average speed**
Reference 12 m bus	MTLB Phase 2	0.923	0.074	0.9354	9.87 kph
Reference 12 m bus	MTLB Overall	0.929	0.071	0.9594	14.1 kph

3.4.2 Dynamometer tests where one vehicle was tested at several different loads

There were three sets of data where dynamometer tests were undertaken on the same vehicle at two different loadings. However, two of these were for hybrid city buses. These data are not representative of trucks in general, and are not analysed further.

The third vehicle is a 44 tonne GVW articulated tractor unit. CO_2 emissions data were collected from driving the FIGE drive cycle[12], with the vehicle's inertia set to 9.0 and 20.0 tonnes (the inertia limit of the dynamometer was just over 20 tonnes, limiting the range of testing that could be undertaken).

The raw data are summarised in Table 3.11. From these the percentage change in inertia from the unloaded tractor-trailer, and the corresponding percentage change in CO_2 emissions can be calculated. The gradient between these two data points is shown in Table 3.12.

Table 3.11: CO_2 emissions from dynamometer testing of a 44 t GVW articulated truck, tested over the three phases of the vehicle FIGE cycle

	CO_2 emissions over the FIGE drive cycle(g/km)			
Test Inertia	**Phase 1**	**Phase 2**	**Phase 3**	**Combined**
20,000 kg	1007.58	761.17	775.34	799.92
9,000 kg	603.91	523.69	617.62	580.50
20,000 kg data relative to 9,000 kg data				
222.2%	166.8%	145.3%	125.5%	137.8%

Table 3.12: Linear regression values for the vehicle weight and CO_2 emissions data from dynamometer testing of 44 tonne GVW articulated truck

		Linear regression values			
Type of vehicle	**Drive cycle**	**Gradient**	**Constant**	**R^2 value**	**Average speed**
44 t articulated truck	FIGE Phase 1	0.0367	273.6	N/A[13]	22.8 kph
44 t articulated truck	FIGE Phase 2	0.0216	329.4	N/A	69.0 kph
44 t articulated truck	FIGE Phase 3	0.0143	488.6	N/A	84.0 kph
44 t articulated truck	**FIGE Overall**	**0.0199**	**401.0**	**N/A**	**58.6 kph**

[12] The emissions from heavy duty vehicles are approved by measurements using an **engine** test, rather than a vehicle test as for light duty vehicles. Consequently, there is no heavy duty vehicle equivalent to the NEDC. This engine test is the European Transient Cycle (ETC). Its origins lie in studies of heavy duty vehicle time speed profiles. A vehicle time speed profile that is relatively representative of the ETC is used for some HDV testing. This is known as the FIGE cycle (after the FIGE Institute in Aachen where it was developed). It comprises three 600 second phases which emulate urban, suburban and motorway driving.

[13] R2 note reported because this is a perfect linear fit between **two** data points

Table 3.13: Linear regression coefficients for the relative vehicle weight and relative CO_2 emissions data from dynamometer testing of 44 tonne GVW articulated truck

		Linear regression values			
Type of vehicle	Drive cycle	Gradient	Constant	R^2 value	Average speed
44 t articulated truck	FIGE Phase 1	0.547	0.453	N/A	22.8 kph
44 t articulated truck	FIGE Phase 2	0.371	0.629	N/A	69.0 kph
44 t articulated truck	FIGE Phase 3	0.209	0.791	N/A	84.0 kph
44 t articulated truck	**FIGE Overall**	**0.309**	**0.691**	**N/A**	**58.6 kph**

For drive cycles with comparable average speeds, Phases 2 and 3 of the FIGE cycle, the percentage change in CO_2 emissions per percentage change in mass is broadly similar (gradient values of 0.209 and 0.371 for 88 kph and 72 kph drive cycles, respectively) relative to those simulated by VECTO (from Table 3.7, coefficients are 0.304 for the 74.8 long haul cycle and 0.419 for the 59.3 kph regional delivery cycle).

3.4.3 Test track driving using a portable emissions measuring system (PEMS)

In addition to dynamometer testing, Millbrook has previously collected CO_2 emissions data for four trucks for real world driving (on a test track) using a portable emissions measuring system, PEMS, to quantify CO_2 emissions. These data are summarised in Table 3.14. As part of this previous data collection exercise, Millbrook developed a "real world urban transient cycle" speed-time profile for the customer who commissioned these tests. This was driven using an in-cabin drivers aid linked to a GPS system. Consequently, there was a high degree of controllability and reproducibility for the cycles driven. Whilst the details of the cycle are confidential, the average speed of Phase 1 is 24.7 km/h and the average speed of Phase 2 is 45.8 km/h.

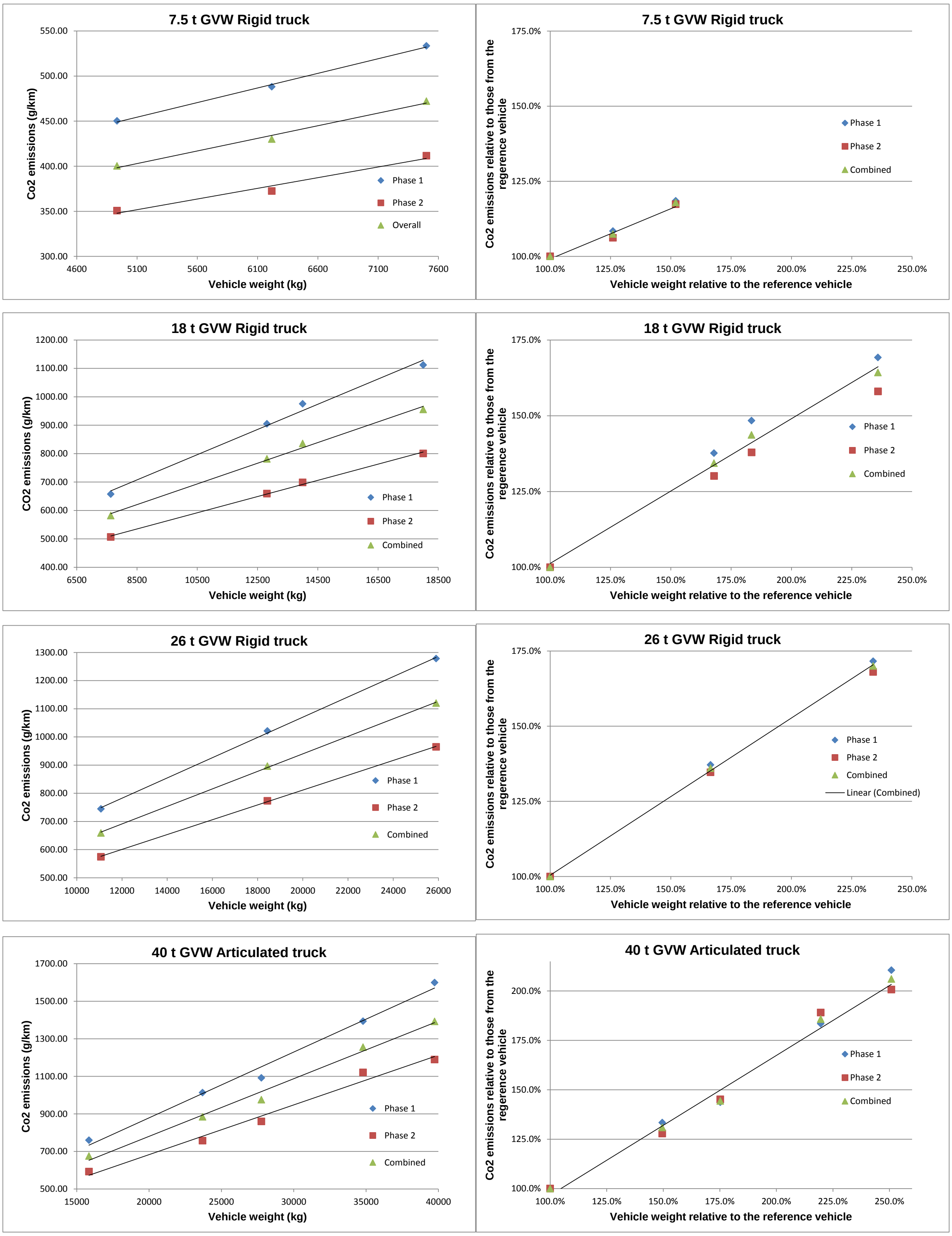
Table 3.14: Summary of real world driving cycles

Vehicle	Test condition	Test Inertial (kg)	Load (kg)	% of maximum load
7.5 Tonne Rigid	50% Load	6,217	1,284	50%
7.5 Tonne Rigid	Fully laden	7,500	2,567	100%
7.5 Tonne Rigid	Empty, reference vehicle	4,933	0	0%
18 Tonne Rigid	Empty, reference vehicle	7,630	0	0%
18 Tonne Rigid	50% Load	12,815	5,185	50%
18 Tonne Rigid	61% Load	14,000	6,370	61%
18 Tonne Rigid	Fully laden	18,000	10,370	100%
26 Tonne Rigid	Fully laden	25,896	14,826	100%
26 Tonne Rigid	50% Load	18,431	7,361	50%
26 Tonne Rigid	Empty, reference vehicle	11,070	0	0%
Artic Truck	Fully laden	39,735	23,895	100%
Artic Truck	79% Load	34,785	18,945	79%
Artic Truck	50% Load	27,757	11,917	50%
Artic Truck	33% Load	23,693	7,853	33%
Artic Truck	Empty, reference vehicle	15,840	0	0%

Figure 3.6 shows the data from these drive cycles, expressed in units of the CO_2 emissions relative to those from the reference truck, plotted against the vehicle weight, again relative to that for the reference

truck. Consequently these data are directly comparable to those from the VECTO simulations given in Figure 3.1 to Figure 3.3.

Figure 3.6: CO_2 emissions data for on-the-road testing of all vehicles



As for the VECTO simulations, all four trucks show a linear relationship between changes in emissions, for graphs of both absolute CO_2 emissions against vehicle weight, and when plotted relative to the reference vehicle. Each figure also includes one least squares regression fit to emphasise this.

Table 3.15 tabulates the data from the linear regressions for the four trucks, for Phase 1, Phase 2 and the whole cycle when the data are plotted as CO_2 emissions against vehicle weight. Table 3.16 tabulates the analogous data from the linear regressions when the data are plotted as relative CO_2 emissions against relative vehicle weight when compared with a reference vehicle. The table also contains the R^2 value for the regression. The way these equations are used to estimate the impact of lightweighting on CO_2 emissions is discussed in the next section.

Table 3.15: Linear regression coefficients from emissions vs vehicle weight graphs from on-the-road testing of all vehicles

		Linear regression values			
Type of vehicle	**Drive cycle**	**Gradient**	**Constant**	**R^2 value**	**Average speed**
7.5 t rigid truck	Phase 1 RWUTC[14]	0.0324	289.2	0.997	24.7 kph
7.5 t rigid truck	Phase 2 RWUTC	0.0237	230.9	0.973	45.8 kph
7.5 t rigid truck	Combined RWUTC	0.0280	260.4	0.990	35.3 kph
18 t rigid truck	Phase 1 RWUTC	0.0444	330.6	0.991	24.7 kph
18 t rigid truck	Phase 2 RWUTC	0.0285	292.6	0.998	45.8 kph
18 t rigid truck	Combined RWUTC	0.0365	311.5	0.994	35.3 kph
26 t rigid truck	Phase 1 RWUTC	0.0360	350.5	0.999	24.7 kph
26 t rigid truck	Phase 2 RWUTC	0.0263	284.4	1.000	45.8 kph
26 t rigid truck	Combined RWUTC	0.0311	317.4	0.999	35.3 kph
40 t articulated truck	Phase 1 RWUTC	0.0350	178.6	0.988	24.7 kph
40 t articulated truck	Phase 2 RWUTC	0.0265	153.9	0.984	45.8 kph
40 t articulated truck	Combined RWUTC	0.0307	167.1	0.991	35.3 kph

Table 3.16: Linear regression coefficients for the Relative vehicle weight and relative CO_2 emissions data from on-the-road testing of all vehicles

		Linear regression values			
Type of vehicle	**Drive cycle**	**Gradient**	**Constant**	**R^2 value**	**Average speed**
7.5 t rigid truck	Phase 1 RWUTC	0.355	0.642	0.997	24.7 kph
7.5 t rigid truck	Phase 2 RWUTC	0.334	0.658	0.973	45.8 kph
7.5 t rigid truck	Combined RWUTC	0.345	0.650	0.990	35.3 kph
18 t rigid truck	Phase 1 RWUTC	0.515	0.503	0.991	24.7 kph
18 t rigid truck	Phase 2 RWUTC	0.429	0.578	0.998	45.8 kph
18 t rigid truck	Combined RWUTC	0.477	0.536	0.994	35.3 kph
26 t rigid truck	Phase 1 RWUTC	0.535	0.471	0.999	24.7 kph
26 t rigid truck	Phase 2 RWUTC	0.508	0.495	1.000	45.8 kph
26 t rigid truck	Combined RWUTC	0.523	0.471	0.999	35.3 kph
40 t articulated truck	Phase 1 RWUTC	0.730	0.235	0.988	24.7 kph
40 t articulated truck	Phase 2 RWUTC	0.707	0.260	0.984	45.8 kph
40 t articulated truck	Combined RWUTC	0.719	0.247	0.991	35.3 kph

[14] RWUTC is the Real World Urban Transient Cycle developed by Millbrook for this real-world track driving cycle

3.5 Task 2.4: Analysis of energy and CO_2 benefits for each light-weighting option and HDV category

The objective for this final subtask was to develop estimates for energy or CO_2 reductions per increment of lightweighting for different heavy duty vehicle types and drive cycles. The following subsections outline the underlying considerations used to define the methodology of utilising the data from the previous subtasks to develop the final set of tabulated output results that will be used to feed into the MAC curve development in later Task 3.

3.5.1 Combining the different energy and CO_2 benefit results - Theoretical considerations

Figure 3.1 to Figure 3.6 show some important aspects of the collated data (both from simulations and from testing actual vehicles) when plotted as absolute CO_2 emissions vs absolute vehicle weights, namely that there is a linear relationship between the two. This applies to both vehicle simulations and to the testing of real vehicles.

When the data are plotted as graphs of the percentage change in vehicle weight (relative to a reference vehicle) against the percentage change in CO_2 emissions (relative to a reference vehicle), it is noted that:

- The lines are generally linear;
- A range of gradients are seen, which are smaller for long haul (0.157 % change in CO_2 occurs for 1.0% change in relative vehicle mass) relative to more transient cycles, (0.73% for the real world urban transient cycle for a 40 tonne GVW articulated truck).

The latter effect is a consequence of the vehicle's energy being used to overcome air resistance/drag, and to accelerate the vehicle, generating kinetic energy. For drive cycles with higher average speeds, more energy is used to overcome drag, which is vehicle weight independent. Therefore for such cycles the gradient is smaller (lower reduction in CO_2 per unit of weight reduction). Indeed two extreme cases can be envisaged:

Case 1 – none of the energy is used to overcome weight based retarding resistances, and

Case 2 - all of the energy is used to overcome weight based retarding resistances.

A consequence of plotting relative changes (when compared with a reference vehicle) is that for these two cases:

- **Case 1:** Relationship is a horizontal line with gradient = 0.00 and intercept = 1.00, i.e. CO_2 emissions are weight independent;
- **Case 2:** Relationship is a straight line that goes through the origin, i.e. when weight = 0 energy required, and CO_2 emitted = 0. For this case with gradient = 1.00 and intercept = 0.00.

Consequently, as a generality both the intercept and the gradient are expected to lie between 0.00 and 1.00, and their sum = 1.00. (For the least squares fitting of real data this may not be the case.)

For a real vehicle operating between the two extreme cases there is another consequence of analysing data in this way; the value of the gradient is dependent on the reference vehicle characteristics, i.e. doubling the reference weight does not simply halve the gradient, the relationship is more complex (see Box 1 for an illustrated explanation).

To summarise: **the gradient and constant from the linear regression are dependent on the reference point chosen**. They change with the choice of reference vehicle, and not in any simple way. Therefore to specify how light-weighting affects the CO_2 emissions, at least **four** data points are required. Generally these will be the gradient and constant for the linear regression from the graphs of relative changes, and the absolute vehicle weight and CO_2 emissions for the reference vehicle.

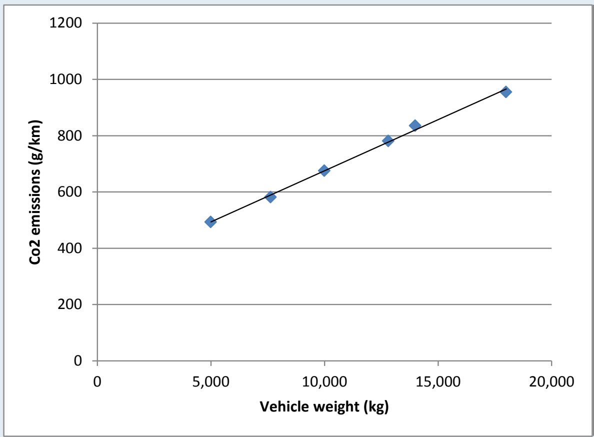
For the relationship between absolute CO_2 emissions and absolute vehicle weights, these do not involve a reference vehicle, and all that needs to be specified is the gradient and constant for the linear regression from the graphs.

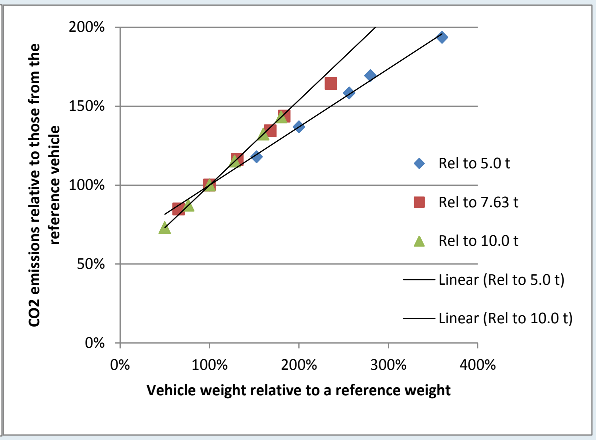
Box 3: Influence of reference vehicle on the linear regression parameters for equations linking the relative vehicle weight and relative CO_2 emissions data from vehicles

In an attempt to provide a more accessible explanation (and avoid some complex mathematics), the influence of the reference vehicle on the linear regression parameters for CO_2 savings by lightweighting shown by way of a worked example below.

In Figure 3.6, data was given for an 18 t Rigid Truck. Whilst Figure 3.6 shows the data plotted in relative percentages, normalised with respect to the unladen truck, the left-hand figure below shows the same data plotted using absolute weights and CO_2 emissions. In addition to the four vehicle weights used, additional unladen weights for 5.0 tonnes (equivalent to around a 35% light-weighting) and 10.0 tonnes have been added/simulated from the linear relationship of the measured four points.

Figure 3.7: Illustration of the effect of choosing difference reference vehicle weights on the correlation of % weight change and % CO_2 emissions change





To the right of the figure is a graph of the CO_2 emissions against vehicle weight each relative to a reference vehicle. Three different reference vehicles were selected, whose weights were 7.63 t, as for data in Figure 5, 5.0 t and 10.0 t. The linear fits for these last two are also shown. The gradients and intercepts for these three series of relative analyses are:

For 18 t GVW Rigid truck		Linear regression values	
Drive cycle	**Ref. vehicle weight**	**Gradient**	**Constant**
Combined RWUTC	7.63 tonnes	0.477	0.536
Combined RWUTC	5.00 tonnes	0.539	0.461
Combined RWUTC	10.00 tonnes	0.368	0.632

The gradient and constant from the linear regression when the reference weight is 7.63 tonnes are those found earlier, and are recorded in Table 3.16.

The important message from this work is that **the gradient and constant from the linear regression are dependent on the reference point chosen**. They change with the choice of reference vehicle, and not in any simple way. For example doubling the reference vehicle weight from 5.0 to 10.0 tonnes leads to a 31.29% change in gradient. The relationship is not arbitrary, but relatively complex, and will neither be derived nor used here.

A corollary to this finding, is that to specify how light-weighting affects CO_2 emissions at least **four** data points are required. Generally these will be the gradient and constant for the linear regression from the relative plots, and the absolute vehicle weight and CO_2 emissions for the reference point.

The principal objective of this task is to determine: "What level of CO_2 saving might a particular level of light-weighting produce?" for the different vehicle categories and usage patterns encountered. These are specified in terms of different vehicle groups (rigid and articulated trucks, buses and coaches), different vehicle weight categories, and different drive cycles.

Data relevant to light-weighting for many of the different vehicle groups has been presented in the previous sections. These have been used as the basis for determining the CO_2 savings for the different vehicle categories (as presented in the next section, 3.5.2).

The vehicle simulation, dynamometer testing and track testing all show that vehicle CO_2 emissions are speed dependent. For example, Figure 3.5 shows emissions from 12 buses for the two components of the MLTB cycle, Phase 1 (average speed 16.8 kph) and Phase 2 (average speed 9.87 kph). From Figure 3.5, the average emissions for Phase 1 are 32% less than for Phase 2.

Therefore, when completing the lightweighting characteristics for the matrix of vehicle categories and their drive cycles when directly relevant data are not available, the average speed of the vehicle category's drive cycle has been taken into consideration. This involved considering how the CO_2 emissions vary with speed from the data closest to the average drive cycle speed, for the reference vehicle that was used. All the drive cycles used in the template for the table of outputs (in section 3.5.2) are defined within the European Commission's VECTO model. The average speed of these EC-JRC-ACEA agreed representative cycles (discussed also in earlier section 3.3.2) were used in this analysis and were determined using one of two approaches:

1. For trucks, simulations were run using the urban delivery, regional delivery and long haul cycles, and for coaches using the coach cycle.
2. For the construction and utility truck cycles, and for the bus cycles, examination of the VECTO drive cycle was used.

The characteristics of all the drive cycles are summarised in Table 3.4 (discussed in earlier section 3.3.2, covering VECTO simulations).

By way of illustration, it is useful to consider the CO_2 emissions from a 7.5 t GVW truck for the urban delivery cycle. Data are available from Millbrook for three vehicle weights over the two phases and the combined Real World Urban Transient Cycle (RWUTC). Figure 3.8 shows these data plotted as a function of average drive cycle speed for each of the three inertias. For the reference/lowest inertia, a linear regression is shown ($R^2 = 0.976$) from which the emissions at the VECTO urban delivery speed of 30 kph is calculated.

However, while interpolation between Phase 1 and Phase 2 of the RWUTC (24.7 kph and 45.8 kph) assuming a linear relationship is reasonable within the context of the estimates being performed, extrapolation outside these speeds is not undertaken because, as will be shown, it would lead to inaccurately low predictions of the CO_2 emissions at the higher speeds.

For speeds higher than 50 kph use is made of CO_2 emissions and fuel consumption data from the EEA Emissions Inventory Guidebook database (EEA, 2013)[15]. Specifically, the fuel consumption for 0% load, and 0% gradient for an appropriate vehicle category was selected. The results are shown in Figure 3.9.

Figure 3.9 shows how CO_2 emissions decrease smoothly between around 25 and 45 kph, and can be approximated by a linear function (the red line). However, for the regional delivery cycle (the green vertical line at 59 kph) and the long haul cycle (the orange vertical line at 78 kph) lie well above this line, and so linear extrapolation are not appropriate. From the EEA Emissions Inventory Guidebook database the value at 59 kph is 77% of the average value of the emissions at 25 and 45 kph, and at 78 kph is 74% of this average value.

[15] EEA Emissions Inventory Guidebook database is available from: http://www.eea.europa.eu//publications/emep-eea-guidebook-2013

Figure 3.8: Change of observed emissions with average drive cycle speed

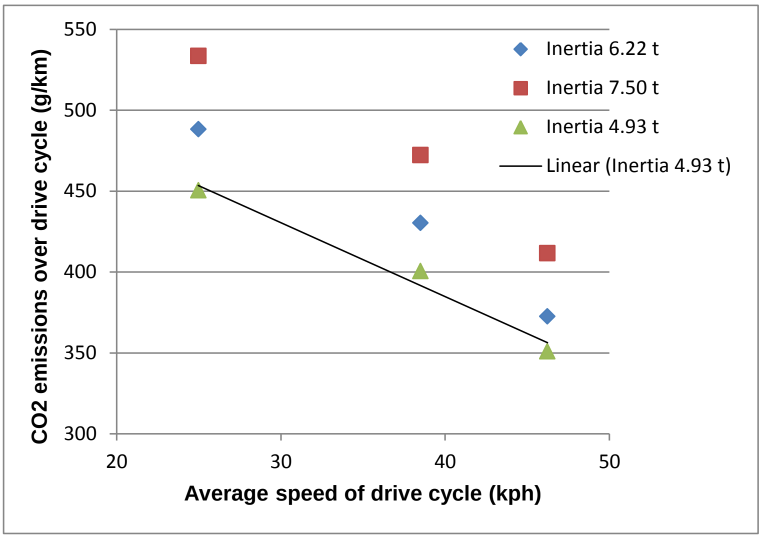
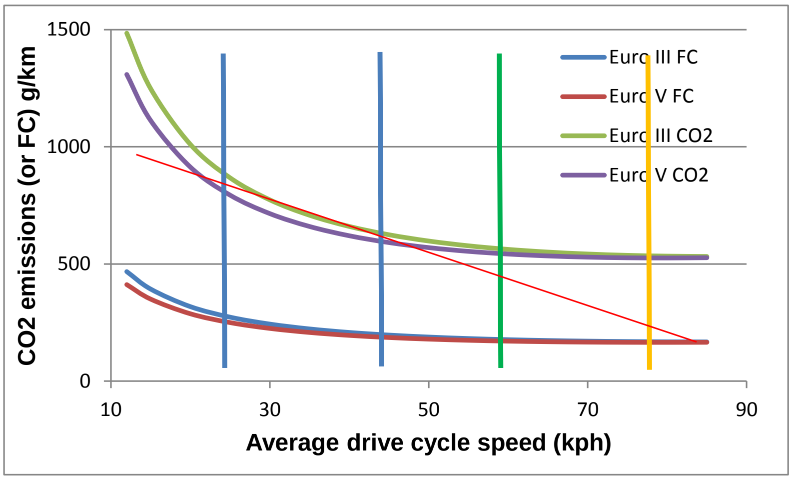


Figure 3.9: Fuel consumption and CO_2 emissions data (g/km) for a 20 – 26 tonne GVW truck with 0% load, and for a 0% gradient



Note: blue vertical lines denote 25 and 46 kph (for phase 1 and 2 of RWUTC) green vertical line is at 59 kph, average speed for VECTO regional delivery cycle, and yellow line is at 75 kph, average speed for VECTO long haul cycle

3.5.2 Summary the CO_2 benefits that result from light weighting

Table 3.17 summarises the developed draft estimates for the relationship between weight reduction and the resulting reduction in CO_2 emissions (expressed as the change in CO_2 emissions per unit change in weight (i.e. gCO_2/km per kg saved) based on the evidence collected and discussed earlier in this chapter. As shown several times this relationship is linear, over an extended range. The CO_2 emissions (per km) cam be related to the vehicle's weight by the equation:

$$CO_2 \text{ (g/km)} = \text{Gradient x vehicle weight + constant.}$$

The values of these gradients and constants are listed in Table 3.17 for different vehicle categories, and different drive cycles.

From these, the change in CO_2 emissions (g/km) caused by a change is vehicle weight is given simply by:

$$\Delta CO_2 \text{ (g/km)} = \text{Gradient x } \Delta \text{Weight (kg).}$$

Table 3.18 summarises the corresponding gradients and constants for changes in vehicle for different vehicle categories, and different drive cycles.

Table 3.17: Recommendations from the evidence collected of the impact of lightweighting on different vehicle categories when driven over different drive cycles expressed as the coefficients in the linear equation linking changes in CO_2 emissions (g CO_2 /km) with changes in vehicle mass

Vehicle Group	Vehicle Category	Drive Cycles	Gradient for linear relationship	Constant for linear relationship	Why
Rigids	<7.5t truck	Urban Delivery	0.0305	276.4	From Millbrook vehicle tests for 7.5 t GVW vehicle over all three RWUTC cycles interpolated for average speed of 30.5 kph
		Utility	0.0392	335.0	From Millbrook vehicle tests for 7.5 t GVW vehicle over all three RWUTC cycles, extrapolated for average speed of 8.6 kph
		Regional Delivery	0.0191	200.7	From Millbrook vehicle tests for 7.5 t GVW vehicle over all three RWUTC cycles extrapolated for average speed of 58.8 kph
		Construction	0.0273	255.0	From Millbrook vehicle tests for 7.5 t GVW vehicle over all three RWUTC cycles interpolated for average speed of 38.5 kph
	7.5t-<16t truck	Urban Delivery	0.0319	317.0	From VECTO simulation of 12 t GVW rigid vehicles
		Utility	0.0392	248.5	From VECTO simulation of 12 t GVW rigid vehicle adjusted for cycle of average speed 10 kph
		Regional Delivery	0.0203	408.7	From VECTO simulation of 12 t GVW rigid vehicles
		Construction	0.0288	343.3	From VECTO simulation of 12 t GVW rigid vehicle adjusted for cycle of average speed 38.5 kph
	16t-32t Rigid truck	Urban Delivery	0.0365	311.5	From Millbrook vehicle test for 18 t GVW vehicle over combined RWUTC adjusted for average speed of 30.5 kph

Vehicle Group	Vehicle Category	Drive Cycles	Gradient for linear relationship	Constant for linear relationship	Why
	16t-32t Rigid truck	Utility	0.0444	330.6	From Millbrook vehicle test for 18 t GVW vehicle over RWUTC Phase 1, adjusted to average speed of 8.6 kph
		Regional Delivery	0.0214	442	From Millbrook vehicle test for 18 t GVW vehicle over combined RWUTC gradient and intercept adjusted for speed, and CO_2 emissions adjusted to 77%
		Long-Haul	0.0156	500	From Millbrook vehicle test for 18 t GVW vehicle over combined RWUTC gradient and intercept adjusted for speed, and CO_2 emissions adjusted to 74%
		Construction	0.0365	311.5	From Millbrook vehicle test for 7.5 t GVW vehicle over combined RWUTC adjusted for average speed of 38.5 kph
	>32t truck (road train = truck+trailer combo)	Long-Haul	0.0143	488.6	Treat as a >32 tonne artic?
Artics	16t-<32t artic	Regional Delivery	0.0216	329.4	From Millbrook dynamometer vehicle test for 40 t GVW vehicle. It is assumed these smaller artics lie on the same CO_2 change per kg change line as the large artics, merely are lighter
		Long-Haul	0.0143	488.6	
		Construction	0.0309	309	
	>32t artic	Regional Delivery	0.0216	329.4	From Millbrook dynamometer vehicle test for 40 t GVW vehicle, from Phase 2 of FIGE cycle
		Long-Haul	0.0143	488.6	From Millbrook dynamometer vehicle test for 40 t GVW vehicle, from Phase 3 of FIGE cycle

Vehicle Group	Vehicle Category	Drive Cycles	Gradient for linear relationship	Constant for linear relationship	Why
	>32t artic	Construction	0.0309	309	From Millbrook dynamometer vehicle test for 40 t GVW vehicle, analysing 3 FIGE phases relative and interpolating to 38.5 kph average speed
Bus/coach	Urban buses	Urban	0.0783	50.0	Gradient and intercept from Millbrook bus tests over combined MLTB cycle CO_2 from extrapolation between Phase 1 and 2 emissions.
		Heavy Urban	0.0952	83.1	From Millbrook bus tests over combined MLTB cycle
	Inter-urban buses	Inter-urban	0.0332	304	[16] Taken from 18t GVW rigid truck – see below
	Coaches	Coach	0.0182	409.6	From VECTO simulation, see Table 3.7

[16] Rather than **extrapolate** from the around 10 and 17 kph phases of the MLTB cycle, for the Inter-urban cycle with its average speed of 40 kph, and < 1 stop per km, the data is **interpolated** from the 18t GVW truck over Phase 2 the RWUTC delivery cycle (7.63t weight and average speed 46 kph)

Table 3.18: Recommendations from the evidence collected of the impact of lightweighting on different vehicle categories when driven over different drive cycles expressed as the coefficients in the linear equation linking % changes in CO_2 emissions relative to a reference vehicle with % changes in vehicle mass relative to a reference vehicle

Vehicle Group	Vehicle Category	Drive Cycles	Reference Mass	Unladen Reference CO_2	Gradient	Const.	Why
Rigids	<7.5t truck	Urban Delivery	4.93 t	430 g/km	0.350	0.645	From Millbrook vehicle test for 7.5 t GVW vehicle over combined RWUTC adjusted for average speed of 30.5 kph
		Utility	4.93 t	530 g/km	0.371	0.624	From Millbrook vehicle test for 7.5 t GVW vehicle over RWUTC Phase 1, adjusted to average speed of 8.6 kph
		Regional Delivery	4.93 t	395 g/km	0.321	0.674	From Millbrook vehicle test for 7.5 t GVW vehicle over RWUTC Phase 2, extrapolated to average speed of 58.8 kph
		Construction	4.93 t	400 g/km	0.345	0.650	From Millbrook vehicle test for 7.5 t GVW vehicle over combined RWUTC adjusted for average speed of 38.5 kph
	7.5t-<16t truck	Urban Delivery	7.75 t	564 g/km	0.439	0.562	From VECTO simulation of 12 t GVW rigid vehicles
		Utility	7.75 t	980 g/km	0.543	0.458	For this low average speed, 8.6 kph, using gradients from 7.5 t truck over utility cycle, and EMEP EEA speed relationship for 12 tonne truck referenced to 30.5 kph urban delivery VECTO CO_2 emissions
		Regional Delivery	7.75 t	566 g/km	0.278	0.722	From VECTO simulation of 12 t GVW rigid vehicles
		Construction	7.75 t	564 g/km	0.396	0.605	From VECTO simulation of 12 t GVW rigid vehicles interpolated for average speed of 38.5 kph
	16t-32t Rigid truck	Urban Delivery	7.63 t	624 g/km	0.477	0.536	From Millbrook vehicle test for 18 t GVW vehicle over combined RWUTC adjusted for average speed of 30.5 kph

Vehicle Group	Vehicle Category	Drive Cycles	Reference Mass	Unladen Reference CO_2	Gradient	Const.	Why
		Utility	7.63 t	775 g/km	0.515	0.503	From Millbrook vehicle test for 18 t GVW vehicle over RWUTC Phase 1, adjusted to average speed of 8.6 kph
		Regional Delivery	7.63 t	450 g/km	0.376	0.625	From Millbrook vehicle test for 18 t GVW vehicle over combined RWUTC gradient and intercept adjusted for speed, and CO_2 emissions adjusted to 77%
		Long-Haul	7.63 t	430 g/km	0.311	0.683	From Millbrook vehicle test for 18 t GVW vehicle over combined RWUTC gradient and intercept adjusted for speed, and CO_2 emissions adjusted to 74%
		Construction	7.63 t	568 g/km	0.477	0.536	From Millbrook vehicle test for 7.5 t GVW vehicle over combined RWUTC adjusted for average speed of 38.5 kph
	>32t truck (road train = truck+trailer combo)	Long-Haul	9.00 t	620 g/km	0.209	0.791	Treat as a >32 tonne artic?
Artics	16t-<32t artic	Regional Delivery	8.00 t	483	0.371	0.629	From Millbrook dynamometer vehicle test for 40 t GVW vehicle, CO_2 scaled by 92% in-line with EEA EMEP fuel consumption curves Gradient and constant the same as for >32 tonne artic
		Long-Haul	8.00 t	570	0.209	0.791	
		Construction	8.00 t	506	0.476	0.524	
	>32t artic	Regional Delivery	9.00 t	525 g/km	0.371	0.629	From Millbrook dynamometer vehicle test for 40 t GVW vehicle, from Phase 2 of FIGE cycle
		Long-Haul	9.00 t	620 g/km	0.209	0.791	From Millbrook dynamometer vehicle test for 40 t GVW vehicle, from Phase 3 of FIGE cycle
		Construction	9.00 t	550 g/km	0.476	0.524	From Millbrook dynamometer vehicle test for 40 t GVW vehicle, analysing 3 FIGE phases relative and interpolating to 38.5 kph average speed

Vehicle Group	Vehicle Category	Drive Cycles	Reference Mass	Unladen Reference CO_2	Gradient	Const.	Why
Artics	>32t artic tractor & empty curtain side trailer	Regional Delivery	15.00 t	653	0.496	0.504	From Millbrook dynamometer vehicle test for 40 t GVW vehicle, from Phase 2 of FIGE cycle interpolated between 9 & 20 t
		Long-Haul	15.00 t	704	0.306	0.695	From Millbrook dynamometer vehicle test for 40 t GVW vehicle, from Phase 3 of FIGE cycle interpolated between 9 & 20 t
		Construction	15.00 t	750	0.603	0.397	From Millbrook dynamometer vehicle test for 40 t GVW vehicle, analysing 3 FIGE phases and interpolating to 38.5 kph average speed and interpolating between 9 & 20 t
Bus/coach	Urban buses	Urban	8.00 t	625 g/km	0.901	0.098	Gradient and intercept from Millbrook bus tests over combined MLTB cycle CO_2 from extrapolation between Phase 1 and 2 emissions.
		Heavy Urban	8.00 t	845 g/km	0.901	0.098	From Millbrook bus tests over combined MLTB cycle
	Inter-urban buses	Inter-urban	8.00 t	560 g/km	0.407	0.522	[17] Taken from 18t GVW rigid truck – see below
	Urban buses	Urban	11.5 t	875 g/km	0.935	0.065	As for 8 tonne bus but referenced to 11.5 tonne reference vehicle
		Heavy Urban	11.5 t	1,180 g/km	0.935	0.065	As for 8 tonne bus but referenced to 11.5 tonne reference vehicle
	Inter-urban buses	Inter-urban	11.5 t	675 g/km	0.472	0.421	As for 8 tonne bus but referenced to 11.5 tonne reference vehicle
	Coaches	Coach	15.7 t	695 g/km	0.412	0.589	From VECTO simulation, see Table 3.7

[17] Rather than **extrapolate** from the around 10 and 17 kph phases of the MLTB cycle, for the Inter-urban cycle with its average speed of 40 kph, and < 1 stop per km, the data is **interpolated** from the 18t GVW truck over Phase 2 the RWUTC delivery cycle (7.63t weight and average speed 46 kph)

Much of the data in Table 3.17 has been presented in earlier tables, as the different sources of evidence were discussed. However, for some of the vehicle categories and drive cycles used no direct evidence was available. In these cases existing evidence was interpolated, extrapolated or otherwise manipulated to give estimated values for the relationship between weight reduction and the resulting reduction in CO_2 emissions based on known measurements or simulations. Table 3.17 briefly summarises the evidence (and further manipulations), as well as providing the gradients and constants for the linear relationships.

However, this relationship is not the most convenient if the analysis indicates that a portfolio of technologies leads to a known estimated percentage lightweighting. What is ideally required is a corresponding percentage reduction in CO_2 emissions. This relative change (expressed as a percentage change relative to a reference vehicle) requires both the characteristics of the reference vehicle to be specified, and the gradient and constant for the linear regression line. Table 3.18 summarises the developed draft estimates on the relationship between weight reduction and CO_2 emissions based on the evidence collected and discussed earlier in this chapter. As with Table 3.17, much of the data in Table 3.18 has been presented in earlier tables. However, in some cases existing evidence had to be interpolated, extrapolated or otherwise manipulated to give the estimated values tabulated. Again, the right hand column of Table 3.18 briefly summarises the origins of the gradients and constants tabulated.

For the different vehicle categories, when driven over their commonly used drive cycles, four key pieces of data are given in the table:

- Reference mass, M_{ref};
- Reference CO_2 emissions (in g CO_2/km) CO_{2ref};
- The gradient in the linear relationship between CO_2 emissions and vehicle light weighting, LWG;
- The constant in the linear relationship between CO_2 emissions and vehicle light weighting, LWC;

The general formula for the emissions from a truck with Y% lightweighting is:

$$CO_2 \text{ emissions/km for lighter vehicle} = CO_{2ref} \times [(1-Y) \times LWG + LWC]$$

By way of an illustrative example, consider the impact of lightweighting on a 16 – 32 tonne rigid truck. These vehicles are used over a range of different drive cycles including delivery cycles, long haul cycles, as well as construction and utility cycles. They are also used over a range of different states of loading.

It is assumed, from the equations, that the CO_2 emissions from a 7.63 tonne kerb weight vehicle varies from 775 g/km, for the very stop-start driving of a utility cycle to 430 g/km for long haul driving. For a regional delivery drive cycle, Y% lightweighting is predicted to lead to CO_2 emissions of:

$$CO_2 \text{ emissions/km for lighter vehicle} = 450 \times [(1-Y) \times 0.375 + 0.625]$$

Note: whilst the reference mass is not used in this equation it is an important caveat to the equation, giving a reference point. In the illustrative example above the reference mass was taken as 7.63 tonnes. If, for example, one was interested in reducing the weight of a concrete mixer truck whose empty weight was double this value (i.e. 15.26 tonnes), in order to consider the impact of a 25% lightweighting, then two calculations would be required:

$$CO_2 \text{ emissions/km for reference vehicle} = 450 \times [(15.26/7.63) \times 0.375 + 0.625]$$

$$CO_2 \text{ emissions/km for lightweighted vehicle} = 450 \times [(1-Y)(15.26/7.63) \times 0.375 + 0.625]$$

The right-hand column of Table 3.18 gives a brief explanation for the values provided in the row. Generally there is only one potential source for the factors, as described earlier.

For the articulated trucks there are three potential sources of data: (i) VECTO simulations, (ii) a small amount of dynamometer testing, and (iii) the results of on-the-road testing. However, these appear to give inconsistent data even when one compares similar cycles (the regional delivery cycle for the VECTO simulation, the FIGE Phase 2, or suburban driving, and the Phase 2 of the real world urban transient cycle):

Table 3.19: Comparioson of laternative potential data sources for articulated trucks

Potential source of data	Reference vehicle weight	CO_2 emissions for regional delivery	CO_2 emissions for long haul
VECTO	14,600	670	675
Dynamometer test	9,000	525	617
On the road driving	15,840	593	

The vehicle reference weight for the VECTO simulation is that for the user defined tractor unit plus a standard trailer (which weighs 7,500 kg). The CO_2 emissions given are for this empty tractor + trailer combination.

A further feature of the VECTO data is a change in CO_2 emissions with changes in mass that are smaller than were measured from vehicles. This could potentially understate the benefit of light-weighting.

The RWUTC is less relevant for this type of vehicle because it does not investigate long haul driving. Phase 2 of the RWUTC only has an average speed of 45.8 kph, whereas Phases 2 and 3 of the FIGE cycle have average speeds of 69.0 kph and 84.0 kph, respectively. Also, whilst the change in CO_2 emissions with changes in mass are potentially underestimated by VECTO simulations (gradients around 0.20 % change in CO_2 per % change in mass) the RWUTC potentially overstates this change, (gradients around 0.70 % change in CO_2 per % change in mass.) However, part of this is caused by the relatively heavy reference mass chosen.

Therefore the data in Table 3.18 for long haul driving have been based on the chassis dynamometer vehicle testing, rather than the VECTO simulation, or the on the road driving over the real world urban transient cycle. If the mass data for the chassis only (i.e. dynamometer test from Table 3.19 above) is increased to 15 tonnes for the tractor – trailer combination, the calculated revised CO_2 emissions for the regional delivery cycle from the dynamometer testing would be estimated to be 653 g/km. This figure is between those predicted by VECTO and inferred from the on-the-road driving.

3.5.3 Estimation of the share of road transport market constrained by weight limitations

Current weight limitations on goods vehicles are based on the total weight of laden vehicles; a reduction of kerb weight might therefore allow for additional payload capacity. Further limitations are linked to the maximum allowed load per axle and to the overall external dimensions of vehicles (length, width and height).

For this reason, in order to evaluate possible benefits and drawbacks of lightweighting it is important to examine the available information and to quantify the share of the road transport market that suffers from weight limitations.

Excluding the exceptional and oversize loads, it is broadly acknowledged that some categories of goods are heavier than others and more easily reach the maximum allowed load. This is the case more frequently for various types of raw materials and bulk products (liquids, cement, sand, minerals, cereals etc.), but also for steel and metal products and construction materials.

The objective of this subtask is to provide an estimate of the share of weight constrained loads separately by truck size and type of service according to the following Table 3.20, so that this may be used in the marginal abatement cost-curve (MACC) analysis to be carried out in later Task 3.

Table 3.20: Matrix of weight constrained duty cycles by weight class

Duty Cycle	***Weight class***			
	<7.5t	**7.5t-16t**	**16t-32t**	**>32t**
Service	✓			
Urban Delivery	✓	✓	✓	

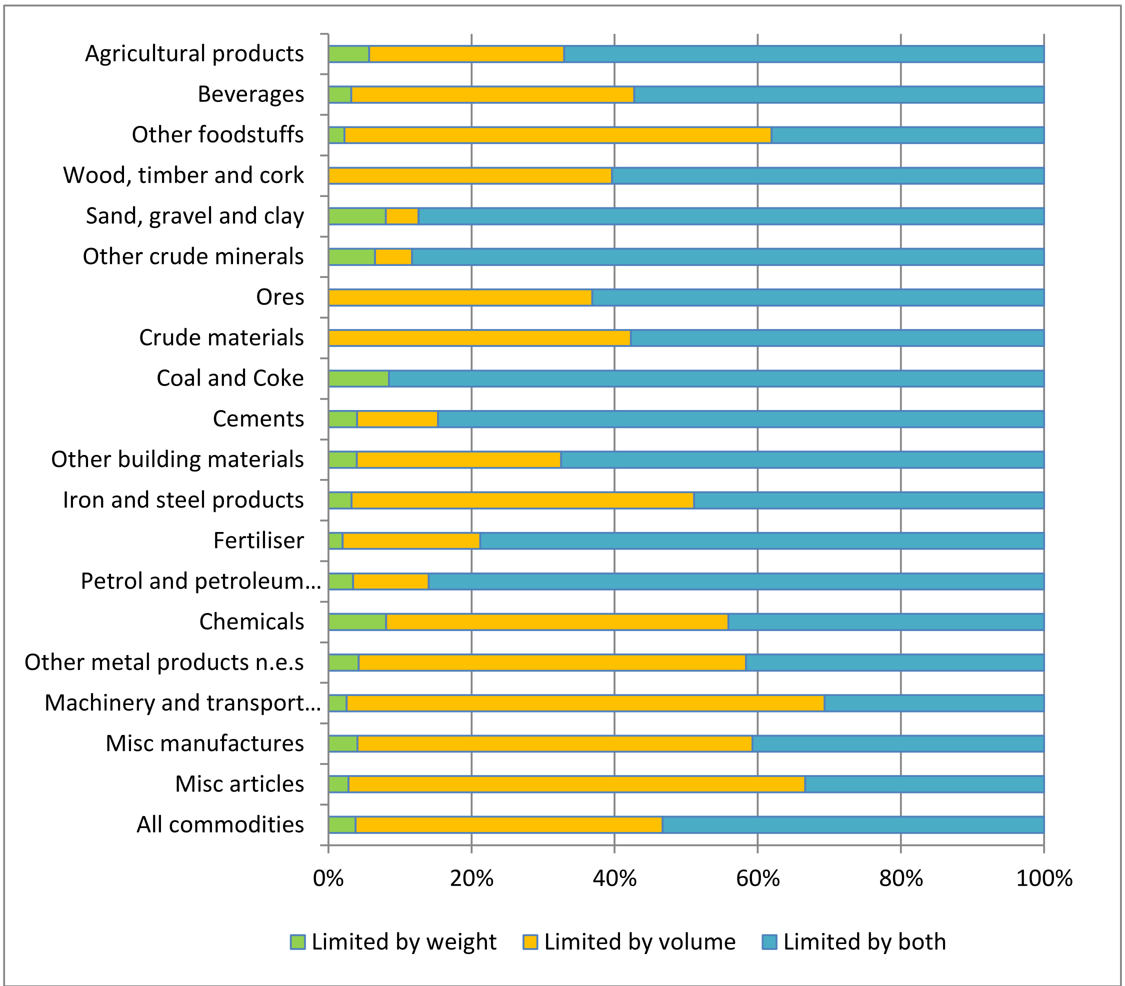
Duty Cycle	*Weight class*			
	<7.5t	7.5t-16t	16t-32t	>32t
Municipal Utility	Maybe	✓	✓	
Regional Delivery	Maybe	✓	✓	✓
Long Haul			✓	✓
Construction	Maybe	Maybe	✓	✓
Bus	✓			
Coach	✓			

The following subsections provide a summary of the available data, its limitations and the methodology proposed to provide estimates for the share of weight limited HDV activity. Key references are provided at the end of this chapter. It is assumed that bus and coach operations are essentially not weight limited to a significant degree.

3.5.3.1 Available Data

Statistics reporting data on this aspect are very uncommon. Analysis of the statistics provided by different sources indicated that the only survey providing sufficient detail on whether loads are constrained by weight/volume or both is the regular Continuing Survey of Road Goods transport (CSRGT) carried out by the UK Department of Transport. The following figure summarises the most recent UK data collected as part of this survey, elaborated on the basis of the tonne-km moved.

Figure 3.10: Goods moved by commodity and limits on load, 2010 - Millions of tonne-km



Source: UK Department for Transport (DfT, 2012)

From the figure above, it emerges clearly that loads constrained purely by weight limits represent a negligible share ranging, according to the typology of goods, from 3% (foodstuffs) to 10% (chemicals, coal and coke). For those loads/journeys that are either weight or volume limited, the largest share appears to be constrained by both weight and volume. This is not necessarily a particularly intuitive result, in particular considering heavy goods categories such as cement, sand, clay, petrol etc. where loads are expected to be mainly weight limited (as also indicated in feedback from the stakeholder consultation). One possible reason could be that the vehicles/trailers used for such operations are specified in a way that means that generally the available volume is scaled to the available weight capacity. However, it could also indicate a level of uncertainty in the responses given to the survey. There is still also a question as to what degree these statistics are representative in relation to the European market as a whole.

Table 3.21 summarises for aggregate categories of goods the respective share according to the source of limitation.

Table 3.21: Share of loads by cause of limitations in Britain in 2010 by type of commodity

Group of goods	Limited by weight	Limited by volume	Limited by both
Food, drink & tobacco	3%	49%	48%
Bulk products + Chemicals, petrol & fertiliser	5%	22%	73%
Miscellaneous products	3%	62%	35%
Construction	4%	23%	73%
All commodities	**4%**	**43%**	**53%**

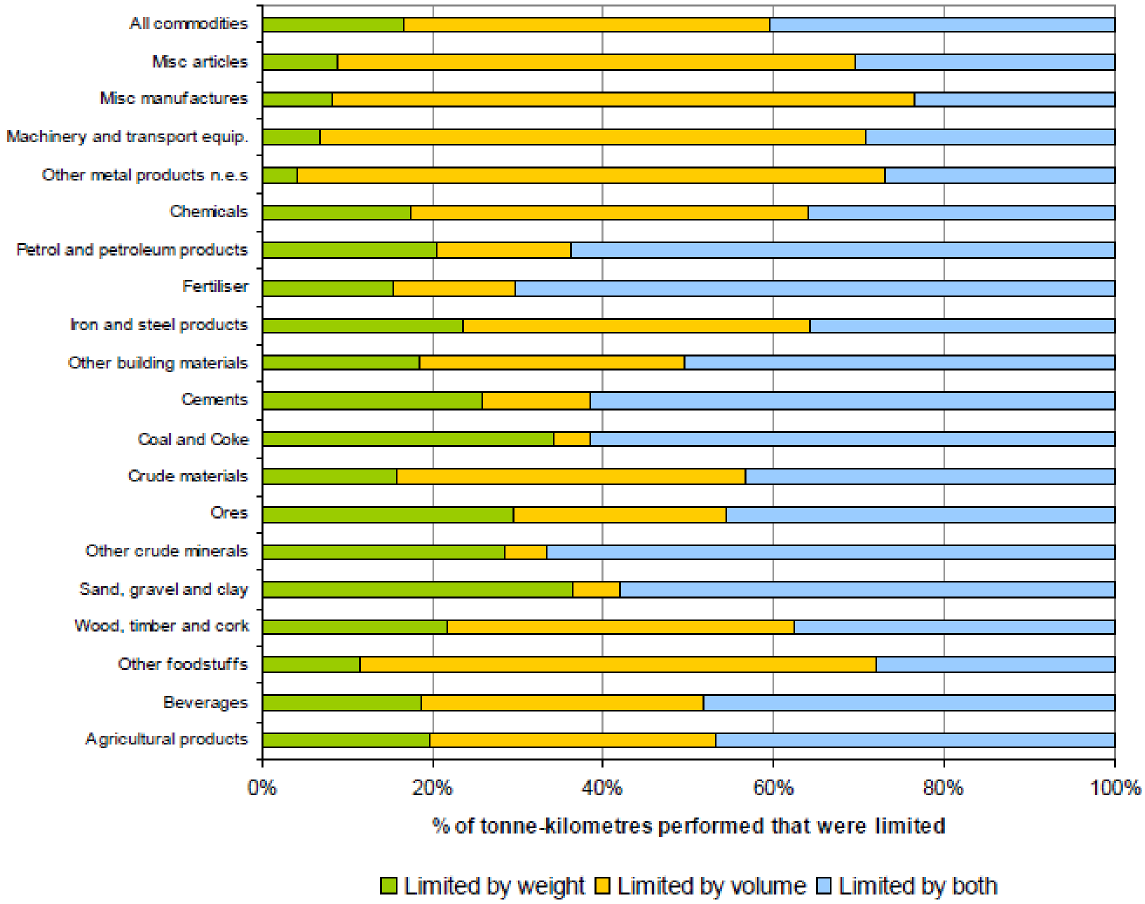
Source: Analysis derived from UK Department for Transport statistics (DfT, 2012)

An analysis of the same data, but referring to previous surveys showed that the figures are evidently oscillating, without apparent reasons for this.

For example (Browne, 2010), working on an older version of the same sources (i.e. DfT statistics for 2007), concluded that the percentage of weight-constrained tonne-km moved was slightly lower than the corresponding weight constrained tonnes lifted, suggesting that heavy loads are transported over a relatively shorter distance than other kinds of loads. (This is also consistent with feedback provided from the stakeholder consultation indicating that long-distance transport of heavy goods is generally handled via the railways). However, the proportion of weight constrained loads in this earlier dataset was close to 20%, significantly higher than the values reported in the more recent dataset for 2010 (see earlier Figure 3.9).

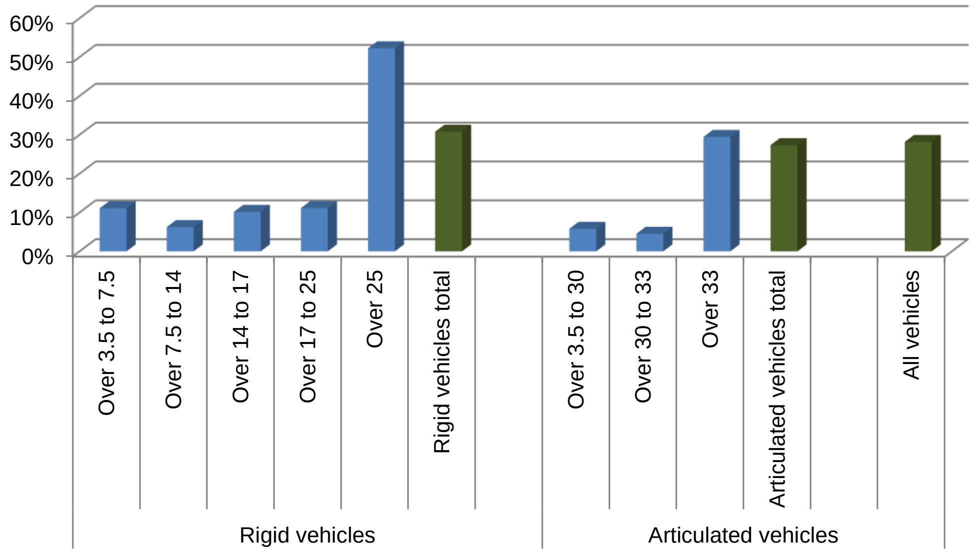
Calculations carried out by DfT with reference to data from an even earlier year, 2002, show that the overall weight limited share of tonne-kilometres performed was estimated as even higher, at 28%, with a breakdown by type of goods demonstrating considerable variation by type of goods transported (e.g. close to 80% of tonne kilometres performed for the haulage of sand, clay and other minerals were weight limited, and on the contrary less than 10% of the tonne-kilometres performed in hauling machinery and transport equipment were weight limited). Importantly, estimates of the constraints by vehicle type were also elaborated in this earlier analysis, demonstrating that weight constraints are much more frequent for heavier trucks.

Figure 3.11: Limits on loads – goods moved by HGV in Britain in 2007 by type of commodity



Source: University of Westminster on DfT, 2010 (Browne, 2010)

Figure 3.12: Share of on loads limited by weight, by vehicle type (goods moved by HGV in UK in 2002)

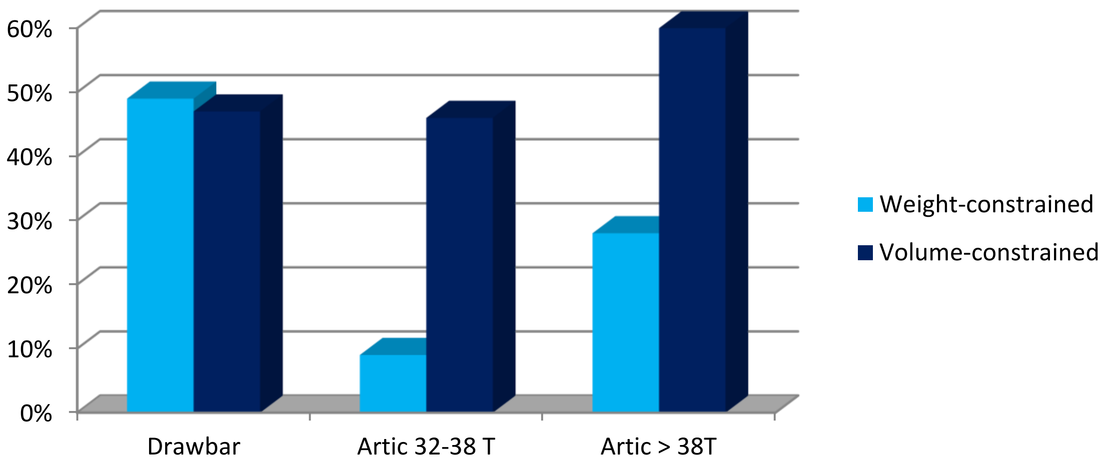


Source: Analysis on CSRGT (GB) 2002 (DfT)

Other papers and reports focusing on green logistics strategies and on load efficiency, highlight the objective of minimising empty trips. All contributions collected recognise that the information on how many vehicles travel under weight or volume constraints would be of help in estimating vehicle efficiency. However, all of the literature identified indicate that there is an evident lack of data with the exception of the UK Department of Transport's CSRGT survey.

McKinnon (2008) indicates higher percentages of weight limited operation than those indicated above, but values are derived from the same data source.

Figure 3.13: Weight and volume constrained load by vehicle type / size



Source: McKinnon, 2008

In order to have a direct feedback from the market, spot interviews with road transport operators were conducted. They indicate that the weight constrained loads are mainly concerned with specific categories of goods: bulk liquids, sands, heavy steel products, chemicals and cereals. In these cases too, sometimes the limitation involves **both weight and volume since loading units are designed according to the limitations applied,** which can be an element explaining the large share of load constrained by both weight and volume reported on the most recent statistics. A quantification of the weight constrained cases is not possible but the opinion expressed is that in general it does not affect more than 10-15% of the journeys for transport operators (general cargo, long haul). However, there are certain categories of goods that are usually transported by vehicles operating at their maximum allowed weights (e.g. tankers, aggregates etc.) and for them the percentage of limited loads could be much higher.

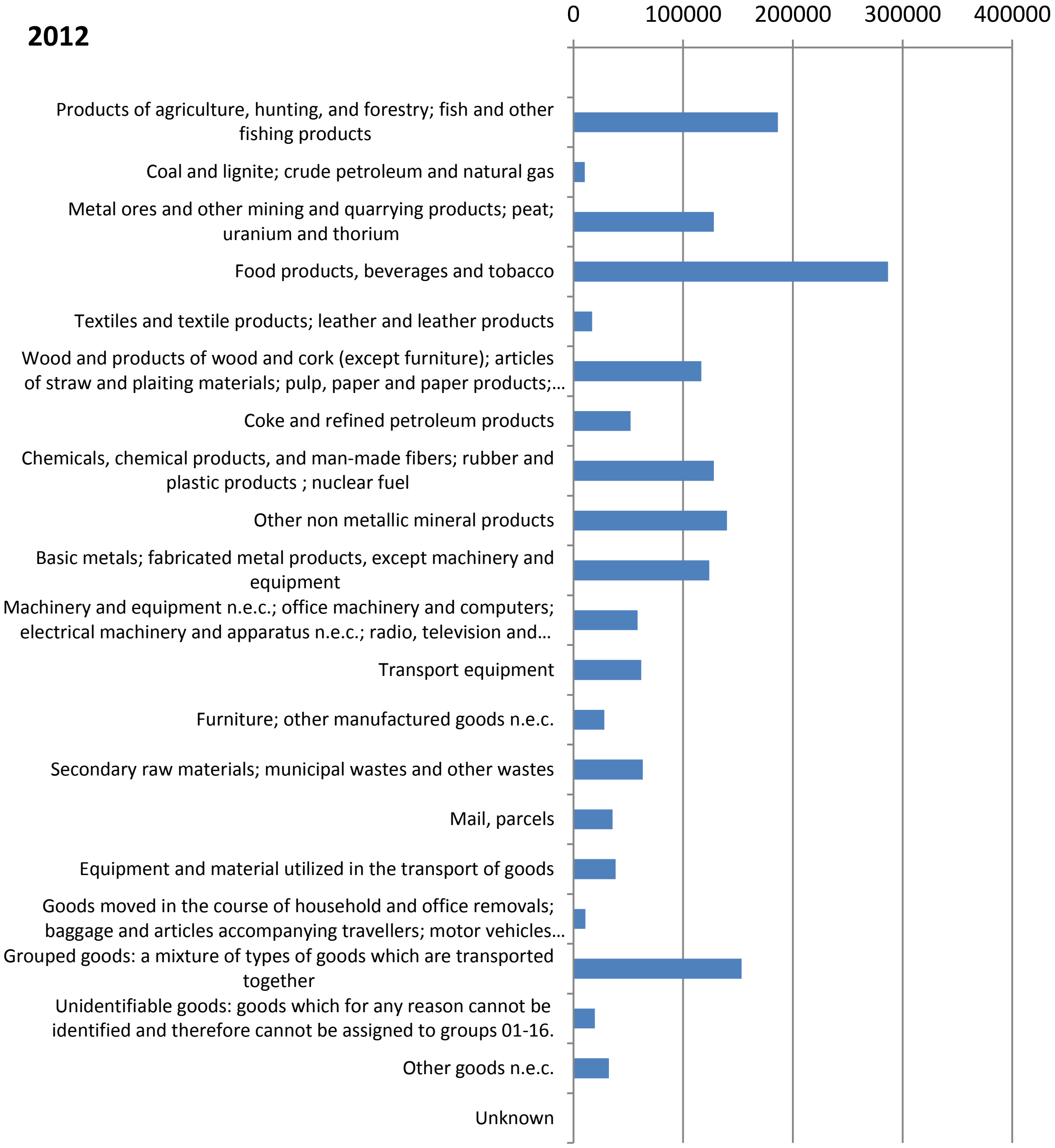
With the above information a tentative approach has been developed to populate the table to serve the purposes of the MACC analysis.

The following steps were followed in order to estimate the shares of weight limited operations for different vehicle types and weight:

1. Overall traffic data (for EU28) were extracted from EUROSTAT (last complete year 2012), respectively by category of goods and distance class, and by vehicle dimension (Eurostat, 2014a).
2. Transport by distance class was attributed to the different services (urban, regional, long haul). Journeys of less than 50 km were split between urban and regional journeys, whilst journeys of more than 300 km were fully attributed to long haul and the rest to regional services.
3. The category of goods attributable to construction were kept separate from the others in order to provide a separate estimate, given the higher sensitivity of this category to heavier loads.
4. The shares reported by the UK Department for Transport for every category of goods were applied to the EU28 total flows by distance class, in order to have the average share of weight-restricted loads valid for EU28. Two different estimates were considered: a low scenario and a high scenario, as defined below.
5. From the above, average constrained factors were fixed for the different types of goods. Finally, the weight constrained share was estimated and inserted in the table in order to provide a consistent data set with average values reflecting the shares calculated above.

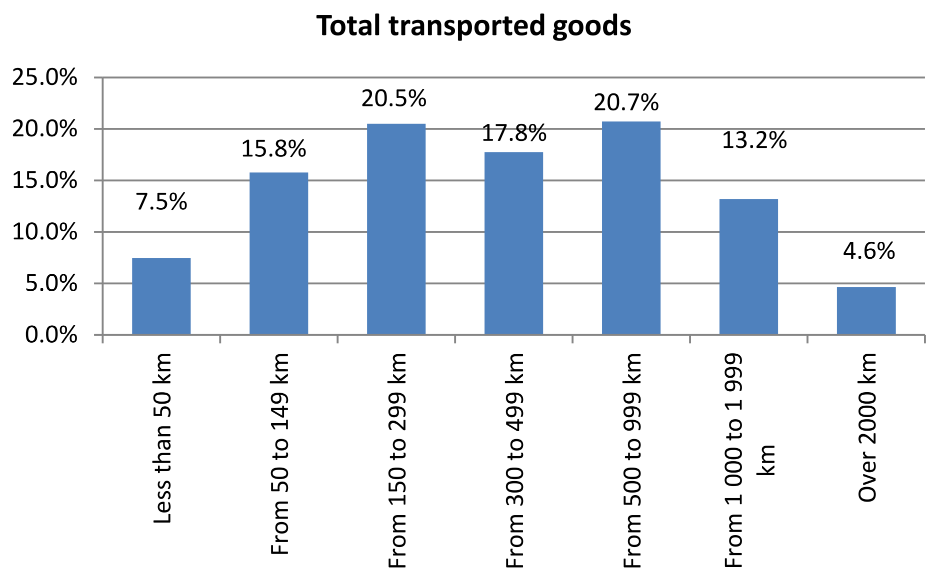
Eurostat data were extracted and analysed, the following Figure 3.14 and Figure 3.15 illustrate the breakdown of road freight traffic by category of goods, distance class and size of vehicles used.

Figure 3.14: Overview of EU28 overall traffic by category of goods (NST 2007 in tonne-km)



Source: Elaboration on Eurostat (Eurostat, 2014a)

Figure 3.15: Overview of EU28 overall traffic by distance class (2012, in tonne-km)



Source: Elaboration on Eurostat (Eurostat, 2014b)

Table 3.22 reports the overall tonne-km moved by vehicle size (Eurostat, 2014b).

Table 3.22: Total EU 28 traffic- 2012, tonnes moved (million tonne-km) by vehicle loading capacity

Vehicle load capacity weight class	2012	% Ratio Capacity/GVW*	Calculated GVW Equivalent, tonnes		Study GVW Allocation
			Minimum	Maximum	
Total	**1 692 396**				
3.5 t or less	5 823	50%	3.5 t	7 t	<7.5t
From 3.6 to 9.5 t	48 200	53%	7 t	18 t	7.5-16 t
From 9.6 to 15.5 t	180 185	56%	17 t	28 t	16-32 t
From 15.6 to 20.5 t	103 799	59%	26 t	35 t	16-32 t
From 20.6 to 25.5 t	495 310	62%	33 t	41 t	>32 t
From 25.6 to 30.5 t	583 400	62%	41 t	49 t	>32 t
Over 30.5 t	275 678	62%	49 t	60 t	>32 t

Source: EUROSTAT - Annual road freight transport, by load capacity of vehicle [road_go_ta_lc], and study analysis by Ricardo-AEA.

Notes: * Based on study Task 1 analysis.

The data above were attributed to the class of vehicles as defined in the MACC model (<7.5 t, 7.5-16t, 16-32t, >32t, as indicated in the table.

The overall levels of transport performed by distance class, is attributed to the different types of services, as in the following Table 3.23. In this table, a total for construction has been calculated from the sum of the respective categories of relevant goods (i.e. metal ores and other mining and quarrying products, other non-metallic mineral products, basic metals; fabricated metal products).

Table 3.23: Total EU 28 traffic- 2012, tonnes moved (million tonne-km) by category of goods and by type of service

NST 2007 category	Urban	Regional	Long
Total transported goods	**63 137**	**675 983**	**951 586**
Products of agriculture, hunting, and forestry; fish and other fishing products	4 904	79 489	102 001
Coal and lignite; crude petroleum and natural gas	612	5 754	3 927
Metal ores and other mining and quarrying products; peat; uranium and thorium	18 480	66 092	17 722
Food products, beverages and tobacco	4 773	115 042	166 943
Textiles and textile products; leather and leather products	173	4 215	12 683
Wood and products of wood and cork (except furniture); articles of straw and plaiting materials; pulp, paper and paper products; printed matter and recorded media	1 692	38 627	76 199
Coke and refined petroleum products	1 928	35 167	15 094
Chemicals, chemical products, and man-made fibres; rubber and plastic products ; nuclear fuel	1 711	37 262	89 078
Other non-metallic mineral products	2 102	14 316	11 566
Basic metals; fabricated metal products, except machinery and equipment	1 417	30 435	73 469
Machinery and equipment n.e.c.; office machinery and computers; electrical machinery and apparatus n.e.c.; radio, television and communication equipment and apparatus; medical, precision and optical instruments; watches and clocks	1 167	14 936	42 250
Transport equipment	739	12 831	48 108
Furniture; other manufactured goods n.e.c.	244	5 871	22 143
Secondary raw materials; municipal wastes and other wastes	5 215	38 480	19 395
Mail, parcels	401	12 779	22 484
Equipment and material utilized in the transport of goods	1 035	14 911	22 469
Goods moved in the course of household and office removals; baggage and articles accompanying travellers; motor vehicles being moved for repair; other non-market goods n.e.c.	563	5 249	5 142
Grouped goods: a mixture of types of goods which are transported together	1 627	48 843	102 870
Unidentifiable goods: goods which for any reason cannot be identified and therefore cannot be assigned to groups 01-16.	458	7 245	11 929
Other goods n.e.c.	624	9 288	22 455
Construction	**13 276**	**79 157**	**63 659**

The corresponding estimated total for transport flows by type of service (Table 3.25) was calculated by combining information from Table 3.22 and Table 3.23 above with also assumptions from Lot 1 study (AEA/Ricardo, 2011). No data are available for service and municipal utility transport, so they were consequently not included in the table.

Table 3.24: Estimated share of vehicle stock, typical annual km and load factor by duty cycle

Duty Cycle	***Weight class***				**Typical Annual km**	**Typical LF by cycle**
	<7.5t	**7.5t-16t**	**16t-32t**	**>32t**		
Service	-					
Urban Delivery	70%	44%	10%		35,000	50%
Municipal Utility	5%	15%	11%		25,000	50%
Regional Delivery	10%	22%	23%	17%	60,000	60%
Long Haul		10%	32%	67%	100,000	70%
Construction	15%	10%	24%	16%	50,000	50%
Total	**100%**	**100%**	**100%**	**100%**		

Source: Study assumptions and information from (AEA/Ricardo, 2011)

Table 3.25: Distribution of transport flows by type of service – EU28 (million tonne-km)

Duty Cycle	***Weight class***				
	<7.5t	**7.5t-16t**	**16t-32t**	**>32t**	**Total**
Service	-				**-**
Urban Delivery	3,639	14,901	12,961		**31,502**
Municipal Utility	-	-	-		**-**
Regional Delivery	1,070	15,385	60,563	146,357	**223,374**
Long Haul		13,200	165,584	1,113,662	**1,292,445**
Construction	1,114	4,714	44,876	94,369	**145,074**
Total	**5,823**	**48,200**	**283,984**	**1,354,388**	**1,692,395**

Notes: Study estimates by TRT based on data from Eurostat (2014)

The required table providing information on weight-constrained movements has been generated using percentages calculated as explained in the following four steps.

Two different set of data are proposed:

- The lower values presented in the first table refer to the average share obtained by applying the UK weight constrained loads share to the EU28 traffic, and considering that at least 10% of the loads declared as volume and weight constrained are effectively weight constrained.
- The higher values are obtained by considering that up to 30% of volume and weight constrained movements would benefit from higher available payload capacities. The underlying assumption is that logistics flows could be allocated differently so that additional weight capacity can be fully exploited. Furthermore, vehicle design plays a role since it takes into account the current weight and volume limitations.
- Another assumption implicit in the table is that urban transport flows are less weight constrained with respect to regional and long haul movements, and that weight restrictions principally affect larger vehicles as demonstrated by the statistics presented.
- No constraints are estimated for service and utility vehicles.

The following Table 3.26 presents the share of weight constrained flows in the case of EU28 and in the case of UK for the two described scenarios.

Table 3.26: Weight constrained km (%) by category of goods, comparison of EU and UK

Category of goods	EU28		UK	
	Low	High	Low	High
Food, drink & tobacco	**10%**	**20%**	**8%**	**17%**
Bulk products + Chemicals, petrol & fertiliser	**10%**	**20%**	**12%**	**27%**
Miscellaneous products	**6%**	**14%**	**7%**	**14%**
Construction	**13%**	**28%**	**13%**	**28%**
All commodities	**9%**	**18%**	**9%**	**20%**

Notes: Study estimates by TRT based on DfT and Eurostat (2014)

High and low overall estimates have been developed for the share of weight constrained tonnes moved by type of service and vehicle size, for use in the Task 3 analysis. These are provided inTable 3.27 and Table 3.28.

Table 3.27: Weight constrained km (%) by type of service and vehicle size – EU28 - low

Duty Cycle	*Weight class*				
	<7.5t	7.5t-16t	16t-32t	>32t	Total
Service	-				**-**
Urban Delivery	2.0%	2.0%	2.0%		**2.0%**
Municipal Utility	-	-	-		**-**
Regional Delivery	2.0%	3.0%	9.0%	9.0%	**8.6%**
Long Haul		3.0%	10.0%	10.0%	**9.9%**
Construction	13.0%	13.0%	13.0%	13.0%	**13.0%**
Total	**4.1%**	**3.7%**	**9.9%**	**10.1%**	**9.9%**

Notes: Study estimates by TRT based on DfT and Eurostat (2014)

Table 3.28: Weight constrained km (%) by type of service and vehicle size – EU28 - high

Duty Cycle	*Weight class*				
	<7.5t	7.5t-16t	16t-32t	>32t	Total
Service	-				**-**
Urban Delivery	2.0%	2.0%	2.0%		**2.0%**
Municipal Utility	-	-	-		**-**
Regional Delivery	4.0%	6.0%	18.0%	18.0%	**17.1%**
Long Haul		6.0%	19.5%	19.5%	**19.4%**
Construction	28.0%	28.0%	28.0%	28.0%	**28.0%**
Total	**7.3%**	**6.9%**	**19.7%**	**19.9%**	**19.5%**

Notes: Study estimates by TRT based on DfT and Eurostat DfT and Eurostat (2014)

4 Task 3: Cost benefit analysis of identified lightweighting options

Box 4: Key points for Task 3

Objectives:

- **Development and analysis of marginal abatement cost curves (MACC) for different light-weighting options using the outputs from all previous project tasks**

Key subtasks:

- **Task 3.1: MACC analysis framework specification**
- **Task 3.2: Additional data collection**
- **Task 3.3: MACC analysis framework development**
- **Task 3.4: Analysis of Results**

Outputs:

- **Marginal abatement cost curves for the EU that provide a disaggregation into cost and reduction potential reflecting the different levels of detail needed for the Task 4 cost-effective lightweighting assessment and Task 5 fleet modelling**
- **Results of the final MACC analysis provided as inputs to the final report and to Task 4 and 5.**

4.1 Overview of Task 3

The aim of this task was to produce vehicle-level marginal abatement cost (MAC) curves, which were then used as a basis for estimating overall EU HDV consumption/CO_2 emissions in Task 5.

Work involved the following four subtasks:

- *Task 3.1: Develop MACC analysis framework and agree assumptions:* The purpose of this subtask was to carry out preliminary planning for the structure and functionality of the MAC curve calculation framework to be used in the analysis.
- *Task 3.2: Additional data collection/development*: This task involved collecting a range of additional data to expand on the datasets already collected under Task 1 and Task 2
- *Task 3.3: Develop MACC analysis framework and generate results for different HDV categories:* In this subtask the Excel-based MACC analysis framework was developed according to the agreed specifications outlined in Task 3.1.
- *Task 3.4: Analysis of results for different HDV categories:* Outputs from Task 1 and Task 2 were incorporated into the calculation/analysis framework in order to generate results for analysis for the 'state-of-the-art' and 'forward looking' scenarios, plus agreed sensitivities. Outputs from Task 3 were used in the assessment of the cost-effective lightweighting potential carried out under the subsequent Task 4.

Full details of the MACC model specification were discussed and agreed with the Commission prior to further work commencing on building the analysis framework and collection of any additional data required. As part of this work Ricardo-AEA adapted the existing MACC model for heavy duty vehicle technologies (the 'MACH' model) developed as part of previous work for the Commission (CE Delft, 2012), in order to develop the cost curves in an efficient way.

4.2 Development of the MACC analysis framework and assumptions

This section provides a summary of the methodology, key datasets and assumptions used in the development of the MACC analysis (i.e. covering Tasks 3.1 and 3.2 of the project).

4.2.1 Overview of the updated MACC model structure and content

As already indicated, Ricardo-AEA have already confirmed to the Commission that adaptation of the existing MACC model produced by (CE Delft, 2012) was allowed. However, modifications as well as additional functionalities were required for the purposes of this study. These will be discussed below.

NOTE: Due to necessary design (and resource) considerations it was not be possible to also include non-lightweighting vehicle efficiency improvement options alongside the lightweighting options being investigated as part of this project.

4.2.1.1 Mode structure

The following matrix of vehicle weights and duty cycles (Table 4.1) was the basis of the MACC analysis, consistent with the objective of focusing analysis on the major HDV categories. This format is compatible with the both the disaggregation for the GHG modelling in this project (discussed further under Task 5, section 6) and also with the format of existing modelling for the Commission (with four truck segments split by the indicated weight ranges).

In the previous HDV GHG LOT 1 project (AEA/Ricardo, 2011) the 'Service' category was reserved for vehicles <7.5 tonnes in the absence of specific analysis/accounting for such vehicles in the LOT 2 project (TU Graz et al, 2012) and industry analysis being carried out in parallel. There has still been no further characterisation of the vehicles in this weight segment. However, statistical sources suggest such vehicles are used in duty cycles corresponding to the other categories – i.e. urban/regional delivery, municipal utility and construction operations. It was therefore decided to merge vehicles in this weight category into these separate mission profiles for this project.

Table 4.1: Matrix of heavy duty vehicle types by weight class covered in the MACC

Duty Cycle	*Weight class*			
	<7.5t	7.5t-16t	16t-32t	>32t
Urban Delivery*	✓	✓	✓	
Municipal Utility*	✓	✓	✓	
Regional Delivery*	✓	✓	✓	✓
Long Haul	-	***	✓	✓
Construction*	***	✓	✓	✓
Bus**	✓			
Coach	✓			

Notes: * The 'Service' category previously reserved for vehicles <7.5 tonnes is proposed to be merged vehicles in this weight category into these separate mission profiles for this project. ** Includes urban and inter-urban buses. *** Available data suggests activity for these vehicles is likely to be marginal/not significant compared to larger vehicles, so may be assumed to be essentially zero for the simplified purposes of the study analysis.

Municipal utility vehicles were estimated to account for only a relatively small contribution to overall HDV emissions in the previous LOT 1 work for the Commission (AEA/Ricardo, 2011). Therefore, given the available resources and the prioritisation already agreed with the Commission (Table 2.1), only very approximate estimates for weight reduction (i.e. directly related to those for other similarly sized HDVs) and their costs was possible.

To serve the purposes of proposed modelling in this project (Task 5, section 6) and outputs consistent with existing modelling for the Commission, the adapted MACC model included a table in the following format with the percentage shares of each duty cycle/weight combination. This allowed aggregated total cost-curve estimates by duty cycle to be produced as outputs to the Task 5 modelling from the product of the percentages in the rows with the relevant costs and savings data for different weight classes.

Table 4.2: Weighting matrix of heavy duty vehicle types by weight class covered in the MACC

Duty Cycle	***Weight class***				***Total***
	<7.5t	**7.5t-16t**	**16t-32t**	**>32t**	
Urban Delivery*	U_1%	U_2%	U_3%		**Sum(U_n) %**
Municipal Utility*	M_1%	M_2%	M_3%		**Sum(M_n) %**
Regional Delivery*	R_1%	R_2%	R_3%	R_4%	**Sum(R_n) %**
Long Haul			L_3%	L_4%	**Sum(L_n) %**
Construction*		C_2%	C_3%	C_4%	**Sum(C_n) %**
Total Truck	**Sum(X_1) %**	**Sum(X_2) %**	**Sum(X_3) %**	**Sum(X_4) %**	**100%**
Bus**	B_1 %				**B_1 %**
Coach	C_1 %				**C_1 %**
Total Bus/Coach	**100%**				**100%**

For Task 3, information from the vehicle simulation analysis from Task 2 was also utilised to more effectively account for the relative fuel efficiency of similar HDV types (e.g. 12 t GVW trucks) operating on different duty cycles/mission profiles (e.g. urban vs regional delivery).

4.2.1.2 Addition of time series

The previous MACC model by CE Delft only looked at one snap shot in time. For the purposes of this study we needed to add in a time series of cost curves out to 2050. As a result of this, the various other variables involved in calculating abatement costs also had to be converted to time series.

Investment (capital costs) may reduce in future years as new technologies become more mature and costs come down through mass-deployment, or change (up- or down-wards) due to future developments in raw material costs. Fuel costs will also change significantly over time. These types of changes can have a significant impact on cost effectiveness that needed to be taken into account.

The addition of a time series also allowed light weighting options to be introduced at certain times along the time series (as they were estimated to become available to the market). Those available from 2015 or using existing technology were known as 'state of the art' (SOTA) and all others to be implemented in later years were known as 'future' technologies. The distinction between these two types of technologies allows a sensitivity analysis to be undertaken where users can select which types of technologies (Future, SOTA or both) that can be viewed on the cost curves in the adapted model.

4.2.1.3 Handling mutually exclusive options

When it comes to a long list of technical lightweighting options it is not possible to add all of them to a vehicle at once. Many of the options are simply variations of other options and so would not be applied to the same vehicle (i.e. they are mutually exclusive).

This issue of compatibility was handled in the engine of the MACC model. For example, for increasingly significant levels of weight reduction (e.g. steel to HSS, to Aluminium, to CFRP) the marginal difference between the different levels of weight reduction (and their associated costs) was used, so that all options could be included in the same curve.

4.2.1.4 Handling weight-limited operations

Reduced vehicle weight due to lightweighting allows increased payloads to be carried in weight limited operations. This also leads to reduced trips and therefore facilitates further fuel savings and non-fuel costs (such as driver salary, maintenance, etc.) to be properly accounted for.

The ability for the MACC model outputs to be switched between four alternate cases of weight limiting assumptions was therefore also added during model development:

i. No weight limited operations, i.e. all savings are due to reduced fuel consumption of the vehicle running lighter,

ii. All weight limited operations, e.g. where it is assumed at least all outward trips/50% of the km are weight limited, so savings are accrued due to reduced % km from these portions (calculated based on weight reduction, increase in payload);

iii. Average (low) weight limited options – assuming the low % weight limited km estimated in Task 2;

iv. Average (high) weight limited options– assuming the high % weight limited km estimated in Task 2;

4.2.1.5 Non fuel costs

The previous MACH model (CE Delft, 2012) only considered the reduction in emissions as well as investment costs and fuel savings to calculate cost effectiveness.

Since this study also considered the effect of lightweighting on weight limited operations, additional non-fuel costs were required to be modelled also. The reasoning here is that with decreased vehicle weight comes the potential for increased loads. Increased loads may mean that a reduced number of trips are required resulting in reduced total vehicle-km (from a fleet perspective at least). Reduced trips mean the potential for a reduction in non-fuel costs for such things as vehicle maintenance, road tolls or driver's salary.

The methodology behind obtaining non-fuel costs for the various modes is described in Section 4.2.4.3.

4.2.2 MACC methodological framework

Next, the methodology used to derive the abatement cost curves is discussed.

First, in Section 4.2.2.1 the way the abatement costs are calculated is presented, while the actual derivation of abatement cost curves is discussed in Section 4.2.2.2. Finally, in Section 4.2.2.3 the opportunities to apply sensitivity analyses with the help of the MACC model are presented.

4.2.2.1 Calculation of abatement costs

The abatement costs of GHG reduction options are defined as the costs of an option divided by its greenhouse gas abatement potential. The abatement costs are expressed in € per ton of CO_2. Costs included here are initial capital costs (CAPX) and benefits due to reductions in fuel use as well as vehicle trips (non-fuel costs such as driver's salary etc.). Broader welfare costs/benefits (co-benefits like increase vehicle safety, reduced emissions of air pollutants) are not taken into account in this analysis.

The approach to calculate the cost effectiveness based on total costs and benefits is therefore;

$$Cost\ effectiveness = \frac{CAPX - NPV\ (fuel\ cost\ savings) - NPV\ (non\ fuel\ cost\ savings)}{Lifetime\ CO_2\ emission\ reducion}$$ **Equation 1**

Lifetime emissions reduction is calculated on a per technology basis where both engine fuel efficiency savings from lightweighting options (discussed in section 2) as well as reductions in fuel use due to reduced mileage (another artefact of lightweighting due to the potential for increased vehicle loading). The total fuel efficiency reduction per technology was therefore calculated to be;

$$Total\ fuel\ consumption\ reduction = Engine\ Savings * (1 - WLO) + Fuel\ km\ savings * (1 - (1 - WLO))$$ **Equation 2**

Where;

<u>*Engine savings*</u> is the engine fuel consumption reduction per lightweighting option (%)

<u>*Fuel km savings*</u> is the fuel use reduction due to decreased mileage per lightweighting option (%)

<u>*WLO*</u> is the percentage of kilometres driven under weight-limited conditions. This variable allows the impact of lightweighting on vehicle kilometres to be properly accounted for.

Converting Equation 2 to CO_2 savings and basing this over the course of a vehicle's lifetime gives the required metric for calculating cost effectiveness as show in Equation 1.

4.2.2.2 Derivation of cost curves

In this project abatement cost curves for HDVs, at the vehicle level, for packages of technical CO_2 emission reduction measures were derived.

On the horizontal axis the cumulative emission reduction (in %) is presented, while on the vertical axis the abatement costs (in €/ton CO_2) is shown.

The derivation of the abatement costs curves for the various vehicle categories consisted of the following two steps:

- **Estimate abatement costs of all individual abatement technologies;** the approach discussed in Section 4.2.2.1 was used to estimate the abatement costs of the various technologies.
- **Rank all abatement technologies based on their abatement costs;** starting with the technology with the lowest abatement costs, followed by the technology with the second-lowest abatement costs, etc. In this way the most efficient package of abatement technologies was composed and cost curves are easiest to interpret.

4.2.2.3 Sensitivity analysis

The cost effectiveness of lightweighting options depends heavily on the values chosen for some of the parameters (discount rate, fuel price, etc.). For that reason the developed MACC model makes it possible to adjust the values of the main parameters. The user of this model has the opportunity to apply some sensitivity analyses themselves and – in this way – test the robustness of the results.

The model provides for the following parameters the opportunity to apply a sensitivity analysis:

- **Fuel efficiency;** it is important to recognise that, through time, vehicle manufacturing improvements mean that the efficiency of HDVs will reduce even without lightweighting measures. To take this into account we must assume an efficiency improvement scenario to ensure impacts from lightweighting alone are sufficiently captured in each time period. Therefore, we give users the option of assuming either a baseline efficiency improvement out to 2050 or a maximum technical scenario (with increased efficiency improvements versus the baseline scenario) out to 2050. This will discussed in more detail in Section 4.2.4.1.

- **Fuel prices;** in this model we present four oil price scenarios (low, reference, high and very low) (see Figure 4.4). This will discussed in more detail in Section 4.2.4.2. Fuel excise duty is only included in 'End user' perspective calculations.

- **Discount rate;** the value of the discount rate to be applied depends, among other things, on the cost perspective applied. In general, an end-user perspective requires a higher discount rate (reflecting the expected rate of return of a company investing in the technology) than a societal perspective. With respect to an end-user perspective, a default discount rate of 8% is included in the model. With respect to a social perspective, a default discount rate of 4% is included in the mode.

- **Annual mileage;** vehicles operating on a certain 'duty cycle' will also show a significant variation in annual/vehicle lifetime activity which will impact on cost-effectiveness. Therefore we allow users to select between central, low and high assumptions on vehicle annual mileage. In the model, the low assumption is 25% less than the central assumption whereas the opposite is the case for the high assumptions. These assumptions are detailed in Table 4.14.

- **Weight limited operations (WLO);** The MACC allows users to choose between four levels of WLO (low, high, fully or none).

- **Technology type ('State of the art'/Future);** Assigning each lightweighting option an 'expected year of uptake' allows further sensitivities to be analysed. The MACC allows for the ability to switch between scenario 'sets' of lightweighting options (e.g. only 'state-of-the-art' options selected, or the complete 'forward looking/future' set of options)

4.2.3 Lightweighting options input assumptions

4.2.3.1 Baseline lightweighting technology dataset inputs

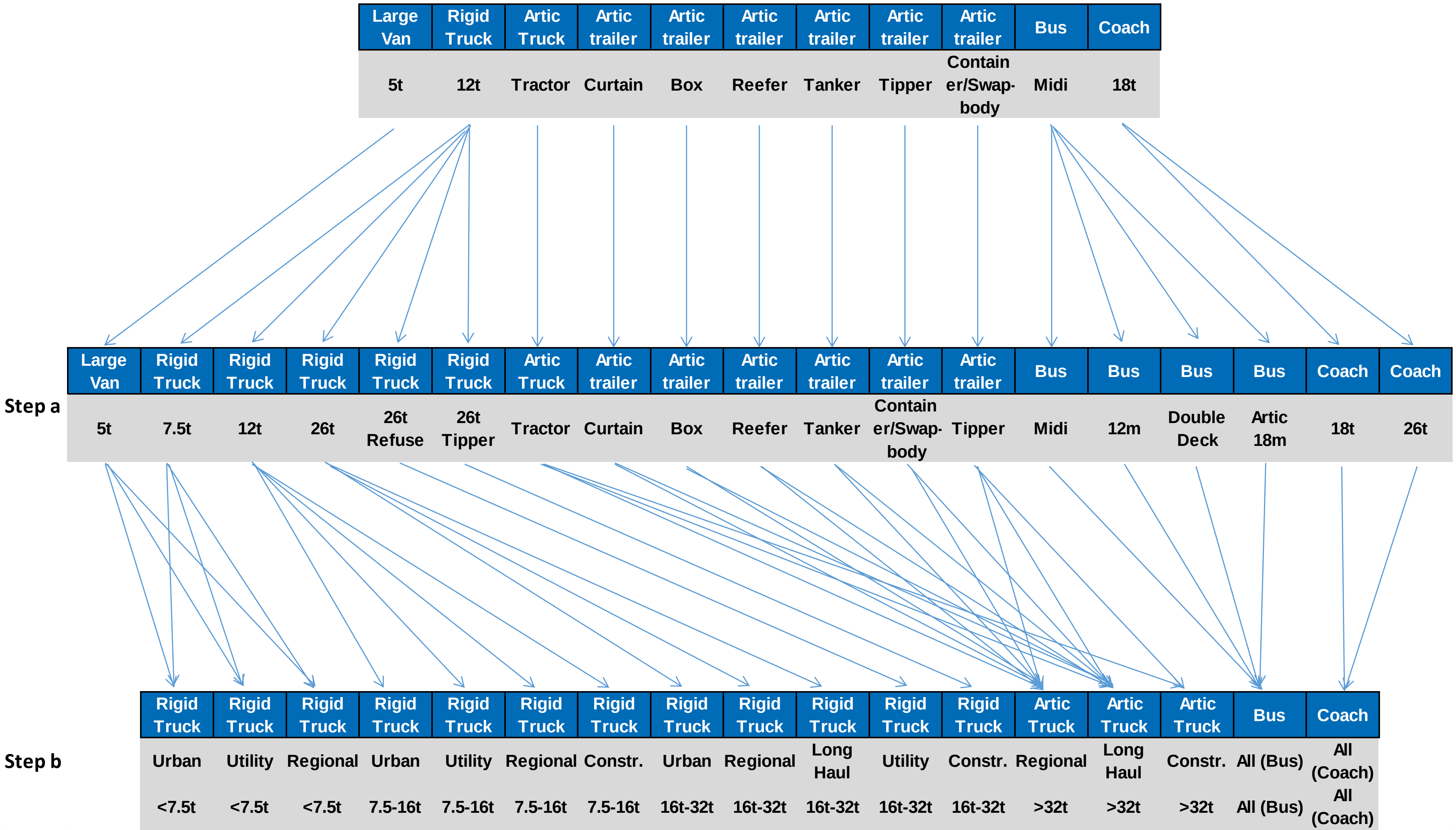
The weight savings and costs analysed for the representative vehicles from Task 1 were initially scaled to cover a number of additional common types of HDV (Step a in Figure 4.1). Scaling was performed on the basis of the ratio between the kerb weight of the vehicle to be scaled to and that of the base vehicle. In the case of trucks, the weight of the body and that of the remaining truck were scaled separately. For example, the kerb weight (excluding body) of the representative 12t GVW truck is 4,350 kg. To estimate the weight savings potentials on a 26t GVW truck with a typical kerb weight (excluding body) of 7,900 kg the weight savings potentials identified for the 12t GVW truck are multiplied by (7,900/4,350).

For body types which were not covered in the virtual teardown analysis, such as a refuse collector body, conservative standard assumptions for lightweighting potentials were used (2% from design/HSS, 15% from aluminium body, 35% from CFRP). In the case of buses, the level 2 costs per kg weight reduction for standard European 12m buses or articulated 18m buses are set at a lower level compared to the midibus with aluminium body from the virtual teardown analysis, which is already lightweight in design and therefore more expensive to take further weight out of. Weight reduction potential was also correspondingly increased for these buses.

A weighted average (by share of vehicle numbers) of different common HDV was then used to create weight savings and cost data by vehicle category and duty cycle (Step b in Figure 4.1). The weights used were according to the estimated mileage share of the different vehicle types. For example, the potentials from the tractor and curtain-sider trailers are estimated to account for around 43% of average long-haul artic truck vehicle km, box vans for 7%, refrigerated box vans ('reefers') for 15%, and so on. These are multiplied by the weight savings potentials of the relevant trailer type to create the average weight savings potentials for the >32t long-haul duty cycle category.

It was assumed that state-of-the-art (SOTA) and Level 1 measures would be available from 2015, Level 2 measures from 2025 and level 3 measures from 2030. For SOTA measures, current uptake levels were estimated. For example, it was assumed that 20% of new trucks use aluminium alloy wheels. Future costs and weight reduction potential from uptake of alloy wheels is thus 20% lower.

Figure 4.1: Illustration of scaling from representative vehilces to vehicle categories in duty cycles



4.2.3.2 Projected future cost-reduction of lightweighting options

Public domain information for future engineering material price forecasts is extremely limited, therefore a pragmatic and subjective approach based on estimations of the contributing cost factors was devised. The price forecasts were compared to historical material price trends where available

The following contributing factors were identified for automotive material prices:

Raw material supply and demand: The fundamental economics of supply and demand, capacity or elasticity in the market can dictate material prices. Where an increased demand for a material is not met with a corresponding increased supply then the price would generally increase. Due to the significant capital investments required for material manufacture and processing, it is difficult for manufacturers to "ramp up" production rates to meet demands. Likewise, manufacturers can be reluctant to shut down expensive production facilities resulting in an over-supply scenario which could result in a reduction in material prices. The contributing factors as described below may also influence material supply and demand.

Energy and oil prices: The conversion of raw materials to a finished product or component involves a significant amount of energy. High temperature processes such as smelting, forging and casting require considerable oil, gas or electricity from renewable sources. Raw materials and finished goods can also be transported significant distances which also draw on fossil fuels. The expectation is that energy prices will generally increase in the future due to a greater demand and constrained supply. It is likely that these additional costs will be passed on to engineering material prices. Oil prices have historically increased consistently over the past 20 years, however the discovery of new fields and new technologies such as fracking have resulted in a recent reduction. This combined with a predicted rise in clean energy supplies from wind and solar power could result in energy prices increases being limited or actually reducing in the near term.

Technology developments in material manufacture and processing: Technology developments can influence material prices in two ways. The creation of a novel, innovative material with unique properties such as very high strength and low weight would be regarded as a "premium product" in the market place and would likely demand a higher price by the material supplier. Materials manufacture and processing is subject to ongoing developments through research and development, in order to reduce costs, improve production volumes or enable the production of a novel material at considerably higher volumes, with the objective being to reduce material prices.

Specific forecasts for future material prices were not produced as part of this project. However, percentage range estimates for future prices were developed based on likely levels of future variation compared to today's prices. These estimates were cross-checked against sources obtained from public domain information where available.

The Table 4.3 summarises the expected drivers and trends for future material prices and Table 4.4 outlines the potential effects on the material prices. The results are displayed graphically in Figure 4.2.

Table 4.3: Expected trends and drivers for future engineering material prices

Material	General supply and demand	Energy and oil prices	Technology developments and breakthrough
Steel	Consistent and increasing demand for automotive steel due to growth in developing countries. General over-capacity in steel production facilities. Steel demand may slow beyond 10 years due to increased competition from aluminium and carbon fibre	Energy and oil prices likely to have a similar influence across all engineering material manufacture	High volume production processes well established and unlikely to undergo considerable change. Steel material technologies likely to see evolution (Nano steel)

Material	General supply and demand	Energy and oil prices	Technology developments and breakthrough
Aluminium	Increasing demand for automotive aluminium in Europe and North America due to fuel economy and CO_2 legislations. Manufactures responding to demand with creation of new facilities and capacity	Consistent increases in energy and oil prices over the past 20 years. Expected increase in demand for energy and oil Trend for material manufacturers to locate facilities close to renewable energy sources such as hydro-electric power stations in an attempt to offset carbon and energy prices New processes for extracting fossil fuels such as fracking may result in short term price reductions	Recycled aluminium production is likely to be the most significant technological growth area. Evolution of material grades and processes expected
Plastics	Sustained demand for plastics. Unlikely to see the rate of growth as aluminium and carbon fibre		Growth in plastics using natural fibres and new production methods
Carbon Fibre	High demand for Carbon Fibre from aerospace sector. Increasing demands forecast from automotive and clean energy sectors over the next 10 to 20 years. Significant investments in new production facilities. Demand likely to outstrip supply until production technology breakthrough		Rapid development of new manufacturing processes, aimed at reducing the expensive polyacrylonitrile (*PAN)* element should result in material price reductions over 10 to 15 years. New manufacture and process developments reducing tact time, enabling higher volume production and improved economies of scale

Table 4.4: Expected influences on engineering material prices

Material	General supply and demand			Energy and oil prices			Technology developments and breakthrough		
	2020	2030	2050	2020	2030	2050	2020	2030	2050
Steel	0% to +5%	0 to -10%	0 to -20%	-5% to +10%	-5% to +15%	-5% to +20%	0	0 to -5%	0 to -10%
Aluminium	-2% to +10%	0 to +20%	0% to +25%				0	0 to -5%	0 to -10%
Plastics	0 to +5%	0 to 10%	0 to +20%				0	0 to -5%	0 to -10%
Carbon Fibre	-5% to +10%	0 to +25%	0 to +40%				0 to -5%	-40 to -60%	-30% to -90%

Material prices can vary widely, depending on grade and quantity. Current and future material price projections are based on the following information sources; steel (Knoema, 2014), aluminium (LME Aluminium, 2014), plastics (Macrotrends, 2014), carbon fibre (SAE, 2013), (SAE, 2013a). The prices of at least steel and aluminium are set globally, so regional variations in production costs are not generally passed onto the aluminium price.

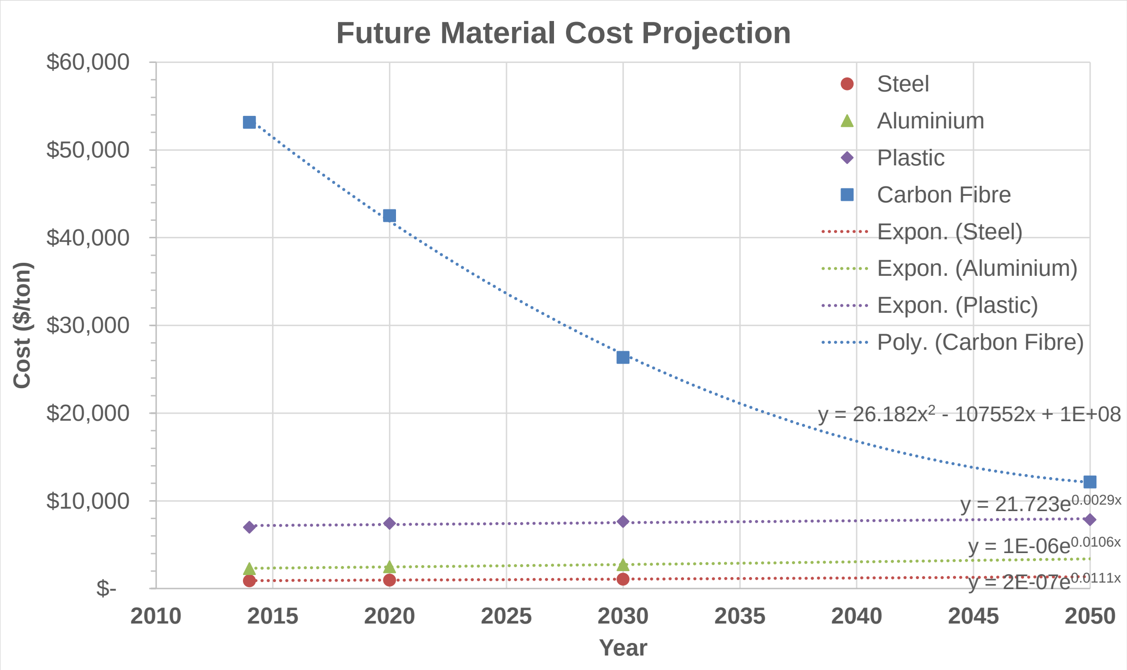
Taking into consideration all of the factors and sensitivities, the following material price variations have been forecast. The costs have been divided, taking into account both the raw material and processing. Costs for 2050 have also been extrapolated. [*Note*: It has also not been possible to factor the higher end of life value of aluminium products into the analysis presented.]

Table 4.5: Engineering material price forecast (%)

	Current			2020			2030			2050 (extrapolated)		
	Cost	Raw Material	Process	Cost	Raw Material	Process	Cost	Raw Material	Process	Cost	Raw Material	Process
	EUR/kg	(% of cost)	(% of cost)	% change	% change	% change	% change	% change	% change	% change	% change	% change
Steel	€0.63-0.79	75%	25%	10.0%	10%	10%	20%	20%	20%	14%	20%	40%
Aluminium	€1.58-2.05	33%	66%	8.9%	10%	10%	19%	20%	20%	21%	20%	40%
Plastic	€3.95-11.85	50%	50%	6.3%	10%	3%	9%	15%	4%	6%	20%	5%
Carbon Fibre	€15.80-35.55	43%	57%	-20.0%	-20%	-20%	-50%	-39%	-59%	-71%	-60%	-90%

The future material cost projections expressed in $ per metric tonne are showed below in Figure 4.2.

Figure 4.2: Estimated future material cost projections



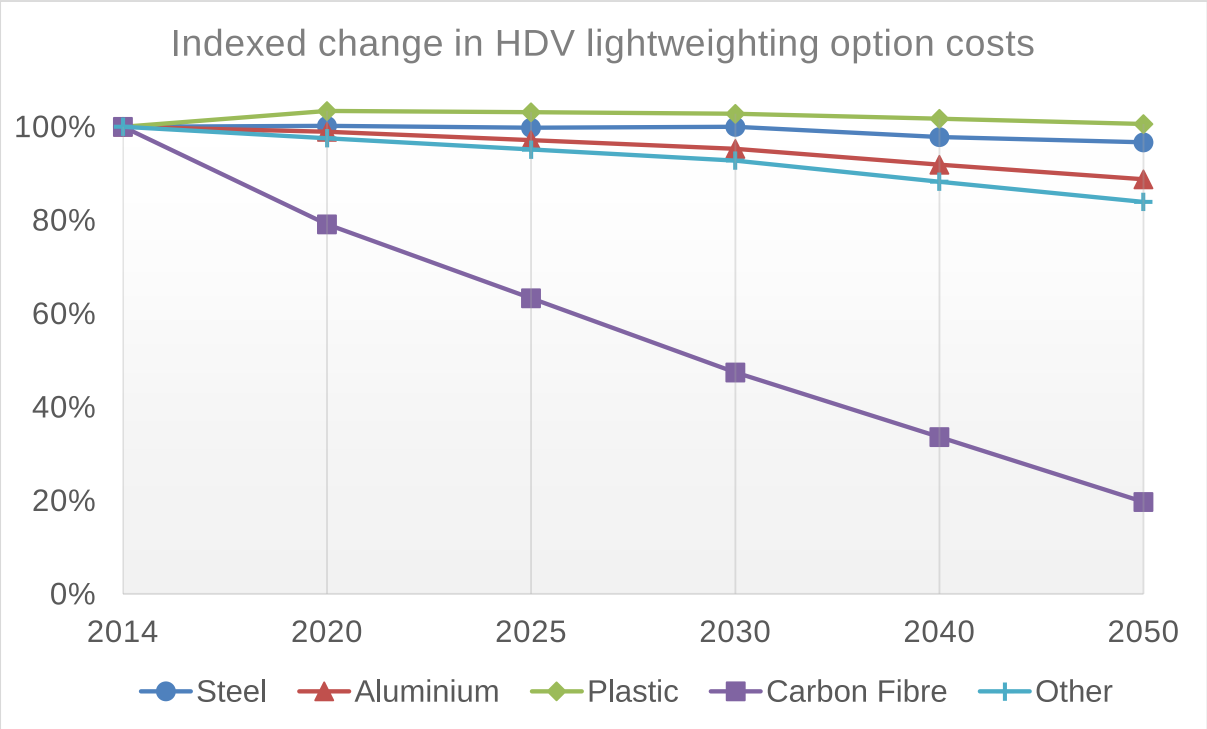
This subjective evaluation for future material prices for the automotive sector, supported by other source/reference data suggests that carbon fibre reinforced plastics are likely to undergo significant cost reduction, mainly due to combination of reductions in raw material costs and improvements in manufacturing processes. By 2050 the price point could be approaching that of plastic, steel and aluminium. By comparison, it is anticipated that prices for steel and aluminium will remain comparably stable with limited material and manufacturing process improvements with the main price influence being energy costs. Given that plastics are mainly derived from crude oil, they are expected to follow crude oil price trends (i.e. increase steadily over the next 20 to 30 years, mainly driven by increasing demand and depleting supply).

Based on the analysis presented above, the resulting estimated future cost trajectories indexed to 2015 are presented in the following Table 4.6 and Figure 4.3, which includes also estimated improvements through learning by OEMs and suppliers/cost reductions for the processing of alternative raw materials into finished HDV components. These figures have been used in the MACC model to scale the costs of different measures forwards from the current estimates to those in future periods.

Table 4.6: Estimated future cost trajectories for different lightweighting options (Index 2015 = 100%)

	2015	2020	2025	2030	2040	2050
Steel	100%	100%	100%	100%	98%	97%
Aluminium	100%	99%	97%	95%	92%	89%
Plastic	100%	103%	103%	103%	102%	101%
Carbon Fibre	100%	79%	63%	47%	34%	20%
Other	100%	98%	95%	93%	88%	84%

Figure 4.3: Estimated future cost trajectories for different lightweighting options (Index 2015 = 100%)



Notes: Projected increases in costs for steel, aluminium and plastic are driven by a combination of increased energy costs for the production process and increased raw material costs. Estimated improvements through learning/cost reductions for the processing of raw materials into finished HDV components is also included.

4.2.4 Other input assumptions for the MACC analysis

4.2.4.1 Fuel consumption

Baseline fuel consumption values were calculated with the aid of previous analysis performed for this study. Table 3.17 within Section 3 of this report presents linear correlations between vehicle efficiency and vehicle mass for different drive cycles. Therefore, using the appropriate constants, 2015 baseline fuel consumption values can be calculated using the following formula;

$$Fuel\ consumption = c + (m * (Kerb\ weight + Payload))$$ **Equation 3**

Where c is the y-intercept of the linear relationship and m is the gradient.

Furthermore, as mentioned earlier in Section 4.2.2.3, due to inevitable vehicle manufacturing improvements through time we must also assume an efficiency improvement scenario throughout time to ensure impacts from lightweighting alone are sufficiently captured in each time period.

Two scenarios are included the model for sensitivity analysis purposes. These were:

(i) PRIMES reference scenario and;

(ii) Alternative baseline assuming maximum cost effective potential from previous MACC analysis by CE Delft is reached by 2030 (and then a 1% p.a. improvement until 2050).

Table 4.7: Average fuel consumption reduction assumed for baseline scenario (versus 2015)

Vehicle type	2020	2025	2030	2040	2050
Urban	4.32%	6.72%	8.87%	11.02%	12.56%
Utility	4.32%	6.72%	8.87%	11.02%	12.56%
Regional	4.32%	6.72%	8.87%	11.02%	12.56%
Construction	4.32%	6.72%	8.87%	11.02%	12.56%
Long Haul	4.32%	6.72%	8.87%	11.02%	12.56%
Bus	2.58%	4.08%	6.94%	8.67%	10.03%
Coach	5.11%	8.55%	10.86%	14.37%	17.04%

Table 4.8: Average fuel consumption reduction assumed for max technical scenario (versus 2015)

Vehicle type	2020	2025	2030*	2040	2050
Urban	9.50%	19.00%	28.50%	35.34%	47.11%
Utility	12.00%	24.00%	36.00%	42.12%	52.66%
Regional	10.67%	21.33%	32.00%	38.50%	49.70%
Construction	12.00%	24.00%	36.00%	42.12%	52.66%
Long Haul	15.00%	30.00%	45.00%	50.26%	59.32%
Bus	14.67%	29.33%	44.00%	49.35%	58.58%
Coach	8.67%	17.33%	26.00%	33.08%	45.26%

* Based on CE Delft MACH model

4.2.4.2 Fuel price scenarios

Four fuel price scenarios have been defined within the model. In order to analyse cost curves in 2050, the fuel price was projected out to 2065 to account for all the various vehicle lifetime ages. The four scenarios are as follows;

- **Reference price scenario;** this was based on the PRIMES reference scenario for diesel prices excluding taxation.
- **High price scenario;** this was based on the PRIMES high scenario for diesel prices excluding taxation however with the 2015 price set equal to the reference scenario. Future (post 2015) costs were based on the growth rate assumed in the original high scenario.
- **Low price scenario;** this was based on the PRIMES low scenario for diesel prices excluding taxation however with the 2015 price set equal to the reference scenario. Future (post 2015) costs were based on the growth rate assumed in the original low scenario.
- **Very price low scenario;** this was an additional scenario added late in the study to reflect the late 2014/early 2015 reductions in oil prices. The 2015 price here was taken to be the current average price of diesel. Future (post 2015) costs were based on the growth rate assumed in the original low scenario.

An illustration of these scenarios is shown below in Figure 4.4 below, with the data in Table 4.9.

Figure 4.4: Fuel price scenarios

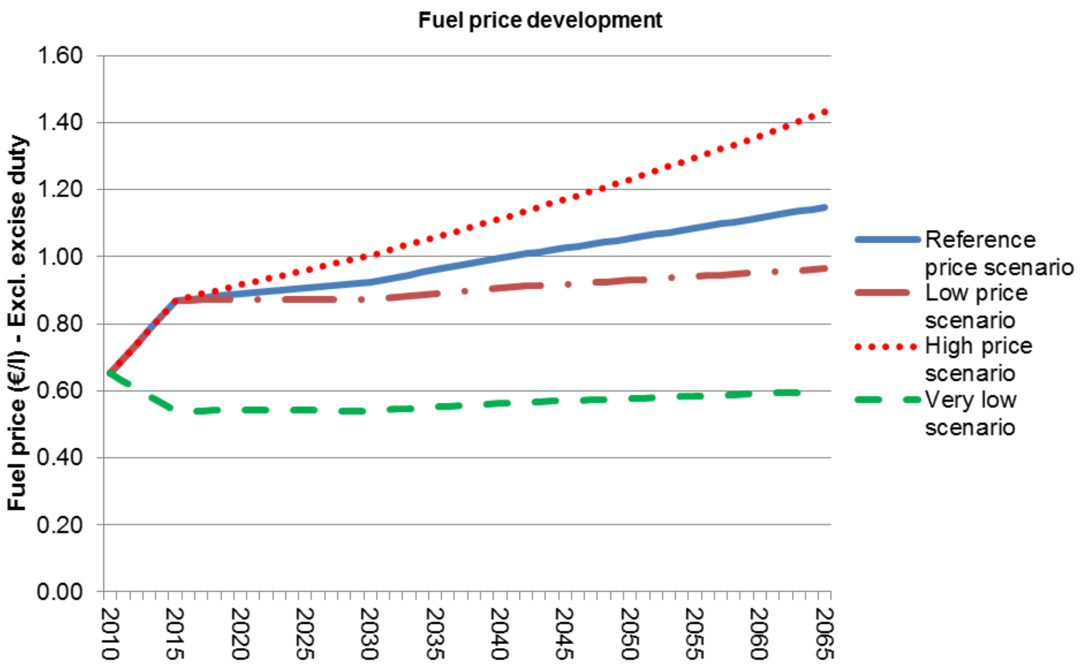


Table 4.9: Fuel price scenarios

Fuel price (€/l) - Excl. excise duty and VAT	2010	2015	2020	2030	2040	2050	2060	2070
Reference price scenario	0.652	0.869	0.889	0.924	0.997	1.055	1.116	1.181
Low price scenario	0.652	0.869	0.874	0.871	0.908	0.930	0.953	0.976
High price scenario	0.652	0.869	0.916	1.004	1.113	1.230	1.360	1.504
Very low scenario	0.652	0.539	0.542	0.540	0.563	0.577	0.591	0.606

4.2.4.3 Non-fuel running costs for trucks

This section presents the methodology used to define the average non-fuel costs incurred by EU freight operators. The cost per km has been defined for seven different types HDVs.

Non-fuel related costs have been used to support the modelling of cost savings achieved by lighter vehicles, due to the increased load that HDVs may be able to carry. Hence, only vehicles that travel at full load (maximum GVW allowed) were considered.

Several sources were used as to develop a starting point for the majority of the analysis. After a careful review process, the top four key sources provided most of the cost data taken forward for use in the MACC model.

Table 4.10: Sources of data on the non-fuel running costs of heavy trucks

Title	Cost year	Description	Link
Key Sources			
RHA cost tables, 2013	2013	Various break down costs for trucks of different sizes (fixed annual + mileage related costs)	http://www.rha.uk.net/docs/Cost%20Tables%202014%20EDITION.pdf
TREMOVE V 3.3. Base Case	2015	Baseline data for four different truck types + projections up to 2030	http://www.tmleuven.com/methode/tremove/home.htm
Italian Government	2014	Minimum costs (with breakdown and cost/km) for 15 HDV transport configurations. Includes ATP (dangerous subs) and: rigid, artic, tanker by type of liquid, skipper, and tractor/trailer only costs	http://www.mit.gov.it/mit/mop_all.php?p_id=19741
Transport Engineer Jan 14	2014	Various break down costs for trucks of different sizes (annual total cost by category)	Hard copy only
Secondary Sources			
TERM indicator Road freight load factor	2008	Average load factor (laden trips) by Member state - time series 1990-2008	http://www.eea.europa.eu/data-and-maps/figures/road-freight-load-factors-during
Hal Load factor analysis	2004	Several data tables and charts at Member State level (load factors, load factors trends, by vehicle size, empty runs, etc)	https://hal.archives-ouvertes.fr/file/index/docid/546125/filename/LTE0419-1.pdf
ACEA	2010	EU Freight transport statistics, including load factors and other useful considerations for capacity limits	http://www.acea.be/uploads/publications/SAG_15_European_Freight_Transport_Statistics.pdf
CTU FCS		Comparative Model Of Unit Costs Of Road And Rail Freight Transport For Selected European Countries	http://www.ejbss.com/Data/Sites/1/vol3no4july2014/ejbss-1423-14-comparativemodelofunitcosts.pdf
European Transport Conference	2008	International Road Freight Transport in Germany and The Netherlands. Driver Costs Analysis and French Perspectives	http://abstracts.aetransport.org/paper/index/id/2856/confid/14
European Commission	2014	EU report, includes useful sources	http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014DC0222&from=EN
AECOM	2014	Recent set of statistics on EU haulage market, including load factors and costs by MS and by truck size	http://ec.europa.eu/transport/modes/road/studies/doc/2014-02-03-state-of-the-eu-road-haulage-market-task-a-report.pdf

A summary table grouped all sources that referred to vehicles of similar size and of a similar type. The different cost types were grouped according to the 11 key categories identified in Table 4.11. When necessary, currency and mileage data have been converted to Euro and kilometres. If costs were not included on a per-distance basis, the cost per kilometre has been calculated according to the annual mileage included for the specific vehicle type by the source.

Table 4.11: Non-fuel cost items considered

Cost Type	Description
1. Variable costs	Tyres
2. Variable costs	Repairs and maintenance
3. Variable costs	Road tolls
4. Variable costs	Other costs
5. Variable costs	Vehicle cost
6. Fixed costs	Driver salary
7. Fixed costs	Licences
8. Fixed costs	Insurance
9. Fixed costs	Interests
10. Fixed costs	Overhead
11. Fixed costs	Other fixed costs

This approach allowed for a comparison of data from all various sources and highlighted the differences in the typologies of costs included. For example, some sources included only tyres and maintenance costs while other sources presented several additional costs. Furthermore, some costs referred to different EU countries and different time periods and therefore were not 100% comparable.

After a consideration of the various sources, the final cost tables were based mostly on the four key sources as indicated in Table 4.10. Costs provided by the four sources covered largely the same years and similar types and sizes of HDVs (heavy goods vehicles).

However, due to the costs referring to different Member States (mainly Italy and UK), they were converted to the EU average using purchasing power standard (PPS) figures as released by Eurostat[18].

Data availability allowed to provide specific costs for the following vehicles typologies:

a. Commercial vehicle above 3.5 tonnes and below 7.5 tonnes
b. Commercial vehicle above 7.5 tonnes and below 11.5 tonnes
c. Commercial vehicle above 11.5 tonnes and below 26 tonnes
d. Large Truck (with trailer) >26 tonnes
e. Reefer vehicle>26 tonnes
f. Tanker >26 tonnes
g. Tipper >26 tonnes

Because of the differences in the number and type of costs considered by the various sources, the average cost/km for each vehicle has been calculated as the sum of the averages of the single cost categories as in Table 4.11 (rather than as the average of the total cost by source). In this way it was possible to include at least one estimate for each type of cost for each vehicle type and all final estimates include the same number of costs types.

The following Table 4.12 presents the final results, which were then used to develop the estimates by vehicle size and duty cycle summarised in Table 4.16.

[18] http://ec.europa.eu/eurostat/tgm/table.do?tab=table&language=en&pcode=tec00114

For future years, these costs were projected forward from 2015 using PRIMES reference scenario data on non-fuel costs.

Table 4.12: Summary of estimated average non-fuel running costs for European trucks

	Description	Cost per km
Truck 1	Above 3.5 tonnes and below 7.5	€ 0.84
Truck 2	Above 7.5 tonnes and below 11.5	€ 0.82
Truck 3	Above 11.5 and below 26 tonnes	€ 1.04
Truck 4	Generic truck >26 tonnes	€ 1.17
Truck 5	Reefer vehicle >26 tonnes	€ 1.41
Truck 6	Tanker >26 tonnes	€ 1.95
Truck 7	Tipper >26 tonnes	€ 1.79

4.2.4.4 Average load factor and relative activity

The development of estimates for the average load factor for different HDV types were important in order to (a) more accurately estimate the baseline fuel consumption for the vehicles in operation under typical conditions, and (b) also facilitate the estimation of the impact of weight limited operations. In the case of the former, the natural result of a vehicle running with a higher average payload is that the effect of lightweighting the vehicle itself has a lower percentage impact fuel consumption.

In earlier section 3.5.3, Eurostat statistics on tonne-km and vehicle-km were used develop average percentage of weight limited km. A similar methodology was also applied to further calculate an estimate of the average vehicle loading in tonnes. These figures were used in combination with the average payload capacities for the vehicles defined in the MACC model to estimate average loading factors for the baseline vehicles. These are presented in the following Table 4.13. For buses and coaches, the average load factors were taken from the TRACCS (Emisia, 2013) database EU28 average for the most recent year (2010).

Table 4.13: Estimated average truck load factors by weight class and duty cycle

Duty Cycle	*Loading Factors (%), by Weight Class*			
	<7.5t	7.5t-16t	16t-32t	>32t
Urban Delivery	37%	41%	48%	
Municipal Utility	37%	41%	48%	
Regional Delivery	37%	48%	57%	49%
Long Haul			61%	56%
Construction		50%	61%	42%
Bus	21%			
Coach	29%			

The assumed average annual mileage of heavy trucks over different duty cycles was based broadly on data from the previous HDV GHG Lot 1 study, and is presented in (AEA/Ricardo, 2011) below. The corresponding figures for buses and coaches were calculated from the TRACCS dataset (Emisia, 2013). For the evaluation of sensitivities to annual mileage assumptions in the MACC, LOW and HIGH figures are also provided representing -25% and +25% of the medium/average case annual km.

Table 4.14: Average annual mileage by duty cycle and +/- 25% sensitivities used in the MACC model

Duty Cycle	*LOW Annual mileage - (km)*	*MED Annual mileage - (km)*	*HIGH Annual mileage - (km)*
Urban Delivery	26,250	35,000	43,750
Municipal Utility	18,750	25,000	31,250
Regional Delivery	45,000	60,000	75,000
Long Haul	37,500	50,000	62,500
Construction	75,000	100,000	125,000
Bus	33,750	45,000	56,250
Coach	43,500	58,000	72,500

In order to estimate the combined impacts of cost-effective lightweighting at the aggregate weight class or duty cycle level it was also necessary to develop estimates for the relative shares of average activity for the different vehicle weight class and duty cycle combinations. Estimates for these are presented in Table 4.15 below. These have been calculated using previous estimates for the shares of trucks of different weight classes developed in the previous HDV GHG Lot 1 study for DG CLIMA (AEA/Ricardo, 2011) in combination with the relative share in stock numbers by weight class based on date from the TRACCS project (Emisia, 2013). The corresponding data for buses and coaches were calculated directly from TRACCS datasets. Similar figures per vehicle-km and per tonne-km are derivable using the assumptions from Table 4.14, and the average payload weight for a given type.

Table 4.15: Estimated share of HDV stock by duty cycle and weight category for trucks and for buses

Duty Cycle	*Share of total HDVs by Weight Class*				
	<7.5t	**7.5t-16t**	**16t-32t**	**>32t**	**Total**
Urban Delivery	17.8%	10.9%	3.1%		**31.8%**
Municipal Utility	1.0%	2.9%	3.1%		**7.0%**
Regional Delivery	3.1%	5.6%	7.0%	4.4%	**20.0%**
Long Haul			10.7%	17.4%	**28.1%**
Construction		2.5%	6.7%	3.8%	**13.1%**
Total Trucks	**21.9%**	**21.9%**	**30.5%**	**25.7%**	**100.0%**
Bus	38.4%				**38.4%**
Coach	61.6%				**61.6%**
Total Buses	**100.0%**				**100.0%**

4.2.4.5 Overview of input assumptions

The following Table 4.16 presented below provides a summary of all the key baseline MACC input parameters/assumptions for the different HDV types by weight and duty cycle category. These represent the assumed average parameters for 2015 model-year new vehicles before any of the identified additional lightweighting measures are applied.

The effective averages presented by aggregated weight category and by aggregated duty cycle category are presented for illustration purposes only.

Table 4.16: Summary of key baseline HDV input assumptions by vehicle type and duty cycle

Modes	*Vehicle Lifetime (years)*	*Fuel Cons. (MJ/km)*	*Base kerb weight (tonnes)*	*GVW Limit (tonnes)*	*Non fuel costs (€/km)*	*Av. load factor*	*Av. weight limited km (low)*	*Av. weight limited km (high)*	*Fully Weight Limited*	*Payload /vehicle (tonnes)*	*Freight efficiency (gCO_2/tkm)*	*Total % Share*
Rigid Truck, <7.5t (Urban)	12	5.3	2.74	5.50	1.05	36.7%	2%	2%	80%	1.01	386.6	16.8%
Rigid Truck, <7.5t (Utility)	12	6.6	2.74	5.50	1.39	36.7%	0%	0%	60%	1.01	476.9	1.0%
Rigid Truck, <7.5t (Regional)	12	3.7	2.74	5.50	0.69	36.7%	2%	4%	80%	1.01	269.4	2.9%
Rigid Truck, 7.5-16t (Urban)	12	8.1	6.35	12.00	1.12	41.1%	2%	2%	80%	2.32	256.3	10.3%
Rigid Truck, 7.5-16t (Utility)	12	8.0	6.35	12.00	1.46	41.1%	0%	0%	60%	2.32	254.0	2.7%
Rigid Truck, 7.5-16t (Regional)	12	8.1	6.35	12.00	0.76	48.4%	3%	6%	80%	2.73	217.3	5.3%
Rigid Truck, 7.5-16t (Construction)	12	8.5	7.51	12.00	0.92	50.0%	13%	28%	80%	2.24	279.1	2.4%
Rigid Truck, 16-32t (Urban)	12	13.2	10.90	26.00	1.17	47.9%	2%	2%	80%	7.24	134.7	2.9%
Rigid Truck, 16-32t (Utility)	12	16.4	14.00	26.00	1.51	47.9%	0%	0%	60%	5.75	210.3	2.9%
Rigid Truck, 16-32t (Regional)	12	11.7	10.90	26.00	0.81	56.8%	9%	18%	80%	8.58	100.3	6.6%
Rigid Truck, 16-32t (Long Haul)	12	11.1	10.90	26.00	0.61	61.3%	10%	20%	80%	9.25	88.2	10.1%
Rigid Truck, 16-32t (Construction)	12	13.8	12.90	26.00	0.98	48.7%	13%	28%	80%	6.38	159.5	6.3%
Artic Truck, >32t (Regional)	10	13.0	15.17	40.00	0.89	55.6%	9%	18%	80%	13.80	69.4	4.1%
Artic Truck, >32t (Long Haul)	10	11.6	15.17	40.00	0.69	41.9%	10%	20%	80%	10.40	82.3	16.5%
Artic Truck, >32t (Construction)	10	14.8	14.70	40.00	1.02	41.9%	13%	28%	80%	10.60	103.1	3.6%
Bus, All (Bus)	15	13.7	10.87	17.07	0.00	21%	0%	0%	80%	1.31	765.1	38.4%
Coach, All (Coach)	15	9.7	14.72	21.45	0.00	29%	0%	0%	80%	1.96	364.7	61.6%
Bus/Coach, All (All Cycles)	15	11.22	13.24	19.77	0.00	26%	0%	0%	80%	1.70	485.7	100.0%
Truck, All (All Cycles)	11.5	9.90	9.45	22.03	0.92	46%	6%	12%	79%	5.99	195.6	100.0%
Average, <7.5t (All Cycles)	12.0	5.15	2.74	5.50	1.01	37%	2%	2%	79%	1.01	374.5	21.9%
Average, 7.5-16t (All Cycles)	12.0	8.11	6.48	12.00	1.05	44%	3%	6%	77%	2.43	246.4	21.9%
Average, 16-32t (All Cycles)	12.0	12.56	11.65	26.00	0.88	55%	9%	17%	78%	7.86	117.7	30.5%
Average, >32t (All Cycles)	10.0	12.33	15.10	40.00	0.77	44%	10%	21%	80%	11.01	82.5	25.7%
Urban	12.0	7.02	4.76	9.70	1.08	42%	2%	2%	80%	2.06	251.2	31.8%

Modes	***Vehicle Lifetime (years)***	***Fuel Cons. (MJ/km)***	***Base kerb weight (tonnes)***	***GVW Limit (tonnes)***	***Non fuel costs (€/km)***	***Av. load factor***	***Av. weight limited km (low)***	***Av. weight limited km (high)***	***Fully Weight Limited***	***Payload /vehicle (tonnes)***	***Freight efficiency (gCO_2/tkm)***	***Total % Share***
Utility	12.0	11.47	9.2	17.2	1.5	45%	0%	0%	60%	3.63	232.8	7.0%
Regional	11.6	9.74	9.3	22.0	0.8	55%	6%	13%	80%	6.93	103.5	20.0%
Constr.	11.4	13.09	12.4	27.4	1.0	45%	13%	28%	80%	6.8	141.2	13.1%
Long Haul	10.8	11.41	13.6	34.7	0.7	47%	10%	20%	80%	9.96	84.4	28.1%

Notes: Average annual mileage is defined by duty cycle, according to Table 4.14; the default private payback period required for payback-limited cost-effectiveness calculations was set to 3 years for long-haul, the lifetime of the bus (15 years) for buses, and 5 years for other vehicles.

4.3 Results of the MACC analysis for different HDV categories

This section provides a summary of key results from the MACC analysis (i.e. covering Tasks 3.3 and 3.4 of the project). The results presented in this section refer to a 'baseline' scenario in both the 2020 and 2030 time periods presented in detail. This 'baseline' scenario is defined by the following variables;

- 'Baseline' fuel efficiency scenario (see Table 4.7);
- Reference annual vehicle km scenario;
- Reference fuel price scenario (see Table 4.9);
- 'Low' weight limited operations scenario (see Table 3.27); and
- Social perspective: 4% discount rate and excluding taxes.

A sensitivity analysis on the above variables is covered in next chapter (under Task 4). Also, as a general point it is important to note that any fluctuation in the lightweighting potential for certain vehicle and duty cycle combinations in later periods is an artefact of the variability in the calculated cost-effective potential. This is due to the relative interaction of the projected future technology costs, fuel prices, and baseline vehicle efficiencies within the model.

Our analysis has also shown that whilst in early periods the potential impact of factoring in CO_2 price in the cost-effectiveness calculation has zero or marginal impact on the available cost-effective lightweighting potential, in later periods (beyond 2030), it may become more significant for some vehicle/duty cycle combinations.

4.3.1 Urban Delivery

The 2020 and 2030 cost curves for all weight categories of urban delivery trucks are found in Figure 4.5 to Figure 4.7. As denoted, the red dashed line is the corresponding price of CO_2 in each time period. In addition, Table 4.17 to Table 4.19 provide a full time-series summary to 2050 of the level of estimated cost-effective weight reduction, the corresponding percentage fuel / CO_2 savings potential, and the impact on overall freight CO_2 efficiency (in gCO_2/tonne-km).

The results show that in 2020, on average, urban delivery trucks might achieve a 4.4% reduction in weight as a result of the lightweighting options that are available and cost-effective over the lifetime of the vehicle. This reduction equates to a 1.17% saving in CO_2 emissions taking into account the duty cycle and average payload of the vehicle.

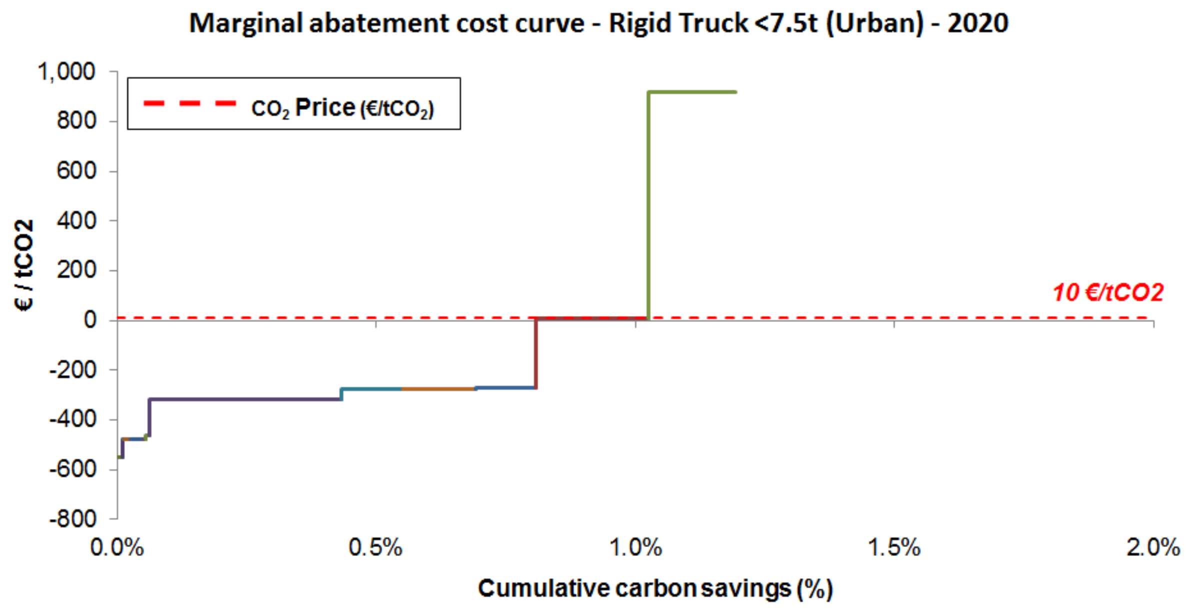
By 2030, this weight reduction potential could potentially reach 10.3% on a similar cost-effective basis, leading to a 2.7% saving in CO_2 emissions. Other than with construction and regional delivery vehicles, this level of weight reduction and emissions savings is greater than can be expected by the other truck duty cycles.

As can be seen in the charts and tables, there is a degree of variability in both the total available weight/CO_2 reduction available and the cost-effective reduction, depending on the specific vehicle size/configuration. In the 2030 case (where all technical options identified are assumed to be available), the calculated maximum feasible CO_2 reduction potential varies between ~6% for the smallest trucks, to ~13% for the largest.

The estimated impacts on freight CO_2 efficiency are also presented in Table 4.19; this shows that by 2030, cost-effective lightweighting for urban delivery vehicles could improve freight CO_2 efficiency by over 7 gCO_2 per tonne-km.

As mentioned at the start of Section 4.3, in later periods there is some variability in the calculated cost-effective potential for certain vehicle and duty cycle combinations, which is due to the relative interaction of the projected future technology costs, fuel prices, and baseline vehicle efficiencies.

Figure 4.5: Marginal abatement cost curves for <7.5 tonne truck over the urban delivery cycle



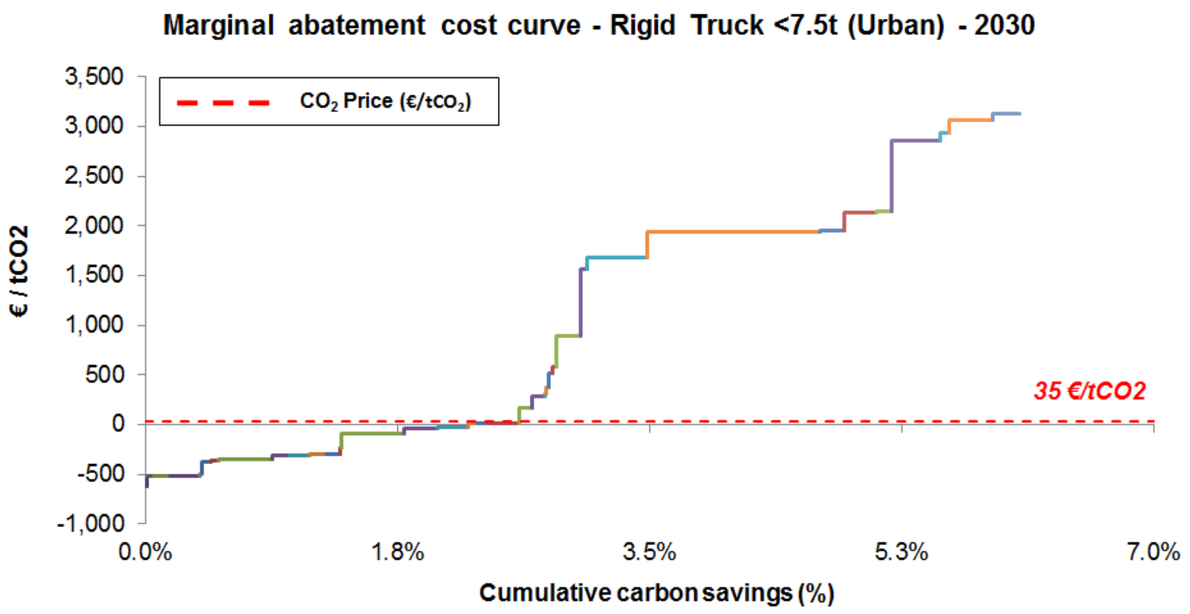
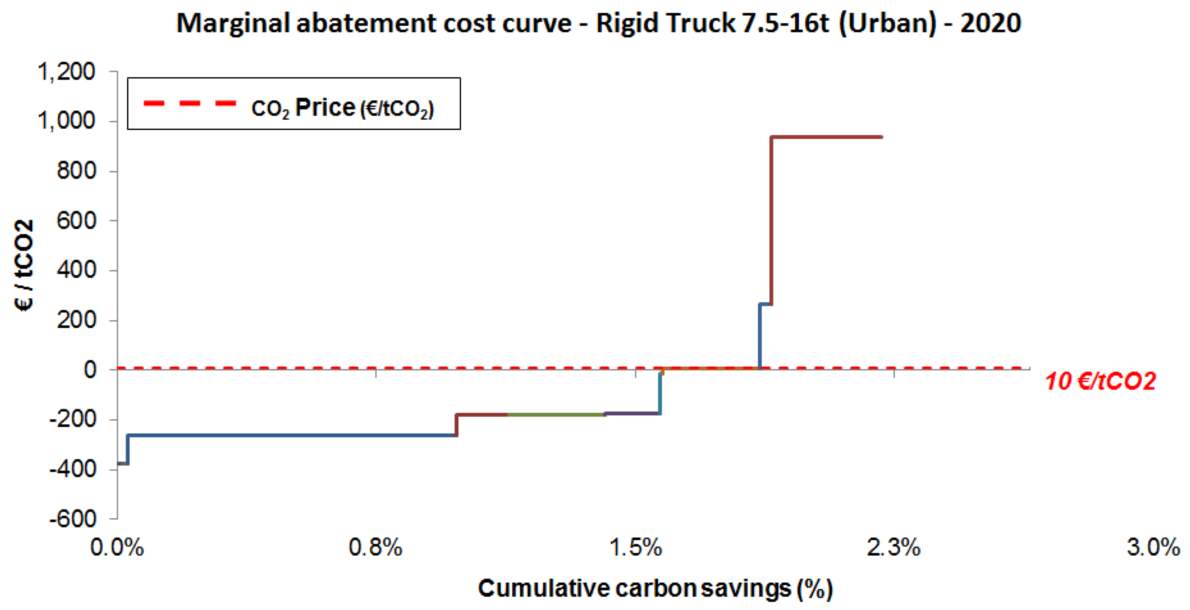


Figure 4.6: Marginal abatement cost curves for 7.5-16 tonne truck over the urban delivery cycle



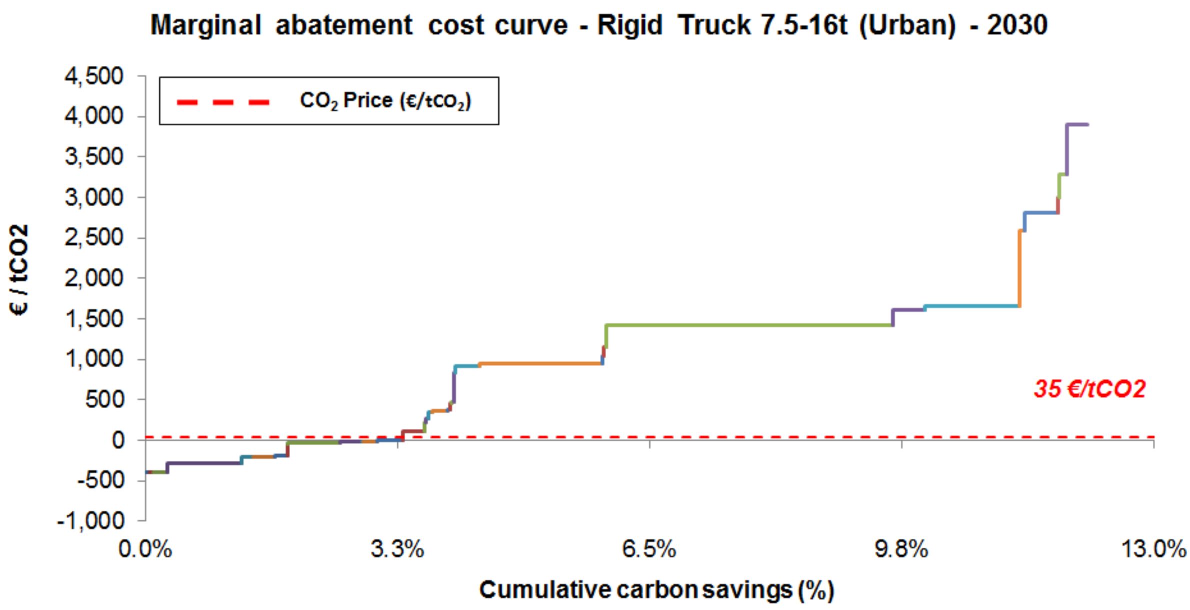
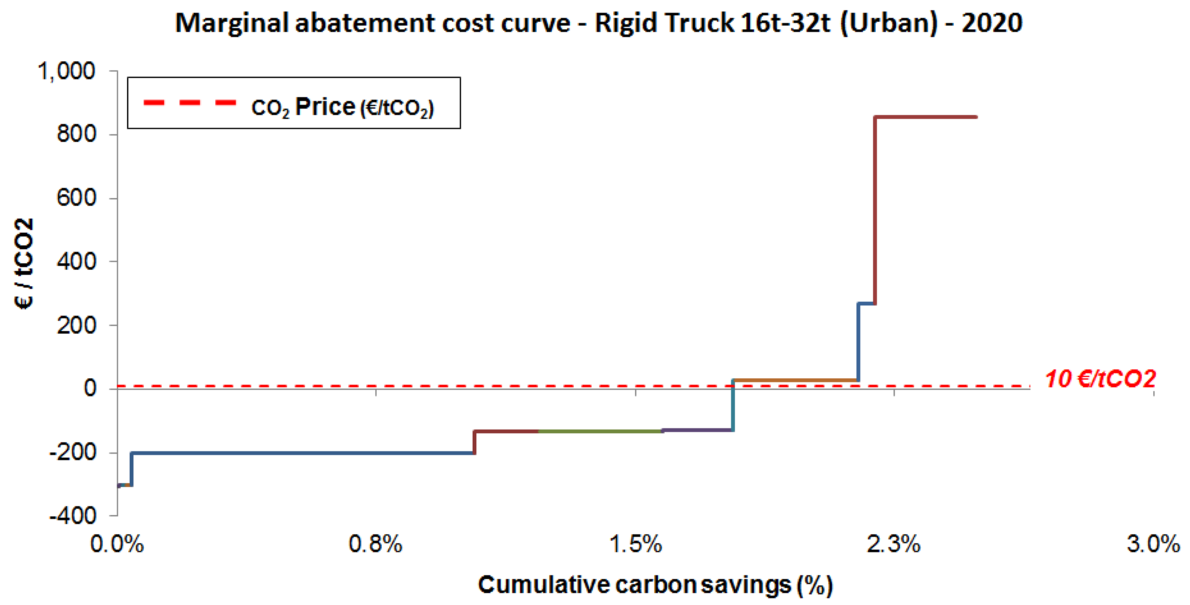


Figure 4.7: Marginal abatement cost curves for 16-32 tonne truck over the urban delivery cycle



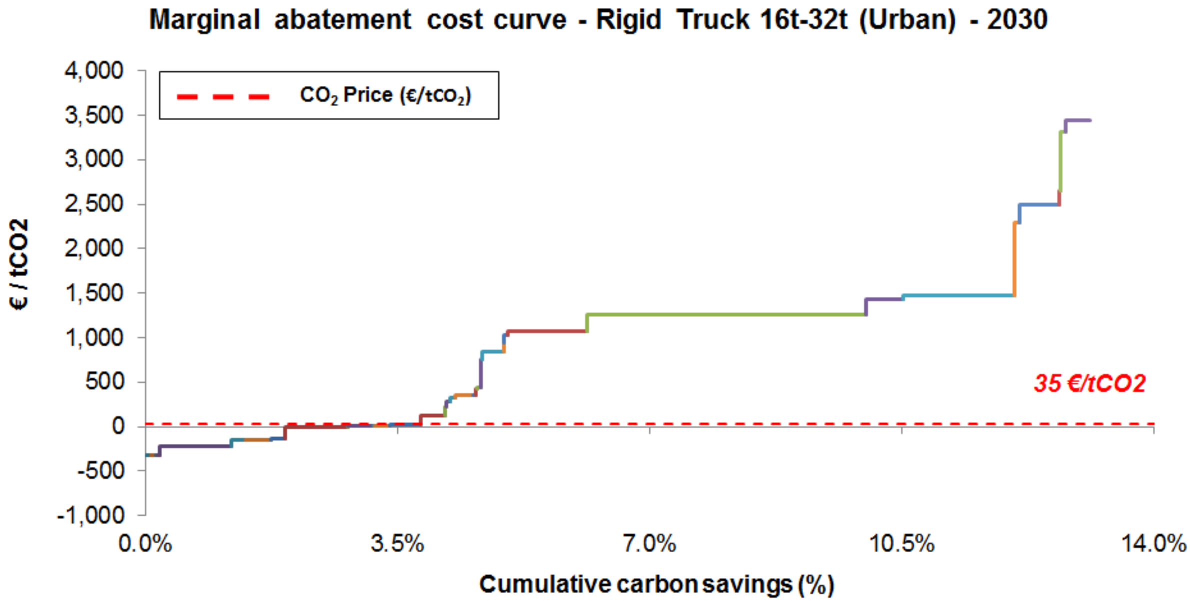


Table 4.17: Calculated cost-effective weight reduction potential (%) versus 2015 baseline vehicle – Urban delivery cycle

Vehicle type	2020	2025	2030	2040	2050
Average	**4.4%**	**8.4%**	**10.3%**	**11.5%**	**11.8%**
<7.5t	4.0%	9.2%	10.8%	12.5%	13.0%
7.5-16t	5.0%	8.0%	10.2%	10.2%	10.2%
16-32t	4.7%	4.9%	7.3%	9.8%	9.8%

Table 4.18: Calculated CO_2 savings potential (%) versus baseline vehicle for model year for cost-effective weight-reduction – Urban delivery cycle

Vehicle type	2020	2025	2030	2040	2050
Average	**1.17%**	**2.14%**	**2.67%**	**2.97%**	**3.03%**
<7.5t	0.81%	1.91%	2.24%	2.60%	2.71%
7.5-16t	1.58%	2.58%	3.32%	3.32%	3.32%
16-32t	1.78%	1.84%	2.81%	3.82%	3.82%

Table 4.19: Calculated improvement in freight efficiency (gCO_2/tkm) versus baseline vehicle for model year for cost-effective weight-reduction – Urban delivery cycle

Vehicle type	2020	2025	2030	2040	2050
Average	**-3.2**	**-6.2**	**-7.4**	**-8.1**	**-8.1**
<7.5t	-3.0	-6.9	-7.9	-8.9	-9.1
7.5-16t	-3.9	-6.2	-7.8	-7.6	-7.4
16-32t	-2.3	-2.3	-3.4	-4.6	-4.5

4.3.2 Utility trucks

The 2020 and 2030 cost curves for all weight categories of utility trucks are found in Figure 4.8 to Figure 4.10. Once again, the red dashed line is the corresponding price of CO_2 in each time period. Table 4.20 to Table 4.22 also provide a full time-series summary to 2050 of the level of estimated cost-effective weight reduction, the corresponding % fuel / CO_2 savings potential, and the impact on overall freight CO_2 efficiency (in gCO_2/tonne-km).

The results show that in 2020, on average, utility trucks might achieve a 3.7% reduction in weight as a result of the lightweighting options that are available and cost-effective over the lifetime of the vehicle (from a societal perspective). This reduction equates to a little under 1.5% saving in CO_2 emissions taking into account the duty cycle and average payload of the vehicle.

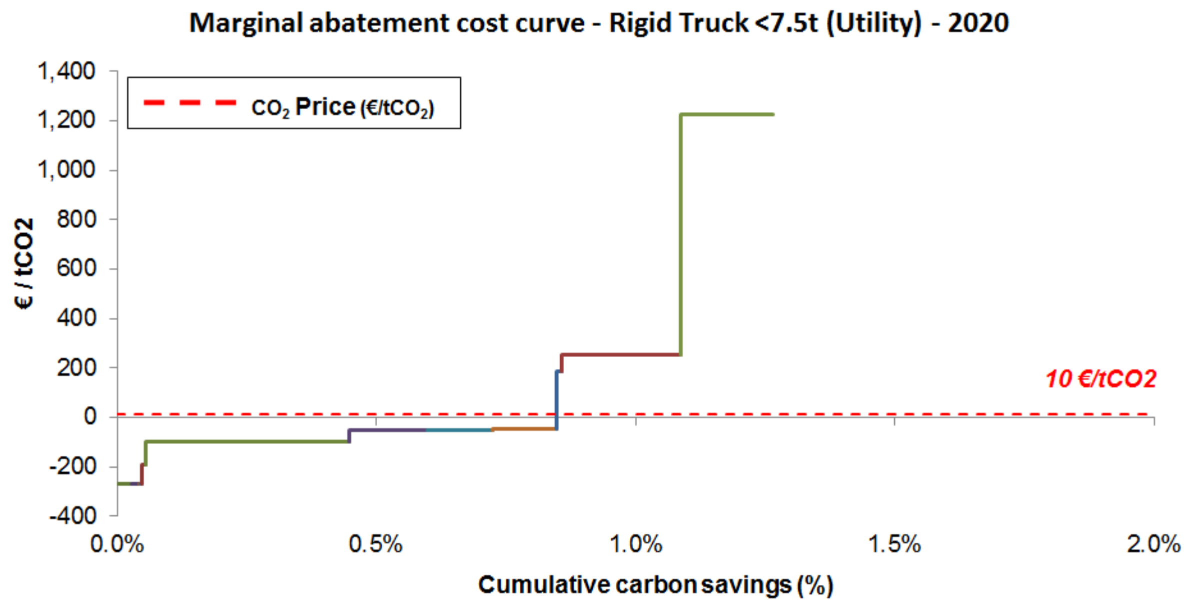
By 2030, this weight reduction potential could potentially reach 4.6% on a similar cost-effective basis, leading to a 1.8% saving in CO_2 emissions. This level of weight reduction is the lowest across all duty cycles analysed within the study. In fact, across 2020 to 2050, utility trucks have the least potential for lightweighting and corresponding % fuel / CO_2 savings of all modes of HDVs.

Like urban trucks, there is a degree of variability in both the total available weight/CO_2 reduction available and the cost-effective reduction, depending on the specific vehicle size/configuration. In the 2030 case (where all technical options identified are assumed to be available), the calculated maximum feasible CO_2 reduction potential varies between ~6% for the smallest trucks, to ~12% for the largest.

The estimated impacts on freight CO_2 efficiency is also presented in Table 4.22; this shows that by 2030, cost-effective lightweighting for utility vehicles could improve freight CO_2 efficiency by over 4 gCO_2 per tonne-km.

Again, in later periods there is some variability in the calculated cost-effective potential for certain vehicle and duty cycle combinations, which is due to the relative interaction of the projected future technology costs, fuel prices, and baseline vehicle efficiencies.

Figure 4.8: Marginal abatement cost curves for <7.5 tonne truck over the utility cycle



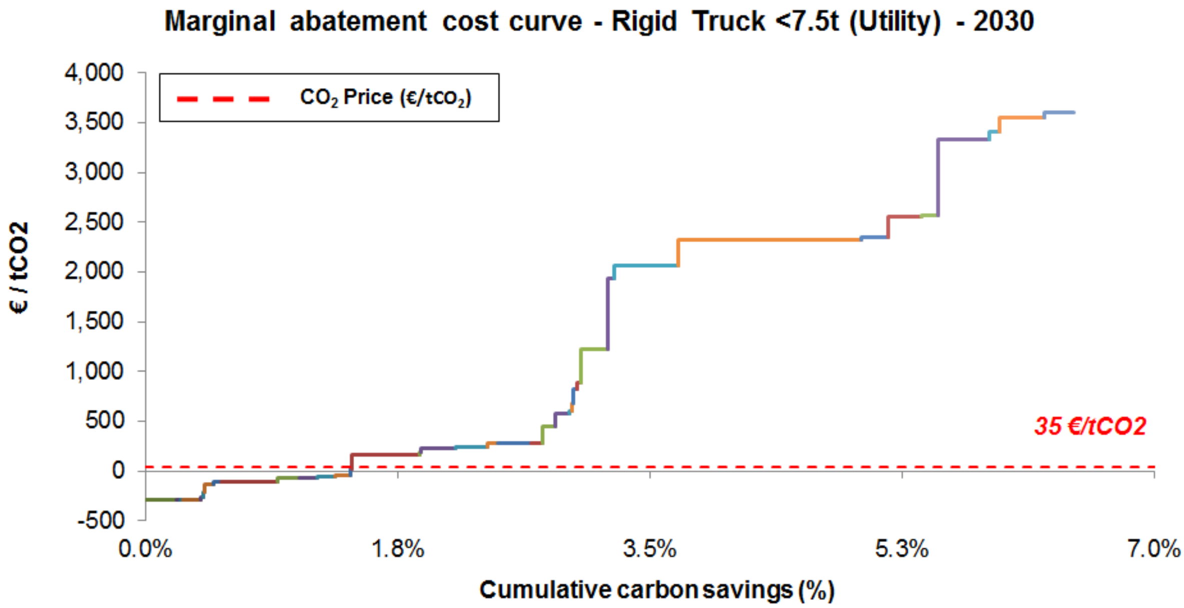
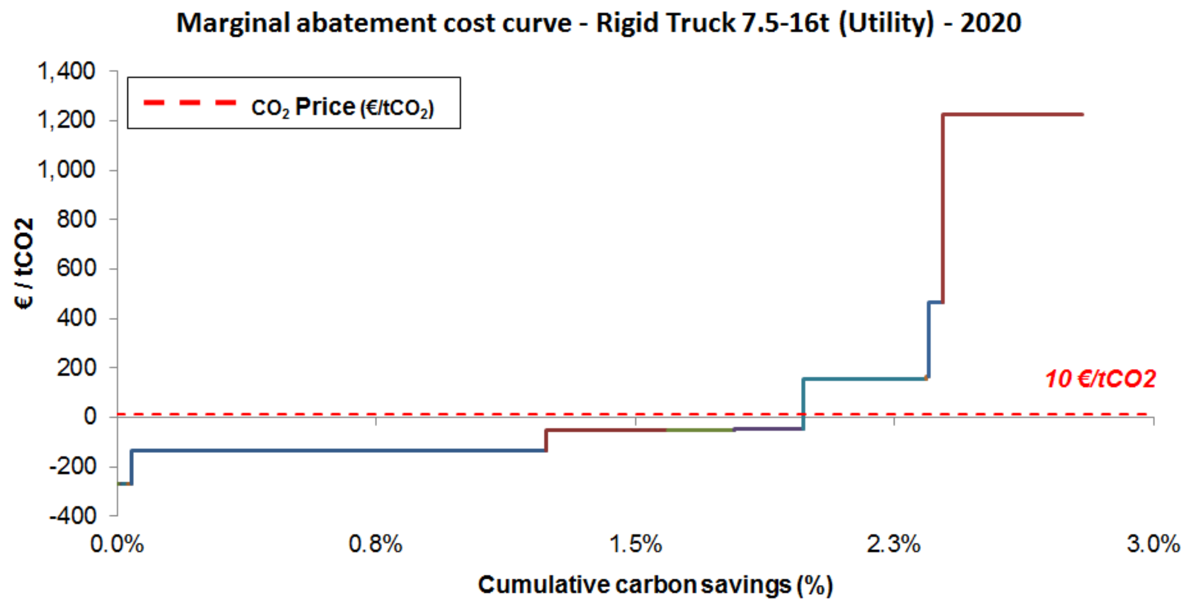


Figure 4.9: Marginal abatement cost curves for 7.5-16 tonne truck over the utility cycle



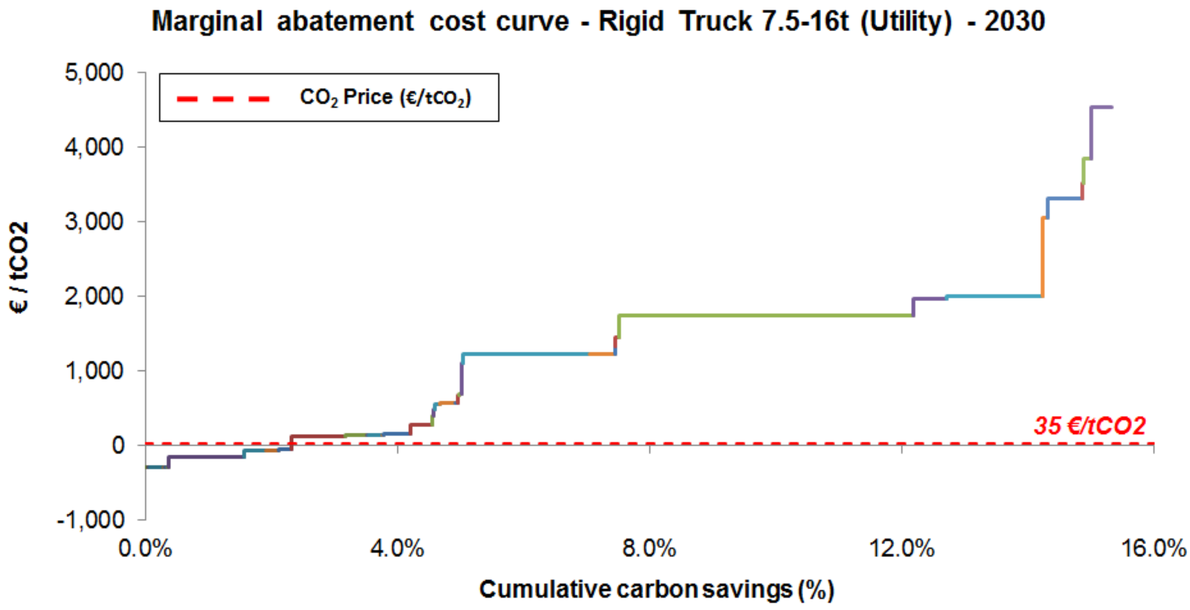
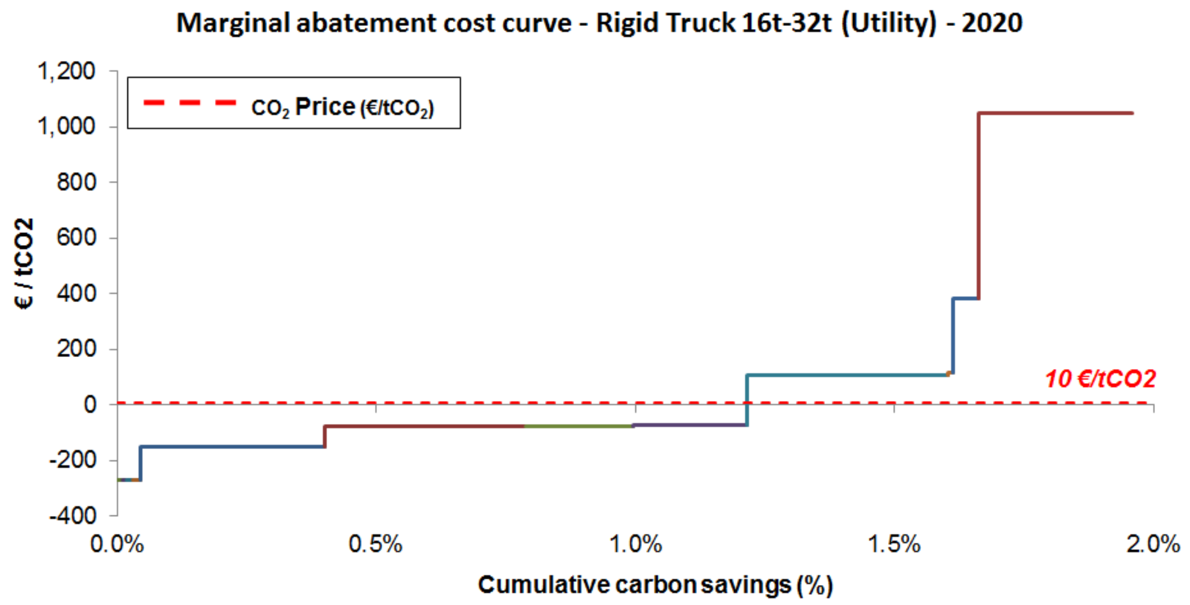


Figure 4.10: Marginal abatement cost curves for 16-32 tonne truck over the utility cycle



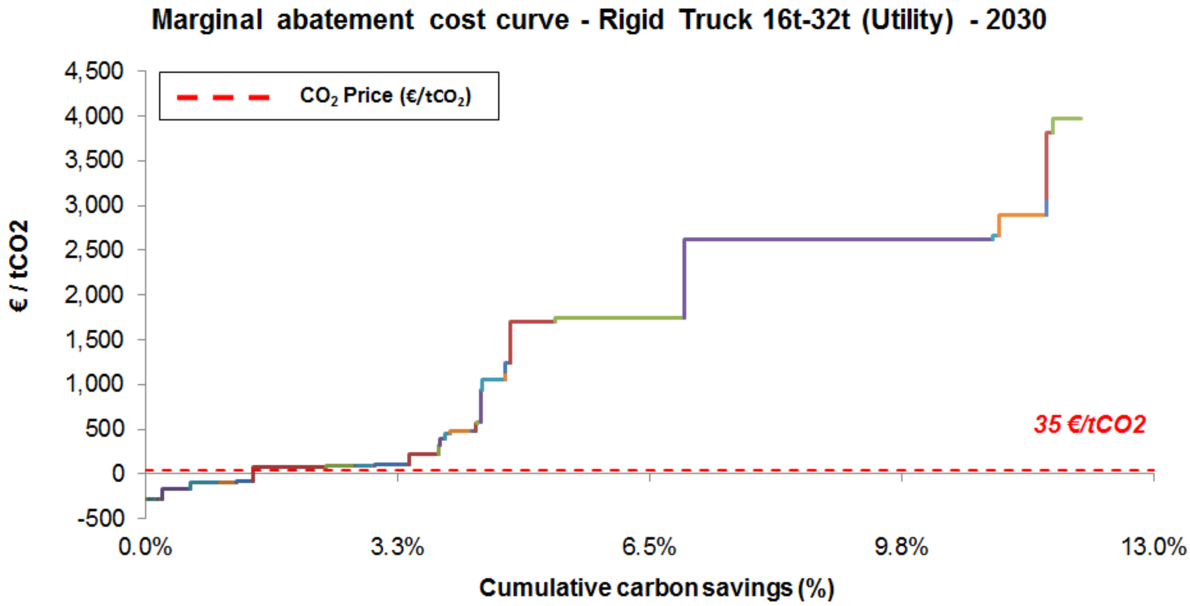


Table 4.20: Calculated cost-effective weight reduction potential (%) versus 2015 baseline vehicle – Utility cycle

Vehicle type	2020	2025	2030	2040	2050
Average	**3.7%**	**4.0%**	**4.6%**	**4.6%**	**4.6%**
<7.5t	3.8%	4.9%	6.4%	6.5%	7.0%
7.5-16t	5.0%	5.1%	5.8%	5.8%	5.8%
16-32t	2.4%	2.6%	2.8%	2.8%	2.8%

Table 4.21: Calculated CO_2 savings potential (%) versus baseline vehicle for model year for cost-effective weight-reduction – Utility cycle

Vehicle type	2020	2025	2030	2040	2050
Average	**1.48%**	**1.57%**	**1.78%**	**1.78%**	**1.80%**
<7.5t	0.85%	1.08%	1.43%	1.44%	1.55%
7.5-16t	1.99%	2.04%	2.32%	2.32%	2.32%
16-32t	1.22%	1.28%	1.39%	1.39%	1.39%

Table 4.22: Calculated improvement in freight efficiency (gCO_2/tkm) versus baseline vehicle for model year for cost-effective weight-reduction – Utility cycle

Vehicle type	2020	2025	2030	2040	2050
Average	**-3.6**	**-3.8**	**-4.3**	**-4.2**	**-4.2**
<7.5t	-3.9	-4.8	-6.2	-6.1	-6.5
7.5-16t	-4.8	-4.8	-5.4	-5.2	-5.1
16-32t	-2.4	-2.5	-2.7	-2.6	-2.6

4.3.3 Regional Delivery

The 2020 and 2030 cost curves for all weight categories of regional delivery trucks are found in Figure 4.11 to Figure 4.14. Once again, the red dashed line is the corresponding price of CO_2 in each time period. Table 4.23 to Table 4.25 also provide a full time-series summary to 2050 of the level of estimated cost-effective weight reduction, the corresponding percentage fuel / CO_2 savings potential, and the impact on overall freight CO_2 efficiency (in gCO_2/tonne-km).

The results show that in 2020, on average, regional delivery trucks might achieve a 4.9% reduction in weight as a result of the lightweighting options that are available and cost-effective over the lifetime of the vehicle. This reduction equates to a little under 1.12% saving in CO_2 emissions taking into account the duty cycle and average payload of the vehicle.

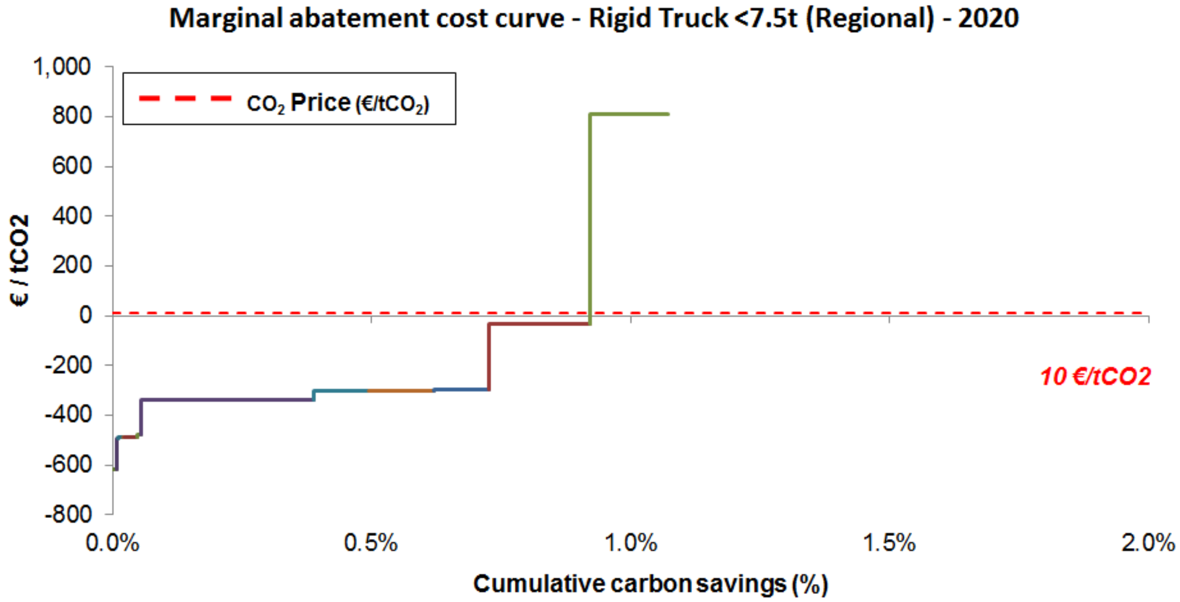
By 2030, this weight reduction potential could potentially reach just below 10% on a similar cost-effective basis, leading to around 2.3% saving in CO_2 emissions. Other than with construction vehicles, this level of weight reduction and emissions savings is greater than can be expected by the other truck duty cycles.

As previously, there is a degree of variability in both the total available weight/CO_2 reduction available and the cost-effective reduction, depending on the specific vehicle size/configuration. In the 2030 case, the calculated maximum feasible CO_2 reduction potential varies between ~6% for the smallest trucks, to ~10% for the largest. This level of variability is less than was observed for urban delivery and utility trucks.

The estimated impacts on freight CO_2 efficiency is also presented in Table 4.23; this shows that by 2030, cost-effective lightweighting for regional delivery trucks could improve freight CO_2 efficiency by 3.2 gCO_2 per tonne-km.

As before, in later periods there is some variability in the calculated cost-effective potential for certain vehicle and duty cycle combinations, which is due to the relative interaction of the projected future technology costs, fuel prices, and baseline vehicle efficiencies.

Figure 4.11: Marginal abatement cost curves for <7.5 tonne truck over the regional delivery cycle



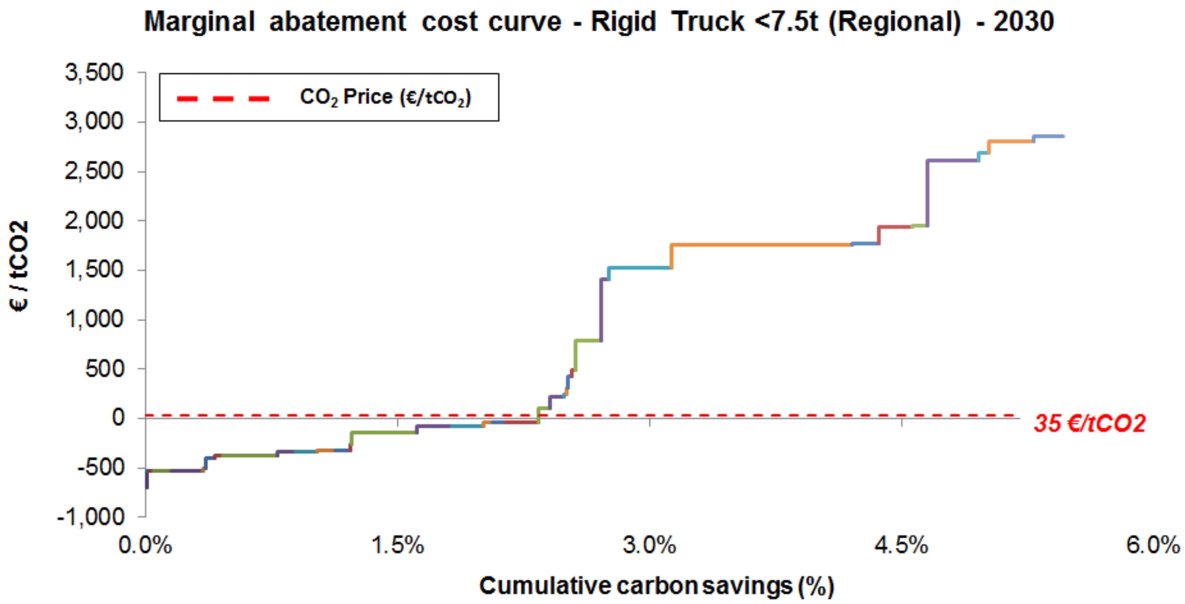
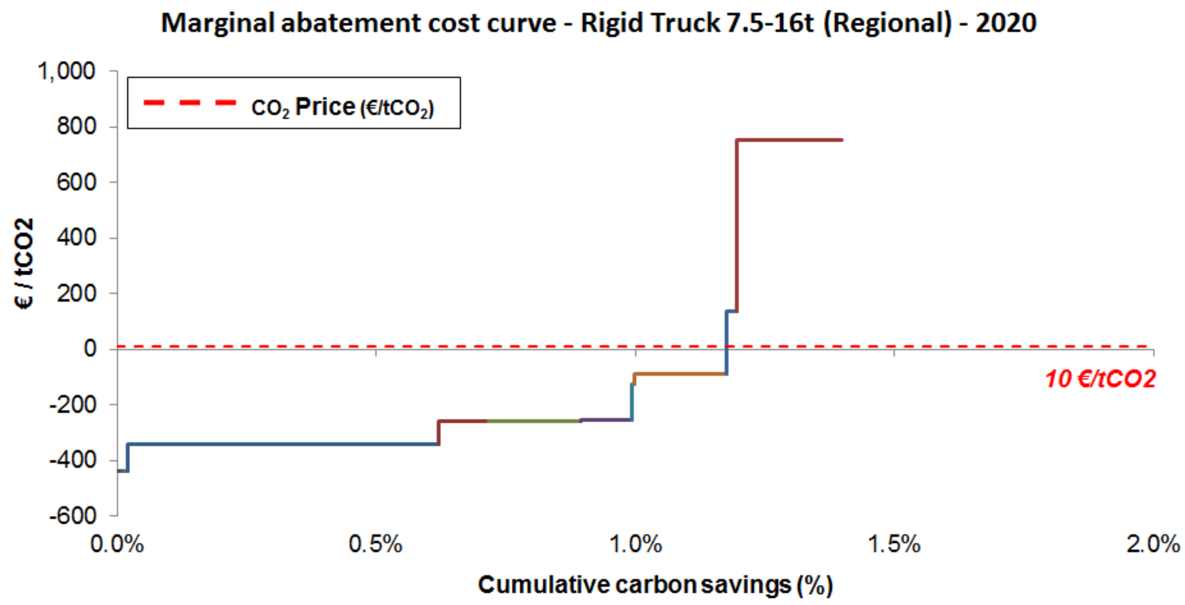


Figure 4.12: Marginal abatement cost curves for 7.5-16 tonne truck over the regional delivery cycle



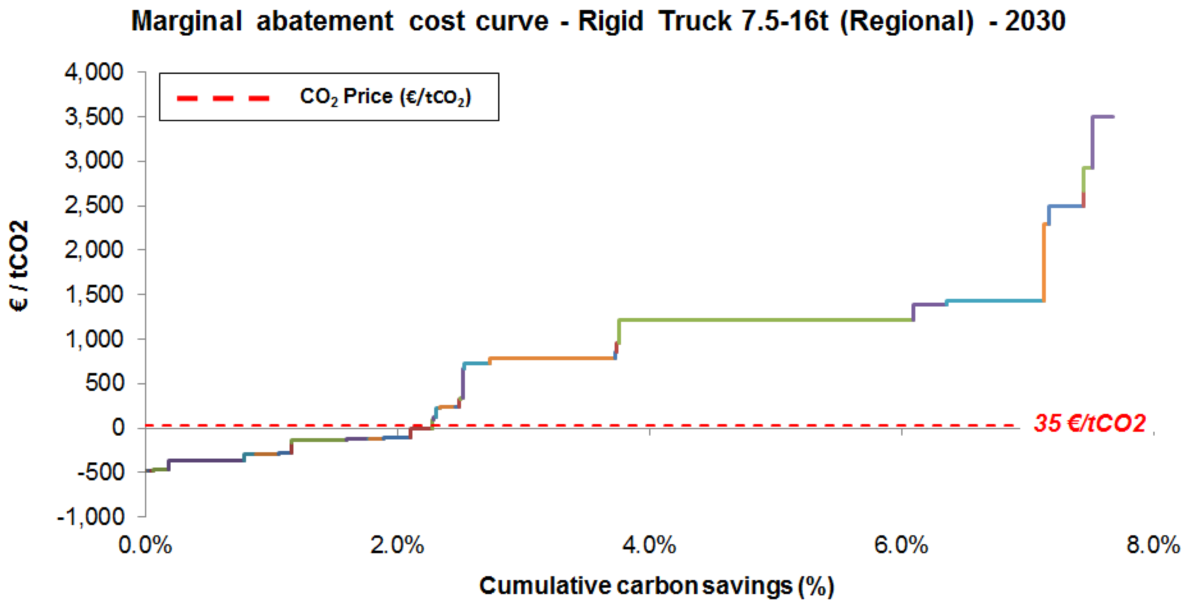
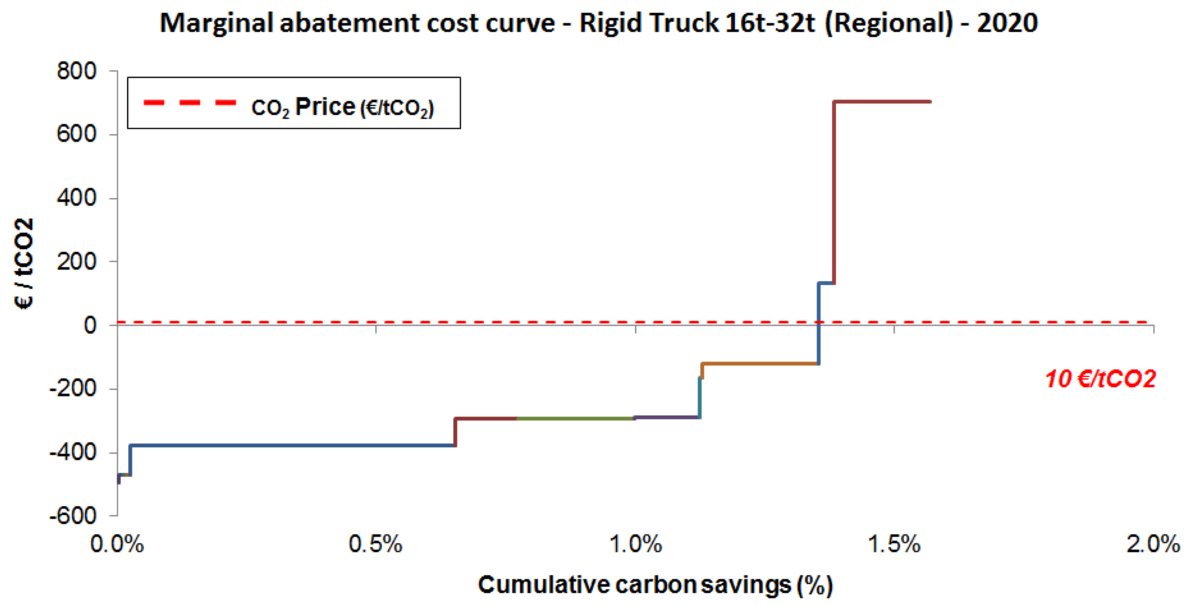


Figure 4.13: Marginal abatement cost curves for 16-32 tonne truck over the regional delivery cycle



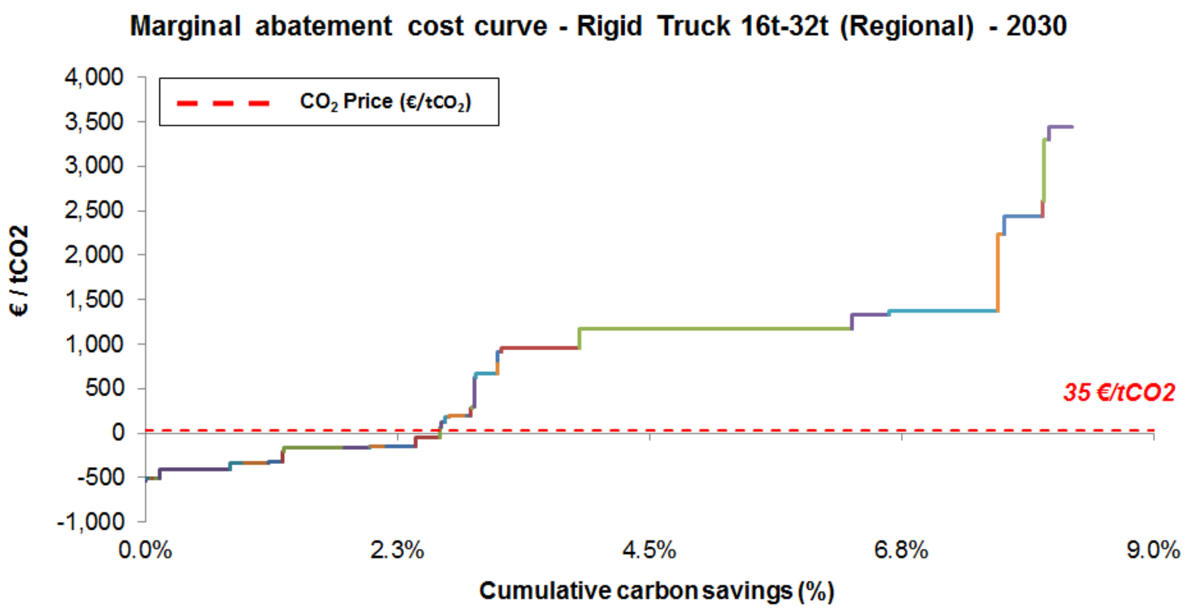
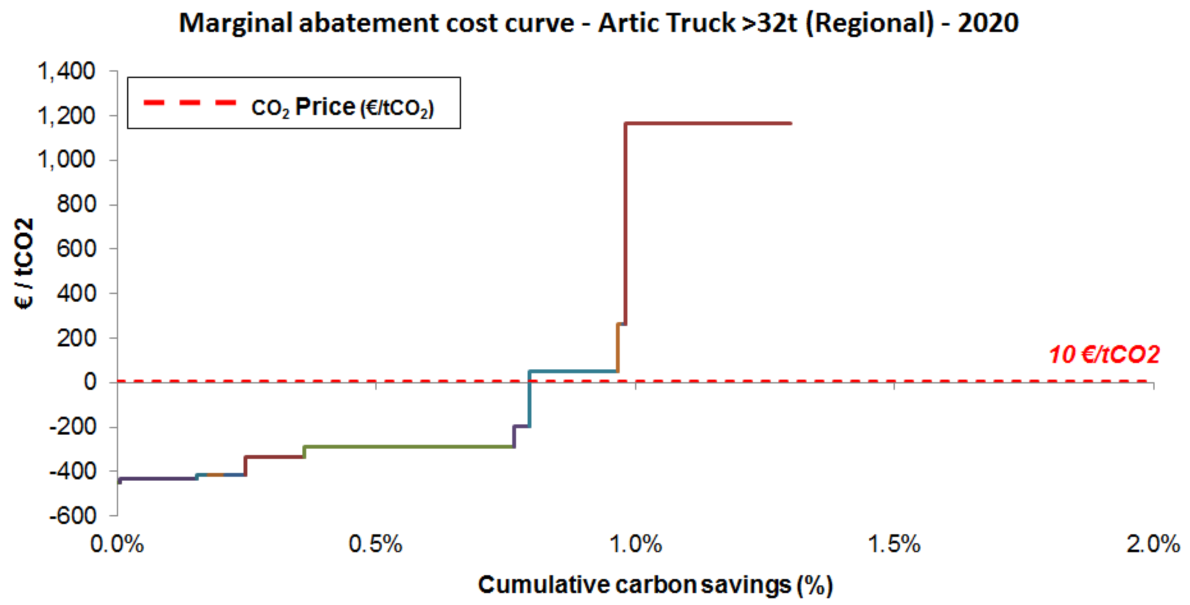


Figure 4.14: Marginal abatement cost curves for >32 tonne truck over the regional delivery cycle



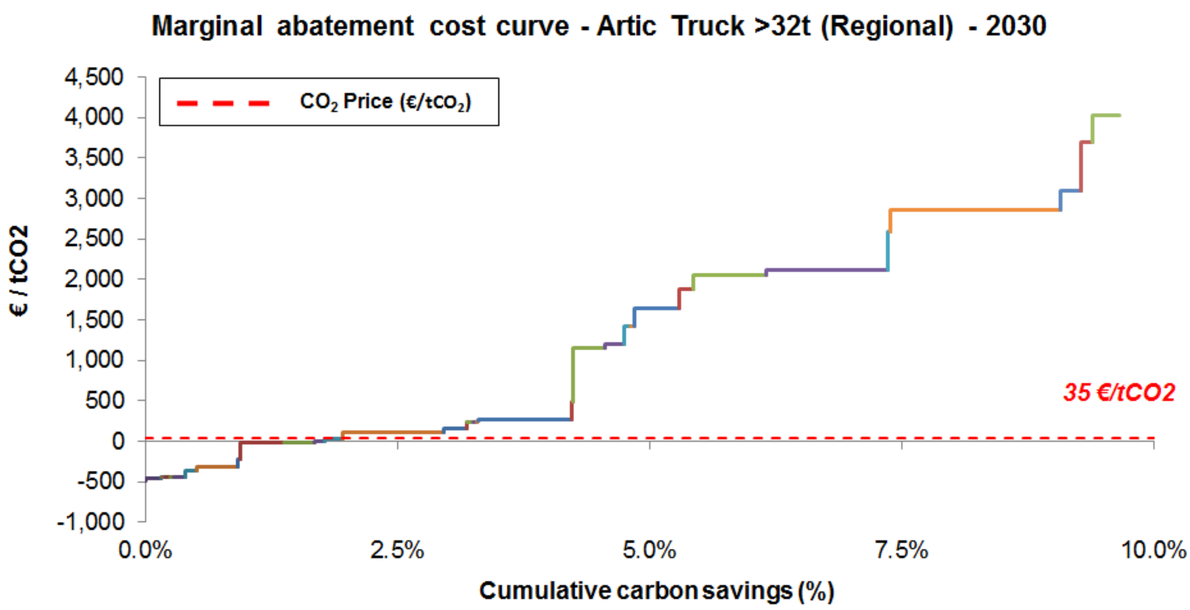


Table 4.23: Calculated cost-effective weight reduction potential (%) versus 2015 baseline vehicle – Regional delivery cycle

Vehicle type	2020	2025	2030	2040	2050
Average	**4.9%**	**8.6%**	**9.9%**	**10.1%**	**10.2%**
<7.5t	5.0%	10.9%	12.5%	12.5%	13.0%
7.5-16t	5.9%	9.6%	11.1%	11.1%	11.1%
16-32t	5.6%	10.4%	10.7%	10.7%	10.7%
>32t	2.6%	2.6%	5.4%	6.2%	6.2%

Table 4.24: Calculated CO_2 savings potential (%) versus baseline vehicle for model year for cost-effective weight-reduction – Regional delivery cycle

Vehicle type	2020	2025	2030	2040	2050
Average	**1.12%**	**1.94%**	**2.28%**	**2.34%**	**2.36%**
<7.5t	0.92%	2.04%	2.34%	2.34%	2.43%
7.5-16t	1.18%	1.97%	2.28%	2.28%	2.28%
16-32t	1.35%	2.56%	2.63%	2.63%	2.64%
>32t	0.80%	0.82%	1.68%	1.95%	1.95%

Table 4.25: Calculated improvement in freight efficiency (gCO_2/tkm) versus baseline vehicle for model year for cost-effective weight-reduction – Regional delivery cycle

Vehicle type	2020	2025	2030	2040	2050
Average	**-1.6**	**-2.9**	**-3.2**	**-3.2**	**-3.2**
<7.5t	-2.4	-5.1	-5.7	-5.6	-5.7
7.5-16t	-2.4	-4.0	-4.5	-4.4	-4.3
16-32t	-1.3	-2.4	-2.4	-2.3	-2.3
>32t	-0.5	-0.5	-1.1	-1.2	-1.2

4.3.4 Construction trucks

The 2020 and 2030 cost curves for all weight categories of construction trucks are found in Figure 4.15 to Figure 4.17. Once again, the red dashed line is the corresponding price of CO_2 in each time period. Table 4.26 to Table 4.28 also provide a full time-series summary to 2050 of the level of estimated cost-effective weight reduction, the corresponding percentage fuel / CO_2 savings potential, and the impact on overall freight CO_2 efficiency (in gCO_2/tonne-km).

The results show that in 2020, on average, construction trucks might achieve a 3.8% reduction in weight as a result of the lightweighting options that are available and cost-effective over the lifetime of the vehicle (from a societal perspective). This reduction equates to a 1.4% saving in CO_2 emissions taking into account the duty cycle and average payload of the vehicle.

By 2030, this weight reduction potential could potentially reach almost 10% on a similar cost-effective basis, leading to a 3.7% saving in CO_2 emissions. This level of weight reduction is the higest across all duty cycles analysed within the study. In fact, across 2020 to 2050, construction trucks have the greatest potential for lightweighting and corresponding percentage fuel / CO_2 savings of all trucks.

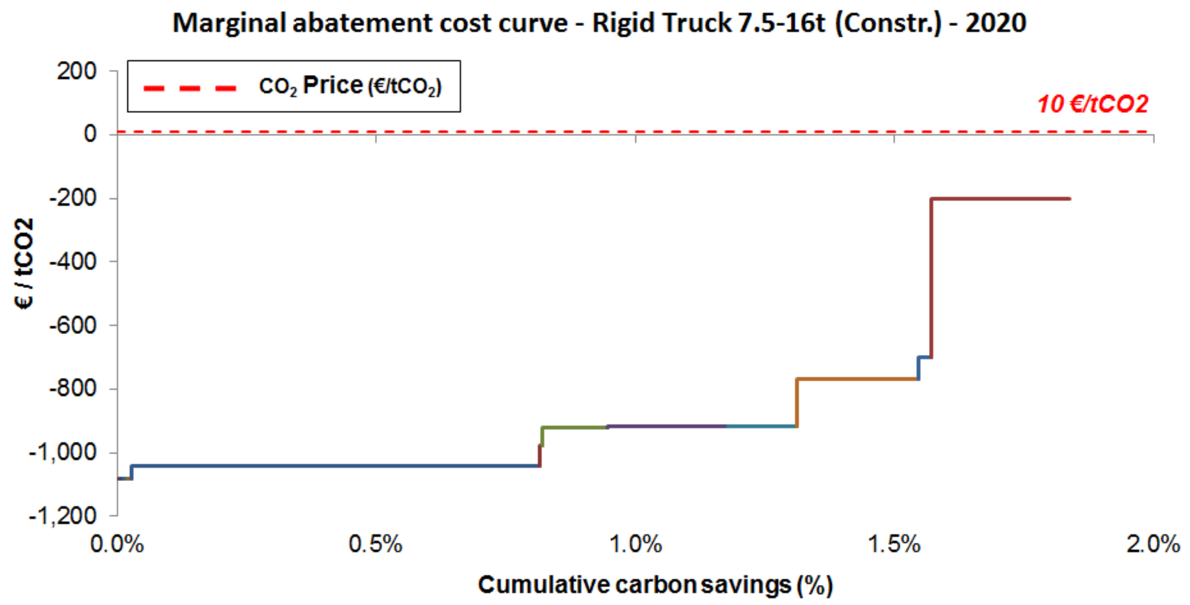
In terms of variability across the weight classes, in 2030 (where all technical options identified are assumed to be available), the calculated maximum feasible CO_2 reduction potential varies between ~10% for the smallest trucks, to ~12% for the largest. That being said, by 2050, the level of lifetime cost effective weight/CO_2 reduction for 7.5-16 tonne construction trucks is considerably greater than the two smaller construction trucks (see Table 4.26).

The estimated impacts on freight CO_2 efficiency are also presented in Table 4.28; this shows that by 2030, cost-effective lightweighting for construction vehicles could improve freight CO_2 efficiency by 5.9 gCO_2 per tonne-km.

As with the other modes, in later periods there is some variability in the calculated cost-effective potential for certain vehicle and duty cycle combinations, which is due to the relative interaction of the projected future technology costs, fuel prices, and baseline vehicle efficiencies.

A comparison is also presented in Figure 4.18 for the alternative cost-curve for 2030 articulated truck over the construction cycle, with the high average % weight limited operation (WLO) assumptions, which shows significantly higher cost-effective CO_2 reduction potential at 4.4% (vs 2.9% under low %WLO). In the fully weight-limited case this cost-effective CO_2 savings potential increases even further to 6.3%.

Figure 4.15: Marginal abatement cost curves for 7.5-16 tonne truck over the construction cycle



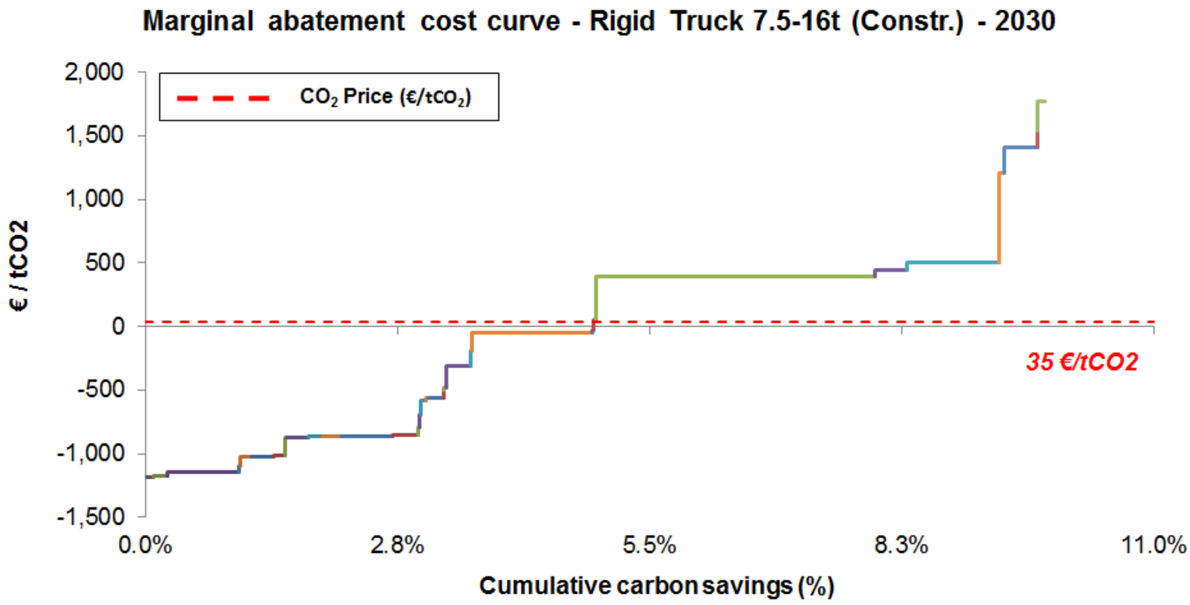
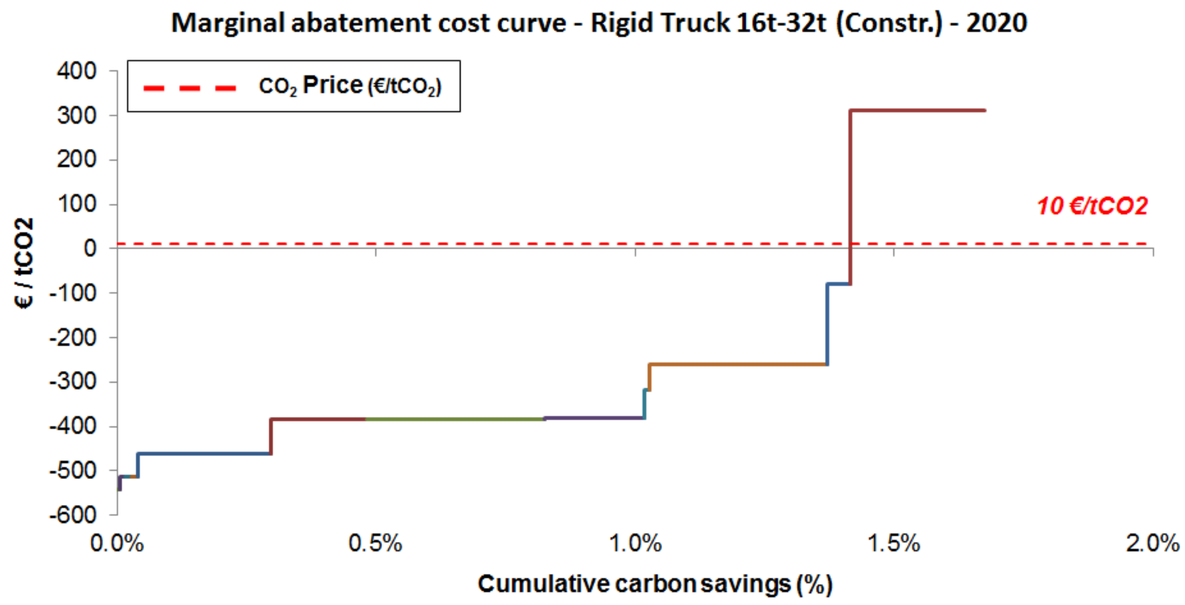


Figure 4.16: Marginal abatement cost curves for 16-32 tonne truck over the construction cycle



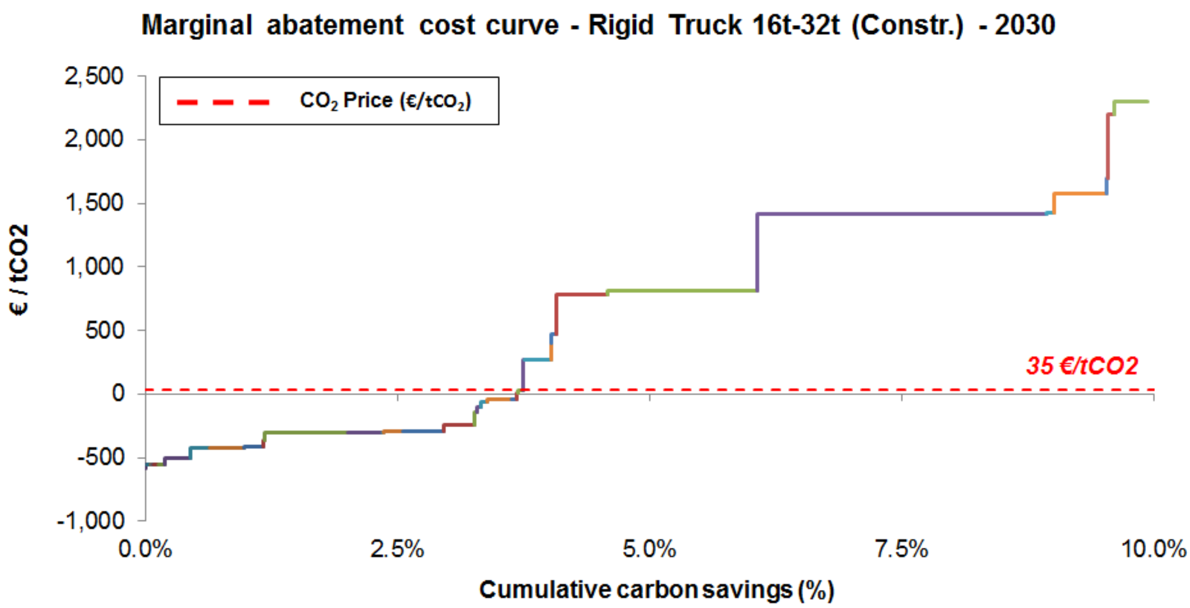
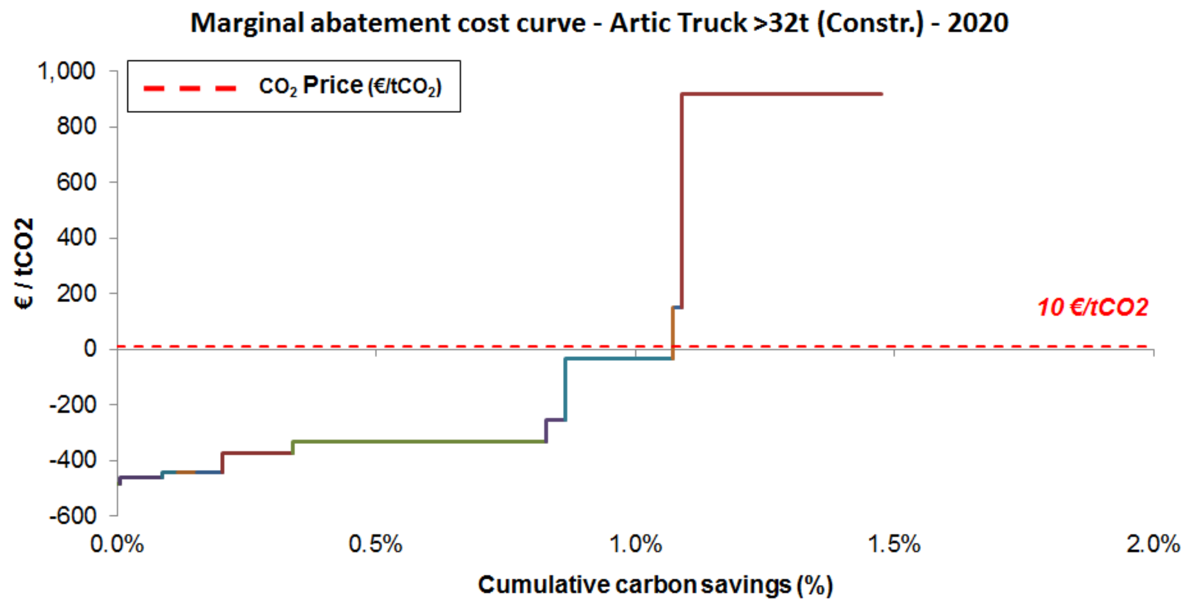


Figure 4.17: Marginal abatement cost curves for >32 tonne truck over the construction cycle



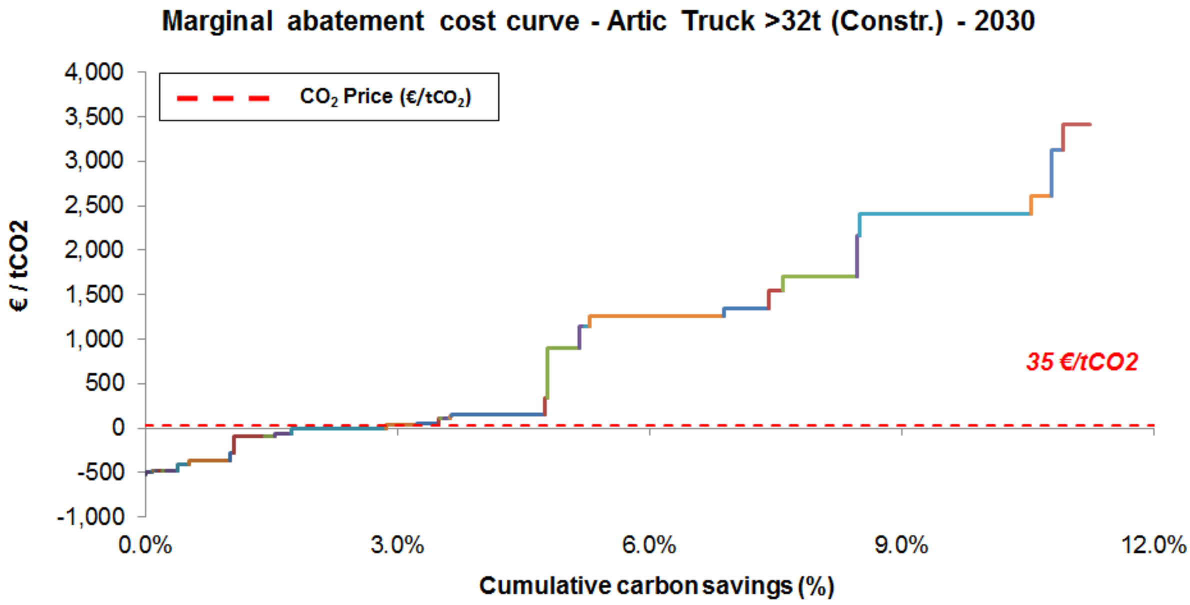


Figure 4.18: Marginal abatement cost curves for >32 tonne truck over the construction cycle (high average % weight limited operation)

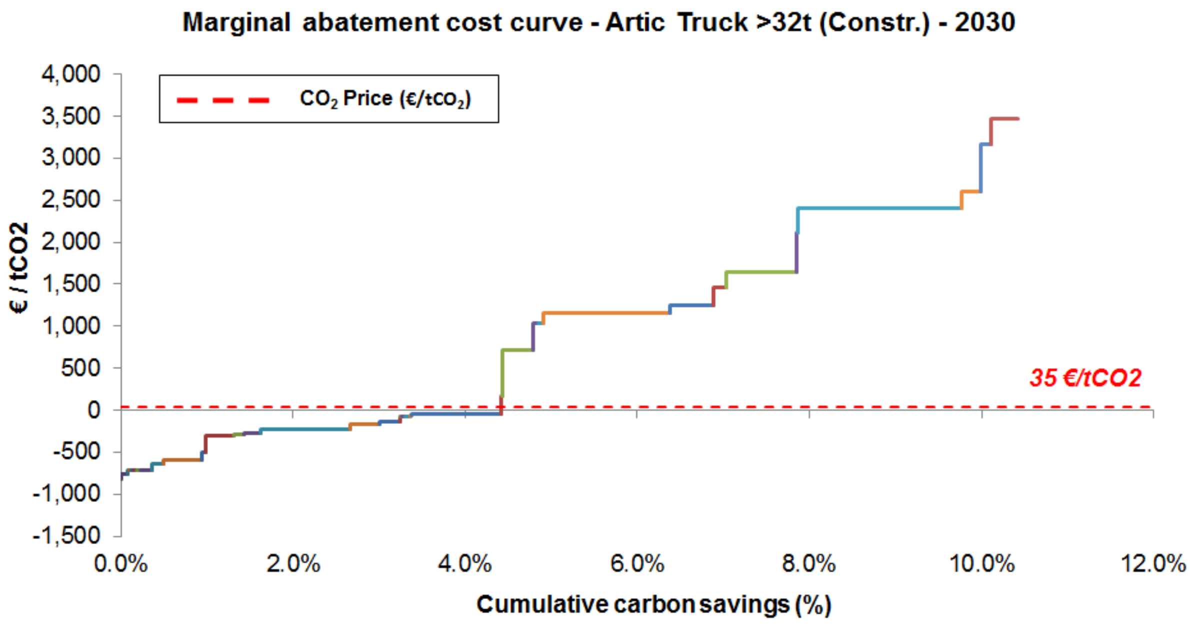


Table 4.26: Calculated cost-effective weight reduction potential (%) versus 2015 baseline vehicle – Construction cycle

Vehicle type	2020	2025	2030	2040	2050
Average	**3.8%**	**8.2%**	**9.9%**	**12.0%**	**13.5%**
7.5-16t	6.1%	14.3%	15.4%	26.1%	28.0%
16-32t	3.4%	8.1%	8.9%	9.1%	10.3%
>32t	2.9%	4.3%	8.1%	8.1%	9.8%

Table 4.27: Calculated CO_2 savings potential (%) versus baseline vehicle for model year for cost-effective weight-reduction – Construction cycle

Vehicle type	2020	2025	2030	2040	2050
Average	**1.40%**	**3.05%**	**3.67%**	**4.38%**	**4.94%**
7.5-16t	1.84%	4.52%	4.88%	8.39%	9.02%
16-32t	1.42%	3.34%	3.68%	3.74%	4.25%
>32t	1.07%	1.59%	2.87%	2.87%	3.50%

Table 4.28: Calculated improvement in freight efficiency (gCO_2/tkm) versus baseline vehicle for model year for cost-effective weight-reduction – Construction cycle

Vehicle type	2020	2025	2030	2040	2050
Average	**-2.4**	**-5.3**	**-5.9**	**-7.5**	**-8.2**
7.5-16t	-4.9	-11.8	-12.4	-20.8	-22.0
16-32t	-2.2	-5.0	-5.4	-5.3	-5.9
>32t	-1.1	-1.5	-2.7	-2.6	-3.2

4.3.5 Long haul trucks

The 2020 and 2030 cost curves for all weight categories of long haul trucks are found in Figure 4.19 and Figure 4.20. Once again, the red dashed line is the corresponding price of CO_2 in each time period. Table 4.29 to Table 4.31 also provide a full time-series summary to 2050 of the level of estimated cost-effective weight reduction, the corresponding percentage fuel / CO_2 savings potential, and the impact on overall freight CO_2 efficiency (in gCO_2/tonne-km).

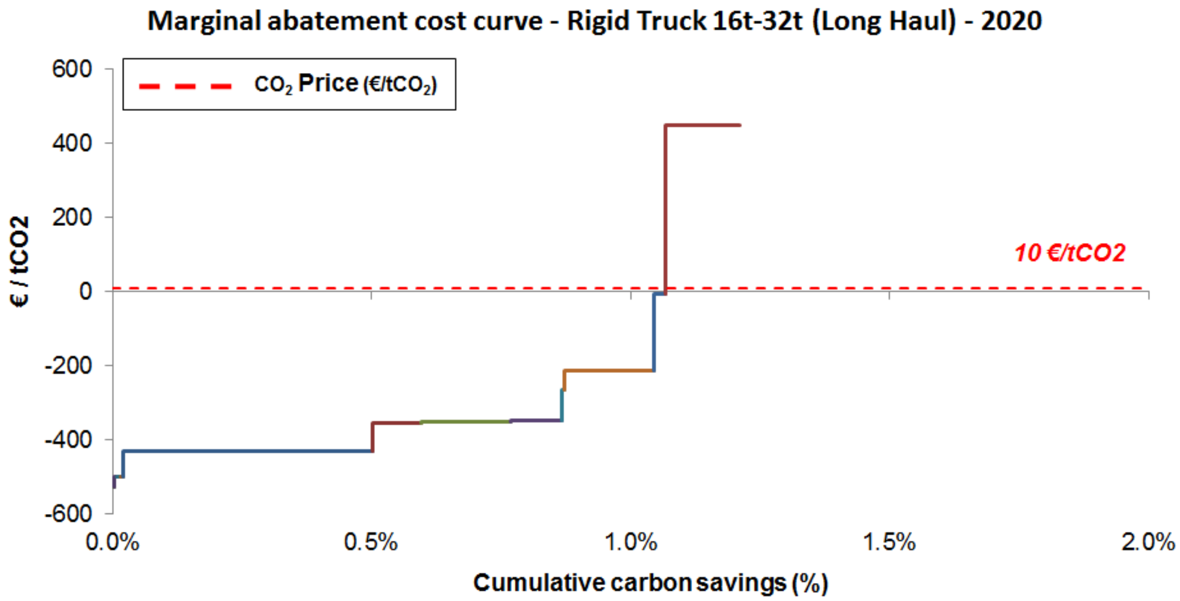
The results show that in 2020, on average, long haul trucks might achieve a 4.1% reduction in weight as a result of the lightweighting options that are available and cost-effective over the lifetime of the vehicle (from a societal perspective). This reduction equates to a little under 0.9% saving in CO_2 emissions taking into account the duty cycle and average payload of the vehicle.

By 2030, this weight reduction potential could potentially reach 8% on a similar cost-effective basis, leading to almost 1.7% saving in CO_2 emissions.

There is a small degree of variability across the two weight categories of long haul trucks with respect to the cost-effective weight/CO_2 reduction. By 2030 (where all technical options identified are assumed to be available), the calculated cost effective CO_2 reduction potential varies between ~6% for the smaller truck, to ~7% for the larger.

The estimated impacts on freight CO_2 efficiency is also presented in Table 4.31; this shows that by 2030, cost-effective lightweighting for long haul trucks could improve freight CO_2 efficiency by a little over 1 gCO_2 per tonne-km.

Figure 4.19: Marginal abatement cost curves for 16-32 tonne truck over the Long haul cycle



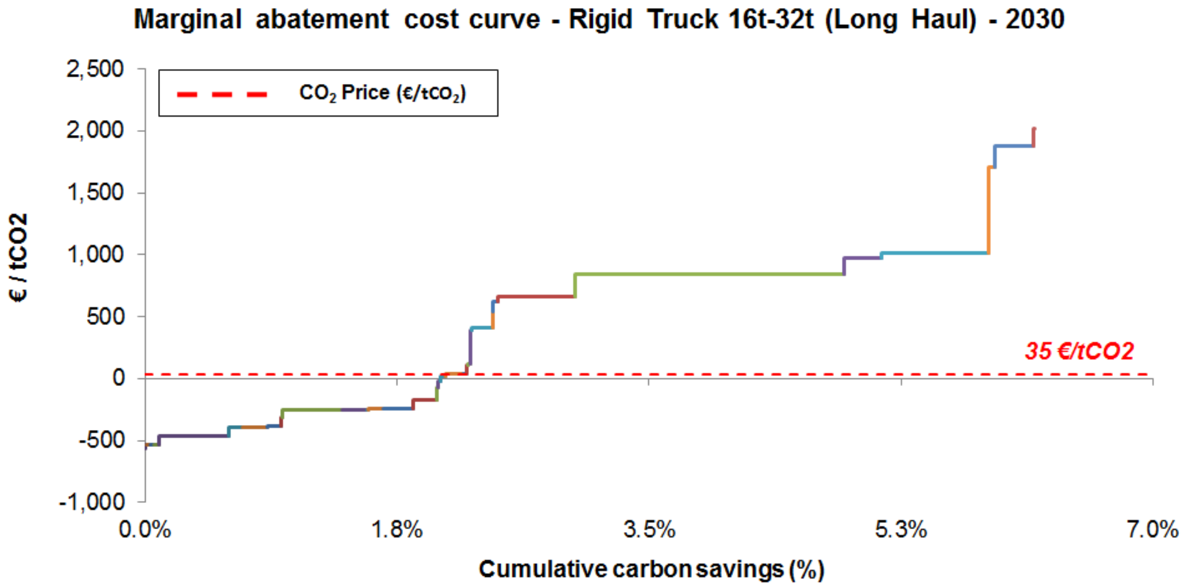
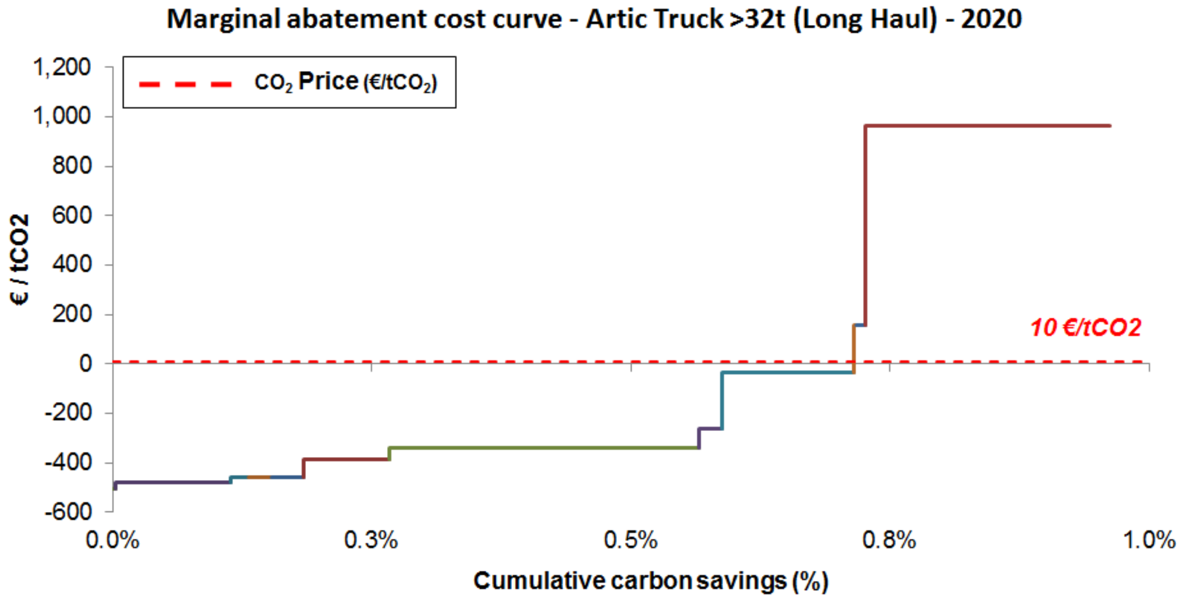


Figure 4.20: Marginal abatement cost curves for >32 tonne truck over the Long haul cycle



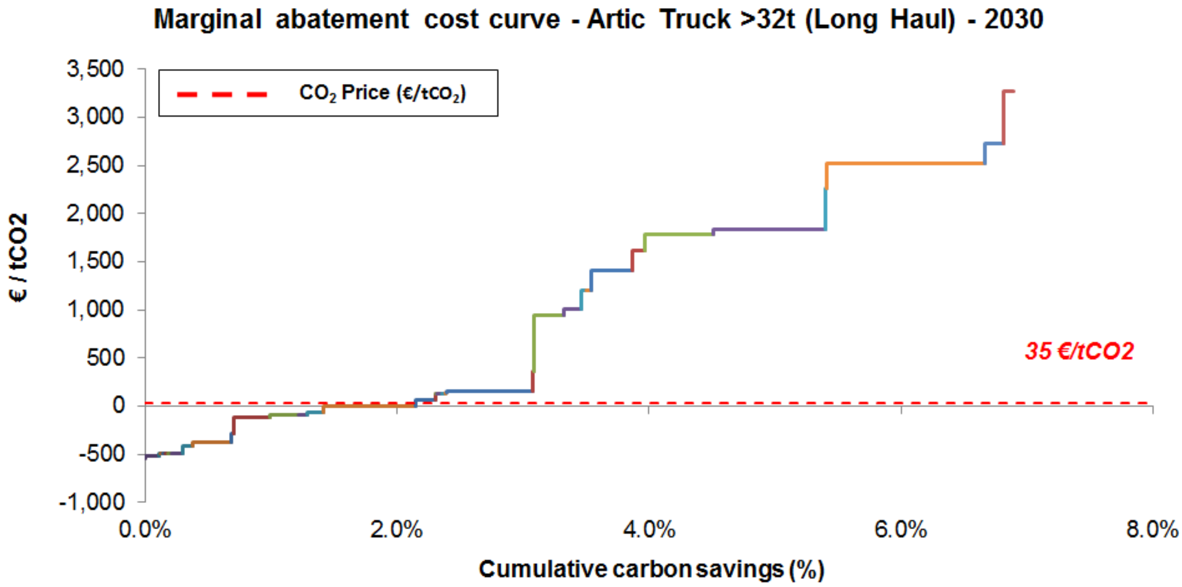


Table 4.29: Calculated cost-effective weight reduction potential (%) versus 2015 baseline vehicle – Long haul cycle

Vehicle type	2020	2025	2030	2040	2050
Average	**4.1%**	**7.6%**	**8.0%**	**10.1%**	**10.6%**
16-32t	5.8%	10.6%	10.9%	11.1%	11.1%
>32t	3.1%	5.8%	6.2%	9.5%	10.2%

Table 4.30: Calculated CO_2 savings potential (%) versus baseline vehicle for model year for cost-effective weight-reduction – Long haul cycle

Vehicle type	2020	2025	2030	2040	2050
Average	**0.85%**	**1.58%**	**1.66%**	**2.13%**	**2.23%**
16-32t	1.07%	2.00%	2.05%	2.11%	2.11%
>32t	0.72%	1.32%	1.42%	2.15%	2.31%

Table 4.31: Calculated improvement in freight efficiency (gCO_2/tkm) versus baseline vehicle for model year for cost-effective weight-reduction – Long haul cycle

Vehicle type	2020	2025	2030	2040	2050
Average	**-0.7**	**-1.3**	**-1.3**	**-1.6**	**-1.6**
16-32t	-0.9	-1.6	-1.7	-1.7	-1.6
>32t	-0.6	-1.0	-1.1	-1.6	-1.7

4.3.6 Buses and Coaches

The 2020 and 2030 cost curves for buses and coaches are found in Figure 4.21 and Figure 4.22. Once again, the red dashed line is the corresponding price of CO_2 in each time period. Table 4.32 to Table 4.34 also provide a full time-series summary to 2050 of the level of estimated cost-effective weight reduction, the corresponding percentage fuel / CO_2 savings potential, and the impact on overall freight CO_2 efficiency (in gCO_2/tonne-km).

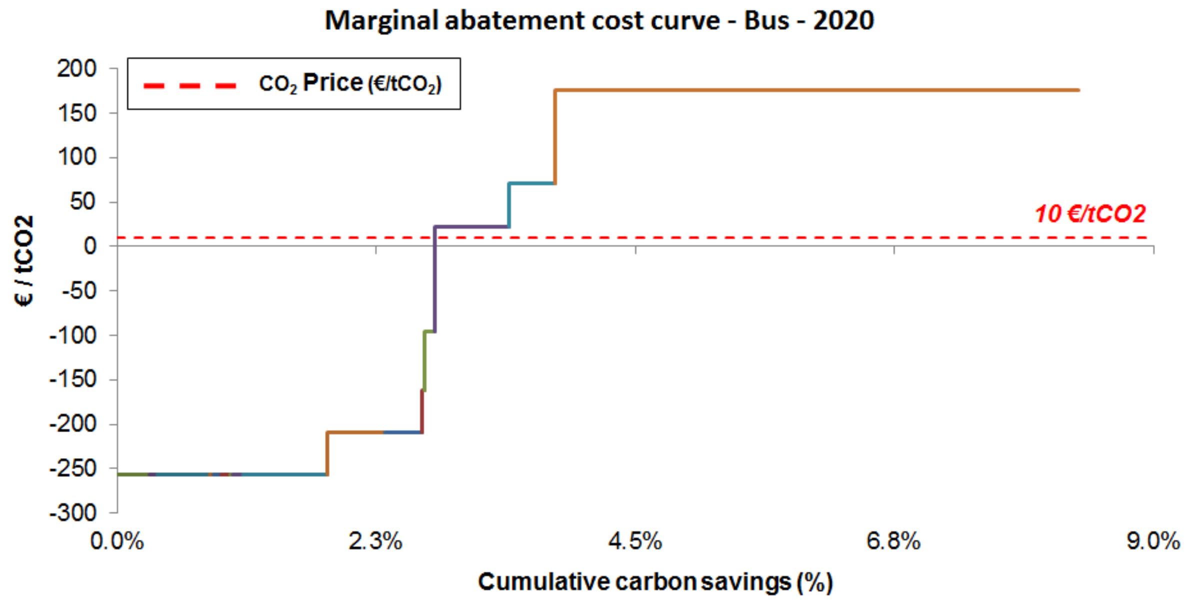
The results show that in 2020, buses and coaches might achieve a 3.5% and 2.3% reduction in weight respectively, as a result of the lightweighting options that are available and cost-effective over the lifetime of the vehicle (from a societal perspective). This reduction equates to a little under 2.8% and 0.9% savings in CO_2 emissions.

By 2030, this weight reduction potential could potentially reach almost 8% for buses and almost 4% for coaches on a similar cost-effective basis, leading to a 6.6%/1.4% saving in CO_2 emissions.

There is a considerable level of variation between these two modes. In the 2030 case (where all technical options identified are assumed to be available), the calculated maximum feasible CO_2 reduction potential varies between ~28% for buses, to ~12% for coaches.

The estimated impacts on freight CO_2 efficiency is also presented in Table 4.34; this shows that by 2030, cost-effective lightweighting for buses and coaches could improve freight CO_2 efficiency by 46.7 and 4.5 gCO_2 per tonne-km respectively. This considerable difference between the two modes is a reflection of the differing levels of lightweighting options available to buses and coaches.

Figure 4.21: Marginal abatement cost curves for buses



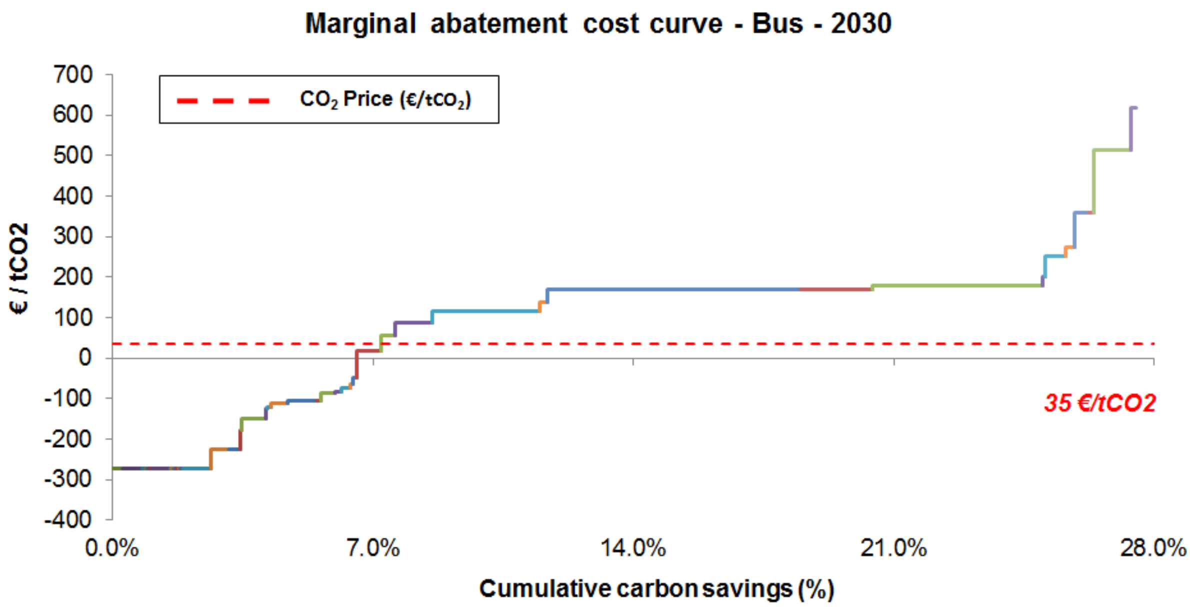
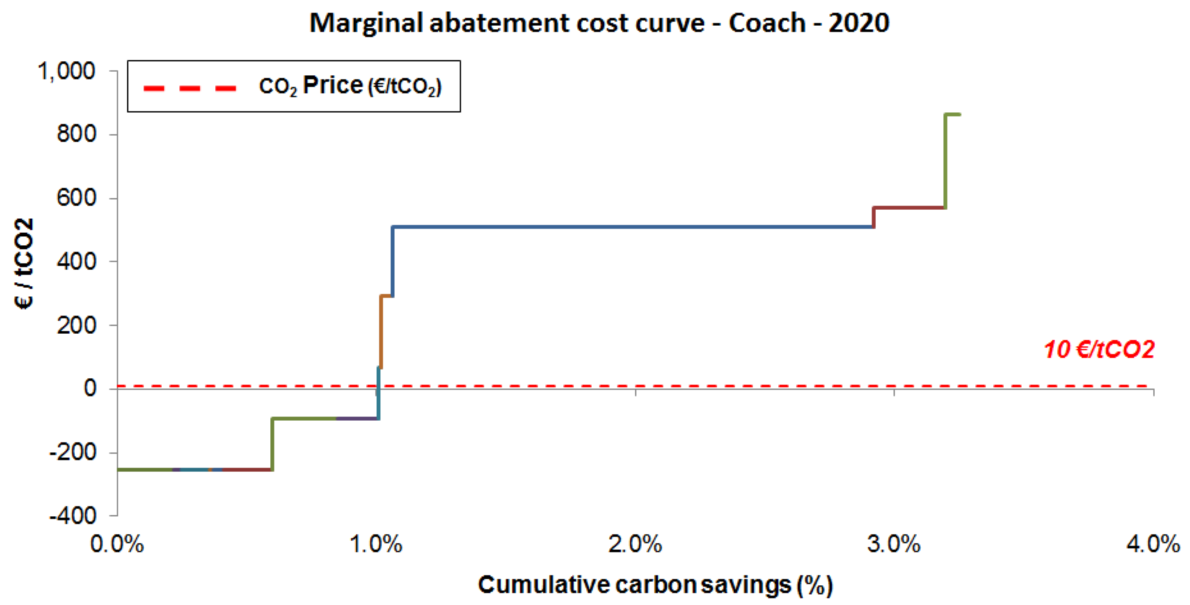


Figure 4.22: Marginal abatement cost curves for coaches



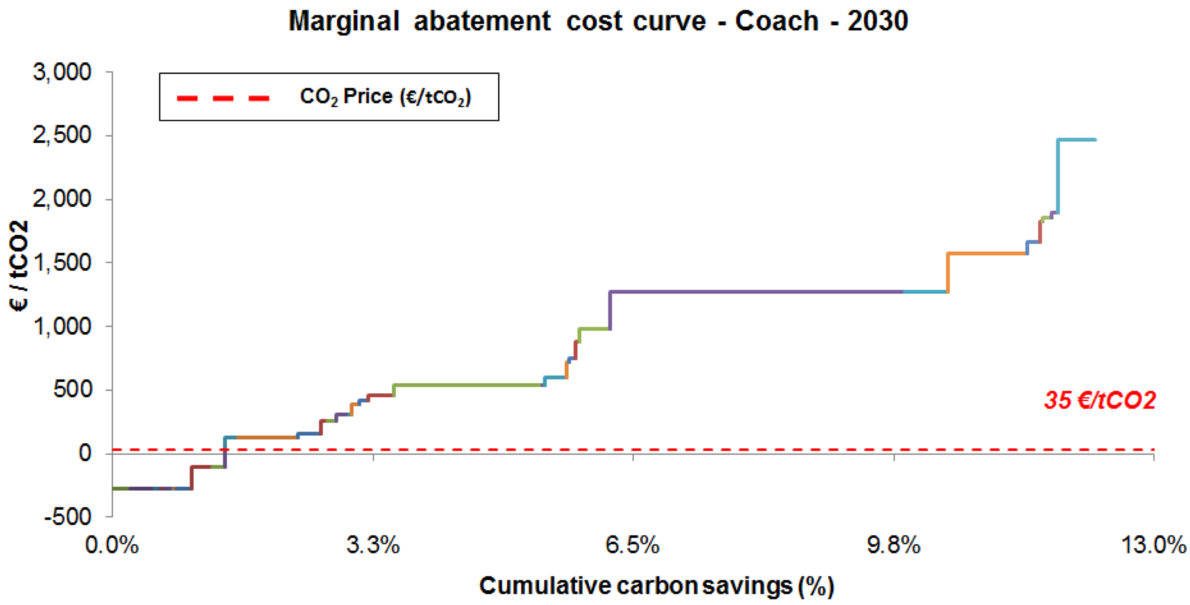


Table 4.32: Calculated cost-effective weight reduction potential (%) versus 2015 baseline vehicle – Bus/Coach

Vehicle type	2020	2025	2030	2040	2050
Average	**2.8%**	**4.2%**	**5.4%**	**5.1%**	**10.5%**
Bus	3.5%	7.1%	8.0%	8.0%	20.5%
Coach	2.3%	2.4%	3.8%	3.3%	4.2%

Table 4.33: Calculated CO_2 savings potential (%) versus baseline vehicle for model year for cost-effective weight-reduction – Bus/Coach

Vehicle type	2020	2025	2030	2040	2050
Average	**1.58%**	**2.78%**	**3.38%**	**3.28%**	**7.54%**
Bus	2.76%	5.81%	6.56%	6.56%	17.12%
Coach	0.85%	0.89%	1.40%	1.24%	1.57%

Table 4.34: Calculated improvement in freight efficiency (gCO_2/tkm) versus baseline vehicle for model year for cost-effective weight-reduction – Bus/Coach

Vehicle type	2020	2025	2030	2040	2050
Average	**-9.7**	**-18.2**	**-20.7**	**-20.0**	**-48.2**
Bus	-20.5	-42.7	-46.7	-45.8	-117.8
Coach	-2.9	-3.0	-4.5	-3.9	-4.7

4.3.7 Overall summary

Table 4.35 to Table 4.37, and Figure 4.23, provide a summary of the overall average cost-effective weight reduction potential, CO_2 savings and impact on freight CO_2 efficiency for different HDV duty cycles.

Looking across all HDV modes, all trucks other than utility trucks are expected to be able to achieve at least a 7% reduction in weight cost-effectively by 2025, under the defined social perspective and payback over the lifetime of the vehicle. By 2050, construction trucks have the most light-weighting potential, expected to be able to reduce weight cost effectively by over 13%.

At the other end, utility trucks have least potential for cost-effective lightweighting with only around 4-5% weight reduction estimated to be attainable throughout all time period.

With respect to CO_2 savings, construction trucks appear to have the greatest cost-effective potential here. Over 3.6% cost-effective CO_2 savings may be achievable by 2030 and 5% by 2050. These figures are substantially greater than that possible of the other truck duty cycles. One of the principal factors contributing to this is their estimated greater levels of weight-limited operation.

Buses have the highest cost-effective weight reduction potential of all HDVs with over 20% cost-effective lightweighting estimated to be possible by 2050. This equates to around 17% reduction in CO_2, due to the highly transient nature of bus duty cycles, with frequent stops. In contrast, coaches are anticipated to have some of the lowest levels of cost-effective weight reduction potential of any HDV type.

The estimated impacts on freight CO_2 efficiency is also presented in Table 4.37; this shows that by 2030, cost-effective lightweighting an average truck could improve freight CO_2 efficiency by over 4 gCO_2 per tonne-km and almost 5 gCO_2 per tonne-km by 2050.

For buses and coaches, on average, by 2030, freight efficiency could be reduced by almost 21 gCO_2 per tonne-km, rising to over 48 gCO_2 per tonne-km by 2050. It should be pointed out here that the baseline freight efficiency of buses and coaches is far greater than that of trucks and therefore the relative reductions in freight efficiency are more comparable between trucks and bus/coaches.

An additional sensitivity is presented in Figure 4.24 for the case using the high average % weight limited operation estimates (see earlier Table 3.28). In this case the average cost-effective CO_2 reduction % is appreciably higher on average for trucks, and in particular for construction vehicles, which are more frequently weight-limited.

Table 4.35: Calculated cost-effective weight reduction potential (%) versus 2015 baseline vehicle

Vehicle type	2020	2025	2030	2040	2050
Average Truck	**4.1%**	**7.4%**	**8.6%**	**9.8%**	**10.2%**
Urban	4.4%	8.4%	10.3%	11.5%	11.8%
Utility	3.7%	4.0%	4.6%	4.6%	4.6%
Regional	4.9%	8.6%	9.9%	10.1%	10.2%
Construction	3.8%	8.2%	9.9%	12.0%	13.5%
Long Haul	4.1%	7.6%	8.0%	10.1%	10.6%
Average Bus	**2.8%**	**4.2%**	**5.4%**	**5.1%**	**10.5%**
Bus	3.5%	7.1%	8.0%	8.0%	20.5%
Coach	2.3%	2.4%	3.8%	3.3%	4.2%

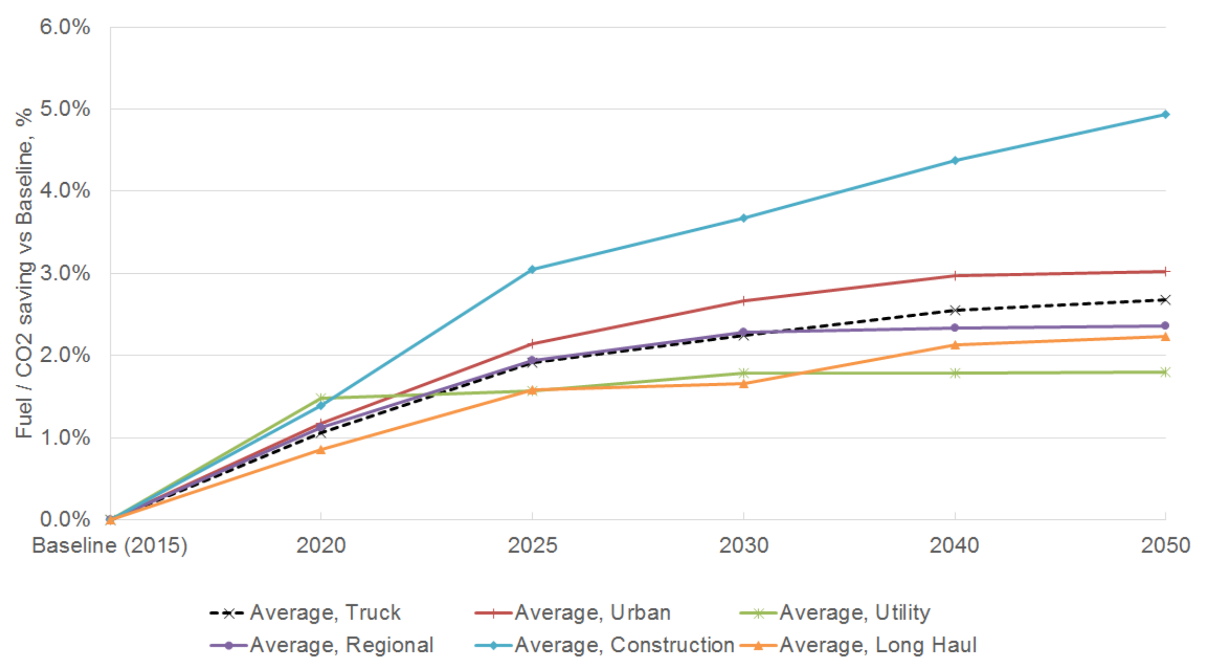
Table 4.36: Calculated CO_2 savings potential (%) versus baseline vehicle for model year for cost-effective weight-reduction

Vehicle type	2020	2025	2030	2040	2050
Average Truck	**1.06%**	**1.91%**	**2.24%**	**2.56%**	**2.68%**
Urban	1.17%	2.14%	2.67%	2.97%	3.03%
Utility	1.48%	1.57%	1.78%	1.78%	1.80%
Regional	1.12%	1.94%	2.28%	2.34%	2.36%
Construction	1.40%	3.05%	3.67%	4.38%	4.94%
Long Haul	0.85%	1.58%	1.66%	2.13%	2.23%
Average Bus	**1.58%**	**2.78%**	**3.38%**	**3.28%**	**7.54%**
Bus	2.76%	5.81%	6.56%	6.56%	17.12%
Coach	0.85%	0.89%	1.40%	1.24%	1.57%

Table 4.37: Calculated improvement in freight efficiency (gCO_2/tkm) versus baseline vehicle for model year due to cost-effective weight-reduction

Vehicle type	2020	2025	2030	2040	2050
Average Truck	**-2.0**	**-3.6**	**-4.2**	**-4.6**	**-4.8**
Urban	-3.2	-6.2	-7.4	-8.1	-8.1
Utility	-3.6	-3.8	-4.3	-4.2	-4.2
Regional	-1.6	-2.9	-3.2	-3.2	-3.2
Construction	-2.4	-5.3	-5.9	-7.5	-8.2
Long Haul	-0.7	-1.3	-1.3	-1.6	-1.6
Average Bus	**-9.7**	**-18.2**	**-20.7**	**-20.0**	**-48.2**
Bus	-20.5	-42.7	-46.7	-45.8	-117.8
Coach	-2.9	-3.0	-4.5	-3.9	-4.7

Figure 4.23: Calculated CO_2 savings potential (%) versus baseline vehicle for model year for cost-effective weight-reduction



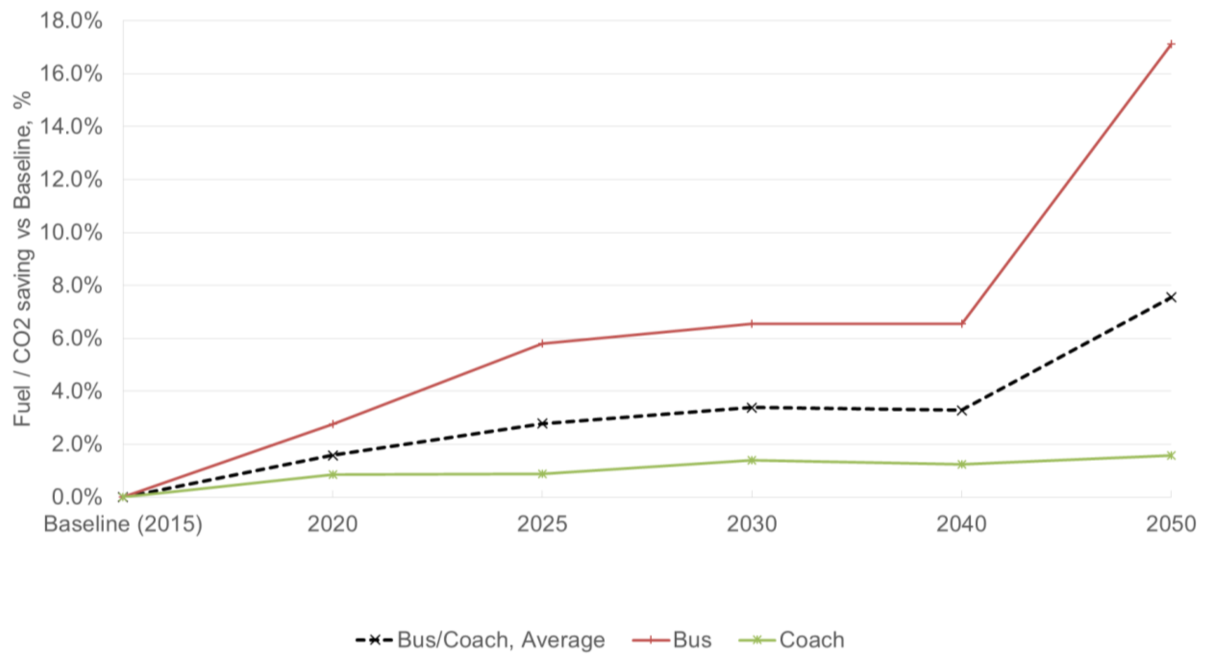
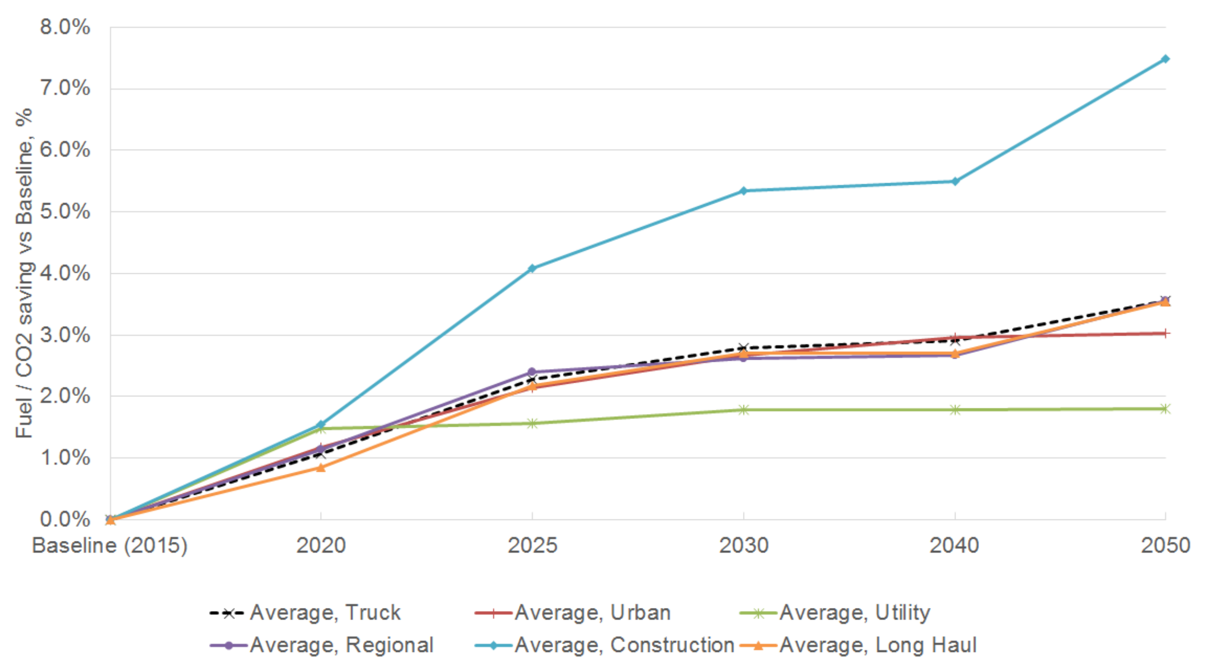


Figure 4.24: Calculated CO_2 savings potential (%) versus baseline vehicle for model year for cost-effective weight-reduction (high average % weight limited operation)



5 Task 4: An assessment of the cost-effective lightweighting potential

Box 5: Key points for Task 4

Objectives:

- **Carry out an assessment of the cost-effective lightweighting potential for different categories of HDVs**

Key subtasks:

- **Task 4.1: Define basis for assessment based on developed MACCs and other considerations**
- **Task 4.2: Carry out assessment and develop results and outputs for Task 5**

Outputs:

- **Results provided as inputs to the draft/final report and to the Task 5 EU fleet modelling**

5.1 Overview of Task 4

This Task covers the definition/characterisation of the scenarios investigated using the modelling described under Task 5 (section 6) in the assessment of the cost-effective potential for HDV lightweighting for different HDV categories. As such this task provides a linkage between the analysis/outputs from the Task 4 MACC development, the EU HDV fleet modelling in Task 5 and the estimation of the fuel consumption and GHG emissions reduction potential. Work on Task 4 was split into two parts:

- *Task 4.1: Define basis for assessment based on developed MACCs:* This subtask established and agreed the combination of values/assumptions for the key criteria (i.e. cost, payback period, fuel price trajectory, etc.) to be used to identify the likely cost-effective potential for lightweighting for different HDV categories for the 'state-of-the-art' and 'future/forward-looking potential' scenarios and a range of variants.
- *Task 4.2: Carry out assessment and develop results and outputs for Task 5:* Based on the agreement of core scenario assumptions and variants from Task 4.1, we have developed trajectories (to 2050) for cost-effective lightweighting potential by HDV category.

The following sections provide a summary of the work completed under this task.

5.2 Definition of sensitivity analyses on cost-effective potential

In order to assess the overall sensitivity of the results of the baseline MACC analysis presented in Section 4 to variations in key parameters/assumptions, a range of alternative scenarios were explored using the developed MACC model functionality. A summary of the different sensitivity parameters and the specific variations explored is provided in the following Table 5.1 below.

Table 5.1: Summary of sensitivites explored

Sensitivity	Variations	Notes
Technical options	• Default (SOTA and future) options • SOTA only	Part of the original specification for the project was to compare what the potential might be for CO_2 savings from lightweighting when considering either only state-of-the-art (SOTA) technologies, or including also all potential future options identified.

Sensitivity	Variations	Notes
Share of weight limited operations	• None • Average low • Average high • Totally weight limited	Lightweighting has the potential to be most cost-effective for weight limited options. These sensitivities explored the potential impacts for the lower and higher average share of weight limited options, as well as a 'totally weight limited' case to see what levels of light weighting might be cost-effective for particularly weight-limited operations.
Costs of lightweighting measures	• Default • Low costs (-25%) • High costs (+25%)	The capital expenditure required for a lightweighting measure (in € per kg saved) is a key determinant for the extent of cost-effective uptake. Therefore a 'low costs' and 'high costs' case are explored to assess the impact of lightweighting measures becoming 25% cheaper/more expensive than in the default scenario.
Fuel prices	• Baseline • High • Very low	These sensitives provide an indication on the potential impact of future fuel prices on lightweighting. Given the very significant drop in fuel prices experienced in late 2014 and early 2015, the original 'low' fuel price scenario sensitivity was instead substituted for a 'very low' scenario to assess what the impact might be of a prolonged period of such lower fuel prices.
Annual km	• Default (Central) • Low (-25%) • High (+25%)	Average annual mileage is defined by duty cycle, according to Table 4.14; sensitivities were explored +/- 25% of the central values to investigate the relative cost-effectiveness of lightweighting for operations with different activity levels.
Social vs End User	• Social • End-user	This sensitivity assesses the impact on the available cost-effective potential for lightweighting depending on whether a social perspective is taken (with 4% discount rate and excluding fuel excise duty) versus an end-user perspective (with 8% discount rate and including fuel excise duty).
Payback period	• Vehicle lifetime (default • Default industry assumption	The default private payback period required for payback-limited cost-effectiveness calculations was set to 3 years for long-haul, the lifetime of the bus (15 years) for buses, and 5 years for other vehicles.
Vehicle fuel consumption	• Baseline (default) • Max cost-effective technical efficiency	Two HDV efficiency improvement scenarios were developed (detailed in earlier section 4.2.2.3). This sensitivity provides an indication of the relative attractiveness of lightweighting in the context of the uptake of other technical measures for improving the fuel efficiency of HDVs.

Notes: SOTA = state-of-the-art lightweighting options, i.e. those already available in the marketplace or developed and ready for implementation.

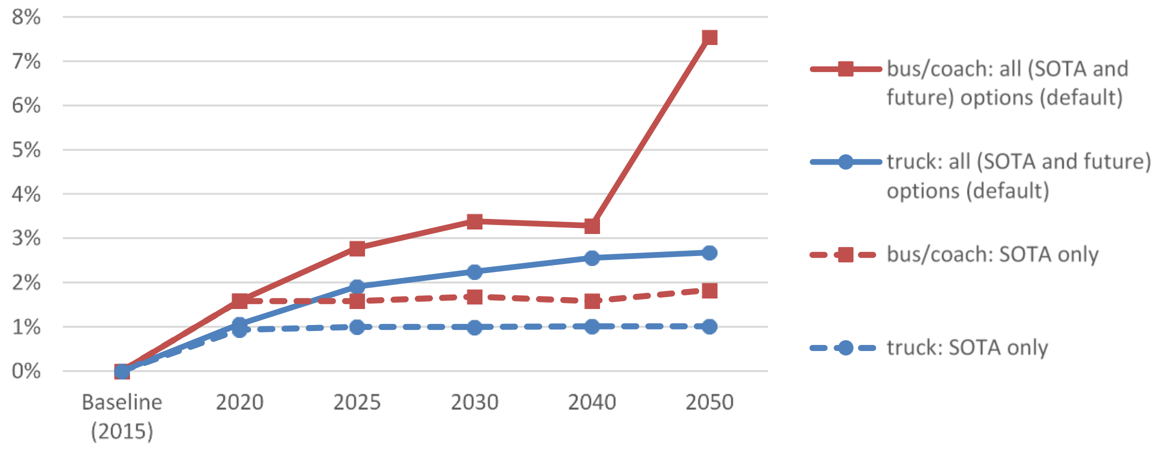
5.3 Results of sensitivity analyses on cost-effective potential

This section briefly discusses the results of each of the sensitivity cases outlined in Table 5.1. More detailed result figures can be found in Appendix 2.

5.3.1 Technical options

If the uptake of lightweighting measures is restricted to proven technologies (some design optimisation, use of higher strength steels, some structural use of aluminium and GFRP in semitrailers and buses/coaches) the cost-effective uptake of lightweighting measures and the associated fuel savings on the average HDV will likely approximately stagnate at the 2020 level going forwards according to the MACC analysis presented in Figure 5.1. Cost-effective savings in fuel/CO_2 achieved for SOTA technologies are only around 1% for trucks and 1.5% for buses, which represent less than half the cost-effective savings for all technical options for trucks, and an even lower proportion going forwards for buses.

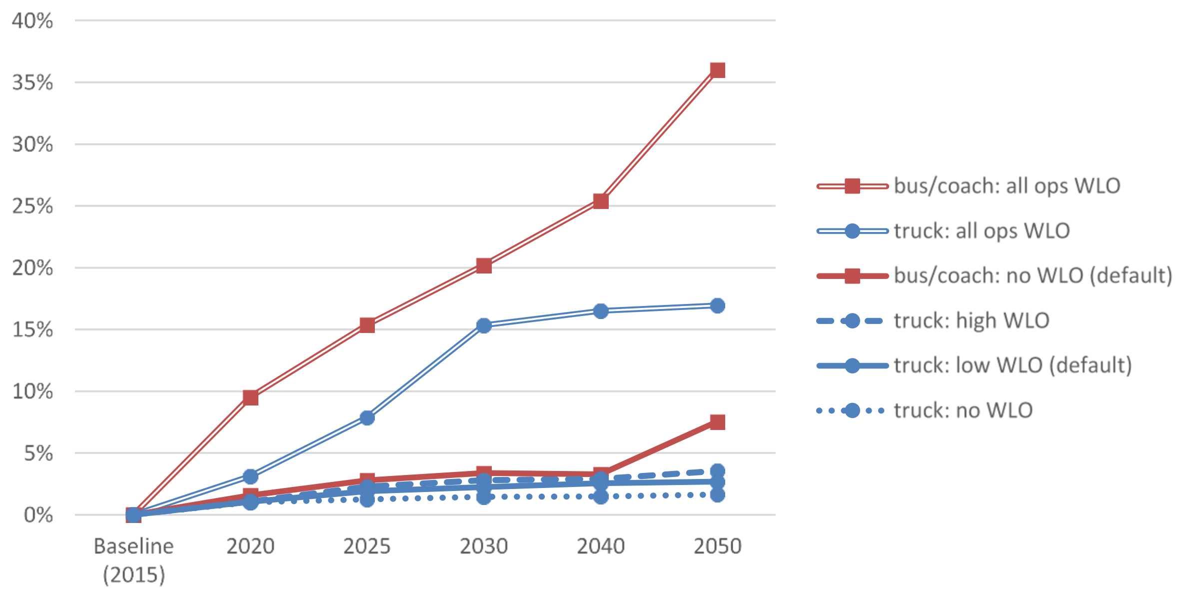
Figure 5.1: Sensitivity: Impact of restricting lightweighting uptake to measures currently available (SOTA) on fuel/CO_2 savings



5.3.2 Share of weight limited operations:

The default assumption is that on an average of 10% of truck vehicle km, the quantity of goods loaded is limited by the maximum permissible payload. Payload is increased though lightweighting measures which leads to fuel savings through a reduction in the number of trips. If there are no weight limited operations, and consequently no reduction in the number of trips is achieved, fuel savings from cost-effective truck lightweighting might be limited to some 1.5% up to 2050. This is partly because fewer lightweighting measures will be cost-effective, and partly because there is no fuel savings benefit from a reduced number of trips. If the high estimate of weight limited km (see earlier Table 3.28) is assumed fuel savings from trucks increase by a third to 3.7% by 2050; the default result (low WLO) being 2.7%. Under the extreme assumption that all truck km were weight limited (e.g. for niche operations), fuel savings due to cost-effective lightweighting might reach as high as 15% by 2030. For buses and coaches the figure increases to 36% by 2050. However, while buses and coaches may, when full, approach or exceed their maximum payload, no instances of genuine weight-limited operation are known, hence this is a somewhat artificial comparison.

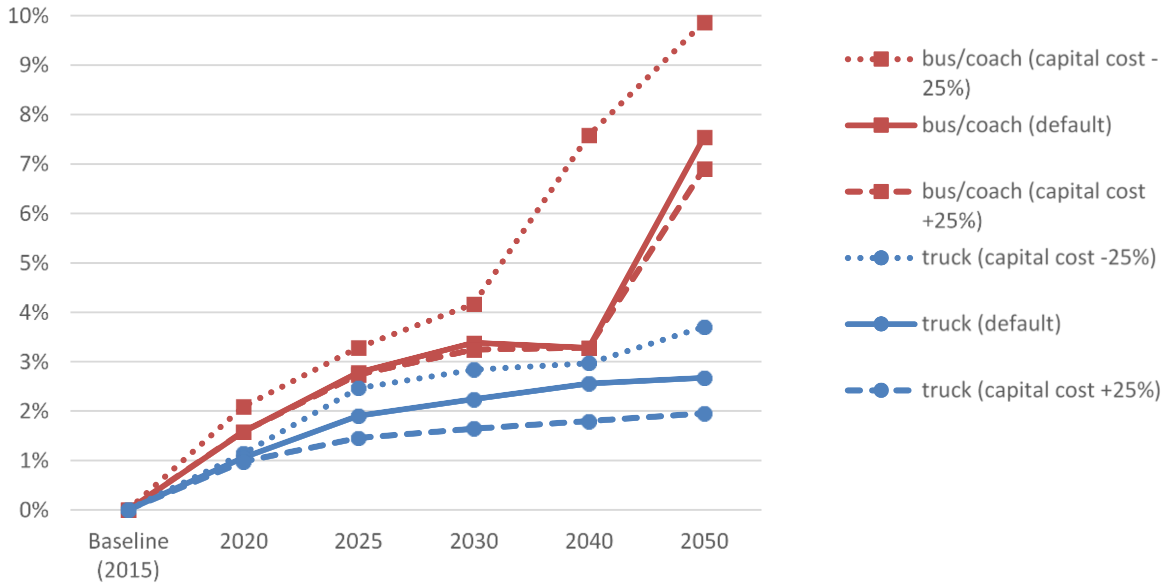
Figure 5.2: Sensitivity: Impact of altering the assumed share of weight limited operations (WLO) on fuel/CO2 savings



5.3.3 Costs of lightweighting measures

The impact of reducing the cost of lightweighting measures is limited up to 2025 for both trucks and buses/coaches. From 2030, the reduced cost of lightweighting has a significant impact on uptake and the resulting fuel savings in both vehicle types. The greatest impact is for trucks in 2050, where fuel savings increase by a third to 3.7% if lightweighting measures are 25% cheaper. In the case of 25% higher lightweighting costs uptake drops and fuel saving is reduced by a third. For buses/coaches, 25% lower capital costs lead to further fuel savings, reaching 10% in 2050. However, 25% higher capital cost has consistently little impact on uptake of lightweighting measures.

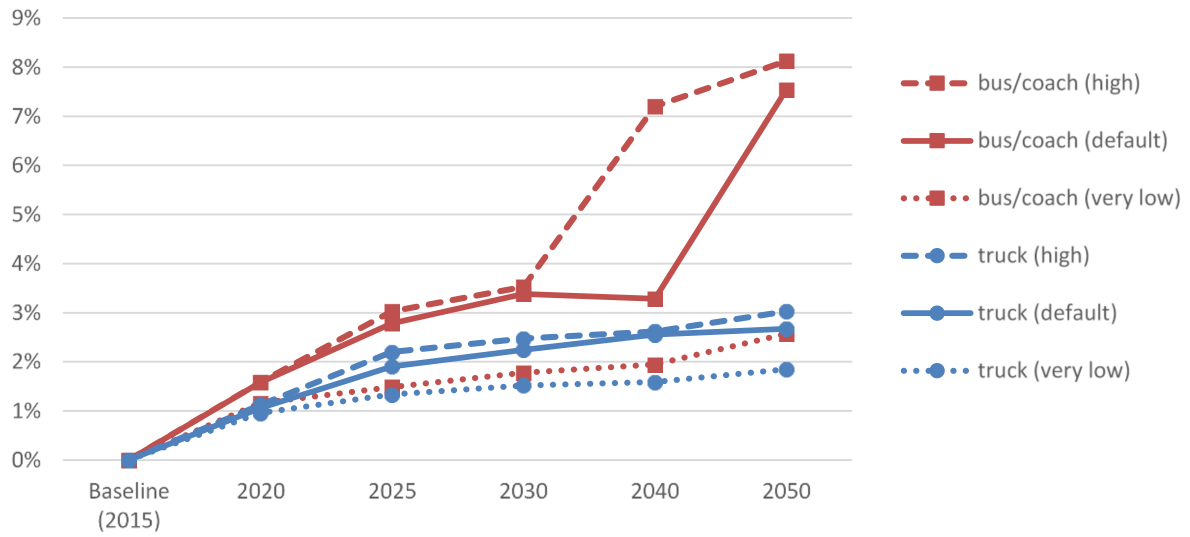
Figure 5.3: Sensitivity: Impact of altering the capital cost of lightweighting measures by ±25% on fuel/CO2 savings



5.3.4 Fuel prices

The impact of the 'very low' and 'high' fuel price scenarios on the uptake of lightweighting measures on trucks and resulting fuel savings is very limited up to 2020. From 2025, under the 'very low' scenario fuel savings from lightweighting are around a third lower than under the default scenario. Fuel savings in the 'high' scenario only exceed those of the default scenario by a small share. For buses and coaches, the impact of 'very low' fuel prices on fuel savings is more pronounced while fuel savings in the 'high' scenario are again only slightly greater than under the default scenario, except for the year 2040 where fuel savings from lightweighting already approach the level which the default fuel price scenario only reaches in 2050.

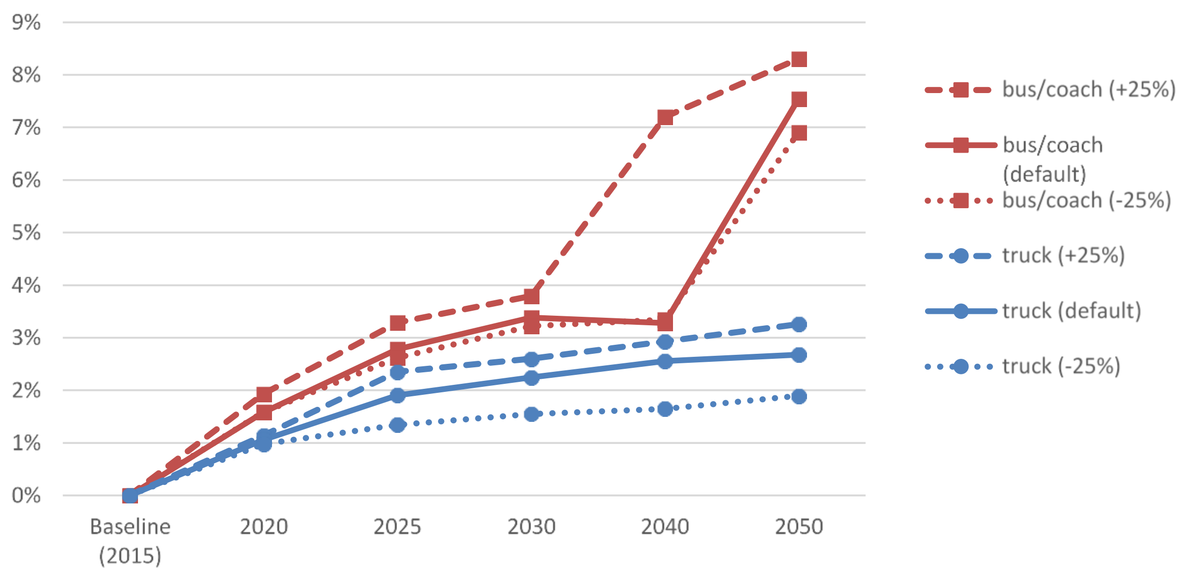
Figure 5.4: Impact of 'high' and 'very low' fuel price scenarios on fuel/CO_2 savings



5.3.5 Annual mileage

The amount of cost-effective lightweighting and the resulting fuel savings are also sensitive to the assumed annual vehicle mileage. Similar to a decrease in fuel price, reduction of annual mileage on trucks reduces fuel savings from cost effective lightweighting by around a third; for buses and coaches however, there is little impact. Increasing truck mileage by 25% increases percentage fuel savings by roughly 20%. For buses, the difference tends to vary substantially over the years, with fuel savings from lightweighting again approaching 2050 default levels in 2040 under the high mileage scenario.

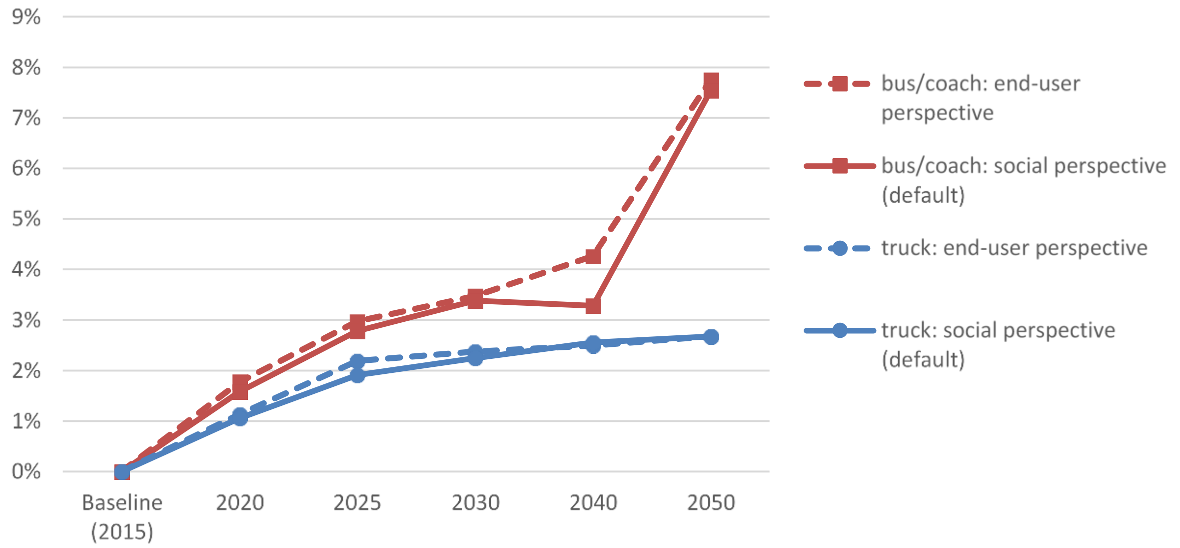
Figure 5.5: Impact of altering assumed annual vehicle mileage by ±25% fuel/CO2 savings



5.3.6 Societal vs end user costs

Increasing the discount rate to 8%, which is more likely to reflect the opportunity costs of lightweighting investments to the end-user, and including fuel excise duties, has a limited impact on the level of lightweighting in both trucks and buses/coaches. Given the high relative increase in fuel cost through the inclusion of excise duties the end-user perspective results in slightly higher fuel savings than the social perspective, despite the higher discount rate applied to the up-front capital costs.

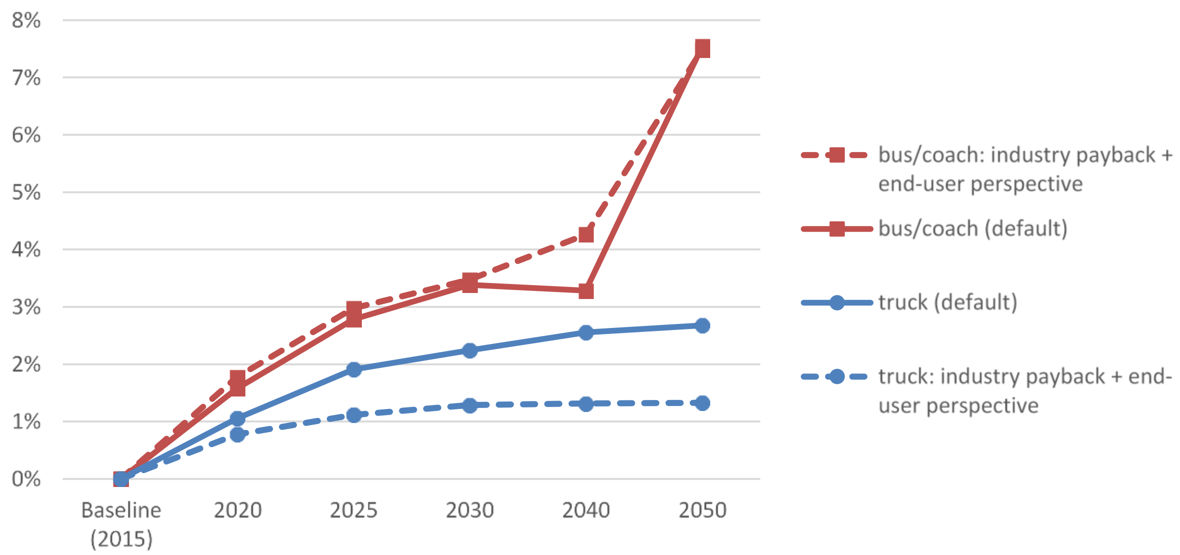
Figure 5.6: Impact of changing cost-effectiveness from societal to end user perspective (discount rate increase from 4% to 8%, inclusion of taxes) on fuel/CO_2 savings



5.3.7 Payback period

Operators often sell their vehicles after a few years in service. The market for second hand vehicles may often not (fully) take into account future fuel savings from vehicle lightweighting (or even penalise lightweighted vehicles) so payback needs to occur within the period of first ownership. If a payback period for trucks of 3-5 years (depending on vehicle type) is required in addition to end-user cost perspective the amount of cost-effective light weighting and resulting fuel saving is greatly reduced. Between 2025 and 2050 the amount of fuel savings barely increases, stagnating at just over 1%. Since expected ownership periods for buses are longer (15 year payback period) the impact on buses and coaches together is lower, and the industry payback assumptions perspective again yields greater savings than the social perspective.

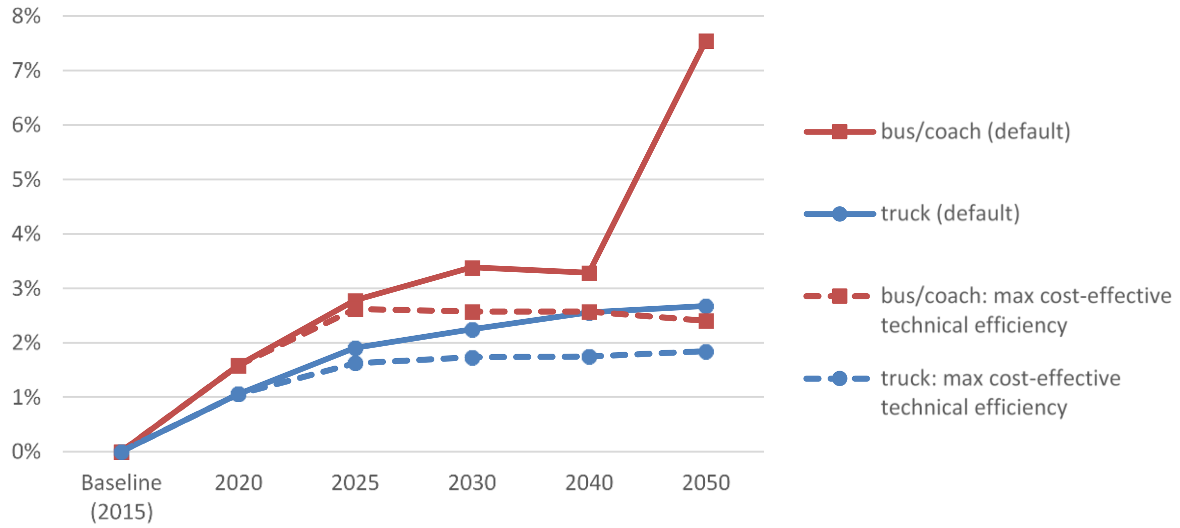
Figure 5.7: Impact of changing the payback period from vehicle lifetime to 3-5 years (bus 15 years), plus end-user cost perspective on fuel/CO_2 savings



5.3.8 Vehicle fuel consumption

Maximum cost-effective implementation of further fuel-savings measures (other than lightweighting) beyond the baseline fuel efficiency improvements lead to reductions in the fuel savings achieved through lightweighting and its cost-effective uptake. For trucks, the impact increases over time. By 2040, fuel savings from cost effective lightweighting under deployment of further fuel savings measures are around a third lower. The impact is for buses and coaches is low up to 2025. However, by 2050, fuel savings from cost-effective lightweighting on buses/coaches under 'max. cost-effective technical efficiency' fall to 2.4% which is less than a third of savings achieved under the default assumption.

Figure 5.8: Impact of changing the assumptions on the uptake of other fuel-saving vehicle technologies (to max. cost-effective measures) on fuel/CO_2 savings



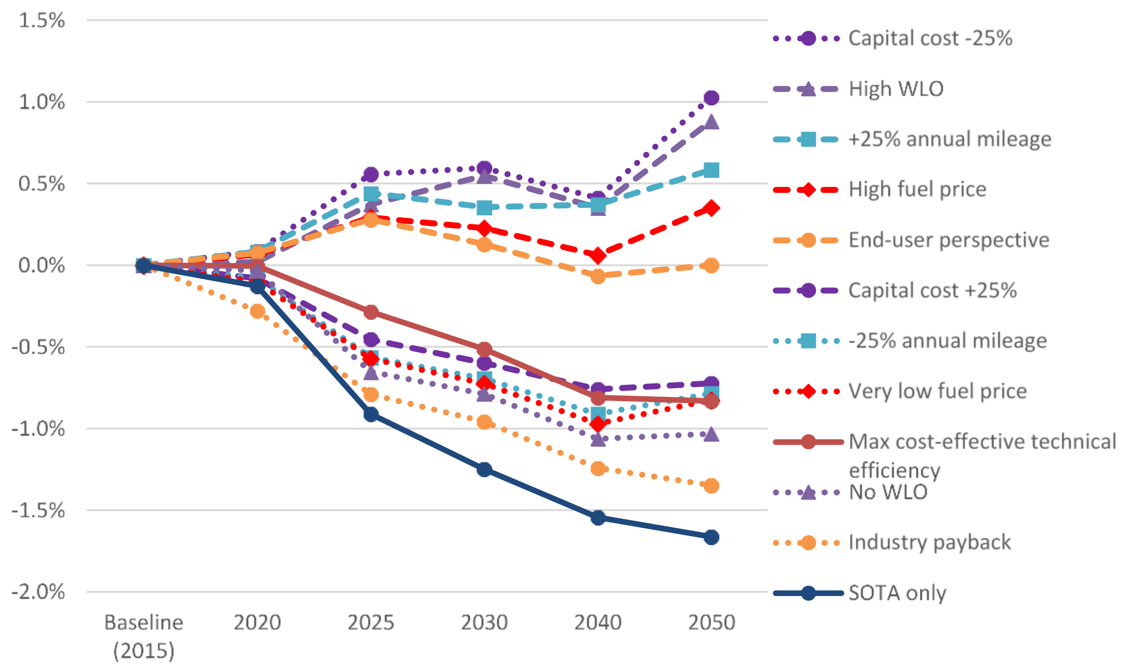
5.4 Summary and conclusions for Task 4

For trucks, the assumption of a 25% reduction in the cost of lightweighting measures has the greatest impact in terms of making more lightweighting measures cost-effective and thereby increasing fuel savings (Figure 5.9). The assumption of higher weight limited operation has the second most significant positive impact on fuel savings due to the application of cost-effective lightweighting. The assumption of 25% increase in annual mileage per vehicle has a similarly high impact in most years. High fuel prices and taking into account the end-user perspective also slightly increase the level of cost-effective lightweighting.

The assumed unavailability of future lightweighting technologies, short industry payback requirements and the assumption of no weight limited operations to benefit from reduced trip numbers have the greatest impact in terms of reducing the cost-effectiveness of lightweighting, leading to increases in fuel consumption over the default scenario. Annual mileage reduction, low fuel prices, high costs of lightweighting measures and maximum uptake of alternative fuel savings technologies also make lightweighting less financially attractive.

Almost all sensitivities have a rather low impact in the short term time horizon up to 2020.

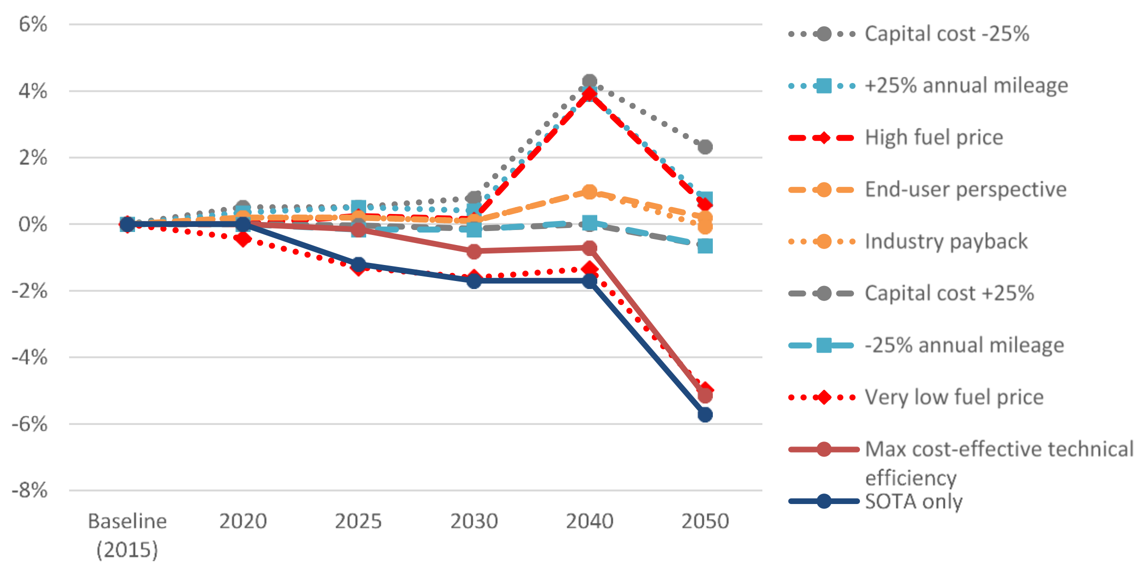
Figure 5.9: Summary: impact of altered assumptions on truck fuel/CO_2 savings relative to the default lightweighting scenario



Notes: WLO = weight limited operation; SOTA = state-of-the-art technologies

In the case of buses/coaches (Figure 5.10) where cost-effective weight reduction potentials lead to significantly greater fuel savings compared to trucks, the assumption of 25% lower capital cost for lightweighting measures has the single greatest positive impact on fuel savings. In second place, 25% annual mileage increase, high fuel prices, end-user perspective and industry payback all have similar, slightly positive consequences for cost-effective lightweighting and fuel savings. Notably, fuel savings are drastically lower under the SOTA assumptions (no future lightweighting measures available). Especially in 2050, maximum uptake of alternative fuel savings technologies and very low fuel prices also greatly reduce fuel savings and levels of lightweighting.

Figure 5.10: Summary: impact of altered assumptions on bus/coach fuel/CO_2 savings relative to the default lightweighting scenario



Notes: WLO = weight limited operation; SOTA = state-of-the-art technologies

The sensitivities performed on the average annual mileage and on the potential impacts of a totally weight limited operation on cost-effective lightweighting potential are only relevant to potential niche/sub-segment operations. These are therefore not suitable to be applied to the EU fleet modelling that was to be carried out in Task 5. However, the MACC outputs from most of the other sensitivities are suitable/relevant for EU fleet modelling, and are discussed further in this context in the next chapter.

6 Task 5: Potential impacts of light-weighting for the EU HDV fleet

Box 6: Key points for Task 5

Objectives:

- **To develop an assessment of the cost-effective lightweighting potential for reductions in fuel consumption and CO_2 emissions from the entire HDV fleet**

Key tasks:

- **Develop analytical framework**
- **Characterise scenarios**
- **Calculation of fuel and energy consumption by HDV category**

Outputs:

- **Overall estimate of the total EU potential for reduction in fuel consumption and CO_2 emissions from all HDVs under 'state-of-the-art' and 'forward-looking' scenarios**
- **Presentation of results to the EC and expert stakeholders at a workshop in month 15 of the project**

6.1 Overview of Task 5

The previous tasks, discussed in the previous report sections, have identified the technical lightweighting options and their potential energy/CO_2 savings and cost-effectiveness for specific types of HDV / duty cycles at a vehicle-level. This final task involved considering the total potential for uptake of light-weighting over time across the whole HDV fleet (at least for the main HDV categories) to get an impression on the overall impact on fuel consumption and CO_2.

This work built upon the outputs from the previous tasks in order to assess two alternative scenarios for the uptake of lightweighting: (i) 'state-of-the-art-technologies' (i.e. the best available technical options currently available in the marketplace for application), (ii) 'forward looking' (including options that are either still in development, or even at the conceptual stage - i.e. for long term application). Some refinements to this approach have been detailed in the sections below.

Our approach to this work was to use a bespoke Excel-based modelling approach, which included three stages/subtasks:

- *Task 5.1: Development of the analytical framework:* This analysis was be built upon the foundation of analysis previously carried out by Ricardo-AEA for DG CLIMA in the HDV Lot 1 study and the further development/adaptation of the SULTAN modelling tool developed for DG CLIMA as part of the EU Transport GHG: Routes to 2050 projects[19]. The approach enabled the estimation of fuel consumption and GHG emissions impacts resulting from different lightweighting scenarios based upon outputs from the MACC analysis in Tasks 4 and 5.
- *Task 5.2: Characterise scenarios:* This subtask covered the definition and characterisation of the scenarios that were investigated, which were to include comparisons of both (i) a 'state-of-the-art' lightweighting scenario and (ii) a 'future/forward-looking potential' lightweighting scenario, compared to a baseline trajectory. This basis has been somewhat expanded, and is detailed below.
- *Task 5.3: Calculation of CO_2 and energy consumption by HDV category:* Once the basis of the scenarios (and variants) were agreed, these scenarios were implemented in the adapted version of SULTAN to generate the final results.

In order to manage the complexity of this analysis we confirmed with the Commission at the inception stage that the analysis was to be focused upon conventionally fuelled (i.e. diesel) vehicles. However, the current framework and assumptions were extended all the way to 2050. The details of the modelling were worked up based on/consistent with the findings from the previous project tasks.

[19] http://www.eutransportghg2050.eu/cms/illustrative-scenarios-tool/

6.2 Methodological framework and baseline input data

This section provides a summary of the process, methodology, assumptions and results from the wider GHG HDV fleet modelling carried out under this project. The objective of this work was to evaluate the total potential for uptake of light-weighting over time across the whole HDV fleet (at least for the main HDV categories) to get an impression on the overall impact on fuel consumption and CO_2.

It should be stressed that only a high-level assessment was possible within the timescales and resources available for this project. Nevertheless the outputs provide a reasonable first-order assessment of the impacts on GHG emissions resulting various lightweighting scenarios. The definition of these scenarios has been informed by the findings from the MACC analysis.

In order to estimate the resulting impacts of different scenarios of lightweighting into the new HDV fleet (in terms of overall fleet numbers, emissions and energy consumption), Ricardo-AEA adapted the SULTAN illustrative scenarios tool previously developed for the European Commission (AEA et al, 2012). SULTAN is a policy scoping-level tool that works on the basis of a vehicle stock model, so is ideal for this kind of analysis. A summary of the SULTAN tool and its broader capabilities is provided in Box 7 below.

Box 7: SULTAN Illustrative Scenarios Tool

Overview of SULTAN

As part of previous work for DG CLIMA (the EU Transport GHG: Routes to 2050 projects), Ricardo-AEA developed a sustainable transport policy tool called SULTAN (SUstainabLe TrANsport) to identify the potential implications for transport's GHG emissions from uptake of a range of technical and non-technical options, supported by appropriate policy instruments (AEA et al, 2012).

EU transport is modelled within the tool in aggregate (i.e. no breakdown by Member State) and is split by 7 passenger modes and 6 freight modes. Within each mode a range of powertrain options were developed, using a combination of different energy carriers (application depending on the mode) including conventional and alternative fuels. The tool also incorporates the main cost elements (capital costs, annual running costs and fuel costs) and taxes, as well as some high-level approximation on other co-benefits (i.e. NOx, PM emissions and also an energy security metric).

One of the advantages of the tool is that it is possible to very quickly get a feel for the scale of the impacts of different policy measures before embarking on costly and time-intensive detailed transport modelling studies. The tool has been developed to be consistent at a high-level with the baseline assumptions used in more detailed models used in European policy analysis (including PRIMES-TREMOVE and TREMOVE).

Analysis of a range of scenarios exploring alternative ways to meet the long-term GHG targets of the transport sector formed the backbone tying the different work-streams together for the second EU Transport GHG: Routes to 2050 project completed for DG CLIMA, and the tool has since been used on a variety of different projects and applications exploring both near-term implications of measures (e.g. impacts of different design options for supercredits for the car CO2 targets for 2020) and also through to the medium-long term (e.g. feeding into analysis of the potential economic impacts of LDV decarbonisation in the EU).

6.2.1 Key modelling assumptions

The main SULTAN inputs and outputs utilised for this project are listed in Table 6.1, together with a summary of the datasets used in the SULTAN modelling analysis. Further information on some of the specific datasets and assumptions is provided below:

- Total HDV activity (in vkm) is based on TRACCS Road Data statistics from 2010 (Emisia, 2013), extrapolated forwards. In order to configure the TRACCS database to the mode structure being used within SULTAN, percentage shares for each mode have been informed by the estimates from the previous HDV GHG Lot 1 project (AEA/Ricardo, 2011), and the assumptions used in the MACC model. Projected activity figures up to 2050 are based on the projected growth rate for trucks, buses and coaches from the PRIMES reference scenario currently used in Commission energy modelling.
- HDV 'stock' is also based on TRACCS Road Data statistics from 2010, extrapolated forwards using the PRIMES reference scenario. The percentage shares for each mode have been informed by/calibrated to the previous HDV GHG Lot 1 study and the input assumptions for the MACC model.

- Fuel well-to-tank (WTT, or upstream) and tank-to-wheel (TTW, or tailpipe) GHG emission factors are based on the emission factors used within the previous Routes to 2050 projects (AEA et al, 2012). Post 2015 projections of these factors have been scaled/extrapolated forward based on data from the PRIMES reference scenario.
- New vehicle fuel consumption values (in MJ/km) are taken directly from the MACC model with projections out to 2050 again scaled based on the baseline efficiency improvements scenario from the PRIMES reference scenario.
- For all modes it is assumed there will be no change in the 2015-2020 technology share in the baseline scenario as well as all lightweighting scenarios. A 100% diesel share is assumed for all modes.

Table 6.1: Main inputs and outputs from the SULTAN Model used in this project

SULTAN Data Area	
Inputs	
Energy consumption (in MJ/km) for the various HDV mode types	Describes the projected evolution of energy efficiency for different modes on a 'tank to wheel' basis.
Energy carrier performance (emissions factors)	Includes the evolution of direct and indirect GHG emission factors for each energy carrier or fuel (in this case only diesel)
Service demand, stock and vehicle loading	Projections of demand for passenger and freight and corresponding vehicles stock levels. Vehicle load factors (passengers/tonnes freight carried per vehicle) can be used to convert to vehicle travel demand.
Survival rates	Describes the expected survival of the various modes through each year of life. Based on the assumed vehicle lifetime in years. These values work alongside the stock data to help form a stock model through time up to 2050.
Outputs	
Activity (vehicle-km or payload-km)	Taken directly from inputs (See above.)
Emissions (CO_2e)	A further key output of SULTAN is a range of measures of environmental emissions, including direct and indirect CO_2e emissions.
Energy (consumption by mode fuel, intensity)	A key output of SULTAN is a detailed breakdown of energy consumption by mode for each year.
Freight efficiency (gCO_2e/pkm or gCO_2e/tkm)	Calculated from the above outputs (payload-km and direct CO_2e emissions)

Table 6.2: Heavy duty vehicle stock

Vehicle type	2015	2020	2025	2030	2040	2050
Urban	2,870,800	3,170,800	3,328,600	3,559,700	3,933,200	4,134,600
Utility	662,500	731,700	768,100	821,500	907,700	954,100
Regional	1,325,000	1,463,500	1,536,300	1,643,000	1,815,300	1,908,300
Construction	1,104,200	1,219,600	1,280,200	1,369,100	1,512,800	1,590,200
Long Haul	1,398,600	1,544,800	1,621,600	1,734,200	1,916,200	2,014,300
Bus	355,200	390,200	402,700	427,800	468,600	492,900
Coach	564,000	608,600	611,400	626,700	674,300	706,300

Table 6.3: Activity/demand (Million payload-km*)

Vehicle type	2015	2020	2025	2030	2040	2050
Urban	214,409	231,914	249,192	267,633	289,303	304,261
Utility	82,962	89,735	96,420	103,556	111,941	117,728
Regional	454,127	491,205	527,801	566,860	612,757	644,439
Construction	371,748	402,099	432,056	464,030	501,602	527,536
Long Haul	993,845	1,074,988	1,155,077	1,240,558	1,341,002	1,410,337
Bus	313,138	336,106	355,669	378,622	410,544	429,917
Coach	911,300	930,656	966,318	1,003,566	1,066,992	1,116,714

Notes: * tonne-km for trucks, passenger-km for buses and coaches.

Table 6.4: New vehicle fuel efficiency (MJ/km)

Vehicle type	2015	2020	2025	2030	2040	2050
Urban	7.02	6.72	6.55	6.40	6.25	6.14
Utility	11.47	10.97	10.70	10.45	10.20	10.03
Regional	9.74	9.32	9.08	8.87	8.66	8.51
Construction	13.09	12.52	12.21	11.93	11.64	11.44
Long Haul	11.41	10.92	10.64	10.40	10.15	9.98
Bus	13.65	13.30	13.10	12.71	12.47	12.28
Coach	9.70	9.20	8.87	8.64	8.30	8.04

6.3 Characterisation of scenarios

The previous section has provided a summary of the basis of the data used to define the baseline scenario in SULTAN. Here we provide a summary of the output results from the calibrated baseline.

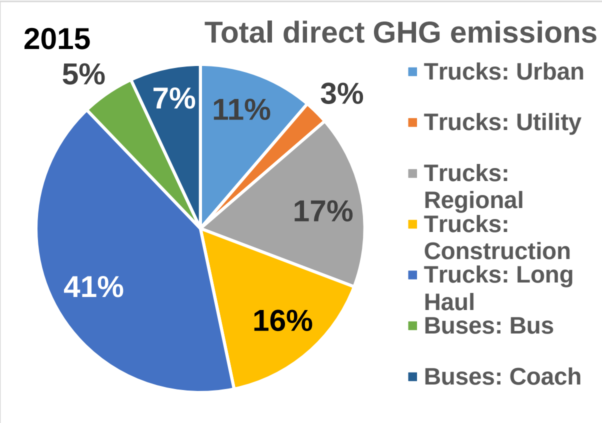
The overall total direct CO_2 emissions from HDVs for 2015 calculated using the SULTAN modelling and the input data on numbers of HDVs, activity and fuel efficiency (discussed in the previous section) are somewhat higher than the estimates derived in our previous HDV GHG Lot 1 study for the Commission (AEA/Ricardo, 2011). These latest results for 2015 (~288 $MtCO_2$) also fall in-between estimates for 2010 derived in the TRACCS project (Emisia, 2013) (~244 $MtCO_2$) and those from the latest PRIMES reference scenario used in Commission modelling analysis, which are much higher (~320 $MtCO_2$).

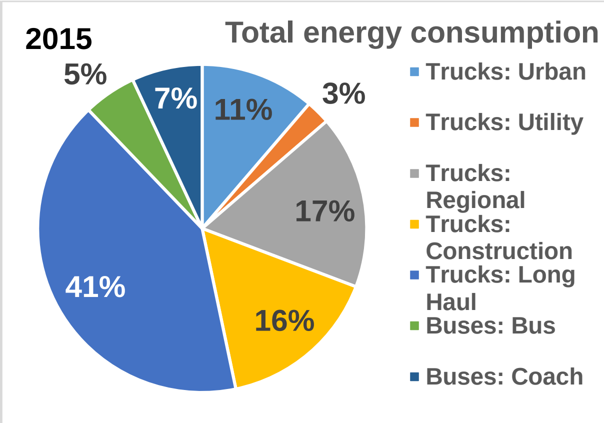
The relative shares by HDV duty cycle in direct GHG emissions, energy consumption and activity in vehicle-km and tonne-km are presented in the following Figure 6.1. The full timeseries trajectories for the BAU scenario are also presented in Figure 6.2. These show *increases* in overall HDV vehicle-km activity, energy consumption and CO_2 emissions of 40%, 22% and 17% respectively by 2050.

As a sensitivity for the MACC analysis of lightweighting cost-effectiveness, an alternative baseline scenario was also set up where the improvement in baseline new HDV technical efficiency was set to a "maximum cost-effective" improvement estimate. The results for estimated energy consumption and CO_2 emissions from the alternative baseline scenario (Alt BAU) are presented in Figure 6.3, with a comparison provided with the standard baseline (BAU). In this alternative scenario (where vehicle-km are assumed to be the same) the total HDV energy consumption and CO_2 emissions *decrease* by 25% and 28% respectively.

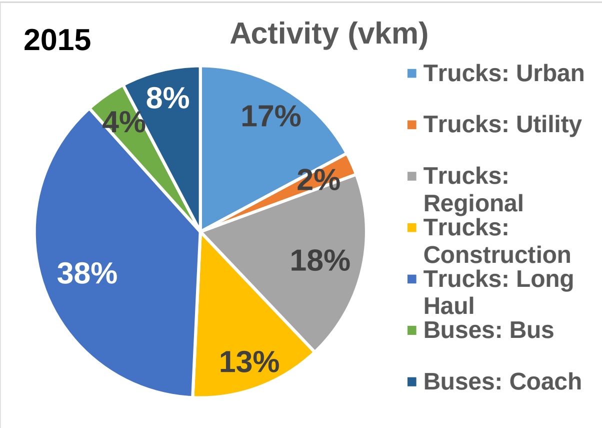
The data tables behind the charts below are also provided in Appendix 3 of this report.

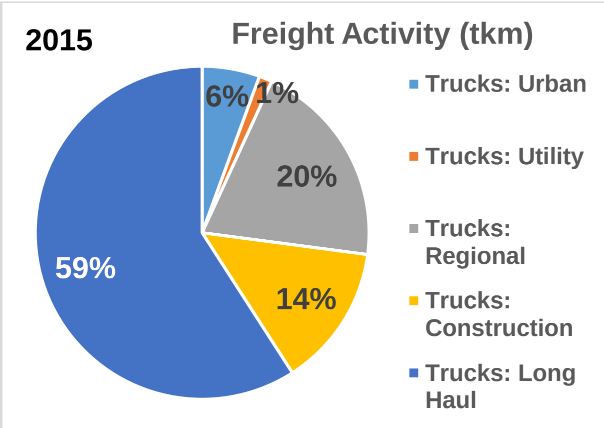
Figure 6.1: Estimated 2015 shares by HDV duty cycle for activity, energy consumption and direct CO_2 emissions for the baseline scenario for the analysis





Direct GHG emissions (Mt CO_2) **Energy Consumption (PJ)**

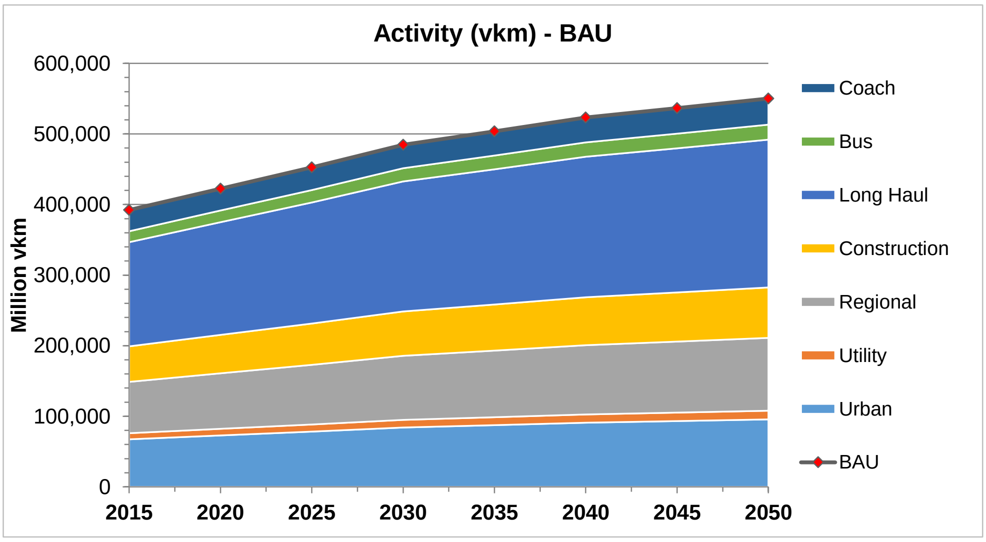




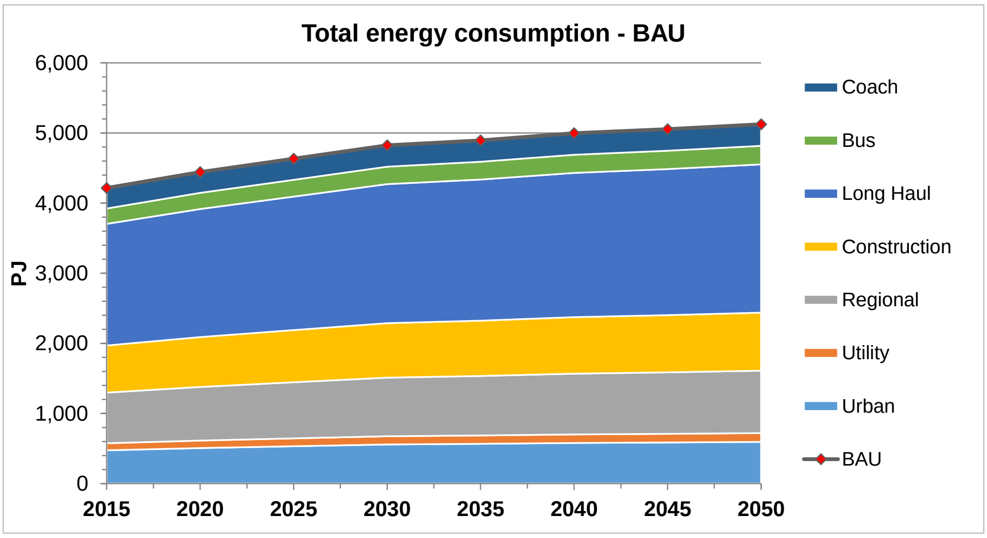
Activity (vkm) **Freight Activity (tkm)**

Figure 6.2: Projected activity, energy consumption and direct CO_2 emissions for the baseline scenario for the analysis

Activity (vkm)



Energy consumption (PJ)



Direct GHG Emissions ($Mtonne \ CO_2$)

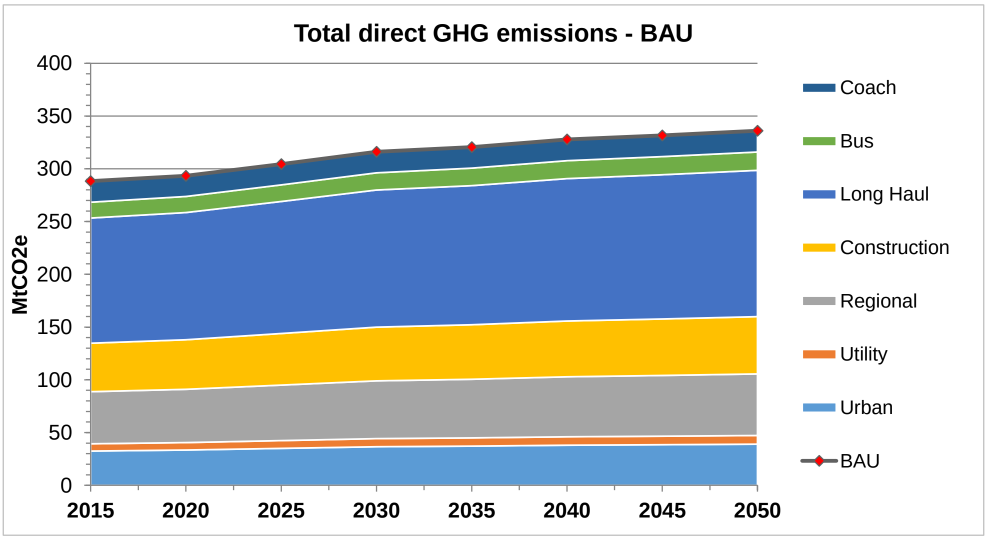
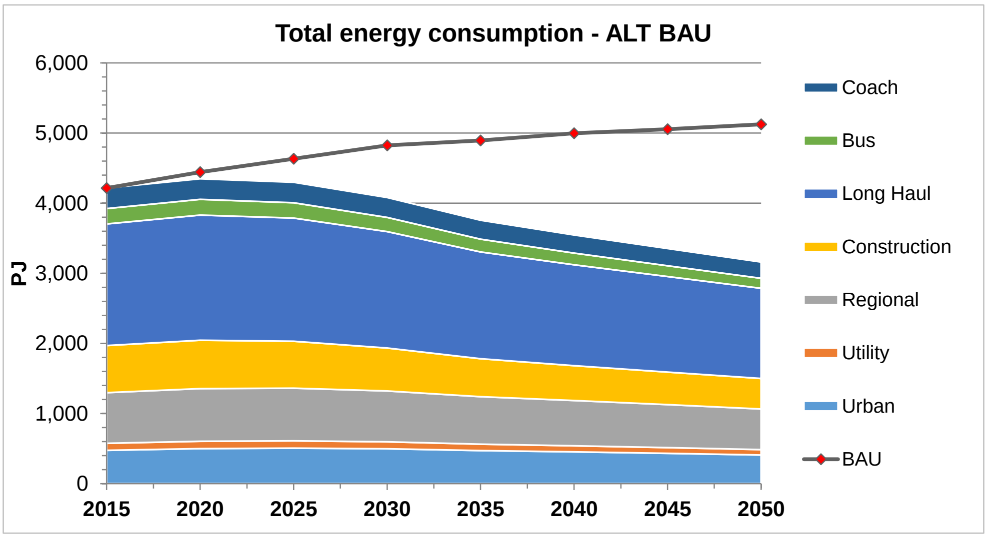
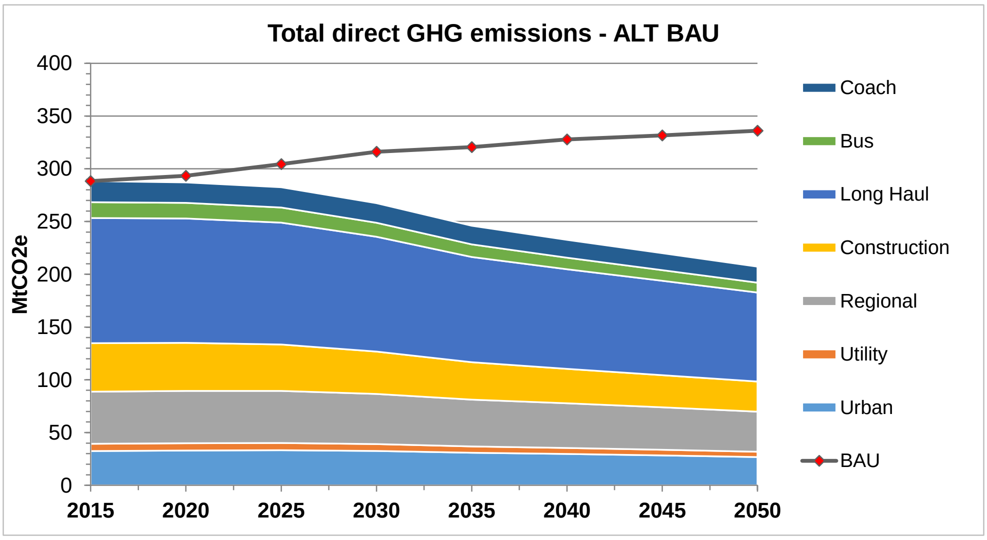


Figure 6.3: Projected energy consumption and direct CO_2 emissions for the alternative baseline scenario for the analysis

Energy consumption (PJ)



Direct GHG Emissions (Mtonne CO_2)



6.3.1 Cost-effective lightweighting scenarios

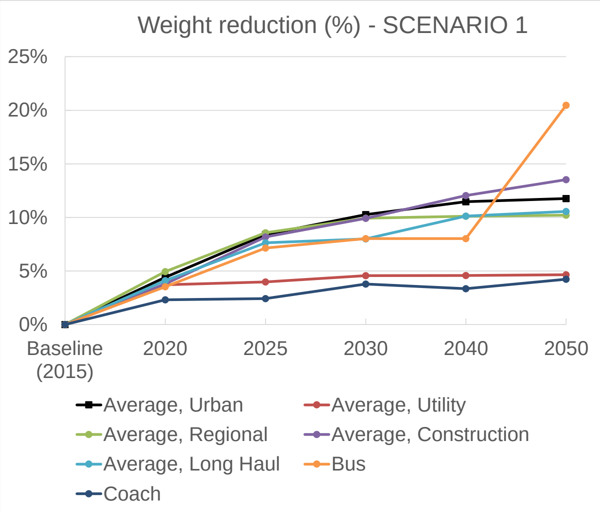
The scenario analysis originally envisaged (i.e. based around two alternate 'SOTA' and 'forward looking'/'Future Potential' core scenarios) has been somewhat refined to focus on exploring the impacts of sensitives versus a baseline that includes all further lightweighting options identified (as outlined in the previous section). The following table provides a summary of the different scenarios modelled in SULTAN, and the key parameter that was varied from scenario-to-scenario.

Table 6.5: Summary of the scenarios investigated in the SULTAN HDV fleet modelling

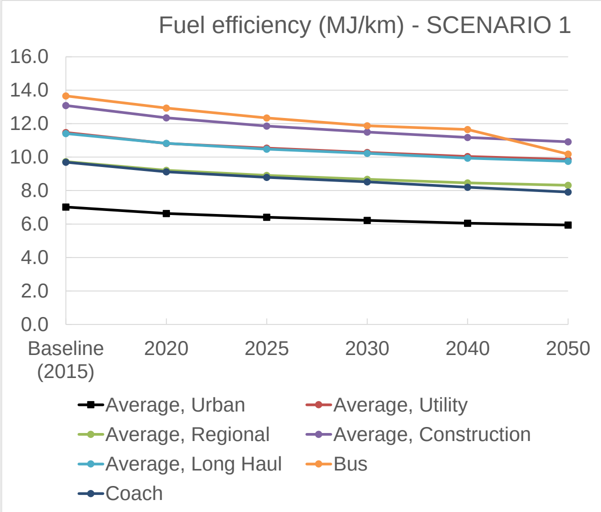
Scenario	Lightweighting Technology	Payback, Cost Basis	Weight limited km	Fuel Price	Baseline MJ/km
BAU	**2015 baseline estimate**	Lifetime, Social Costs	Low	Reference	Baseline
Scenario 1	All options	Lifetime, Social Costs	Low	Reference	Baseline
Scenario 2	All options	Lifetime, Social Costs	**High**	Reference	Baseline
Scenario 3	**SOTA only**	Lifetime, Social Costs	Low	Reference	Baseline
Scenario 4	All options	**Private Payback, End-user Costs**	Low	Reference	Baseline
Scenario 5	All options	Lifetime, Social Costs	Low	**Very low**	Baseline
Scenario 6	**All options, LOW Cost**	Lifetime, Social Costs	Low	Reference	Baseline
Alternative BAU	**2015 baseline estimate**	Lifetime, Social Costs	Low	Reference	**Max CE**
Scenario 7	All options	Lifetime, Social Costs	Low	Reference	**Max CE**

In defining the input assumptions (of MJ/km new vehicle efficiency and change in total vkm travelled) from the outputs of the MACC model, it was necessary to apply a small degree of smoothing of the MACC outputs in some cases, where unlikely period-to-period transitions occurred. For example, in some instances the total cost-effective lightweighting potential fluctuated somewhat up and down, due to the interplay between the changing costs of individual measures, fuel prices and baseline vehicle efficiency relative to each other. In a real market situation such fluctuation would be unlikely - i.e. manufacturers are unlikely to introduce a particular measure in 2020, remove it again for 2030, and add it back in for 2040. Therefore in such cases the trajectories for weight reduction uptake were smoothed out, and the MJ/km and % change vkm figures adjusted accordingly in consistency with this. The following Figure 6.4 provides a summary of the key output data from the MACC model calculations used for the input assumptions to SULTAN for Scenario 1

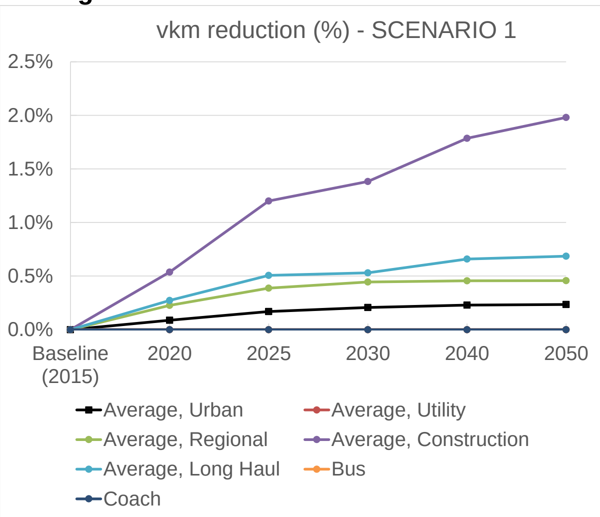
Figure 6.4: Example summary of input data for Scenario 1



% Weight reduction vs baseline



Fuel consumption (MJ/km)



Change in Activity (vkm)

6.4 Results from the EU fleet modelling

The following Table 6.6 to Table 6.8 provide a summary of the results of the fleet modelling analysis for the different scenarios in terms of total direct CO_2 emissions (in $MtCO_2$), total energy consumption (in PJ) and overall freight CO_2 efficiency (in gCO_2/tkm). Summaries of the respective fleet-wide CO_2 savings for particular HDV duty cycles are also presented in Figure 6.5 to Figure 6.12.

Under the default MACC assumptions (in scenario #1), fleet-wide CO_2 emissions are reduced by 2.1% by 2030, and by 3.7% by 2050. If the higher estimates for the share of weight limited operations are assumed (scenario #2) then these savings rise significantly to 3.5% in 2030 and 5.8% by 2050. Overall savings also rise significantly for the Low lightweighting CAPX sensitivity with savings of 2.7% in 2030 and to 5.2% by 2050. The reductions in overall energy savings follow a similar pattern. In all of the other scenarios modelled, the level of cost-effective lightweighting is reduced and consequently also the energy and CO_2 savings potential also.

In considering the results by duty cycle (Figure 6.5 to Figure 6.12), the overall levels of savings are highest for construction trucks (mainly due to higher levels of weight limited operations) and buses (due to the transient operational cycle), and lowest for utility trucks (low annual mileage) and coaches (relatively intransient cycles and essentially not weight limited).

The other sensitivity scenarios explored (scenarios #3-5, 7) all lead to significantly smaller reductions in CO_2 emissions: by 2030 between 1.1% (for SOTA technologies only) and 1.7% (for the alternative baseline including uptake of all other cost-effective CO_2 reduction measures), and by 2050 between 1.3% and 2.5%.

Whilst the overall conclusion from this analysis might be that the potential cost-effective CO_2 savings from HDV lightweighting are relatively modest, it should be emphasised that they could still form an important component in the overall strategy to reduced CO_2 emissions from HDVs. Lightweighting has also been shown to be a potentially highly significant and cost-effective option for certain types of operations, in particular for buses and operations that are often weight- (rather than volume-) limited, such as construction.

Table 6.6: Total HDV direct CO_2 emissions by scenario, Mtonnes CO_2

#	Scenario	2015	2020	2025	2030	2035	2040	2045	2050
	BAU	288.3	293.3	304.5	316.1	320.5	327.7	331.6	336.0
1	Cost-Eff LW	288.3	291.7	300.3	309.5	312.0	317.6	320.4	323.7
2	CE LW High WL	288.3	290.9	297.6	305.1	307.2	312.8	314.6	316.5
3	CE SOTA Only	288.3	291.8	301.9	312.6	316.6	323.5	327.2	331.5
4	CE Payback	288.3	291.9	301.6	311.7	315.2	321.6	325.0	328.8
5	CE V Low Fuel Prices	288.3	291.8	301.2	311.2	314.5	320.9	324.2	328.0
6	CE LW + Low CAPX	288.3	291.6	299.4	307.6	309.4	314.6	316.4	318.6
	Alt BAU	288.3	287.0	282.5	267.4	246.0	232.6	220.0	207.2
7	Alt Cost-Eff LW	288.3	285.5	279.1	262.8	240.9	227.3	214.8	202.2
#	**Scenario vs BAU***	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
	BAU	0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
1	Cost-Eff LW	0%	-0.5%	-1.4%	-2.1%	-2.7%	-3.1%	-3.4%	-3.7%
2	CE LW High WL	0%	-0.8%	-2.2%	-3.5%	-4.2%	-4.6%	-5.1%	-5.8%
3	CE SOTA Only	0%	-0.5%	-0.8%	-1.1%	-1.2%	-1.3%	-1.3%	-1.3%
4	CE Payback	0%	-0.5%	-0.9%	-1.4%	-1.7%	-1.9%	-2.0%	-2.2%
5	CE V Low Fuel Prices	0%	-0.5%	-1.1%	-1.6%	-1.9%	-2.1%	-2.2%	-2.4%
6	CE LW + Low CAPX	0%	-0.6%	-1.7%	-2.7%	-3.5%	-4.0%	-4.6%	-5.2%
	Alt BAU	0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
7	Alt Cost-Eff LW	0%	-0.5%	-1.2%	-1.7%	-2.1%	-2.3%	-2.4%	-2.5%

Note: * For the Alt BAU and Scenario 7, this is vs the Alt BAU scenario.

Table 6.7: Total HDV energy consumption, PJ

#	Scenario	2015	2020	2025	2030	2035	2040	2045	2050
	BAU	4,217	4,443	4,634	4,824	4,895	4,997	5,054	5,126
1	Cost-Eff LW	4,217	4,419	4,570	4,724	4,765	4,842	4,884	4,938
2	CE LW High WL	4,217	4,407	4,530	4,656	4,691	4,769	4,795	4,828
3	CE SOTA Only	4,217	4,421	4,595	4,772	4,835	4,932	4,988	5,057
4	CE Payback	4,217	4,422	4,590	4,758	4,814	4,904	4,953	5,015
5	CE V Low Fuel Prices	4,217	4,421	4,583	4,750	4,804	4,893	4,942	5,003
6	CE LW + Low CAPX	4,217	4,417	4,556	4,695	4,726	4,796	4,823	4,860
	Alt BAU	4,217	4,349	4,299	4,081	3,757	3,547	3,353	3,161
7	Alt Cost-Eff LW	4,217	4,326	4,247	4,011	3,679	3,466	3,274	3,084

#	Scenario vs BAU*	2015	2020	2025	2030	2035	2040	2045	2050
	BAU	0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
1	Cost-Eff LW	0%	-0.5%	-1.4%	-2.1%	-2.7%	-3.1%	-3.4%	-3.7%
2	CE LW High WL	0%	-0.8%	-2.2%	-3.5%	-4.2%	-4.6%	-5.1%	-5.8%
3	CE SOTA Only	0%	-0.5%	-0.8%	-1.1%	-1.2%	-1.3%	-1.3%	-1.3%
4	CE Payback	0%	-0.5%	-0.9%	-1.4%	-1.7%	-1.9%	-2.0%	-2.2%
5	CE V Low Fuel Prices	0%	-0.5%	-1.1%	-1.6%	-1.9%	-2.1%	-2.2%	-2.4%
6	CE LW + Low CAPX	0%	-0.6%	-1.7%	-2.7%	-3.5%	-4.0%	-4.6%	-5.2%
	Alt BAU	0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
7	Alt Cost-Eff LW	0%	-0.5%	-1.2%	-1.7%	-2.1%	-2.3%	-2.4%	-2.5%

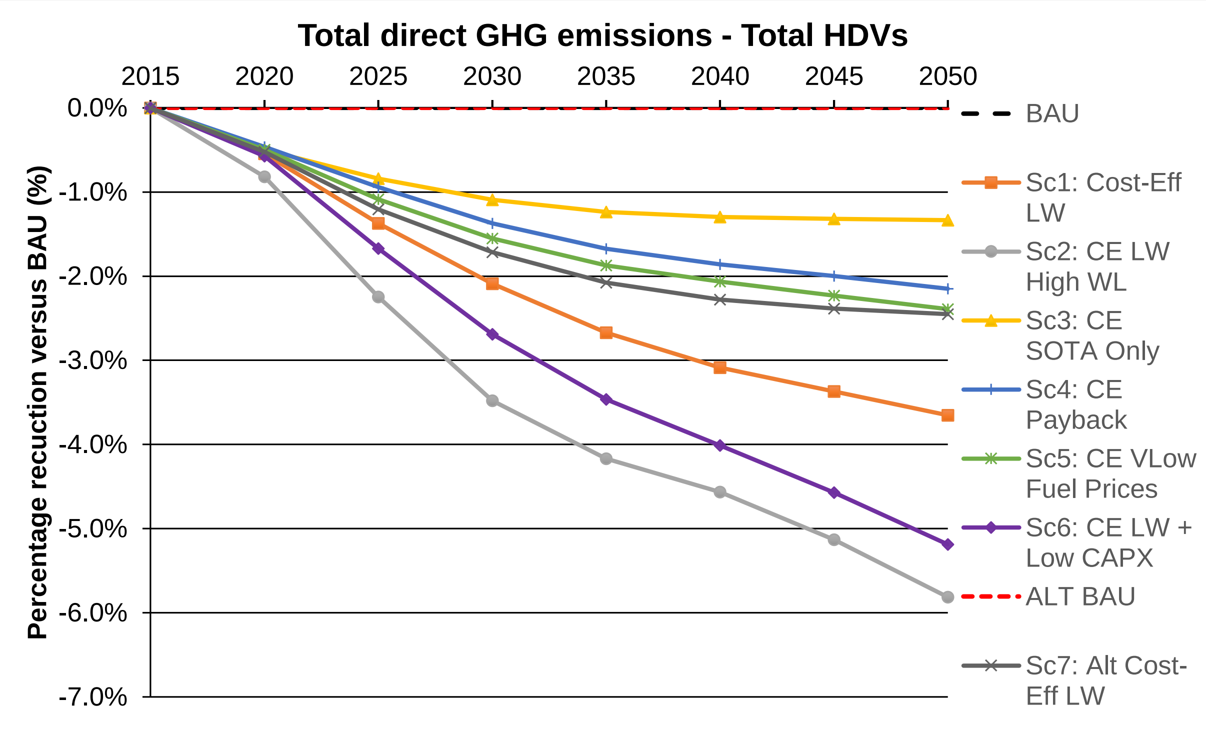
Note: * For the Alt BAU and Scenario 7, this is vs the Alt BAU scenario.

Table 6.8: Total heavy duty truck freight CO_2 efficiency by scenario, gCO_2 per tonne-km

#	Scenario	2015	2020	2025	2030	2035	2040	2045	2050
	BAU	101.8	96.0	93.0	90.1	87.9	86.6	85.5	84.5
1	Cost-Eff LW	101.8	95.8	92.2	88.8	86.2	84.6	83.3	82.3
2	CE LW High WL	101.8	95.8	92.1	88.4	85.7	84.0	82.7	81.6
3	CE SOTA Only	101.8	95.8	92.5	89.4	87.1	85.7	84.6	83.7
4	CE Payback	101.8	95.8	92.4	89.3	86.9	85.5	84.4	83.4
5	CE V Low Fuel Prices	101.8	95.8	92.3	89.1	86.7	85.2	84.0	83.0
6	CE LW + Low CAPX	101.8	95.8	92.1	88.4	85.7	84.0	82.7	81.5
	Alt BAU	101.8	94.0	86.1	75.8	67.0	61.0	56.3	51.7
7	Alt Cost-Eff LW	101.8	93.7	85.4	74.9	66.0	59.9	55.3	50.8
#	**Scenario vs BAU***	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
	BAU	0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
1	Cost-Eff LW	0%	-0.3%	-0.9%	-1.5%	-2.0%	-2.3%	-2.5%	-2.7%
2	CE LW High WL	0%	-0.3%	-1.0%	-1.9%	-2.6%	-3.0%	-3.2%	-3.5%
3	CE SOTA Only	0%	-0.3%	-0.6%	-0.8%	-0.9%	-1.0%	-1.0%	-1.0%
4	CE Payback	0%	-0.2%	-0.6%	-0.9%	-1.2%	-1.3%	-1.3%	-1.3%
5	CE V Low Fuel Prices	0%	-0.3%	-0.7%	-1.1%	-1.4%	-1.6%	-1.7%	-1.8%
6	CE LW + Low CAPX	0%	-0.3%	-1.0%	-1.9%	-2.6%	-3.0%	-3.2%	-3.6%
	Alt BAU	0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
7	Alt Cost-Eff LW	0%	-0.3%	-0.7%	-1.2%	-1.5%	-1.7%	-1.8%	-1.8%

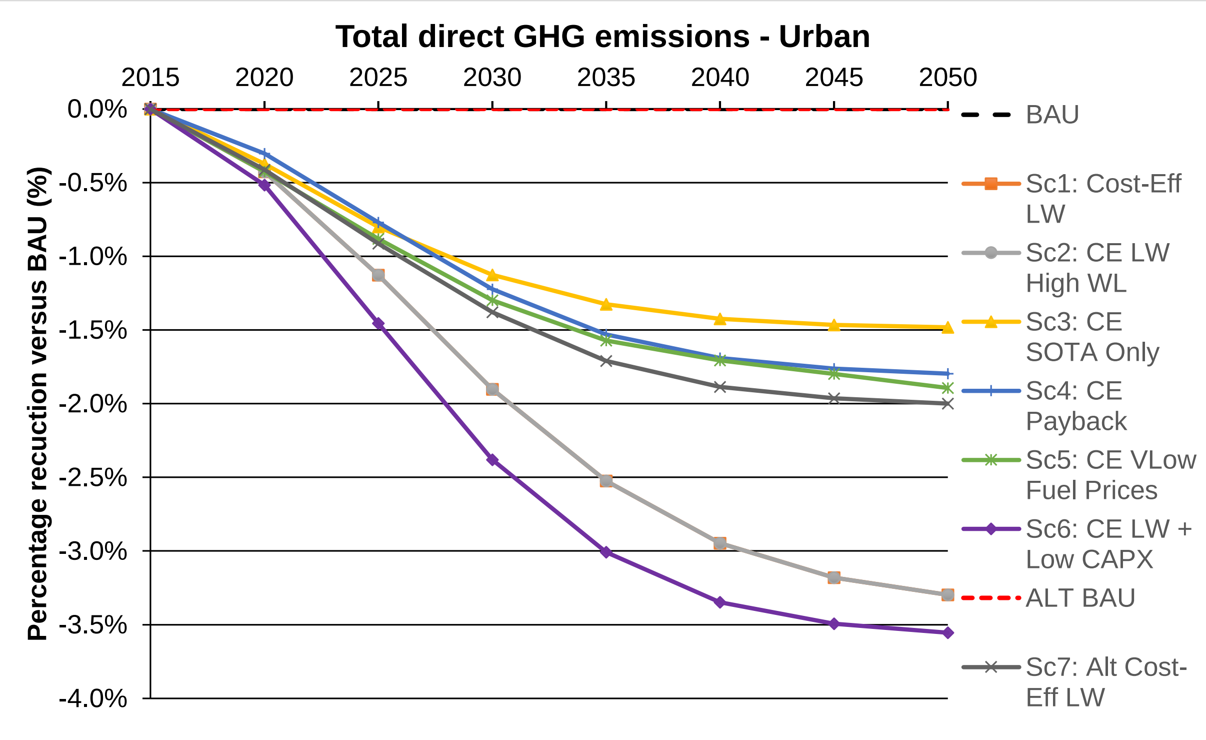
Note: * For the Alt BAU and Scenario 7, this is vs the Alt BAU scenario.

Figure 6.5: Summary of the change in projected direct CO_2 emissions from all HDVs due to cost-effective uptake of lightweighting in the EU fleet for different scenarios vs the relevant BAU scenario



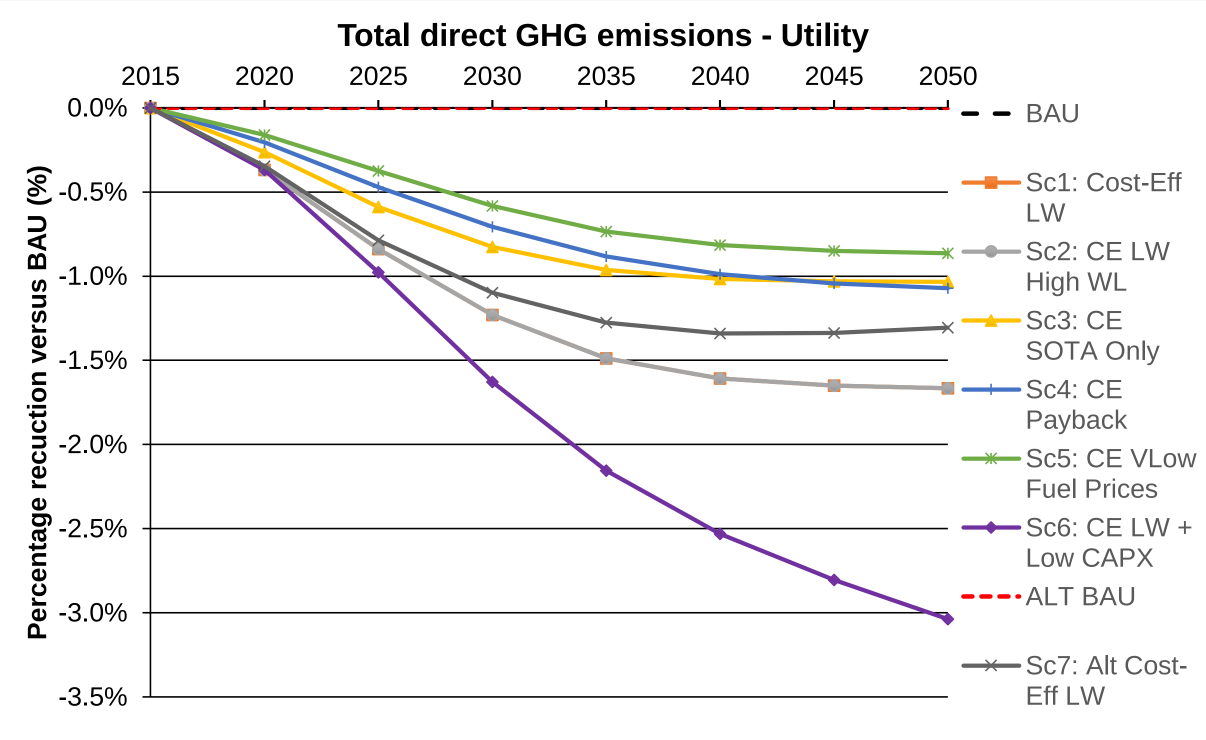
Note: * For the Alt BAU and Alt Cost-Eff LW, % reduction is calculated vs the Alt BAU scenario.

Figure 6.6: Summary of the change in projected direct CO_2 emissions from urban delivery trucks due to cost-effective uptake of lightweighting in the EU fleet for different scenarios vs the relevant BAU scenario



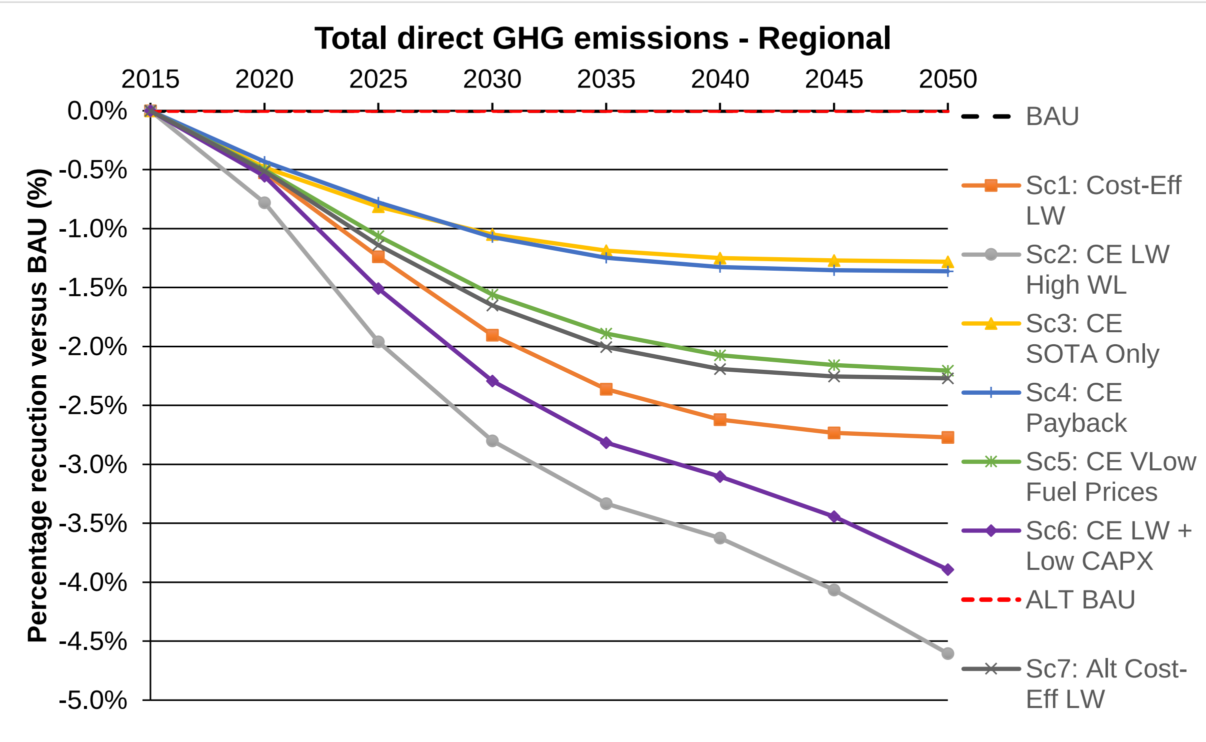
Note: * For the Alt BAU and Alt Cost-Eff LW, % reduction is calculated vs the Alt BAU scenario.

Figure 6.7: Summary of the change in projected direct CO_2 emissions from municipal utility trucks due to cost-effective uptake of lightweighting in the EU fleet for different scenarios vs the relevant BAU scenario



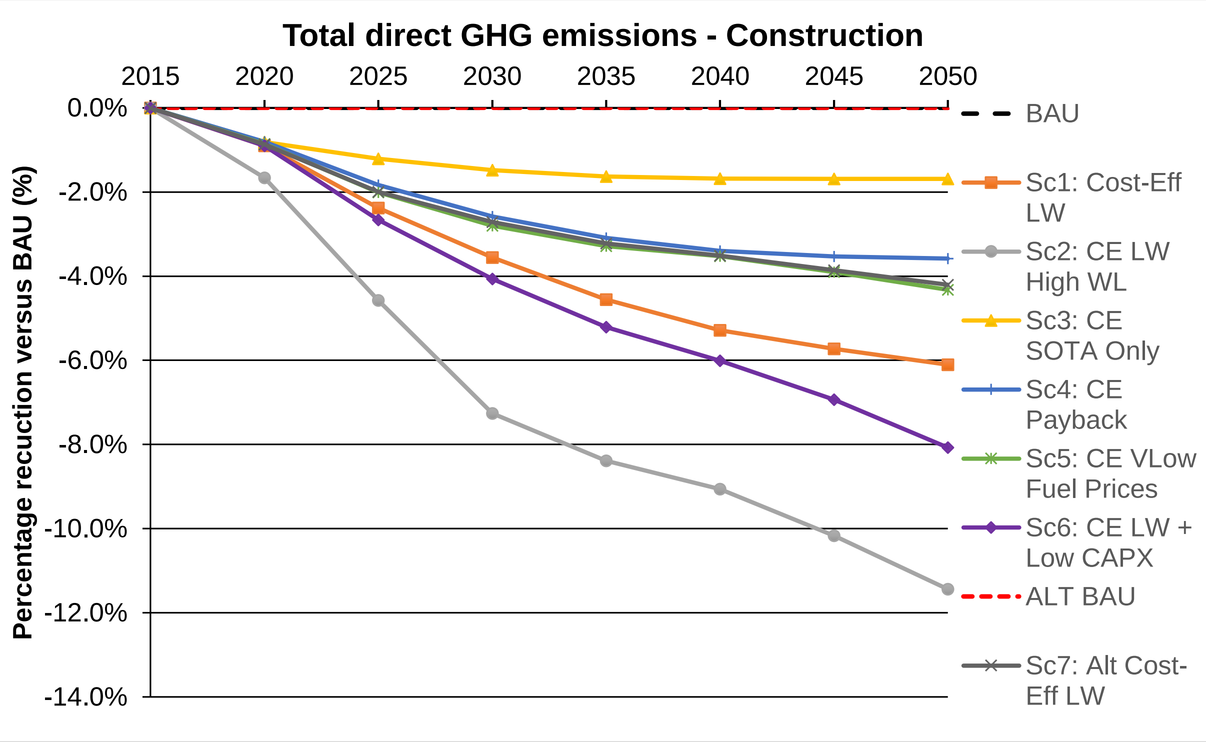
Note: * For the Alt BAU and Alt Cost-Eff LW, % reduction is calculated vs the Alt BAU scenario.

Figure 6.8: Summary of the change in projected direct CO_2 emissions from regional delivery trucks due to cost-effective uptake of lightweighting in the EU fleet for different scenarios vs the relevant BAU scenario



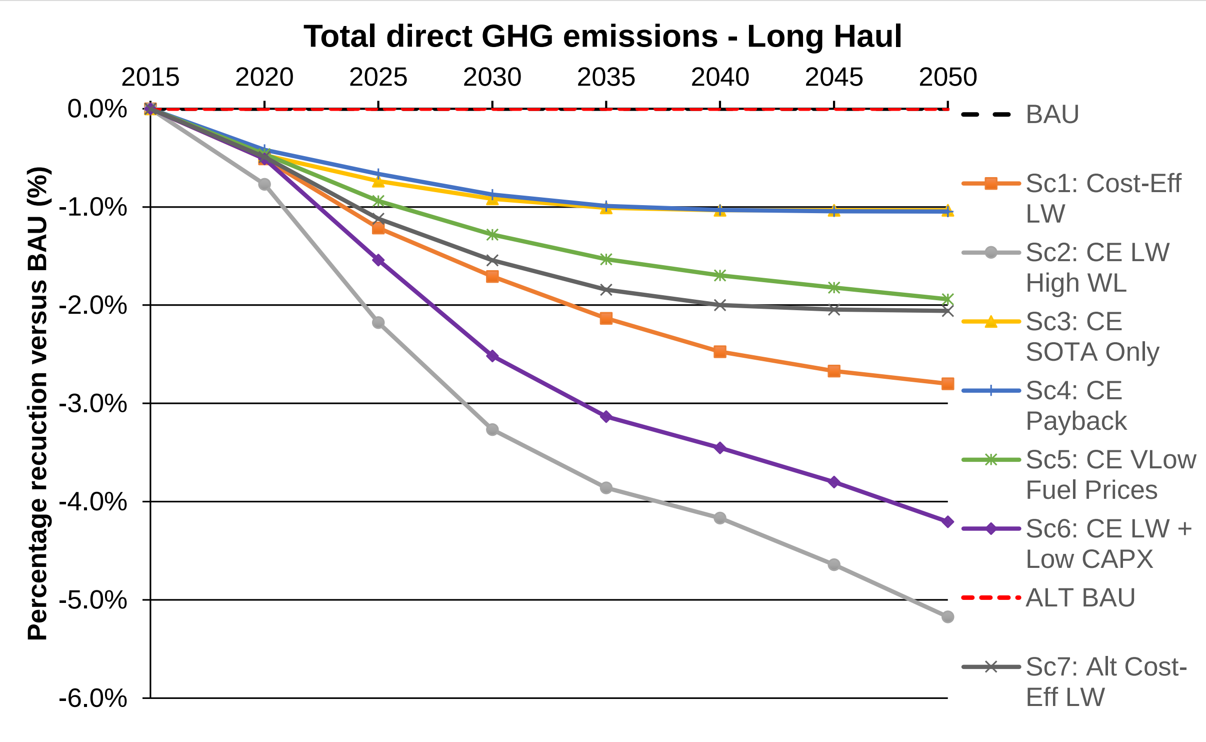
Note: * For the Alt BAU and Alt Cost-Eff LW, % reduction is calculated vs the Alt BAU scenario.

Figure 6.9: Summary of the change in projected direct CO_2 emissions from construction trucks due to cost-effective uptake of lightweighting in the EU fleet for different scenarios vs the relevant BAU scenario



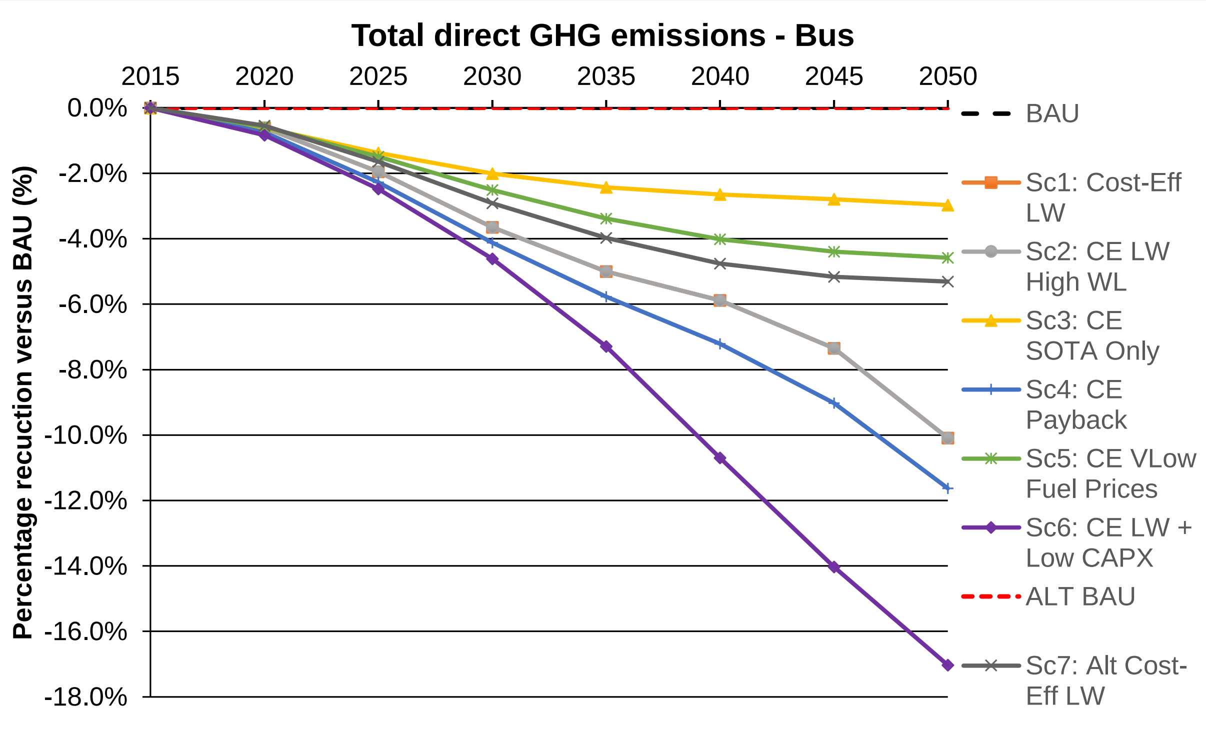
Note: * For the Alt BAU and Alt Cost-Eff LW, % reduction is calculated vs the Alt BAU scenario.

Figure 6.10: Summary of the change in projected direct CO_2 emissions from long-haul trucks due to cost-effective uptake of lightweighting in the EU fleet for different scenarios vs the relevant BAU scenario



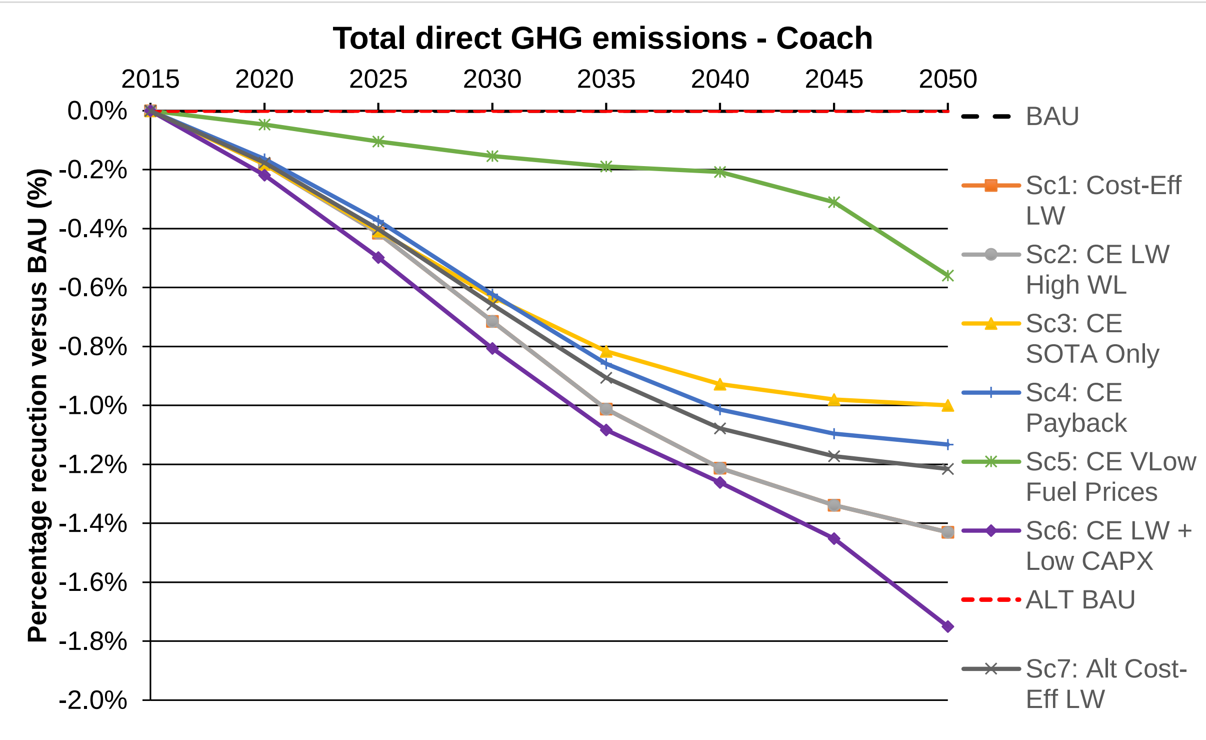
Note: * For the Alt BAU and Alt Cost-Eff LW, % reduction is calculated vs the Alt BAU scenario.

Figure 6.11: Summary of the change in projected direct CO_2 emissions from urban buses due to cost-effective uptake of lightweighting in the EU fleet for different scenarios vs the relevant BAU scenario



Note: * For the Alt BAU and Alt Cost-Eff LW, % reduction is calculated vs the Alt BAU scenario.

Figure 6.12: Summary of the change in projected direct CO_2 emissions from coaches due to cost-effective uptake of lightweighting in the EU fleet for different scenarios vs the relevant BAU scenario



Note: * For the Alt BAU and Alt Cost-Eff LW, % reduction is calculated vs the Alt BAU scenario.

7 Summary and Conclusions

7.1 HDV lightweighting options

The objective of the first task for the project was to identify options for lightweighting of different types of HDVs, and also gather information on their likely costs. The work involved carrying out a review of available literature, developing draft estimates for HDV lightweighting options and their potential, and consulting with relevant stakeholders to seek feedback on/help refine these estimates into a final list.

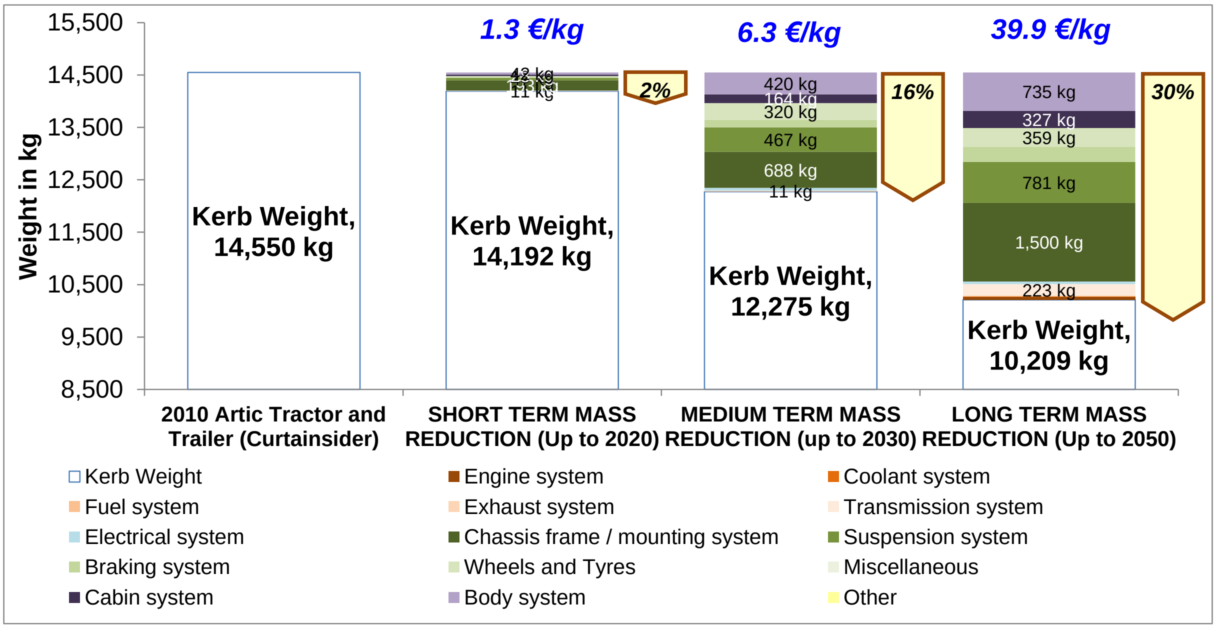
A key sub-task included the development of a 'virtual tear-down' of a set of five representative HDV types, using Ricardo's internal expertise and publically available data sources to provide a breakdown of the vehicle's mass and materials by system and sub-system. The five HDV types identified included:

1. Heavy van (5t GVW)
2. Rigid truck (12t GVW)
3. Artic truck (40t GVW)
4. City bus (12t GVW)
5. Coach (19t GVW)

Very little information was identified in the available in public information sources on individual lightweighting measures, nor the overall weight reduction potential of HDVs. Therefore Ricardo used their internal engineering expertise to develop an indicative bottom-up list of options for weight reduction and their costs and effectiveness for the five different representative HDV types. The results of this assessment were also sense-checked in the stakeholder consultation process to further refine them.

An example of the final results is presented in the following Figure 7.1 below, providing a summary of the estimated weight reduction potential for an articulated truck.

Figure 7.1: Estimated mass reduction potential by system and costs for an articulated truck



Source: Study analysis by Ricardo-AEA and Ricardo UK.

Notes: Estimates are based on current costs for weight reduction measures.

As part of this study we also carried out a review of publically available information sources to develop indicative estimates of the additional weight of alternative fuel and/or powertrain systems. The results of this review suggest that that for fully electric vehicles at least, the 1 tonne additional weight allowance proposed for the amendment of the EC Directive covering the weights and dimensions of HDVs may not be sufficient to balance the additional weight due to batteries for larger vehicles. Though clearly this depends on a number of factors including the efficiency/electric range of the vehicle and improvements to battery energy density in the coming years (which is anticipated to potentially halve by 2020).

7.2 Impact of lightweighting on fuel consumption and CO_2 emissions

The previous task provided a comprehensive assessment of the options and technical developments for light-weighting. It generated a list of potential weight savings for the different light-weighting options and technical developments. The important linked question is: *"What levels of energy and CO_2 savings might this light-weighting produce?"*

This second task compiled the results of three different sources in order to estimate the potential energy and CO_2 savings resulting from HDV lightweighting:

1. Literature sources
2. HDV simulations (using the VECTO model)
3. Pervious HDV testing (from dynamometer tests and test track driving with PEMS[20])

The analysis of the data from these sources confirmed the linear relationship of weight reduction and fuel consumption/CO_2 emissions for a series of different HDV types and duty cycles. The principal output from this task was the development of a series of linear equations for the relationship between the vehicle's weight and its CO_2 emissions (per km) for different HDV type and duty cycle combinations, i.e.:

$$CO_2 \text{ (g/km)} = \text{Gradient x vehicle weight + constant.}$$

The values of these gradients and constants are listed in Table 3.17 of this report for different vehicle categories, and different drive cycles.

An additional output from this task was the development of low and high estimates of the average share of km that are weight limited, for different HDV types and duty cycles.

7.3 Marginal abatement cost-curve analysis of HDV lightweighting

The aim of the third and fourth tasks were to produce vehicle-level marginal abatement cost (MAC) curves, and hence estimates for the cost-effective lightweighting potential of different HDV types, which were then used as a basis for estimating overall EU HDV consumption/CO_2 emissions in Task 5. As part of this work Ricardo-AEA adapted/built upon the framework from the previously developed MACC model previously developed by CE Delft for DG Climate Action[21]. The new HDV Lightweighting MACC Model was populated with information/outputs from the previous project tasks, plus additional information to help characterise the development of the future performance of HDVs to 2050 and the costs of the identified lightweighting options.

The developed model was designed to output results for a series of 17 different vehicle combinations of HDV weight classes and duty cycles for a series of different time periods from 2015 to 2050. An example of one the MAC curve generated for a 16-32 tonne construction truck for the 2030 time-period is presented in the following Figure 7.2 below.

The developed model was then used to provide a series of summary outputs on the overall cost-effective weight/CO_2 reduction potential for HDVs, and also the exploration of a range of sensitivities on this. Table 7.1 and Table 7.2, provide a summary of the results for the overall average cost-effective weight reduction potential and CO_2 savings for different HDV duty cycles under the default/core set of assumptions.

The results show that when looking across all HDV modes, all trucks other than utility trucks are expected to be able to achieve at least a 7% reduction in weight cost-effectively by 2025, under the defined social perspective and payback over the lifetime of the vehicle. By 2050, construction trucks have the most cost-effective light-weighting potential, expected to be able to reduce weight cost effectively by over 13%.

At the other end, utility trucks appear to have least potential for cost-effective lightweighting with only around 4-5% weight reduction estimated to be attainable throughout all time period.

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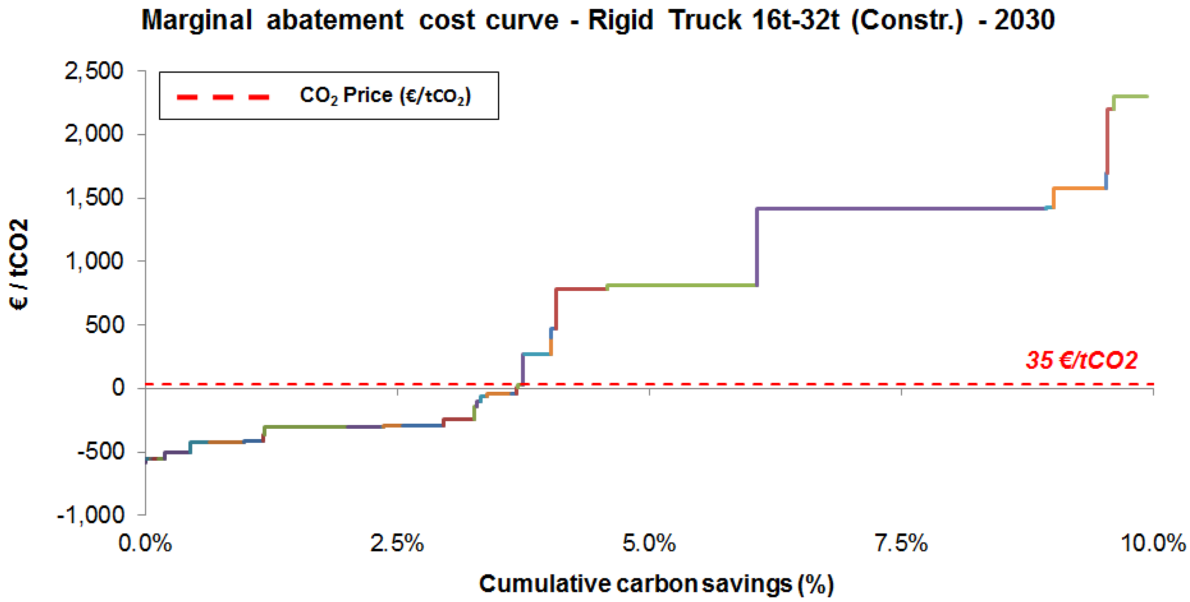
[20] PEMS = Portable Emissions Measuring System
[21] CE Delft. (2012). 'Marginal abatement cost curves for Heavy Duty Vehicles'. Final report for DG Climate Action. European Commission. http://www.cedelft.eu/publicatie/marginal_abatement_cost_curves_for_heavy_duty_vehicles_/1318?PHPSESSID=fd472a7cb3cf9d7ca910579edf80e4b4.

Figure 7.2: Marginal abatement cost curve for 16-32 tonne construction truck for 2030



The situation is also similar with respect to CO_2 savings: construction trucks have the greatest cost-effective potential of all truck duty cycles. Almost 3.7% cost-effective weight reduction may be achievable by 2030 and 5% by 2050. These figures are substantially greater than those of the other truck duty cycles; one of the principal factors contributing to this is their greater levels of weight-limited operation.

Of all HDVs, buses have the highest cost-effective weight reduction potential, with over 20% cost-effective lightweighting estimated to be possible by 2050. This equates to around 17% reduction in CO_2, due to the highly transient nature of bus duty cycles, with frequent stops. In contrast, coaches are anticipated to have some of the lowest levels of cost-effective weight reduction potential.

Table 7.1: Calculated cost-effective weight reduction potential (%) versus 2015 baseline vehicle

Vehicle type	2020	2025	2030	2040	2050
Average Truck	**4.1%**	**7.4%**	**8.6%**	**9.8%**	**10.2%**
Urban	4.4%	8.4%	10.3%	11.5%	11.8%
Utility	3.7%	4.0%	4.6%	4.6%	4.6%
Regional	4.9%	8.6%	9.9%	10.1%	10.2%
Construction	3.8%	8.2%	9.9%	12.0%	13.5%
Long Haul	4.1%	7.6%	8.0%	10.1%	10.6%
Average Bus	**2.8%**	**4.2%**	**5.4%**	**5.1%**	**10.5%**
Bus	3.5%	7.1%	8.0%	8.0%	20.5%
Coach	2.3%	2.4%	3.8%	3.3%	4.2%

Table 7.2: Calculated CO_2 savings potential (%) versus baseline vehicle for model year for cost-effective weight-reduction

Vehicle type	2020	2025	2030	2040	2050
Average Truck	**1.06%**	**1.91%**	**2.24%**	**2.56%**	**2.68%**
Urban	1.17%	2.14%	2.67%	2.97%	3.03%

Vehicle type	2020	2025	2030	2040	2050
Utility	1.48%	1.57%	1.78%	1.78%	1.80%
Regional	1.12%	1.94%	2.28%	2.34%	2.36%
Construction	1.40%	3.05%	3.67%	4.38%	4.94%
Long Haul	0.85%	1.58%	1.66%	2.13%	2.23%
Average Bus	**1.58%**	**2.78%**	**3.38%**	**3.28%**	**7.54%**
Bus	2.76%	5.81%	6.56%	6.56%	17.12%
Coach	0.85%	0.89%	1.40%	1.24%	1.57%

A range of sensitivities were also explored using the MACC model, in order to estimate the potential impacts of different assumptions/outcomes for key parameters, including fuel prices, capital costs of lightweighting, annual mileage, share of weight-limited operations, capital payback period, social vs end-user perspectives, etc.

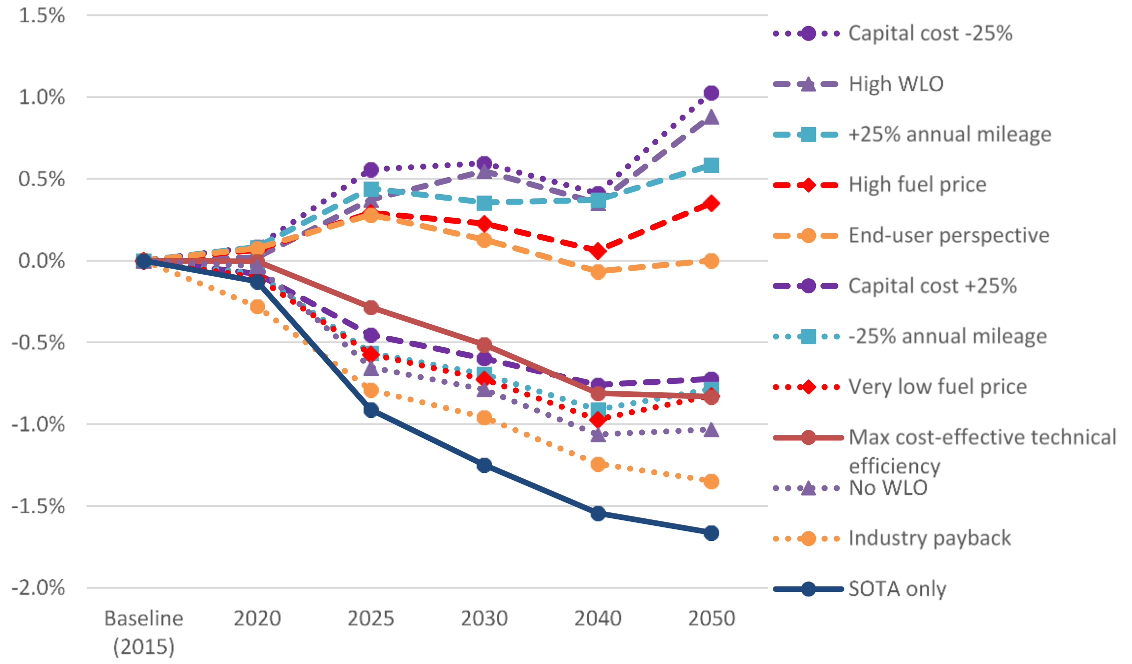
For trucks, it was found that the assumption of a 25% reduction in the cost of lightweighting measures has the greatest impact in terms of making more lightweighting measures cost-effective and thereby increasing fuel savings (Figure 7.3). The assumption of higher weight limited operation has the second most significant positive impact on fuel savings due to the application of cost-effective lightweighting. The assumption of 25% increase in annual mileage per vehicle has a similarly high impact in most years. High fuel prices and taking into account the end-user perspective also slightly increase the level of cost-effective lightweighting.

The assumed unavailability of future lightweighting technologies, short industry payback requirements and the assumption of no weight limited operations to benefit from reduced trip numbers have the greatest impact in terms of reducing the cost-effectiveness of lightweighting, leading to increases in fuel consumption over the default scenario. Annual mileage reduction, low fuel prices, high costs of lightweighting measures and maximum uptake of alternative fuel savings technologies also make lightweighting less financially attractive.

Almost all sensitivities have rather low impact in the short term time horizon up to 2020.

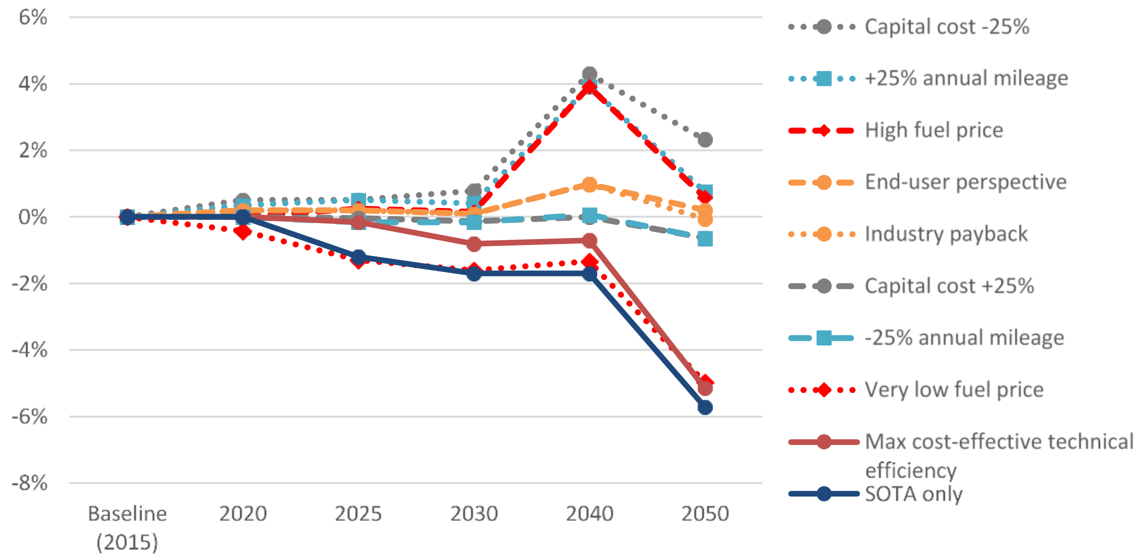
In the case of buses/coaches (Figure 7.4) where cost-effective weight reduction potentials lead to significantly greater fuel savings compared to trucks, the assumption of 25% lower capital cost for lightweighting measures has the single greatest positive impact on fuel savings. In second place, 25% annual mileage increase, high fuel prices, end-user perspective and industry payback all have similar, slightly positive consequences for cost-effective lightweighting and fuel savings. Notably, fuel savings are drastically lower under the SOTA assumptions (no future lightweighting measures available). Especially in 2050, maximum uptake of alternative fuel savings technologies and very low fuel prices also greatly reduces fuel savings and levels of lightweighting.

Figure 7.3: Summary: impact of altered assumptions on truck fuel/CO_2 savings relative to the default lightweighting scenario



Notes: WLO = weight limited operation; SOTA = state-of-the-art technologies

Figure 7.4: Summary: impact of altered assumptions on bus/coach fuel/CO_2 savings relative to the default lightweighting scenario



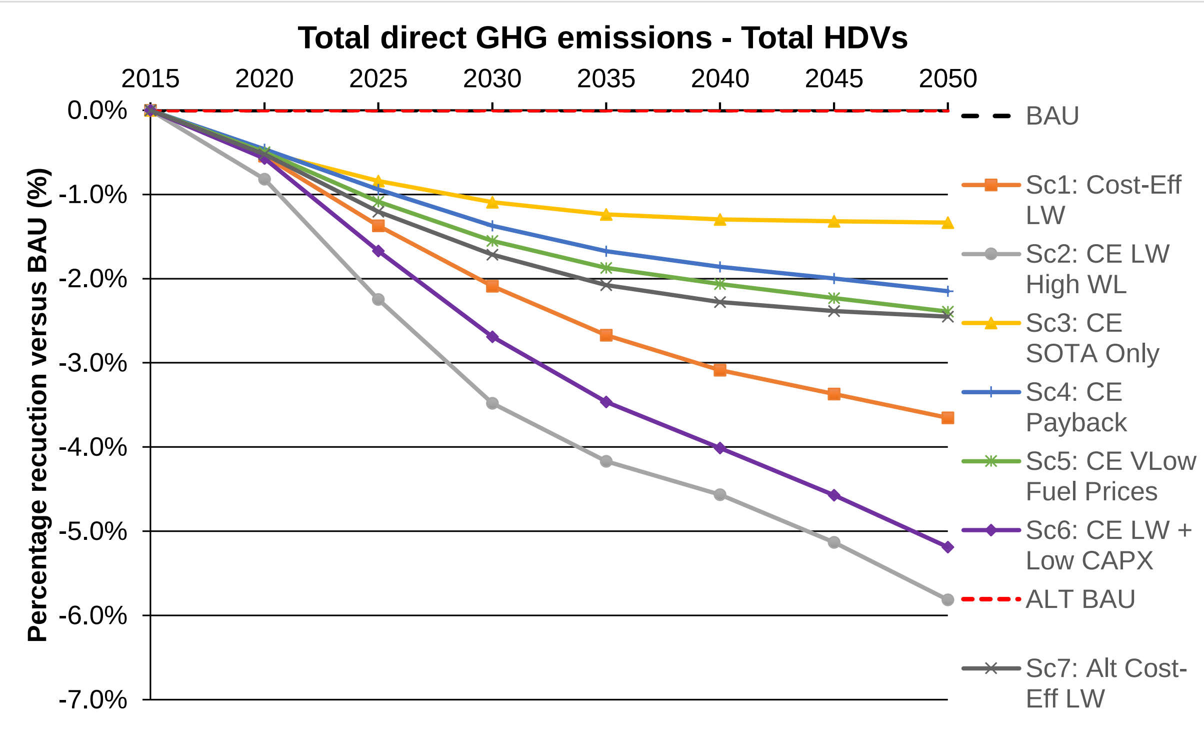
Notes: WLO = weight limited operation; SOTA = state-of-the-art technologies

7.4 Potential impacts of light-weighting for the EU HDV fleet

The final task in this project involved the estimation of the potential impacts for take-up of cost-effective lightweighting on overall fuel consumption and CO_2 emissions from the European HDV fleet. Outputs from the previous MACC modelling analysis were used within an adapted version of the SULTAN model previously developed by Ricardo-AEA for DG Climate Action[22], in order to estimate these impacts.

The following Figure 7.5 and Table 7.3 provide a summary of the overall results of the European HDV fleet modelling in terms of the estimated changes in overall direct CO_2 emissions for different HDV lightweighting scenarios. In the core/baseline lightweighting scenario (#1, Cost-Eff LW), it is estimated that the application of cost-effective lightweighting could reduce emissions from the European HVD fleet by around 2.1% by 2030 and 3.7% by 2050. A range of sensitivities were also explored on the levels of weight limited operations, assumptions on industry payback requirements, fuel prices and capital costs and on the impacts of including other cost-effective HDV CO_2 reduction technologies. These are also presented in the table and figure, and show that as a consequence, emission reductions could be as little as half of those in the core/baseline scenario (#1), or up to almost double the size.

Figure 7.5: Summary of the change in projected direct CO_2 emissions from all HDVs due to cost-effective uptake of lightweighting in the EU fleet for different scenarios vs the relevant BAU scenario



Note: * For the Alt BAU and Alt Cost-Eff LW, % reduction is calculated vs the Alt BAU scenario.

Table 7.3: Total HDV direct CO_2 emissions by scenario, Mtonnes CO_2

#	Scenario	2015	2020	2025	2030	2035	2040	2045	2050
	BAU	*288.3*	*293.3*	*304.5*	*316.1*	*320.5*	*327.7*	*331.6*	*336.0*
1	Cost-Eff LW	288.3	291.7	300.3	309.5	312.0	317.6	320.4	323.7
2	CE LW High WL	288.3	290.9	297.6	305.1	307.2	312.8	314.6	316.5
3	CE SOTA Only	288.3	291.8	301.9	312.6	316.6	323.5	327.2	331.5
4	CE Payback	288.3	291.9	301.6	311.7	315.2	321.6	325.0	328.8
5	CE V Low Fuel Prices	288.3	291.8	301.2	311.2	314.5	320.9	324.2	328.0

[22] AEA et al. (2012). Developing a better understanding of the secondary impacts and key sensitivities for the decarbonisation of the EU's transport sector by 2050 - Final Project Report. A report by AEA, TNO, CE Delft and TEPR for the European Commission, DG Climate Action. Retrieved from http://www.eutransportghg2050.eu/cms/reports/

#	Scenario	2015	2020	2025	2030	2035	2040	2045	2050
6	CE LW + Low CAPX	288.3	291.6	299.4	307.6	309.4	314.6	316.4	318.6
	Alt BAU	*288.3*	287.0	282.5	267.4	246.0	232.6	220.0	207.2
7	Alt Cost-Eff LW	288.3	285.5	279.1	262.8	240.9	227.3	214.8	202.2

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Appendices

Appendix 1: Additional supporting material for Task 1

Appendix 2: Additional supporting material for Task 4

Appendix 3: Additional supporting material for Task 5

Appendix 1 – Additional supporting material for Task 1

Summary of initially reviewed literature

Table 8.1: Reviewed literature with high relevance

Author	Brief description	Vehicles covered	Components covered
EDAG, 2013	Presents concept of a lightweight cabin BIW. Weighs 319kg rather than 380-420kg.	Artic truck	Cabin BIW
K+P Transport Consultants and HWH, 2012	Study commissioned by Berger on fuel economy and cost reductions from using the Berger Ecotrail instead of a conventional HDV semi-trailer. The manufacturer gave contact details of 18 logistics firms who are customers of the product. 13 of these were interviewed via telephone or in person. The information gathered in the interviews includes type of goods transported, the firm's estimate of increase in payload through the lightweight trailer, purchase costs, fuel savings, overall experiences, etc. In a second step a field test was carried out in Thuringia. Fuel consumption for the Berger Ecotrail and three different standard trailers was measured on a total of 16 standardised 228km trips with two tractor units. The Berger Ecotrail trailer weighs 4.7t. It was compared to trailer models weighing 6.3t, 6.4t and 6.6t using a standard payload of 24 t potting soil (Kögel, one of the largest trailer manufacturers states that its standard trailer weighs 6t and its lightweighted trailer weighs 5.2t (http://www.koegel.com/uploads/media/brochure_platform_trailers_01.pdf)). On average around 2l of Diesel savings per 100 km were recorded. This was higher than what most of the logistics firms had reported. It should, however, be noted that Thuringia is a fairly hilly region and lightweight vehicles tend to have over-proportionate savings on hilly terrain (see 2006 IFEU study). The Berger Ecotrail study also examined the case of making complete use of the higher payload. It finds that this could lead to 7% fewer trips for transporting a given quantity. It is also worth noting that most of the interviewees did not use weight-reduced tractor units stating that standard tractors offer greater flexibility but also due to concerns about the resale value of those trucks. Some interviewees also expected inferior resale value for the lightweighted trailers. The trucks are often sold to Russia where there is little interest in weight reduction but concern that weight reduced vehicles may cause higher operating cost.	Semi-trailer	Study on fuel/cost savings of the truck-trailer system using a lightweight trailer

Author	Brief description	Vehicles covered	Components covered
Engineering Centre Steyr, 2013	Cabin weight: Cabin-in-White about one third of cabin weight; exterior and interior components including doors and glazing account for over 60%. Fibre-reinforced composites allow for weight reduction in the roof module of around 30% taking into account the need for reinforced roof elements for crash safety requirements according to ECE R29-3 Modular lightweight cabin to save 150 kg in total -- not clear if this is from fibre composite roof alone. Tractor frame: savings potential of 30% - around 250 kg, by reducing sheet thickness. The frame design also allows for easier fitting of front independent wheel suspension. Magna state that total weight savings of up to one tonne are possible combining the lightweight frame, lightweight cabin, "single parabolic leaf springs + stabiliser, super single tyres, light weight tanks and load data management (truck is optimised for transport task and not for second life)" The engineer who designed the monocoque frame concept claims that full weight-optimisation of the frame and frame-mounted subsystems 'can knock 700 kg off the kerb weight of the vehicle'. (http://www.autocarpro.in/ap/features/3267/2012-lightweighting-special-framework-revolution)	Tractor unit	roof of tractor cabin tractor frame
Aluminium Association, 2011	Presentation on weight savings potentials in different vehicle body parts from using aluminium	articulated US-style truck: tractor and trailer	various components
US National Research Council, 2010	Study commissioned in response to Energy Independence and Security Act of 2007 which requires the DoT to establish fuel economy standards for HDV. The National Research Council study provides a comprehensive review of HDV fuel savings options, including a small section on lightweighting from page 116 and estimates for lightweighting potential and cost through material substitution over the coming years from page 135.	All HDV	Weight composition of a US style tractor, impacts of weight reduction on fuel consumption, mention of industry developments such use of aluminium in different components such as the cab, wheels, etc. (Table 5-17 in document)

Table 8.2: Reviewed literature with medium relevance

Author	Brief description	Vehicles covered	Components covered
ATZ, 2012	Component research: Paper describes a project in which a lightweight chassis frame with independent wheel suspension was designed for a 4x4 HDV of the 12t GVW category. It claims weight savings of 4-6% over comparable conventional designs as well as a 20% reduction in unsprung weight.		Chassis frame for a 5.5t to 12t GVW truck.
Don-Bur, 2013	Component research	Body panels for HDVs	5 different panel materials which Don-Bur's customers can choose from
Eberle and Smith, 2003	Article provides an overview over six US research programmes in the early 2000s on replacing truck parts with fibre plastics. Programmes include cab parts (x2), hood, tie rods, chassis/frame components, and doors.	Tractor unit	Cab parts (x2), hood, tie rods, chassis/frame components, and doors.
European Aluminium Association, 2011	162 page report giving high level overview of where and how Al can be used in commercial vehicles (mainly HGVs). Page 13 includes diagram with typical kg weight savings. Document highlights EAA's savings calculator: http://www.alueurope.eu/financial-benefits-simulator/	Mainly HGVs - chassis / tippers / tankers. Briefly mentions rail, air and sea.	Wide variety (see page 13).
IAI, 2010	Lightweighting research: Study provides an overview citing various sources on GHG reductions from weight savings on road and rail vehicles. Some examples of weight savings potentials by replacing steel parts by aluminium parts but none specific to HDVs.		Wide variety

Author	Brief description	Vehicles covered	Components covered
FKA, 2011	The article is mainly about general design alterations to the tractor unit for improved safety of occupants and others, and fuel saving. This includes a short section on the weight impacts of the new design. - Windscreen: + 12.3 kg from increasing size from 2 sqm to 3sqm. - Front bumper cover: -6.1kg from reducing size from 2.7 sqm to 1.8 sqm - Conventional steel bumper weighs 53.6 kg while proposed new design weighs 60 kg. To compensate for the net weight increase, two weight reduction measures are proposed (already identified in sources above): *One example for such a measure is the usage of an aluminium fifth-wheel plate instead of a conventional steel device. This way a mass reduction between 33 kg (37 %) to 45 kg is possible. If the slider combination beneath it is also modified and adapted a reduction of even 58 kg is achievable.* *Furthermore, aluminium wheels are an option to reduce weight. For a tractor with six wheels a total weight reduction of 120 kg can be realised, but the high cost of about 3000 € avoid a higher market penetration. Aluminium wheels are more damageable as steel wheels when assembling the tyre.*	Tractor unit	Windscreen Front bumper cover Front bumper As compensating measures: Aluminium wheels Aluminium 5th wheel
Navistar, NETL and DoE, 2012	A DoE sponsored development and demonstration project for a fuel efficient semi-trailer truck also includes lightweighting measures. Page 12 of the report summarises some of the intended weight reductions in different areas	articulated US-style truck: tractor and trailer	Axles, brake system, single prop shaft, tyres and wheels, body cab, plastic fuel tank, composite trailer load floor, trailer suspension, chassis
Navistar, NETL and DoE, 2013	Slides 17 and 18 give details on the lightweighting of the tractor frame - 20kg are saved by using 2 carbon fibre cross-members in the frame	articulated US-style truck: tractor and trailer	tractor frame
SAE, 2012	Magazine article about a ZF prototype of a glass-fibre plastic four-point link saving some 11kg over the standard 46kg cast component.	Tractor unit	Four point link: a device in the rear axle's suspension
UK DfT, 2012	Lightweighting research - This Case Study highlights the benefits that MEMS achieved by reducing the weight of the truck chassis and auxiliary equipment resulting in an increased payload. MEMS were looking to reduce the number of trips required for each diesel generator delivery they handle. By doing this they wanted to reduce their mileage, fuel usage and ultimately decrease their expenditure.	MEMS operate a mixed fleet of rigid HGVs, rigid HGVs with lorry mounted cranes, articulated tractor units and flatbed trailers and a variety of support	Chassis

Author	Brief description	Vehicles covered	Components covered
		vehicles including refuelling tankers, road tow fuel tanks, fuel bowsers and Landrovers.	
US DoE, 2013	Lightweighting research - Report of a Lightweight and propulsion materials workshop held in the US. This meeting focused on gaining industry's perspective on the out-year material requirements of trucks and heavy duty vehicles (HDVs) as well as current technology gaps that limit adoption of designs utilising these lighter weight materials.	All vehicles over 10,000 lbs GVW (>4.5t) (cat 3-8 USA)	Body and cab, chassis, powertrain
US National Research Council, 2012	Pages 85-87 discuss weight reduction without providing any particularly detailed examples. Some research funding from the 21st Century Truck Partnership is channelled towards lightweighting, especially under the SuperTruck projects (see above).	articulated US-style truck: tractor and trailer	all/unspecific
Schroeter, 2011	Weighs 17kg rather than 66kg for steel leaf spring	Artic truck	Suspension
Volvo, 2010	New Volvo 8900 with body made of Steel, Aluminium and Composites saves 200-300 kg over steel predecessor Volvo 8700 in base version, and 800kg in 3-axle version	Interurban bus	Body
Verkehrsrundschau, 2013	Fuel economy league table also provides the weight of the 36 tractor units featuring in the ranking, information which can otherwise be difficult to access.	Tractor unit	n/a

Table 8.3: Reviewed literature with low relevance

Author	Brief description	Vehicles covered	Components covered
ATZ, 2013	Component research	Several lightweight design/material examples for cars	Composite convertible roof design, lightweight steel body, magnesium sliding door design
Cheah, 2010	The material and energy impacts of passenger vehicle weight reduction in the U.S.	Passenger cars and some light trucks	All (chassis, structure, components, powertrain etc.)

Author	Brief description	Vehicles covered	Components covered
Davies, 2012	Textbook on materials and associated manufacturing techniques and challenges in the production of passenger car bodies.	Passenger cars	body
US EPA, 2012	Downweighting research	Car: Toyota Venza	The study performs a follow-up study on the Lotus study including a more detailed tear-down of the vehicle. All components of the car are weighed individually and weight reduction potential in each component is estimated with the aim of creating overall vehicle weight savings of 20%
Hirsh, 2011	Component research and cost effectiveness/impact of using aluminium materials in car manufacturing and design	Passenger cars (mid-sized)	All (chassis, structure, components, powertrain etc.)
Kim et al., 2010	Article covers lightweighting potential in a selection of different passenger car components based on a reference car (Ford Focus), similar to Lotus, 2010 and EPA, 2012, although the description in the article is less detailed. 5 levels of lightweighting with total kerb weight reductions up to 23% are developed as cases, based on different combinations of lightweighting measures using high-strength steel and aluminium. The lifetime fuel savings and GHG savings for each case are estimated.	Passenger car (Ford Focus)	A variety of passenger car components
Lesemann et al., 2008	Downweighting research	Passenger cars (mid-sized)	A lightweight multi material BIW structure
Lotus Engineering, 2010	Downweighting research	Car: Toyota Venza	The study performs a tear-down of the vehicle in which vehicle components are weighed and lightweighting options for these components assessed. Two outcomes are modelled: one making the vehicle 20% lighter and one making it 40% lighter.
MIT, 2008	Lightweighting research - Very broad general paper on the different ways to downweight vehicles and cost estimates of such downweighting. Not purely HGV specific.	Ford F-150 (Light truck/pickup truck)	
Pagerit et al., 2006	Weight Specific Vehicle Research	Passenger cars	Powertrains

Author	Brief description	Vehicles covered	Components covered
Roland Berger, 2012	Lightweighting research		
Solbus, 2013	Presentation of the LNG powered Solcity Bus. Points out that the weight of the Solcity bus was reduced by 500kg through 'stripping out weight wherever possible'. Not clear how exactly and relative to what the 500kg weight savings were achieved.	City bus	Entire bus
DAF Trucks, 2011	The article does not give any numbers on the extent on weight savings potentials but rather describes a modelling approach towards optimising the frame design for meeting 'all strength and stiffness requirements at the lowest weight' possible.	Tractor unit/truck	frame
Midlands Business News, n.d.	New 7.5t trucks in the fleet of Bensons, a bed furniture retailer, deliver weight savings of around 500kg thanks to lightweight plastic panels.	Rigid panel truck	Panel

Table 8.4: Irrelevant reviewed literature

Author	Brief description	Vehicles covered	Components covered
Cheah and Heywood, 2011	Article examining the options for light duty vehicles to meet 2016 US fuel economy standards.	Passenger cars	The article does not discuss lightweighting at the component level
US EPA, 2008	Report on engine and transmission oriented fuel saving technologies for passenger cars.	Passenger cars	No lightweighting technologies considered
FKA, 2007	Weight Specific Vehicle Research	Passenger cars: small, middle, large	n/a. Artilce discusses fuel economy impact from a given weight saving, not technologies to save weight.

Appendix 2 – Additional supporting material for Task 4

Default lightweighting scenario

Default	Baseline (2015)	2020	2025	2030	2040	2050
Trucks, Urban	0.0%	1.2%	2.1%	2.7%	3.0%	3.0%
Trucks, Utility	0.0%	1.5%	1.6%	1.8%	1.8%	1.8%
Trucks, Regional	0.0%	1.1%	1.9%	2.3%	2.3%	2.4%
Trucks, Construction	0.0%	1.4%	3.1%	3.7%	4.4%	4.9%
Trucks, Long Haul	0.0%	0.8%	1.6%	1.7%	2.1%	2.2%
Trucks <7.5t (All Cycles)	0.0%	0.8%	1.9%	2.2%	2.5%	2.6%
Trucks 7.5-16t (All Cycles)	0.0%	1.6%	2.6%	3.1%	3.5%	3.6%
Trucks 16t-32t (All Cycles)	0.0%	1.3%	2.3%	2.6%	2.7%	2.8%
Trucks >32t (All Cycles)	0.0%	0.8%	1.3%	1.7%	2.2%	2.4%
Bus	0.0%	2.8%	5.8%	6.6%	6.6%	17.1%
Coach	0.0%	0.8%	0.9%	1.4%	1.2%	1.6%
Average all HDVs	*0.0%*	*1.1%*	*2.0%*	*2.4%*	*2.6%*	*3.3%*
Average Trucks	*0.0%*	*1.1%*	*1.9%*	*2.2%*	*2.6%*	*2.7%*
Average Buses/Coaches	*0.0%*	*1.6%*	*2.8%*	*3.4%*	*3.3%*	*7.5%*

Technical options

Sensitivity: SOTA only	Baseline (2015)	2020	2025	2030	2040	2050
Trucks, Urban	0.0%	1.0%	1.2%	1.2%	1.3%	1.3%
Trucks, Utility	0.0%	1.1%	1.1%	1.1%	1.1%	1.1%
Trucks, Regional	0.0%	1.0%	1.0%	1.0%	1.1%	1.1%
Trucks, Construction	0.0%	1.3%	1.3%	1.3%	1.3%	1.3%
Trucks, Long Haul	0.0%	0.8%	0.8%	0.8%	0.8%	0.8%
Trucks <7.5t (All Cycles)	0.0%	0.7%	0.9%	0.9%	0.9%	0.9%
Trucks 7.5-16t (All Cycles)	0.0%	1.4%	1.5%	1.5%	1.5%	1.5%
Trucks 16t-32t (All Cycles)	0.0%	1.1%	1.1%	1.1%	1.2%	1.2%
Trucks >32t (All Cycles)	0.0%	0.7%	0.7%	0.7%	0.8%	0.8%
Buses	0.0%	2.8%	2.8%	2.8%	2.8%	3.4%
Coaches	0.0%	0.8%	0.8%	1.0%	0.8%	0.8%
Average all HDVs	*0.0%*	*1.0%*	*1.1%*	*1.1%*	*1.1%*	*1.1%*
Average Trucks	*0.0%*	*0.9%*	*1.0%*	*1.0%*	*1.0%*	*1.0%*
Average Buses/Coaches	*0.0%*	*1.6%*	*1.6%*	*1.7%*	*1.6%*	*1.8%*

Share of weight limited operations

Sensitivity: No WLO	Baseline (2015)	2020	2025	2030	2040	2050
Trucks, Urban	0.0%	1.2%	1.3%	1.6%	1.6%	1.8%
Trucks, Utility	0.0%	1.5%	1.6%	1.8%	1.8%	1.8%
Trucks, Regional	0.0%	1.0%	1.1%	1.2%	1.2%	1.6%
Trucks, Construction	0.0%	1.3%	2.2%	2.4%	2.8%	2.9%
Trucks, Long Haul	0.0%	0.8%	1.1%	1.2%	1.2%	1.2%
Trucks <7.5t (All Cycles)	0.0%	0.8%	1.0%	1.4%	1.4%	1.5%
Trucks 7.5-16t (All Cycles)	0.0%	1.5%	1.5%	1.8%	1.9%	1.9%
Trucks 16t-32t (All Cycles)	0.0%	1.3%	1.9%	2.1%	2.1%	2.5%
Trucks >32t (All Cycles)	0.0%	0.7%	0.7%	0.9%	0.9%	1.0%
Buses	0.0%	2.8%	5.8%	6.6%	6.6%	17.1%
Coaches	0.0%	0.8%	0.9%	1.4%	1.2%	1.6%
Average all HDVs	*0.0%*	*1.1%*	*1.4%*	*1.7%*	*1.7%*	*2.4%*
Average Trucks	*0.0%*	*1.0%*	*1.3%*	*1.5%*	*1.5%*	*1.6%*
Average Buses/Coaches	*0.0%*	*1.6%*	*2.8%*	*3.4%*	*3.3%*	*7.5%*

Sensitivity: High WLO	Baseline (2015)	2020	2025	2030	2040	2050
Trucks, Urban	0.0%	1.2%	2.1%	2.7%	3.0%	3.0%
Trucks, Utility	0.0%	1.5%	1.6%	1.8%	1.8%	1.8%
Trucks, Regional	0.0%	1.1%	2.4%	2.6%	2.7%	3.5%
Trucks, Construction	0.0%	1.5%	4.1%	5.3%	5.5%	7.5%
Trucks, Long Haul	0.0%	0.8%	2.2%	2.7%	2.7%	3.5%
Trucks <7.5t (All Cycles)	0.0%	0.8%	1.9%	2.2%	2.5%	2.6%
Trucks 7.5-16t (All Cycles)	0.0%	1.6%	2.7%	3.7%	3.8%	3.9%
Trucks 16t-32t (All Cycles)	0.0%	1.3%	2.4%	2.7%	2.8%	5.0%
Trucks >32t (All Cycles)	0.0%	0.8%	2.6%	3.2%	3.2%	3.2%
Buses	n/a	n/a	n/a	n/a	n/a	n/a
Coaches	n/a	n/a	n/a	n/a	n/a	n/a
Average all HDVs	*0.0%*	*1.1%*	*2.3%*	*2.9%*	*3.0%*	*4.1%*
Average Trucks	*0.0%*	*1.1%*	*2.3%*	*2.8%*	*2.9%*	*3.6%*
Average Buses/Coaches	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*

Sensitivity: All ops weight limited	Baseline (2015)	2020	2025	2030	2040	2050
Trucks, Urban	0.0%	4.2%	10.1%	21.7%	21.8%	21.8%
Trucks, Utility	0.0%	3.0%	6.9%	12.4%	13.1%	15.6%
Trucks, Regional	0.0%	3.5%	8.7%	17.0%	17.9%	18.7%
Trucks, Construction	0.0%	3.2%	7.9%	16.4%	17.5%	18.4%
Trucks, Long Haul	0.0%	2.3%	6.6%	10.5%	13.4%	13.4%
Trucks <7.5t (All Cycles)	0.0%	3.8%	8.9%	18.9%	18.9%	18.9%
Trucks 7.5-16t (All Cycles)	0.0%	5.0%	12.3%	26.6%	26.7%	26.7%
Trucks 16t-32t (All Cycles)	0.0%	3.0%	6.8%	14.6%	15.3%	16.0%
Trucks >32t (All Cycles)	0.0%	1.8%	6.3%	7.1%	11.0%	11.9%
Buses	0.0%	5.8%	10.4%	17.5%	30.1%	31.7%
Coaches	0.0%	11.9%	18.5%	21.9%	22.5%	38.7%
Average all HDVs	*0.0%*	*3.9%*	*8.8%*	*16.0%*	*17.6%*	*19.3%*
Average Trucks	*0.0%*	*3.1%*	*7.9%*	*15.4%*	*16.5%*	*16.9%*
Average Buses/Coaches	*0.0%*	*9.5%*	*15.4%*	*20.2%*	*25.4%*	*36.0%*

Costs of lightweighting measures

Sensitivity: Capital costs -25%	Baseline (2015)	2020	2025	2030	2040	2050
Trucks, Urban	0.0%	1.4%	2.8%	3.1%	3.1%	3.2%
Trucks, Utility	0.0%	1.5%	2.0%	2.4%	2.7%	3.3%
Trucks, Regional	0.0%	1.2%	2.5%	2.6%	2.7%	3.6%
Trucks, Construction	0.0%	1.4%	3.6%	4.3%	4.9%	7.2%
Trucks, Long Haul	0.0%	0.8%	2.2%	2.8%	2.8%	3.6%
Trucks <7.5t (All Cycles)	0.0%	1.0%	2.2%	2.6%	2.6%	2.7%
Trucks 7.5-16t (All Cycles)	0.0%	1.7%	3.0%	3.3%	3.7%	3.9%
Trucks 16t-32t (All Cycles)	0.0%	1.3%	2.7%	2.9%	3.0%	5.3%
Trucks >32t (All Cycles)	0.0%	0.8%	2.5%	3.3%	3.3%	3.4%
Buses	0.0%	3.8%	6.9%	8.6%	17.5%	21.7%
Coaches	0.0%	1.0%	1.1%	1.4%	1.4%	2.5%
Average all HDVs	*0.0%*	*1.3%*	*2.6%*	*3.0%*	*3.5%*	*4.5%*
Average Trucks	*0.0%*	*1.1%*	*2.5%*	*2.8%*	*3.0%*	*3.7%*
Average Buses/Coaches	*0.0%*	*2.1%*	*3.3%*	*4.2%*	*7.6%*	*9.9%*

Sensitivity: Capital costs +25%	Baseline (2015)	2020	2025	2030	2040	2050
Trucks, Urban	0.0%	1.2%	1.3%	1.6%	1.8%	1.9%
Trucks, Utility	0.0%	1.1%	1.4%	1.6%	1.8%	1.8%
Trucks, Regional	0.0%	1.0%	1.7%	1.9%	1.9%	2.0%
Trucks, Construction	0.0%	1.3%	2.5%	2.8%	2.8%	3.7%
Trucks, Long Haul	0.0%	0.8%	1.3%	1.4%	1.6%	1.7%
Trucks <7.5t (All Cycles)	0.0%	0.8%	1.1%	1.4%	1.8%	1.9%
Trucks 7.5-16t (All Cycles)	0.0%	1.4%	1.8%	2.1%	2.2%	2.6%
Trucks 16t-32t (All Cycles)	0.0%	1.3%	2.2%	2.3%	2.3%	2.4%
Trucks >32t (All Cycles)	0.0%	0.7%	0.9%	1.1%	1.3%	1.4%
Buses	0.0%	2.8%	5.7%	6.5%	6.6%	15.5%
Coaches	0.0%	0.8%	0.9%	1.2%	1.2%	1.6%
Average all HDVs	*0.0%*	*1.1%*	*1.6%*	*1.8%*	*2.0%*	*2.6%*
Average Trucks	*0.0%*	*1.0%*	*1.5%*	*1.6%*	*1.8%*	*2.0%*
Average Buses/Coaches	*0.0%*	*1.6%*	*2.7%*	*3.2%*	*3.3%*	*6.9%*

Fuel prices

Sensitivity: Very low fuel prices	Baseline (2015)	2020	2025	2030	2040	2050
Trucks, Urban	0.0%	1.2%	1.3%	1.6%	1.6%	1.9%
Trucks, Utility	0.0%	0.7%	0.8%	1.0%	1.0%	1.0%
Trucks, Regional	0.0%	1.0%	1.5%	1.7%	1.8%	1.9%
Trucks, Construction	0.0%	1.3%	2.5%	2.7%	2.7%	3.6%
Trucks, Long Haul	0.0%	0.8%	1.1%	1.2%	1.4%	1.6%
Trucks <7.5t (All Cycles)	0.0%	0.8%	1.0%	1.4%	1.4%	1.8%
Trucks 7.5-16t (All Cycles)	0.0%	1.4%	1.6%	1.9%	2.0%	2.5%
Trucks 16t-32t (All Cycles)	0.0%	1.2%	2.2%	2.2%	2.2%	2.2%
Trucks >32t (All Cycles)	0.0%	0.7%	0.7%	0.8%	1.0%	1.3%
Buses	0.0%	2.7%	3.5%	4.3%	4.7%	4.7%
Coaches	0.0%	0.2%	0.2%	0.2%	0.2%	1.2%
Average all HDVs	*0.0%*	*1.0%*	*1.4%*	*1.6%*	*1.6%*	*1.9%*
Average Trucks	*0.0%*	*1.0%*	*1.3%*	*1.5%*	*1.6%*	*1.9%*
Average Buses/Coaches	*0.0%*	*1.2%*	*1.5%*	*1.8%*	*1.9%*	*2.6%*

Sensitivity: High fuel prices	Baseline (2015)	2020	2025	2030	2040	2050
Trucks, Urban	0.0%	1.4%	2.4%	3.0%	3.0%	3.1%
Trucks, Utility	0.0%	1.5%	1.6%	1.8%	1.8%	2.7%
Trucks, Regional	0.0%	1.1%	2.2%	2.3%	2.3%	2.6%
Trucks, Construction	0.0%	1.4%	3.4%	3.7%	4.6%	5.0%
Trucks, Long Haul	0.0%	0.8%	2.0%	2.1%	2.3%	3.0%
Trucks <7.5t (All Cycles)	0.0%	1.0%	1.9%	2.5%	2.5%	2.6%
Trucks 7.5-16t (All Cycles)	0.0%	1.7%	2.9%	3.1%	3.5%	3.7%
Trucks 16t-32t (All Cycles)	0.0%	1.3%	2.5%	2.7%	2.7%	3.7%
Trucks >32t (All Cycles)	0.0%	0.8%	2.1%	2.2%	2.4%	2.7%
Buses	0.0%	2.8%	6.5%	7.2%	16.5%	18.6%
Coaches	0.0%	0.8%	0.9%	1.2%	1.4%	1.6%
Average all HDVs	*0.0%*	*1.2%*	*2.3%*	*2.6%*	*3.2%*	*3.7%*
Average Trucks	*0.0%*	*1.1%*	*2.2%*	*2.5%*	*2.6%*	*3.0%*
Average Buses/Coaches	*0.0%*	*1.6%*	*3.0%*	*3.5%*	*7.2%*	*8.1%*

Annual km

Sensitivity: Annual mileage -25%	Baseline (2015)	2020	2025	2030	2040	2050
Trucks, Urban	0.0%	1.2%	1.3%	1.6%	1.6%	1.9%
Trucks, Utility	0.0%	1.1%	1.2%	1.4%	1.6%	1.8%
Trucks, Regional	0.0%	1.0%	1.4%	1.8%	1.9%	1.9%
Trucks, Construction	0.0%	1.3%	2.5%	2.6%	2.8%	3.5%
Trucks, Long Haul	0.0%	0.8%	1.1%	1.2%	1.4%	1.6%
Trucks <7.5t (All Cycles)	0.0%	0.8%	1.0%	1.4%	1.4%	1.9%
Trucks 7.5-16t (All Cycles)	0.0%	1.4%	1.6%	1.9%	2.1%	2.6%
Trucks 16t-32t (All Cycles)	0.0%	1.3%	2.2%	2.3%	2.3%	2.3%
Trucks >32t (All Cycles)	0.0%	0.7%	0.7%	0.8%	1.1%	1.3%
Buses	0.0%	2.8%	5.4%	6.4%	6.5%	15.5%
Coaches	0.0%	0.8%	0.9%	1.2%	1.4%	1.6%
Average all HDVs	*0.0%*	*1.1%*	*1.5%*	*1.8%*	*1.9%*	*2.5%*
Average Trucks	*0.0%*	*1.0%*	*1.3%*	*1.6%*	*1.6%*	*1.9%*
Average Buses/Coaches	*0.0%*	*1.6%*	*2.6%*	*3.2%*	*3.3%*	*6.9%*

Sensitivity: Annual mileage +25%	**Baseline (2015)**	**2020**	**2025**	**2030**	**2040**	**2050**
Trucks, Urban	0.0%	1.4%	2.7%	3.0%	3.1%	3.2%
Trucks, Utility	0.0%	1.5%	1.6%	1.8%	2.5%	2.7%
Trucks, Regional	0.0%	1.2%	2.2%	2.6%	2.6%	2.7%
Trucks, Construction	0.0%	1.4%	3.6%	3.9%	4.9%	5.4%
Trucks, Long Haul	0.0%	0.8%	2.2%	2.3%	2.8%	3.6%
Trucks <7.5t (All Cycles)	0.0%	1.0%	2.2%	2.5%	2.6%	2.7%
Trucks 7.5-16t (All Cycles)	0.0%	1.7%	2.9%	3.1%	3.6%	3.7%
Trucks 16t-32t (All Cycles)	0.0%	1.3%	2.6%	2.8%	2.9%	3.9%
Trucks >32t (All Cycles)	0.0%	0.8%	2.3%	2.6%	3.3%	3.3%
Buses	0.0%	3.4%	6.9%	7.6%	16.5%	18.8%
Coaches	0.0%	1.0%	1.1%	1.4%	1.4%	1.7%
Average all HDVs	*0.0%*	*1.2%*	*2.5%*	*2.7%*	*3.5%*	*3.9%*
Average Trucks	*0.0%*	*1.1%*	*2.3%*	*2.6%*	*2.9%*	*3.3%*
Average Buses/Coaches	*0.0%*	*1.9%*	*3.3%*	*3.8%*	*7.2%*	*8.3%*

Social versus End User

Sensitivity: End-user perspective	**Baseline (2015)**	**2020**	**2025**	**2030**	**2040**	**2050**
Trucks, Urban	0.0%	1.4%	2.5%	2.8%	3.0%	3.0%
Trucks, Utility	0.0%	1.5%	1.6%	1.8%	1.8%	2.4%
Trucks, Regional	0.0%	1.1%	2.2%	2.3%	2.3%	2.4%
Trucks, Construction	0.0%	1.4%	3.1%	3.4%	3.7%	4.6%
Trucks, Long Haul	0.0%	0.8%	2.0%	2.1%	2.2%	2.2%
Trucks <7.5t (All Cycles)	0.0%	1.0%	1.9%	2.2%	2.5%	2.6%
Trucks 7.5-16t (All Cycles)	0.0%	1.7%	2.7%	3.0%	3.0%	3.4%
Trucks 16t-32t (All Cycles)	0.0%	1.3%	2.5%	2.7%	2.7%	2.9%
Trucks >32t (All Cycles)	0.0%	0.8%	2.1%	2.2%	2.4%	2.4%
Buses	0.0%	3.4%	6.5%	7.2%	9.3%	17.6%
Coaches	0.0%	0.8%	0.8%	1.1%	1.1%	1.6%
Average all HDVs	*0.0%*	*1.2%*	*2.3%*	*2.5%*	*2.7%*	*3.3%*
Average Trucks	*0.0%*	*1.1%*	*2.2%*	*2.4%*	*2.5%*	*2.7%*
Average Buses/Coaches	*0.0%*	*1.8%*	*3.0%*	*3.5%*	*4.3%*	*7.7%*

Payback period

Sensitivity: Industry assumption	**Baseline (2015)**	**2020**	**2025**	**2030**	**2040**	**2050**
Trucks, Urban	0.0%	0.7%	1.3%	1.6%	1.6%	1.6%
Trucks, Utility	0.0%	0.8%	0.9%	1.1%	1.2%	1.2%
Trucks, Regional	0.0%	0.8%	1.0%	1.2%	1.2%	1.2%
Trucks, Construction	0.0%	1.3%	2.3%	2.5%	2.7%	2.6%
Trucks, Long Haul	0.0%	0.7%	0.7%	0.8%	0.8%	0.8%
Trucks <7.5t (All Cycles)	0.0%	0.1%	1.0%	1.3%	1.3%	1.4%
Trucks 7.5-16t (All Cycles)	0.0%	1.4%	1.6%	1.8%	1.8%	1.8%
Trucks 16t-32t (All Cycles)	0.0%	1.1%	1.5%	1.5%	1.6%	1.6%
Trucks >32t (All Cycles)	0.0%	0.7%	0.7%	0.9%	0.9%	0.8%
Buses	0.0%	3.4%	6.5%	7.2%	9.3%	17.6%
Coaches	0.0%	0.8%	0.8%	1.1%	1.1%	1.1%
Average all HDVs	*0.0%*	*0.9%*	*1.3%*	*1.6%*	*1.7%*	*2.1%*
Average Trucks	*0.0%*	*0.8%*	*1.1%*	*1.3%*	*1.3%*	*1.3%*
Average Buses/Coaches	*0.0%*	*1.8%*	*3.0%*	*3.5%*	*4.3%*	*7.5%*

Vehicle fuel consumption

Sensitivity: Max cost-effective technical efficiency	**Baseline (2015)**	**2020**	**2025**	**2030**	**2040**	**2050**
Trucks, Urban	0.0%	1.2%	1.6%	1.8%	1.8%	1.9%
Trucks, Utility	0.0%	1.5%	1.4%	1.2%	1.2%	1.0%
Trucks, Regional	0.0%	1.1%	1.8%	1.9%	1.9%	2.0%
Trucks, Construction	0.0%	1.4%	2.6%	2.7%	2.7%	3.4%
Trucks, Long Haul	0.0%	0.8%	1.5%	1.5%	1.6%	1.6%
Trucks <7.5t (All Cycles)	0.0%	0.8%	1.5%	1.8%	1.8%	1.9%
Trucks 7.5-16t (All Cycles)	0.0%	1.6%	1.9%	2.1%	2.1%	2.5%
Trucks 16t-32t (All Cycles)	0.0%	1.3%	2.3%	2.3%	2.3%	2.2%
Trucks >32t (All Cycles)	0.0%	0.8%	1.1%	1.1%	1.2%	1.2%
Buses	0.0%	2.8%	5.4%	4.7%	4.7%	4.3%
Coaches	0.0%	0.8%	0.9%	1.2%	1.2%	1.2%
Average all HDVs	*0.0%*	*1.1%*	*1.7%*	*1.8%*	*1.9%*	*1.9%*
Average Trucks	*0.0%*	*1.1%*	*1.6%*	*1.7%*	*1.7%*	*1.8%*
Average Buses/Coaches	*0.0%*	*1.6%*	*2.6%*	*2.6%*	*2.6%*	*2.4%*

Appendix 3 – Additional supporting material for Task 5

Baseline Scenario

Table 8.5: Data tables for the BAU scenario from Figure 6.2

Activity, vehicle-km	***2015***	***2020***	***2025***	***2030***	***2035***	***2040***	***2045***	***2050***
Urban	104,119	112,620	121,010	129,965	135,118	140,488	144,064	147,752
Utility	22,856	24,722	26,564	28,530	29,661	30,840	31,624	32,434
Regional	65,524	70,874	76,154	81,790	85,033	88,412	90,662	92,983
Construction	54,442	58,886	63,274	67,956	70,651	73,458	75,328	77,256
Long Haul	99,742	107,885	115,923	124,501	129,438	134,582	138,007	141,540
Bus	15,478	16,614	17,581	18,715	19,529	20,293	20,784	21,251
Coach	30,228	30,871	32,053	33,289	34,300	35,393	36,190	37,042
Total	**392,389**	**422,471**	**452,559**	**484,747**	**503,729**	**523,467**	**536,659**	**550,259**

Total energy consumption, PJ	***2015***	***2020***	***2025***	***2030***	***2035***	***2040***	***2045***	***2050***
Urban	475.1	506.9	533.1	558.3	567.5	579.8	586.7	595.3
Utility	100.5	106.9	112.2	117.3	119.2	121.8	123.2	125.0
Regional	722.2	764.8	800.3	835.6	848.4	866.7	877.2	890.2
Construction	672.1	711.5	744.4	777.2	789.2	806.2	816.1	828.2
Long Haul	1,734.8	1,826.3	1,903.6	1,983.3	2,012.9	2,057.3	2,083.3	2,114.7
Bus	219.5	230.8	239.4	248.7	253.8	259.1	261.9	265.0
Coach	292.6	295.6	300.7	303.9	304.3	305.8	305.9	307.2
Total energy use	**4,216.7**	**4,442.9**	**4,633.7**	**4,824.4**	**4,895.4**	**4,996.7**	**5,054.3**	**5,125.6**
BAU	**4,216.7**	**4,442.9**	**4,633.7**	**4,824.4**	**4,895.4**	**4,996.7**	**5,054.3**	**5,125.6**

Total direct GHG emissions, MtCO2	***2015***	***2020***	***2025***	***2030***	***2035***	***2040***	***2045***	***2050***
Urban	32.5	33.5	35.0	36.6	37.2	38.0	38.5	39.0
Utility	6.9	7.1	7.4	7.7	7.8	8.0	8.1	8.2
Regional	49.4	50.5	52.6	54.7	55.6	56.8	57.5	58.4
Construction	46.0	47.0	48.9	50.9	51.7	52.9	53.5	54.3
Long Haul	118.6	120.6	125.1	129.9	131.8	134.9	136.7	138.6
Bus	15.0	15.2	15.7	16.3	16.6	17.0	17.2	17.4
Coach	20.0	19.5	19.8	19.9	19.9	20.1	20.1	20.1
Total direct GHG emissions	**288.3**	**293.3**	**304.5**	**316.1**	**320.5**	**327.7**	**331.6**	**336.0**
BAU	**288.3**	**293.3**	**304.5**	**316.1**	**320.5**	**327.7**	**331.6**	**336.0**

Alternative Baseline Scenario

Table 8.6: Data tables for the Alternative BAU scenario from Figure 6.3

Total energy consumption, PJ	*2015*	*2020*	*2025*	*2030*	*2035*	*2040*	*2045*	*2050*
Urban	475.1	499.7	506.4	497.3	471.5	453.4	432.2	408.6
Utility	100.5	104.7	104.1	99.4	91.6	86.4	81.6	76.9
Regional	722.2	751.3	751.2	725.2	677.4	645.8	613.4	579.2
Construction	672.1	690.1	669.5	613.0	541.7	497.3	464.0	435.7
Long Haul	1,734.8	1,785.2	1,757.4	1,660.7	1,522.9	1,439.3	1,363.5	1,286.3
Bus	219.5	224.5	218.3	202.5	182.4	166.7	153.6	142.8
Coach	292.6	293.2	292.2	283.4	269.5	257.9	245.2	231.7
Total energy use	**4,216.7**	**4,348.7**	**4,299.1**	**4,081.4**	**3,756.9**	**3,546.9**	**3,353.5**	**3,161.2**
BAU	**4,216.7**	**4,442.9**	**4,633.7**	**4,824.4**	**4,895.4**	**4,996.7**	**5,054.3**	**5,125.6**

Total direct GHG emissions, MtCO2	*2015*	*2020*	*2025*	*2030*	*2035*	*2040*	*2045*	*2050*
Urban	32.5	33.0	33.3	32.6	30.9	29.7	28.4	26.8
Utility	6.9	6.9	6.8	6.5	6.0	5.7	5.4	5.0
Regional	49.4	49.6	49.4	47.5	44.4	42.4	40.2	38.0
Construction	46.0	45.6	44.0	40.2	35.5	32.6	30.4	28.6
Long Haul	118.6	117.8	115.5	108.8	99.7	94.4	89.5	84.3
Bus	15.0	14.8	14.3	13.3	11.9	10.9	10.1	9.4
Coach	20.0	19.4	19.2	18.6	17.6	16.9	16.1	15.2
Total direct GHG emissions	**288.3**	**287.0**	**282.5**	**267.4**	**246.0**	**232.6**	**220.0**	**207.2**
BAU	**288.3**	**293.3**	**304.5**	**316.1**	**320.5**	**327.7**	**331.6**	**336.0**

Scenario Analysis

All HDVs

Table 8.7: Data tables for direct CO_2 emissions ($MtCO_2$) from all HDVs from Figure 6.5

#	Abbreviation.	2015	2020	2025	2030	2035	2040	2045	2050
BAU	BAU	288.3	293.3	304.5	316.1	320.5	327.7	331.6	336.0
SCEN1	Cost-Eff LW	288.3	291.7	300.3	309.5	312.0	317.6	320.4	323.7
SCEN2	CE LW High WL	288.3	290.9	297.6	305.1	307.2	312.8	314.6	316.5
SCEN3	CE SOTA Only	288.3	291.8	301.9	312.6	316.6	323.5	327.2	331.5
SCEN4	CE Payback	288.3	291.9	301.6	311.7	315.2	321.6	325.0	328.8
SCEN5	CE VLow Fuel Prices	288.3	291.8	301.2	311.2	314.5	320.9	324.2	328.0
SCEN6	CE LW + Low CAPX	288.3	291.6	299.4	307.6	309.4	314.6	316.4	318.6
Alt BAU	Alt BAU	288.3	287.0	282.5	267.4	246.0	232.6	220.0	207.2
SCEN7	Alt Cost-Eff LW	288.3	285.5	279.1	262.8	240.9	227.3	214.8	202.2
#	Abbreviation.	2015	2020	2025	2030	2035	2040	2045	2050
BAU	BAU	0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SCEN1	Cost-Eff LW	0%	-0.5%	-1.4%	-2.1%	-2.7%	-3.1%	-3.4%	-3.7%
SCEN2	CE LW High WL	0%	-0.8%	-2.2%	-3.5%	-4.2%	-4.6%	-5.1%	-5.8%
SCEN3	CE SOTA Only	0%	-0.5%	-0.8%	-1.1%	-1.2%	-1.3%	-1.3%	-1.3%
SCEN4	CE Payback	0%	-0.5%	-0.9%	-1.4%	-1.7%	-1.9%	-2.0%	-2.2%
SCEN5	CE VLow Fuel Prices	0%	-0.5%	-1.1%	-1.6%	-1.9%	-2.1%	-2.2%	-2.4%
SCEN6	CE LW + Low CAPX	0%	-0.6%	-1.7%	-2.7%	-3.5%	-4.0%	-4.6%	-5.2%
Alt BAU	Alt BAU	0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SCEN7	Alt Cost-Eff LW	0%	-0.5%	-1.2%	-1.7%	-2.1%	-2.3%	-2.4%	-2.5%

Urban

Table 8.8: Data tables for direct CO_2 emissions ($MtCO_2$) from urban delivery trucks from Figure 6.6

#	Abbreviation.	2015	2020	2025	2030	2035	2040	2045	2050
BAU	BAU	32.5	33.5	35.0	36.6	37.2	38.0	38.5	39.0
SCEN1	Cost-Eff LW	32.5	33.3	34.6	35.9	36.2	36.9	37.3	37.7
SCEN2	CE LW High WL	32.5	33.3	34.6	35.9	36.2	36.9	37.3	37.7
SCEN3	CE SOTA Only	32.5	33.3	34.7	36.2	36.7	37.5	37.9	38.4
SCEN4	CE Payback	32.5	33.4	34.8	36.1	36.6	37.4	37.8	38.3
SCEN5	CE VLow Fuel Prices	32.5	33.3	34.7	36.1	36.6	37.4	37.8	38.3
SCEN6	CE LW + Low CAPX	32.5	33.3	34.5	35.7	36.0	36.8	37.1	37.6
Alt BAU	Alt BAU	32.5	33.0	33.3	32.6	30.9	29.7	28.4	26.8
SCEN7	Alt Cost-Eff LW	32.5	32.8	33.0	32.1	30.3	29.2	27.8	26.3
#	Abbreviation.	2015	2020	2025	2030	2035	2040	2045	2050
BAU	BAU	0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SCEN1	Cost-Eff LW	0%	-0.4%	-1.1%	-1.9%	-2.5%	-2.9%	-3.2%	-3.3%
SCEN2	CE LW High WL	0%	-0.4%	-1.1%	-1.9%	-2.5%	-2.9%	-3.2%	-3.3%
SCEN3	CE SOTA Only	0%	-0.4%	-0.8%	-1.1%	-1.3%	-1.4%	-1.5%	-1.5%
SCEN4	CE Payback	0%	-0.3%	-0.8%	-1.2%	-1.5%	-1.7%	-1.8%	-1.8%
SCEN5	CE VLow Fuel Prices	0%	-0.4%	-0.9%	-1.3%	-1.6%	-1.7%	-1.8%	-1.9%
SCEN6	CE LW + Low CAPX	0%	-0.5%	-1.5%	-2.4%	-3.0%	-3.3%	-3.5%	-3.6%
Alt BAU	Alt BAU	0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SCEN7	Alt Cost-Eff LW	0%	-0.4%	-0.9%	-1.4%	-1.7%	-1.9%	-2.0%	-2.0%

Utility

Table 8.9: Data tables for direct CO_2 emissions ($MtCO_2$) from municipal utility trucks from Figure 6.7

#	Abbreviation.	2015	2020	2025	2030	2035	2040	2045	2050
BAU	BAU	6.9	7.1	7.4	7.7	7.8	8.0	8.1	8.2
SCEN1	Cost-Eff LW	6.9	7.0	7.3	7.6	7.7	7.9	8.0	8.1
SCEN2	CE LW High WL	6.9	7.0	7.3	7.6	7.7	7.9	8.0	8.1
SCEN3	CE SOTA Only	6.9	7.0	7.3	7.6	7.7	7.9	8.0	8.1
SCEN4	CE Payback	6.9	7.0	7.3	7.6	7.7	7.9	8.0	8.1
SCEN5	CE VLow Fuel Prices	6.9	7.0	7.3	7.6	7.7	7.9	8.0	8.1
SCEN6	CE LW + Low CAPX	6.9	7.0	7.3	7.6	7.6	7.8	7.9	7.9
Alt BAU	Alt BAU	6.9	6.9	6.8	6.5	6.0	5.7	5.4	5.0
SCEN7	Alt Cost-Eff LW	6.9	6.9	6.8	6.4	5.9	5.6	5.3	5.0
#	Abbreviation.	2015	2020	2025	2030	2035	2040	2045	2050
BAU	BAU	0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SCEN1	Cost-Eff LW	0%	-0.4%	-0.8%	-1.2%	-1.5%	-1.6%	-1.7%	-1.7%
SCEN2	CE LW High WL	0%	-0.4%	-0.8%	-1.2%	-1.5%	-1.6%	-1.7%	-1.7%
SCEN3	CE SOTA Only	0%	-0.3%	-0.6%	-0.8%	-1.0%	-1.0%	-1.0%	-1.0%
SCEN4	CE Payback	0%	-0.2%	-0.5%	-0.7%	-0.9%	-1.0%	-1.0%	-1.1%
SCEN5	CE VLow Fuel Prices	0%	-0.2%	-0.4%	-0.6%	-0.7%	-0.8%	-0.8%	-0.9%
SCEN6	CE LW + Low CAPX	0%	-0.4%	-1.0%	-1.6%	-2.2%	-2.5%	-2.8%	-3.0%
Alt BAU	Alt BAU	0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SCEN7	Alt Cost-Eff LW	0%	-0.3%	-0.8%	-1.1%	-1.3%	-1.3%	-1.3%	-1.3%

Regional

Table 8.10: Data tables for direct CO_2 emissions ($MtCO_2$) from regional delivery trucks from Figure 6.8

#	Abbreviation.	2015	2020	2025	2030	2035	2040	2045	2050
BAU	BAU	49.4	50.5	52.6	54.7	55.6	56.8	57.5	58.4
SCEN1	Cost-Eff LW	49.4	50.2	51.9	53.7	54.2	55.4	56.0	56.7
SCEN2	CE LW High WL	49.4	50.1	51.6	53.2	53.7	54.8	55.2	55.7
SCEN3	CE SOTA Only	49.4	50.2	52.2	54.2	54.9	56.1	56.8	57.6
SCEN4	CE Payback	49.4	50.3	52.2	54.2	54.9	56.1	56.8	57.6
SCEN5	CE VLow Fuel Prices	49.4	50.2	52.0	53.9	54.5	55.7	56.3	57.1
SCEN6	CE LW + Low CAPX	49.4	50.2	51.8	53.5	54.0	55.1	55.6	56.1
Alt BAU	Alt BAU	49.4	49.6	49.4	47.5	44.4	42.4	40.2	38.0
SCEN7	Alt Cost-Eff LW	49.4	49.3	48.8	46.7	43.5	41.4	39.3	37.1
#	Abbreviation.	2015	2020	2025	2030	2035	2040	2045	2050
BAU	BAU	0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SCEN1	Cost-Eff LW	0%	-0.5%	-1.2%	-1.9%	-2.4%	-2.6%	-2.7%	-2.8%
SCEN2	CE LW High WL	0%	-0.8%	-2.0%	-2.8%	-3.3%	-3.6%	-4.1%	-4.6%
SCEN3	CE SOTA Only	0%	-0.5%	-0.8%	-1.0%	-1.2%	-1.2%	-1.3%	-1.3%
SCEN4	CE Payback	0%	-0.4%	-0.8%	-1.1%	-1.2%	-1.3%	-1.4%	-1.4%
SCEN5	CE VLow Fuel Prices	0%	-0.5%	-1.1%	-1.6%	-1.9%	-2.1%	-2.2%	-2.2%
SCEN6	CE LW + Low CAPX	0%	-0.6%	-1.5%	-2.3%	-2.8%	-3.1%	-3.4%	-3.9%
Alt BAU	Alt BAU	0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SCEN7	Alt Cost-Eff LW	0%	-0.5%	-1.1%	-1.7%	-2.0%	-2.2%	-2.3%	-2.3%

Construction

Table 8.11: Data tables for direct CO_2 emissions ($MtCO_2$) from construction trucks from Figure 6.9

#	Abbreviation.	2015	2020	2025	2030	2035	2040	2045	2050
BAU	BAU	46.0	47.0	48.9	50.9	51.7	52.9	53.5	54.3
SCEN1	Cost-Eff LW	46.0	46.5	47.8	49.1	49.3	50.1	50.5	51.0
SCEN2	CE LW High WL	46.0	46.2	46.7	47.2	47.3	48.1	48.1	48.1
SCEN3	CE SOTA Only	46.0	46.6	48.3	50.2	50.8	52.0	52.6	53.4
SCEN4	CE Payback	46.0	46.6	48.0	49.6	50.1	51.1	51.6	52.4
SCEN5	CE VLow Fuel Prices	46.0	46.6	47.9	49.5	50.0	51.0	51.4	51.9
SCEN6	CE LW + Low CAPX	46.0	46.5	47.6	48.8	49.0	49.7	49.8	49.9
Alt BAU	Alt BAU	46.0	45.6	44.0	40.2	35.5	32.6	30.4	28.6
SCEN7	Alt Cost-Eff LW	46.0	45.2	43.1	39.1	34.3	31.5	29.3	27.4
#	Abbreviation.	2015	2020	2025	2030	2035	2040	2045	2050
BAU	BAU	0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SCEN1	Cost-Eff LW	0%	-0.9%	-2.4%	-3.6%	-4.6%	-5.3%	-5.7%	-6.1%
SCEN2	CE LW High WL	0%	-1.7%	-4.6%	-7.3%	-8.4%	-9.1%	-10.2%	-11.4%
SCEN3	CE SOTA Only	0%	-0.8%	-1.2%	-1.5%	-1.6%	-1.7%	-1.7%	-1.7%
SCEN4	CE Payback	0%	-0.8%	-1.8%	-2.6%	-3.1%	-3.4%	-3.5%	-3.6%
SCEN5	CE VLow Fuel Prices	0%	-0.9%	-2.0%	-2.8%	-3.3%	-3.5%	-3.9%	-4.3%
SCEN6	CE LW + Low CAPX	0%	-0.9%	-2.7%	-4.1%	-5.2%	-6.0%	-6.9%	-8.1%
Alt BAU	Alt BAU	0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SCEN7	Alt Cost-Eff LW	0%	-0.9%	-2.0%	-2.7%	-3.2%	-3.5%	-3.9%	-4.2%

Long-haul

Table 8.12: Data tables for direct CO_2 emissions ($MtCO_2$) from long-haul trucks from Figure 6.10

#	Abbreviation.	2015	2020	2025	2030	2035	2040	2045	2050
BAU	BAU	118.6	120.6	125.1	129.9	131.8	134.9	136.7	138.6
SCEN1	Cost-Eff LW	118.6	119.9	123.6	127.7	129.0	131.6	133.0	134.8
SCEN2	CE LW High WL	118.6	119.6	122.4	125.7	126.7	129.3	130.3	131.5
SCEN3	CE SOTA Only	118.6	120.0	124.2	128.7	130.5	133.5	135.3	137.2
SCEN4	CE Payback	118.6	120.0	124.3	128.8	130.5	133.5	135.3	137.2
SCEN5	CE VLow Fuel Prices	118.6	120.0	123.9	128.3	129.8	132.6	134.2	136.0
SCEN6	CE LW + Low CAPX	118.6	119.9	123.2	126.7	127.7	130.3	131.5	132.8
Alt BAU	Alt BAU	118.6	117.8	115.5	108.8	99.7	94.4	89.5	84.3
SCEN7	Alt Cost-Eff LW	118.6	117.3	114.2	107.1	97.9	92.5	87.6	82.6
#	Abbreviation.	2015	2020	2025	2030	2035	2040	2045	2050
BAU	BAU	0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SCEN1	Cost-Eff LW	0%	-0.5%	-1.2%	-1.7%	-2.1%	-2.5%	-2.7%	-2.8%
SCEN2	CE LW High WL	0%	-0.8%	-2.2%	-3.3%	-3.9%	-4.2%	-4.6%	-5.2%
SCEN3	CE SOTA Only	0%	-0.5%	-0.7%	-0.9%	-1.0%	-1.0%	-1.0%	-1.0%
SCEN4	CE Payback	0%	-0.4%	-0.7%	-0.9%	-1.0%	-1.0%	-1.0%	-1.0%
SCEN5	CE VLow Fuel Prices	0%	-0.5%	-0.9%	-1.3%	-1.5%	-1.7%	-1.8%	-1.9%
SCEN6	CE LW + Low CAPX	0%	-0.5%	-1.5%	-2.5%	-3.1%	-3.5%	-3.8%	-4.2%
Alt BAU	Alt BAU	0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SCEN7	Alt Cost-Eff LW	0%	-0.5%	-1.1%	-1.5%	-1.8%	-2.0%	-2.0%	-2.1%

Bus

Table 8.13: Data tables for direct CO_2 emissions ($MtCO_2$) from urban buses from Figure 6.11

#	Abbreviation.	2015	2020	2025	2030	2035	2040	2045	2050
BAU	BAU	15.0	15.2	15.7	16.3	16.6	17.0	17.2	17.4
SCEN1	Cost-Eff LW	15.0	15.1	15.4	15.7	15.8	16.0	15.9	15.6
SCEN2	CE LW High WL	15.0	15.1	15.4	15.7	15.8	16.0	15.9	15.6
SCEN3	CE SOTA Only	15.0	15.1	15.5	16.0	16.2	16.5	16.7	16.9
SCEN4	CE Payback	15.0	15.1	15.4	15.6	15.7	15.8	15.6	15.4
SCEN5	CE VLow Fuel Prices	15.0	15.1	15.5	15.9	16.1	16.3	16.4	16.6
SCEN6	CE LW + Low CAPX	15.0	15.1	15.3	15.5	15.4	15.2	14.8	14.4
Alt BAU	Alt BAU	15.0	14.8	14.3	13.3	11.9	10.9	10.1	9.4
SCEN7	Alt Cost-Eff LW	15.0	14.7	14.1	12.9	11.5	10.4	9.6	8.9
#	**Abbreviation.**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
BAU	BAU	0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SCEN1	Cost-Eff LW	0%	-0.6%	-2.0%	-3.7%	-5.0%	-5.9%	-7.3%	-10.1%
SCEN2	CE LW High WL	0%	-0.6%	-2.0%	-3.7%	-5.0%	-5.9%	-7.3%	-10.1%
SCEN3	CE SOTA Only	0%	-0.6%	-1.4%	-2.0%	-2.4%	-2.6%	-2.8%	-3.0%
SCEN4	CE Payback	0%	-0.7%	-2.3%	-4.1%	-5.8%	-7.2%	-9.0%	-11.6%
SCEN5	CE VLow Fuel Prices	0%	-0.6%	-1.5%	-2.5%	-3.4%	-4.0%	-4.4%	-4.6%
SCEN6	CE LW + Low CAPX	0%	-0.8%	-2.5%	-4.6%	-7.3%	-10.7%	-14.0%	-17.0%
Alt BAU	Alt BAU	0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SCEN7	Alt Cost-Eff LW	0%	-0.5%	-1.6%	-2.9%	-4.0%	-4.8%	-5.2%	-5.3%

Coach

Table 8.14: Data tables for direct CO_2 emissions ($MtCO_2$) from coaches from Figure 6.12

#	Abbreviation.	2015	2020	2025	2030	2035	2040	2045	2050
BAU	BAU	20.0	19.5	19.8	19.9	19.9	20.1	20.1	20.1
SCEN1	Cost-Eff LW	20.0	19.5	19.7	19.8	19.7	19.8	19.8	19.9
SCEN2	CE LW High WL	20.0	19.5	19.7	19.8	19.7	19.8	19.8	19.9
SCEN3	CE SOTA Only	20.0	19.5	19.7	19.8	19.8	19.9	19.9	19.9
SCEN4	CE Payback	20.0	19.5	19.7	19.8	19.8	19.9	19.9	19.9
SCEN5	CE VLow Fuel Prices	20.0	19.5	19.7	19.9	19.9	20.0	20.0	20.0
SCEN6	CE LW + Low CAPX	20.0	19.5	19.7	19.8	19.7	19.8	19.8	19.8
Alt BAU	Alt BAU	20.0	19.4	19.2	18.6	17.6	16.9	16.1	15.2
SCEN7	Alt Cost-Eff LW	20.0	19.3	19.1	18.4	17.5	16.7	15.9	15.0
#	**Abbreviation.**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
BAU	BAU	0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SCEN1	Cost-Eff LW	0%	-0.2%	-0.4%	-0.7%	-1.0%	-1.2%	-1.3%	-1.4%
SCEN2	CE LW High WL	0%	-0.2%	-0.4%	-0.7%	-1.0%	-1.2%	-1.3%	-1.4%
SCEN3	CE SOTA Only	0%	-0.2%	-0.4%	-0.6%	-0.8%	-0.9%	-1.0%	-1.0%
SCEN4	CE Payback	0%	-0.2%	-0.4%	-0.6%	-0.9%	-1.0%	-1.1%	-1.1%
SCEN5	CE VLow Fuel Prices	0%	0.0%	-0.1%	-0.2%	-0.2%	-0.2%	-0.3%	-0.6%
SCEN6	CE LW + Low CAPX	0%	-0.2%	-0.5%	-0.8%	-1.1%	-1.3%	-1.5%	-1.8%
Alt BAU	Alt BAU	0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SCEN7	Alt Cost-Eff LW	0%	-0.2%	-0.4%	-0.7%	-0.9%	-1.1%	-1.2%	-1.2%

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