Ricardo
Energy & Environment

Heavy Duty Vehicles Technology Potential and Cost Study

Final Report for the International Council on Clean Transportation (ICCT)

ED 61727 | Issue Number 5b | Date 27/04/2017

Customer:

International Council on Clean Transport (ICCT)

Customer reference:

HDV Technology Potential and Cost Study

Confidentiality, copyright & reproduction:

Contact:

John Norris
Ricardo Energy & Environment
Gemini Building, Harwell, Didcot, OX11 0QR, United Kingdom

t: +44 (0) 1235 75 3685

e: john.norris@ricardo.com

Ricardo-AEA Ltd is certificated to ISO9001 and ISO14001

Author:

John Norris and Giulia Escher

Approved By:

Nikolas Hill

Date:

27 April 2017

Ricardo Energy & Environment reference:

Ref: ED61727- Issue Number 5b

Executive summary

Trucks, buses and coaches currently produce about a quarter of carbon dioxide (CO_2) emissions from road transport in the EU and some 5% of the EU's total greenhouse gas (GHG) emissions[1]; this share is expected to grow in the future, as emissions from cars and vans further reduce due to CO_2 regulations.

Although EU legislation has set binding emissions targets for new passenger car and van fleets, there is currently no similar legislation for HDV. The European Union (EU) is pursuing a strategy to curb CO_2 emissions from HDVs over the coming years. The commitment to speed up the analytical work required to support a rapid introduction of HDV emissions / CO_2 standards was also reconfirmed as part of the European Strategy for low-emission mobility[2], released on 20th July 2016.

The International Council on Clean Transportation (ICCT) has previously conducted and also commissioned a range of work in this area. In particular, recent analysis by ICCT of the impact of the proposed US Phase 2 regulations indicates that the fuel efficiency of EU tractor-trailers will fall behind those of US tractor-trailers in 2020 (Delgado et al, 2016). In this context, the key questions are:

- What are the potential of new technologies to reduce GHG emissions from European HDVs?
- Which technologies have a significant fuel consumption reduction potential for current vehicles in the identified segments, and what is their reduction potential?
- What is the cost-effectiveness of these important technologies?

Outline of the study objectives

ICCT commissioned Ricardo Energy & Environment to conduct an analysis into the implications of the most recent information on HDV technologies on future potential for reduction in fuel consumption and GHG emissions. The overall objective of this new analysis is to provide a new, evidenced-based and detailed authoritative analysis of the potential technologies that could reduce fuel consumption for HDVs within the EU market, in the timeframe 2020 to 2030. The initial objective of this work was to see which of the technologies that were considered for the US HDV regulation would also apply in EU, and to translate their effectiveness and cost from US to EU. The focus was therefore principally on those technologies that were considered as part of the US Phase 2 analysis. The overall objective of the project has been met by using the most recent information from a variety of published studies, from consultations and from Ricardo's in-house knowledge.

The resulting analysis by the project team has found the technology potential, and costs, of fuel consumption reduction technologies suitable for heavy duty vehicles by 2030, relative to European 2015 baseline vehicles. This was from a combination of published studies, in particular United States (US) research that underpins the US Phase 2 rulemaking, new European and US studies, and consultations with technology and vehicle experts.

The technology potentials and costs were detailed for three vehicle segments:

- **Rigid panel vans** between 3.5 and 7.5 tonnes gross vehicle weight (GVW), which undertake urban delivery (or service) activities;
- **Rigid box-trucks** around 12 tonnes GVW, which undertake regional delivery activities;
- **Tractor-trailer combinations** typically of 40 tonnes GVW, which undertake long haul journeys.

Baseline vehicles

Baseline vehicles were defined for the three vehicle segments for both the US and European markets. The detailed characteristics of the US vehicles were taken principally from the EPA studies. For Europe an iterative process was used, starting with literature information which was then refined with views of experts. The refined information was then checked further with additional literature searching and consultations. This enabled many parameters to be characterised, but not fuel consumption, for which little European data is given in standard databases and references.

[1] http://ec.europa.eu/clima/policies/transport/vehicles/heavy/index_en.htm
[2] http://europa.eu/rapid/press-release_MEMO-16-2497_en.htm

Key differences identified between US and EU baseline vehicles include:

- **Panel vans**: Fundamentally different vehicles with the European vehicle being a panel van, whereas US "service" vehicle investigated by SWRI was a heavy-duty pickup truck or a van.
- **Rigid box-trucks: Superficially quite similar vehicles, both being rigid box cargo trucks.** However, there are differences which lead to the in-use fuel consumption per vehicle km being calculated to be around 31% higher for the European vehicle (from a VECTO simulation) compared with the EPA/NHTSA RIA value. The 15% lower typical payload for the US vehicle means that fuel consumption per tonne-km is around 11% lower for the US vehicle.
- **Long haul tractor trailer combination vehicles:** Table 3.4 details some marked differences between the European and US baseline vehicles, but overall the vehicles are moderately similar. However, the fuel economy for tractor-trailer combinations for the European segment (35.7 litres/100km) was around 21% lower than for its US equivalent (43.1 litres/100 km). This was principally caused by different average speeds over long-haul operations rather than any major differences between the two baseline vehicles.

  However, there is a major difference in the load carrying capacity of the two vehicles, it being 3,713 kg (8,000 lb) greater for the European vehicle. This is reflected in the typical payloads, 19.3 t for the European tractor-trailer combination, around 2 tonnes more than for the US truck. This increases the difference in the fuel consumption per 100 km per tonne of payload to 35%, (it being 1.848 litres /100 tonne km for Europe, and 2.50 litres /100 tonne km for US.

It was noted that there is considerable diversity in the characteristics of long haul tractor trailer combinations. Therefore, in addition to an "average" European tractor-trailer combination, characteristics for "premium" and "economy" vehicles were also developed. For these vehicles, fuel consumption was 31.6 and 38.7 litres/100 km, respectively, straddling the 35.7 litres/100km figure for the "average" vehicle (all three vehicles have similar payload capacities and fuel consumption per tonne of payload follow the patterns for the whole vehicle).

Fuel efficiency improvement technologies

The potential of fuel consumption reduction technologies was considered, for the technologies separately, and in combinations (i.e. considering potential overall engine, transmission and vehicle technology improvements). When considering the improvement potential reported in the EPA Phase 2 studies, allowance was made for translation from US to European markets. Two key influences were considered:

a. Differences between the baseline vehicles, (covered above); and
b. Differences in usage patterns/driving characteristics for the two geographic areas – which for tractor-trailer combinations undertaking long-haul journeys are principally caused by the higher permitted speeds in the US relative to Europe (where HDVs are limited to 90 km/h).

In addition to the fuel consumption reduction potentials of the technologies, their capital costs, or operational costs for tyres and low viscosity lube-oils, were collected.

Technology applicability

Overall it was found that nearly all of the technologies that the US studies included in the regulatory impact analysis (EPA RIA, 2016) could be applied to European baseline trucks and the fuel-consumption reduction potentials that they bring are substantial. Notwithstanding there were some marked differences in the reduction potentials. These arise principally for the following reasons:

- For some technologies, e.g. transmissions, the differences between the baseline vehicle technologies mean that the European technology potential (for panel vans and rigid-box trucks) are larger than for the US potentials.
- For other technologies, e.g. aerodynamics and rolling resistance, the slightly more advanced European baseline vehicles, mean that the European technology potential (for tractor-trailer combinations) are smaller than for the US potentials.
- For vehicle usage patterns vary systematically between the US and Europe, with the principal difference being the 90 kph upper speed limit in Europe, where as in the US truck maximum speed limits for the interstate roads (which are set by individual states) are generally 112 kph

(70 mph) for most of the US but 120 – 128 kph (76 – 80 mph) for the central and west US area except California and Oregon[3]. This leads to systematically different technology needs, especially for tractor-trailer combinations undertaking long haul operations, and systematically different technology potentials, especially for improved aerodynamics.

The impact of fuel price

The cost of fuel to users/operators is significantly higher in Europe than the US, principally because of the duties and taxes levied on fuels. Practically this has encouraged the uptake of some fuel consumption reduction technologies relative to the US, driven by their commercial attractiveness. This is seen by some systematic differences in the baseline vehicle data.

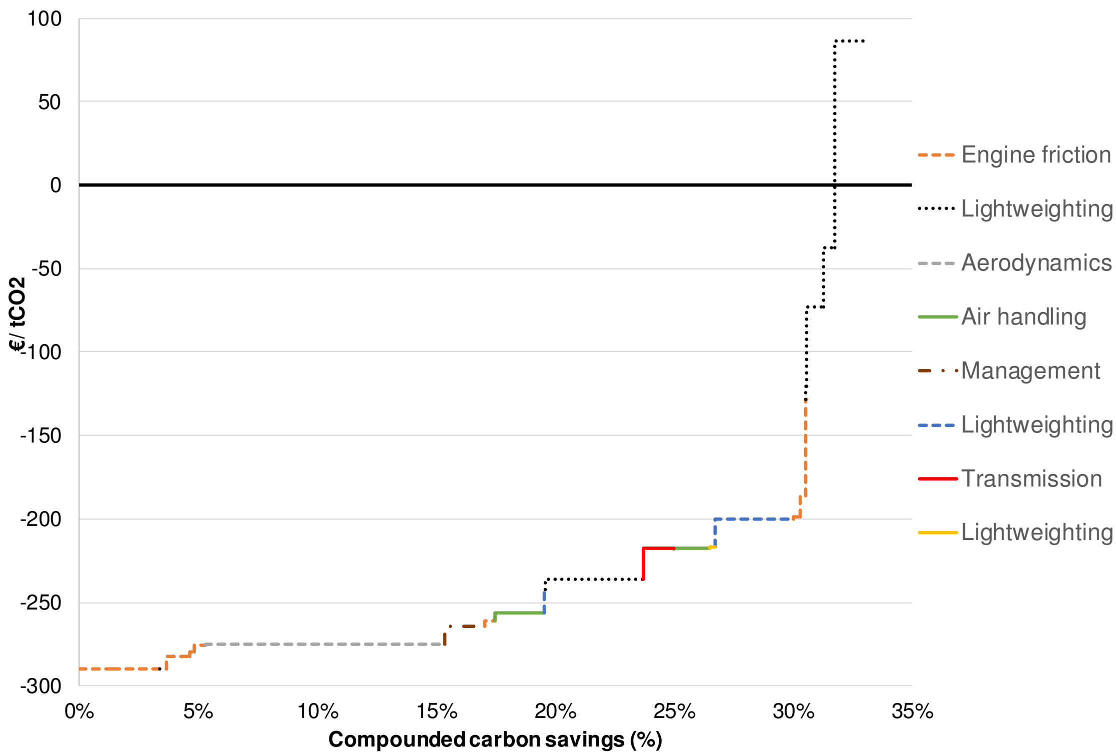
When assessing the cost-effectiveness of technologies, the cost of fuel is a key component, since the capital (or operational) costs are offset by the cost of the fuel not used. However, the incremental cost-fuel consumption reduction potential analysis undertaken uses the Social Discount Rate, i.e. the lower rate (typically ~4% at the European level) applied when considering investments at the society level (i.e. vs private) with the fuel price also excluding taxes and duties. Because of the high levels of fuel duty and taxes, this will systematically overestimate the time required for a technology to produce a net positive return on the capital investment of new technologies when considering the end-user perspective, though the higher discount rates (e.g. 8%) seen by private companies will counteract this.

Results from incremental cost-fuel consumption reduction potential analysis

The incremental costs and fuel consumption reduction potentials of individual technologies were assessed. The result was the development of incremental costs/fuel consumption reduction curves to for each vehicle segment. Figure ES1 below shows the incremental cost-potential fuel reduction curve for the tractor-trailer combination. This illustrates that the overall compounded fuel savings potential, relative to the 2015 baseline vehicle, is 33% on a social cost perspective (at 4% discount rate and excluding fuel taxes).

[3] State truck speed limits on their interstate taken from http://www.iihs.org/iihs/topics/laws/speedlimits/mapmaxspeedonruralinterstates?topicName=Speed

Figure ES1: Incremental cost-fuel consumption reduction potential curve for long haul tractor-trailer for 2030 (relative to average European 2015 truck)

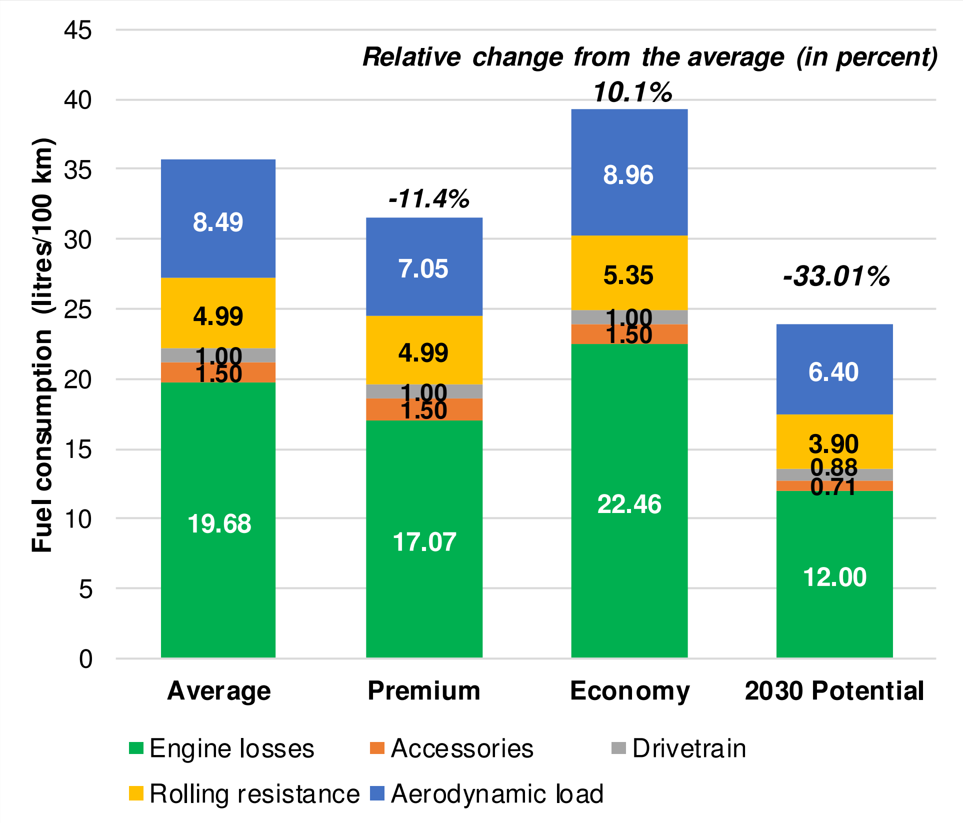


Around 30.3% of the 33% figure occurs for technologies where the return is > €200 /tCO_2 saved over the vehicle's lifetime. (This corresponds to a payback period of less than 3 years.) In terms of the technologies, the largest CO_2 savings (fuel consumption reductions) come from aerodynamic improvements (~10.6%), low rolling resistance tyres (5.1%) waste heat recovery (4.5%), and using improved air handling (2.5%) in order of their cost-effectiveness.

If these potentials were realised the fuel consumption from the average European tractor-trailer combination would reduce from 35.7 litres/100 km to 23.9 litres/100 km with an assumed payload of 19.3 tonnes (including vehicle management fuel consumption reduction technologies like predictive cruise control, but excluding vehicle platooning).

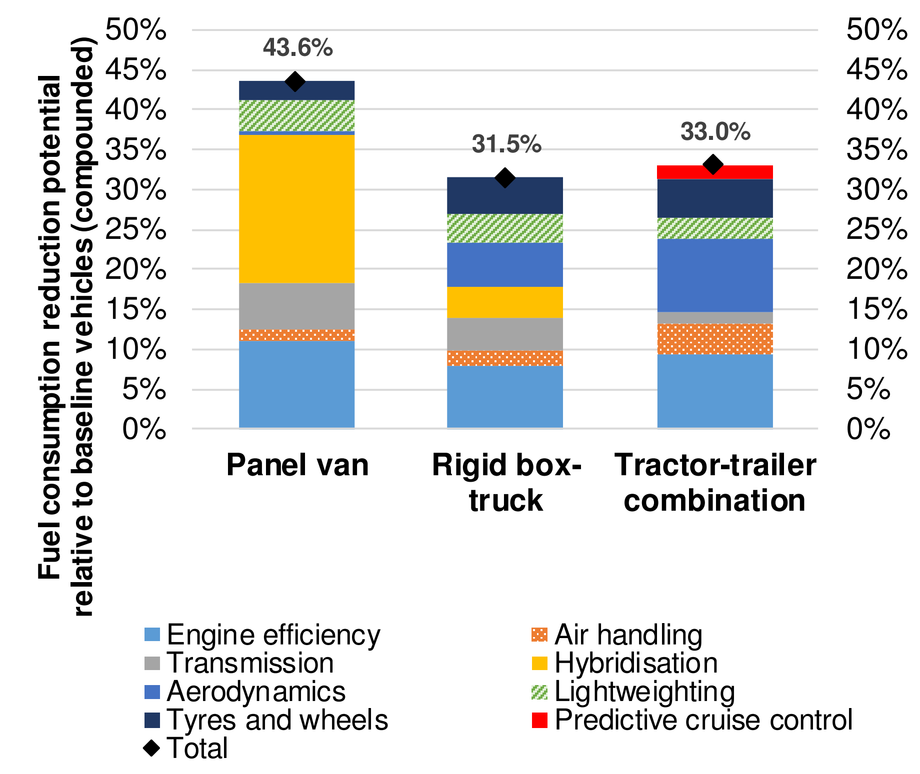
These fuel consumption values can be broken down in terms of how the fuel is used (e.g. due to engine losses, rolling resistance, aerodynamic drag etc.). This is shown in Figure ES2 for the "average" European tractor-trailer combination, and the 2030 potential vehicle. A similar breakdown is also provided for the "premium" and "economy" baseline trucks. This figure illustrates the inter-relatedness of the losses, i.e. reducing aerodynamic losses means the engine has to produce less useable mechanical work, and consequently engine losses also reduce, in addition to any engine efficiency improvements that have been made also. However, vehicle road load improvement reduces the torque demands and shift the operational points of the engine to lower efficiency areas, so engine losses increase (engine efficiency is reduced) with aerodynamic improvements unless an appropriate AMT adjusts the gearing back to the point of high engine efficiency.

Figure ES2: Schematic breakdown regarding where fuel is consumed (litres/100km) for long haul tractor trailer combinations (2015 baseline vehicles versus 2030 potential)



A summary of the calculated maximum technical reduction potential (from the technologies analysed during the project) for all three of the main European vehicle segments is provided in Figure ES3.

Figure ES3: Potential 2030 EU vehicle fuel consumption reductions relative to 2015 baseline vehicles



Notes: Includes accounting for technological overlap/mutual exclusivity between AT and Full Hybrids.

Incremental costs-fuel consumption reduction potential curves for the panel van and rigid box-truck segments are provided in the body of the main report. Overall the maximum saving potential identified for uptake of all technologies was 44.7% for the panel van undertaking urban deliveries and 31.7% for the rigid box-truck undertaking regional deliveries.

A summary of the largest fuel savings technologies, and their approximate marginal pay-back period are also provided in Table ES1 below for the two vehicle segments.

Table ES1: Summary of technologies with the largest fuel savings potential for panel vans

Panel van	Saving potential	Payback period (years)
Overall saving potential of all technologies	43.6%	
Full hybrid from MT baseline	28%	11.3
Automated manual transmission from MT	7%	7.4
Various engine improvements	8.5%	~ 1 year (Note 2)
Low viscosity oil	2.5%	~ 4 years (Note 1)

Notes for Table ES1:

Note 1 – for low viscosity oils and lower rolling resistance tyres costs occur during the lifetime of the vehicle, operational costs, and are not simply capital costs. The payback period quoted is the equivalent figure that would occur when all the additional operational costs are summed over the lifetime of the vehicle.

Note 2 – Some engine improvements will be incremental, incorporated into new engines, and will not incur additional capital expenditure costs. Therefore, these payback periods are somewhat reduced.

For the panel van segment savings are dominated by the possibility of full hybridisation. Addition of a stop/start system rather than full hybrid would replace the 28% potential saving with a much reduced 7% saving potential, but at a much improved payback period (3.5 rather than 11.3 years). It is also noted that for these low speed vehicles aerodynamic improvements make only a small (0.6%) reduction in fuel consumption.

Table ES2: Summary of technologies with the largest fuel savings potential for rigid box-trucks

Rigid box-truck	Saving potential	Payback period (years)
Overall saving potential of all technologies	31.5%	
Futuristic aerodynamics	6.3%	0.45 years
Automated manual transmission from MT	5%	3.6 years
Various engine improvements	7.4%	2.0 (Note 2)
Low rolling resistance tyres	4.7%	~ 2 years (Note 1)
Mild hybridisation	4.5%	~ 2 years

Notes for Table ES2:

Note 1 – for low viscosity oils and lower rolling resistance tyres, costs occur during the lifetime of the vehicle, operational costs, and are not simply capital costs. The payback period quoted is the equivalent figure that would occur when all the additional operational costs are summed over the lifetime of the vehicle.

Note 2 – Some engine improvements will be evolutionary, incorporated into new engines, and will not incur additional capital expenditure costs. Therefore, these payback periods are somewhat reduced.

For rigid box-trucks there are five technologies that offer 3 – 7% reductions in fuel consumption, but no technology that dominates unlike for panel vans (where full hybridisation has the potential to deliver a 28% fuel consumption reduction) and for tractor-trailer combinations (where advanced aerodynamics applied to both the tractor and the trailer units has the potential to deliver a 10.6% fuel consumption reduction).

Table ES3: Summary of technologies with the largest fuel savings potential for tractor-trailer combinations

Tractor trailer combination	Saving potential	Payback period (years)
Overall saving potential of all technologies	33.0%	
Futuristic aerodynamics	10.6%	0.46 years
Various engine improvements	5.4%	< 2 (Note 1)
Low rolling resistance tyres	5.1%	~ 2 years (Note 2)
Waste heat recovery	4.5%	2.8 years
Improved air handling and energy recovery through turbo-compounding	4.5%	~ 2.2 years

Notes for Table ES3:

Note 1 – Some engine improvements will be evolutionary, incorporated into new engines, and will not incur additional capital expenditure costs. Therefore, these payback periods are somewhat reduced.

Note 2 – for low viscosity oils and lower rolling resistance tyres, costs occur during the lifetime of the vehicle, operational costs, and are not simply capital costs. The payback period quoted is the equivalent figure that would occur when all the additional operational costs are summed over the lifetime of the vehicle.

What is also noticeable from Table ES1 to Table ES3 is how different technologies are more important for the different vehicle segments. The relative rankings of different technologies for the three vehicle segments are given in Table ES4, with technologies that are of only minor importance for vehicles excluded for a simpler illustrative comparison. This illustrates the variety of dominant technologies.

However, it must not be assumed that smaller savings, e.g. due to lightweighting or other engine improvements are not important, because the overall fuel saving reduction potential is a consequence of the sum of all the contributions listed.

Table ES4: Summary of the rankings, in terms of fuel consumption reduction, from the technologies considered for the three vehicle segments

Technology	Panel van	Rigid box-truck	Tractor trailer combination
Engine efficiency – friction, including some vehicle accessories but excluding low viscosity oils	2	1	2
Air handling (turbo-charging and EGR)			4 =
Low viscosity oils	4		
Waste heat recovery & thermal management			4 =
Transmission & driveline	3	3	5
Hybridisation	1 (Full hybrid)	5 (non-integral mild)	
Aerodynamics		2	1
Tyres & wheels		4	3

Abbreviations

Abbreviation	Definition
2ST	Advanced boosting using two stage turbocharging
ALVW	Adjusted loaded vehicle weight - Vehicle test weight for pickup trucks equal to the empty weight plus half of the payload that can go in the bed, with no trailer
AMT	Automated manual transmission
ASC	Ammonia slip catalyst
AST	Asymmetric turbocharger
AT	Automatic transmission
ATIS	Automatic tyre inflation system
BISG	Belt driven integrated starter/generator
BMEP	Brake mean effective pressure, i.e. the power at the engine's output shaft
BSFC	Brake specific fuel consumption
BTE	Brake thermal efficiency (measure as to how well an engine converts fuel energy to mechanical energy)
C_D	Drag coefficient
C_{RR}	Coefficient of rolling resistance
CISG	Crank driven integrated starter/generator
CVT	Continuously variable transmission
DCT	Dual clutch transmission
DD15	Heavy-duty diesel engine (Detroit Diesel 15 litre)
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
ECU	Engine control unit
EGR	Exhaust gas recirculation
EPA	Environmental Protection Agency (US)
ERG	Eastern Research Group
EU	European Union
FE	Fuel economy
FHWA	Federal Highway Administration (US agency)
FMEP	Friction mean effective pressure;
FTA	UK Freight Transport Association
FTP-City	Federal test procedure city cycles, also known as FTP-75 (US test cycle)
GEM	Greenhouse gas emission model
GHG	Greenhouse gas
GMEP	Gross mean effective pressure, i.e. the power at the pistons;
GVW	Gross vehicle weight
HDV	Heavy-duty vehicle
HHDDT	Heavy heavy-duty diesel truck (vehicle driving cycle)
HTUF 6	Hybrid truck users forum drive cycle 6: Parcel delivery cycle
ICCT	International Council on Clean Transportation
kW	Kilowatts
MACC	Marginal abatement cost curve
MB	Mercedes Benz
MEP	Mean effective pressure

Abbreviation	Definition
MT	Manual transmission
MY	Manufacture year
NESCCAF	Northeast States Center for a Clean Air Future
NHTSA	National Highway Traffic Safety Administration
NIMEP	Net indicated mean effective pressure
NREL	National Renewable Energy Laboratory
OEM	Original equipment manufacturer
PMEP	Pumping mean effective pressure;
R245	A refrigerant (Pentafluoropropane)
RAM	Pickup truck manufactured by what was the Chrysler Group
SARTRE	Safe road trains for the environment, an EU funded Framework 7 programme
SCR	Selective catalytic reduction
SS	Steady-speed
SUV	Sport utility vehicle
SWRI	Southwest Research Institute
TIAX (LLC)	A laboratory-based technology development company
TPMS	Tyre pressure monitoring system
US	United States
US DOE	US Department of Energy
VECTO	Vehicle Energy Consumption Calculator TOol - EU HDV simulation model
VGT	Variable geometry turbine turbocharger
WGT	Waste-gated turbocharger

Table of contents

1 Introduction ... 1
1.1 Overview ... 1
1.2 Study methodology and structure of the report ... 2

2 Scope, assumptions and key information sources ... 5
2.1 Selection of HDV segments for inclusion in the study ... 5
2.2 List of key information sources ... 5

3 Selection of baseline reference vehicles and identification of their performance characteristics ... 11
3.1 European and US baseline vehicle characteristics ... 11
3.2 Differences between European and US market baseline vehicles ... 22

4 Fuel efficiency improvement technologies ... 24
4.1 Technologies included ... 24
4.2 Translation of improvements between US and European markets ... 24
4.3 Improvements for individual technologies ... 27
4.3.1 Engine efficiency technologies ... 28
4.3.1.1 Engines - Friction ... 28
4.3.1.2 Engines - Reduction of auxiliary (parasitic) loads ... 32
4.3.1.3 Air handling (Turbo charging and EGR) ... 34
4.3.1.4 Waste heat recovery and thermal management ... 38
4.3.2 Transmission and driveline technologies ... 42
4.3.3 Hybridisation ... 44
4.3.4 Aerodynamics ... 46
4.3.5 Light-weighting ... 50
4.3.6 Tyres and wheels ... 54
4.3.7 Overnight hoteling loads (extended Idle) reduction technologies ... 59
4.3.8 Vehicle management technologies ... 59
4.4 Improvements for packages of technologies ... 61
4.4.1 Overview ... 61
4.4.2 Reduction potential from technology packages for tractor-trailer combinations ... 62
4.4.2.1 Data on technology packages from this study's analysis ... 62
4.4.2.2 Comparison of estimated reduction potentials with other available data ... 63
4.5 Summary of fuel consumption reduction potential for all technologies ... 64

5 Cost effectiveness of technologies for improving the fuel efficiencies of HDVs 67
5.1 Sources of information on costs ... 67
5.2 Cost for single technologies ... 67
5.2.1 Engine efficiency technologies ... 67
5.2.1.1 Engines - Friction ... 67
5.2.1.2 Engines – Reduction of auxiliary parasitic loads ... 68
5.2.1.3 Engines – Air handling ... 68
5.2.1.4 Engines – Waste heat recovery and thermal management ... 68
5.2.1.5 Summary of Engine technology costs ... 69
5.2.2 Transmission and driveline ... 69
5.2.3 Hybridisation ... 70
5.2.4 Aerodynamics ... 71
5.2.5 Light-weighting ... 71
5.2.6 Tyres and wheels ... 72
5.2.7 Overnight hoteling loads reduction and vehicle management technologies ... 73
5.3 Cost-effectiveness, incremental cost analysis and payback periods for single technologies ... 73
5.3.1 Overview of methodology ... 73
5.3.2 Analysis for panel van (urban delivery) segment ... 76
5.3.3 Analysis for rigid box-van vehicle segment ... 78
5.3.4 Analysis for tractor-trailer combinations ... 82
5.4 Summary of cost-effectiveness and pay back periods ... 83

6 Stakeholder consultation 85

7 Conclusions and discussion 86

7.1 Conclusions of the fuel consumption reduction potential and its cost-effectiveness from this study 86

7.1.1 Purpose of project and role of consultation 86

7.1.2 Definition of vehicle segments 86

7.1.3 Baseline vehicles 86

7.1.4 Fuel efficiency improvement technologies 87

7.1.5 Technology applicability 87

7.1.6 Impact of fuel price 87

7.1.7 Results from incremental cost-fuel consumption reduction potential analysis 88

7.2 Uncertainties 91

7.2.1 Completeness of the list of technologies 91

7.2.2 Size of the potential savings for the individual technologies 91

7.2.3 Potential costs 93

7.2.4 The use of potential costs in the incremental cost – potential fuel consumption reductions analysis 93

8 References 94

Appendices

Appendix 1 Fuel efficiency of European baseline vehicles

Appendix 2 Driving patterns of baseline vehicles in US and Europe

Appendix 3 VECTO model version and files used for simulations

Table of figures

Figure 1.1: HDV CO_2 emissions and energy consumption, 2010 (from Hill et al, 2011) 1

Figure 1.2: Overview of methodology 3

Figure 1.3: Further details on the methodological approach used for this study 3

Figure 4.1: Illustrative breakdown of NIMEP into FMEP and BMEP at different engine speeds for high and low duty diesel engine operation 29

Figure 4.2: Illustrative breakdown as to how the original fuel energy becomes distributed in a truck 39

Figure 4.3: Fuel savings reported from Don-Bur trailers 49

Figure 4.4: Estimated mass reduction potential by system for an articulated truck 51

Figure 4.5: Illustrative schematic of the energy loss components from vehicle fuel use 62

Figure 4.6: Potential 2030 EU vehicle fuel consumption reductions relative to 2015 baseline vehicles 65

Figure 5.1: Incremental cost-fuel consumption reduction potential curve for panel van for 2030 77

Figure 5.2: Incremental cost-fuel consumption reduction potential curve for panel van for the rigid box-truck for 2030 78

Figure 5.3: Incremental cost-fuel consumption reduction potential curve for long haul tractor-trailer (relative to average European 2015 truck) 82

Figure 5.4: Summary of the 2030 cost-effectiveness potential under various payback period assumptions for different technologies for the three vehicle segments 84

Figure 7.1: Incremental cost-fuel consumption reduction potential curve for long haul tractor-trailer for 2030 (relative to average European 2015 truck) 88

Figure 7.2: Schematic breakdown regarding where fuel is consumed (litres/100km) for long haul tractor trailer combinations (2015 baseline vehicles versus 2030 potential) 89

Table of tables

Table 2.1: Key information sources reviewed 7
Table 3.1 Test vehicles used in SWRI studies 11
Table 3.2: Characteristics of US and European vehicles for panel van segment 12
Table 3.3: Characteristics of US and European vehicles for rigid box-truck segment 14
Table 3.4: Characteristics of US and European vehicles for tractor-trailer combination segment 17
Table 3.5: Characteristics of three types of European vehicles for tractor-trailer combinations 20
Table 4.1: Characteristics of drive cycles over which technology potential was assessed for US vehicles 25
Table 4.2: Characteristics for the US and European driving cycles 26
Table 4.3: US drive cycles that are relevant to the European driving patterns 26
Table 4.4: Summary of the technologies considered, and the vehicle segments to which they apply 27
Table 4.5: Reductions in fuel consumption generated by changes FMEP for both US (as indicated in EPA Report #1) and translated to European vehicles and driving patterns 31
Table 4.6: Reductions in fuel consumption generated by changes FMEP for European vehicle segments disaggregated by technologies 32
Table 4.7: Reductions in fuel consumption generated by technology changes for some auxiliaries for European vehicle segments 34
Table 4.8: Currently fitted turbocharging systems to US and European trucks for the three vehicle segments 36
Table 4.9: Fuel consumption reduction potential in US and Europe generated by improvements in air handling technologies 38
Table 4.10: Reductions in fuel consumption generated by use of heat recovery systems from US EPA Report #1 40
Table 4.11: Fuel consumption reduction potential in US and Europe generated by improvements in thermal management technologies 41
Table 4.12: Fuel consumption reduction potential in US and Europe generated by improvements in transmission and driveline technologies 43
Table 4.13: Reductions in fuel consumption generated by the use of hybrid systems on a Class 6 truck over various driving cycles (from NREL study) 45
Table 4.14 Use of hybrid systems currently, and potentially in 2030 for US and European trucks for the three vehicle segments 46
Table 4.15: Key characteristics of representative European and US driving cycles 47
Table 4.16: Ratio of averaged speed squared relative to the VECTO urban delivery cycle 47
Table 4.17: Reductions in fuel consumption generated by changes in aerodynamic treatments from US EPA Report #1 model, VECTO modelling and case studies, and overall technology potential 50
Table 4.18: Estimated mass reduction potential by system for an articulated truck 51
Table 4.19: Reductions vehicle weight caused by light-weighting for European vehicles and driving patterns 52
Table 4.20: Reductions in fuel consumption generated by changes in potential light-weighting translated to European vehicles and driving patterns 53
Table 4.21: Average rolling resistances and vehicle weights for the baseline European and US trucks for the three vehicle segments 55
Table 4.22: Reductions in fuel consumption generated by changes in rolling resistance from US SWRI Report #1 and applied to European vehicles and driving patterns 58
Table 4.23: Reductions in fuel consumption generated by vehicle management technologies from the EPA RIA (August 2016) and applied to European vehicles and driving patterns 61
Table 4.24: Key parameters impacting on vehicle energy consumption 62

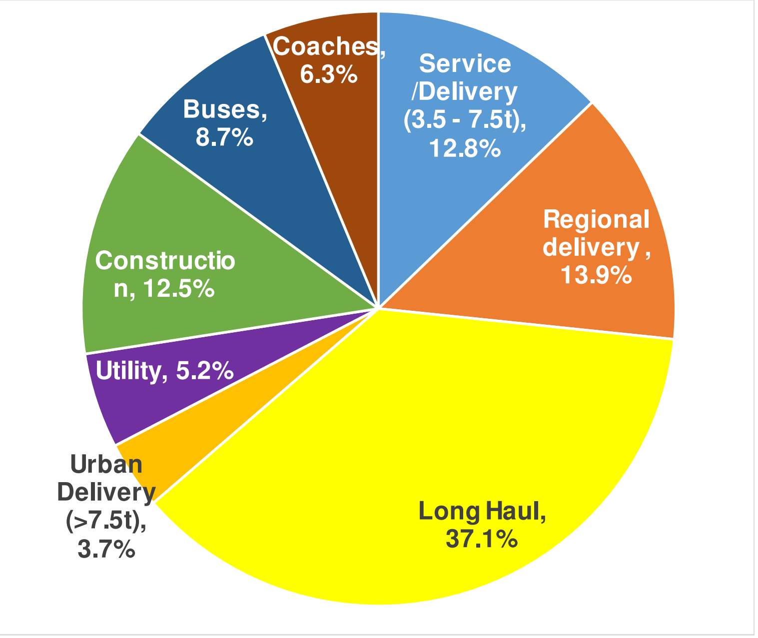
Table 4.25: Potential fuel consumption reductions for groups of technologies for tractor-trailer combinations 63
Table 4.26: Potential 2030 EU vehicle fuel consumption reductions relative to 2015 baseline vehicles from all technologies 66
Table 5.1: Summary of estimated 2030 EU engine technology costs relative to 2015 baseline vehicles (in 2015 €) 69
Table 5.2: Summary of estimated 2030 EU transmission and driveline technology costs relative to 2015 baseline vehicles (in 2015 €) 70
Table 5.3: Summary of estimated 2030 EU hybridisation technology costs relative to 2015 baseline vehicles (in 2015 €) 70
Table 5.4: Summary of estimated 2030 EU aerodynamic improvement technology costs relative to 2015 baseline vehicles (in 2015 €) 71
Table 5.5: Summary of estimated 2030 EU lightweighting technology costs relative to 2015 baseline vehicles (in 2015 €) 72
Table 5.6: Summary of estimated 2030 EU tyre and wheel technology costs relative to 2015 baseline vehicles (in 2015 €) 73
Table 5.7: Fuel price (€/l) - Excl. excise duty and VAT for the reference price scenario from PRIMES-TREMOVE model 75
Table 5.8: Other input assumptions used in the incremental cost calculations 76
Table 5.9: Incremental cost-fuel consumption reduction potential data for the panel van for 2030 79
Table 5.10: Incremental cost-fuel consumption reduction potential data for the rigid box-truck for 2030 80
Table 5.11: Incremental cost-fuel consumption reduction potential data for the tractor-trailer combinations for 2030 81
Table 5.12: Summary of 2030 fuel saving potential for different technologies for the three vehicle segments 83
Table 5.13: Summary of the 2030 cost-effectiveness potential under various payback period assumptions for different technologies for the three vehicle segments 84
Table 6.1: Consultations undertaken as part of this study 85
Table 7.1: Summary of technologies with the largest fuel savings potential for panel vans 89
Table 7.2: Summary of technologies with the largest fuel savings potential for rigid box-trucks 90
Table 7.3: Summary of technologies with the largest fuel savings potential for tractor-trailer combinations 90
Table 7.4: Summary of the technologies considered, and the vehicle segments to which they apply. 91

1 Introduction

1.1 Overview

Trucks, buses and coaches currently produce about a quarter of carbon dioxide (CO_2) emissions from road transport in the EU and some 5% of the EU's total greenhouse gas (GHG) emissions[4]; this share is expected to grow in the future, as emissions from cars and vans further reduce due to CO_2 regulations. A further breakdown of these emissions across the different heavy-duty vehicle (HDV) usage profiles is set out in Figure 1.1 below (data taken from Hill et al., 2011).

Figure 1.1: HDV CO_2 emissions and energy consumption, 2010 (from Hill et al, 2011)



From the figure the three largest usage profiles occur for freight activities: long haul, regional delivery and service/delivery. Together they contribute close to two thirds of the HDV energy consumption and GHG emissions.

Although EU legislation has set binding emissions targets for new passenger car and van fleets, there is currently no similar legislation for HDVs. The European Union (EU) is pursuing a strategy to curb CO_2 emissions from HDVs over the coming years. The commitment to speed up the analytical work required to support a rapid introduction of HDV emissions / CO_2 standards was also reconfirmed as part of the European Strategy for low-emission mobility[5], released on 20th July 2016.

Other nations, US, China, Japan and Canada, have already implemented efficiency standards for HDVs. The US finalised "Phase 2" of its regulations in August 2016, and the associated research is an important source of evidence for this study[6].

Recent research by the International Council on Clean Transportation (ICCT) concludes (using evidence from a range of sources) that the "efficiency of tractor-trailers, has remained constant for more than a decade" (Muncrief R, and Sharpe B., 2015). The data indicates that the "best in class" vehicles have been improving, but the "average" of the new vehicle fleet has not been improving, or at least not at a significant rate. More recent analysis by ICCT of the impact of the proposed US Phase 2 regulations indicates that the fuel efficiency of EU tractor-trailers will fall behind those of US tractor-trailers in 2020 (Delgado et al, 2016).

[4] http://ec.europa.eu/clima/policies/transport/vehicles/heavy/index_en.htm
[5] http://europa.eu/rapid/press-release_MEMO-16-2497_en.htm
[6] The US Phase 2 rulemaking is a rulemaking under development to control CO_2 emissions from model year 2018 and later HDVs.

In this context, key questions are:

- What is the potential of new technologies to reduce GHG emissions from European HDVs?
- Which technologies have a significant fuel consumption reduction potential for current vehicles in the identified segments, and what is their reduction potential?
- What is the cost-effectiveness of these important technologies?

ICCT commissioned Ricardo Energy & Environment to conduct an analysis into the implications of the most recent information on HDV technologies on future potential for reduction in fuel consumption and GHG emissions. The overall objective of this new analysis is to provide a new, evidenced-based and detailed authoritative analysis of the potential technologies that could reduce fuel consumption for HDVs within the EU market, in the timeframe 2020 to 2030. The initial objective of this work was to see which of the technologies that were considered for the US HDV regulation would also apply in EU, and to translate their effectiveness and cost from US to EU. The focus was therefore principally on those technologies that were considered as part of the US Phase 2 analysis. The overall objective of the project has been met by using the most recent information from a variety of published studies, from consultations and from Ricardo's in-house knowledge. These literature sources are detailed in Section 2.2.

1.2 Study methodology and structure of the report

The project involved the gathering of technical data on the baseline vehicles and potential fuel consumption reductions for technologies principally from two categories of sources:

- **Literature:** a range of recent literature sources, including the evidence gathered by the Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA) in support of the Phase 2 US HDV GHG/FE proposal and other recent studies.
- **Consultations:** with engineering and technology experts and with industry experts.

The project was undertaken as a collaboration between the Ricardo Energy & Environment team and ICCT. Both parties have relevant detailed technical knowledge that was optimally utilised when pooled. Collaboration occurred through frequent, informal contacts and the sharing of information as it was collected and analysed.

A summary of the overall methodology is shown schematically in Figure 1.2, with some further details provided also in Figure 1.3. This shows how both published evidence in the literature (coloured blue), and information from consultations (coloured green) were used to assess technologies' potentials and to undertake the cost analysis.

Figure 1.2: Overview of methodology

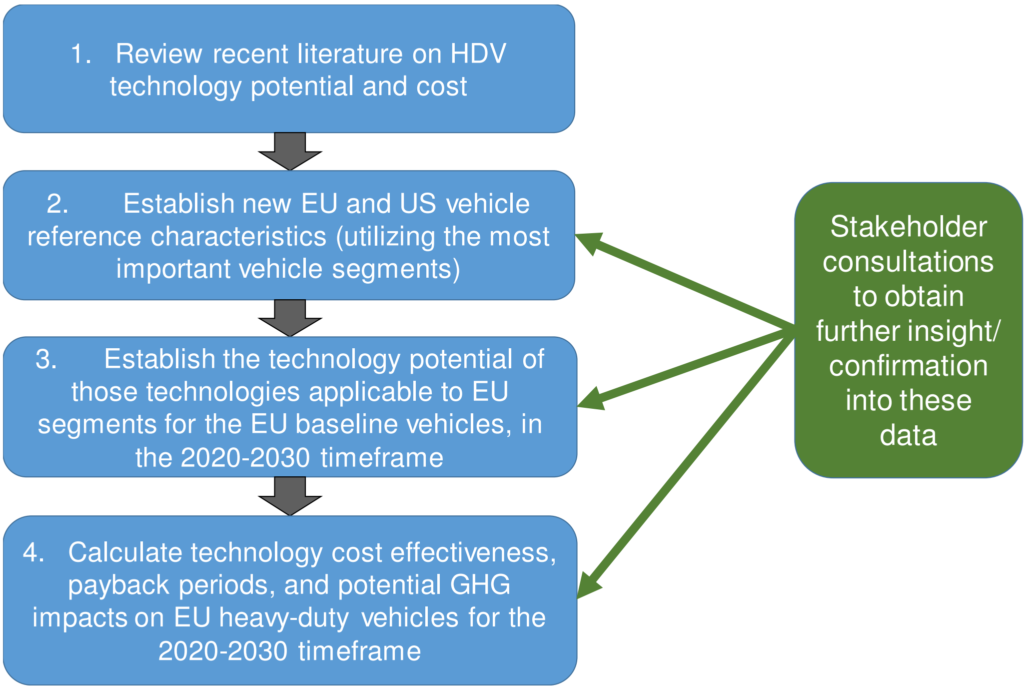
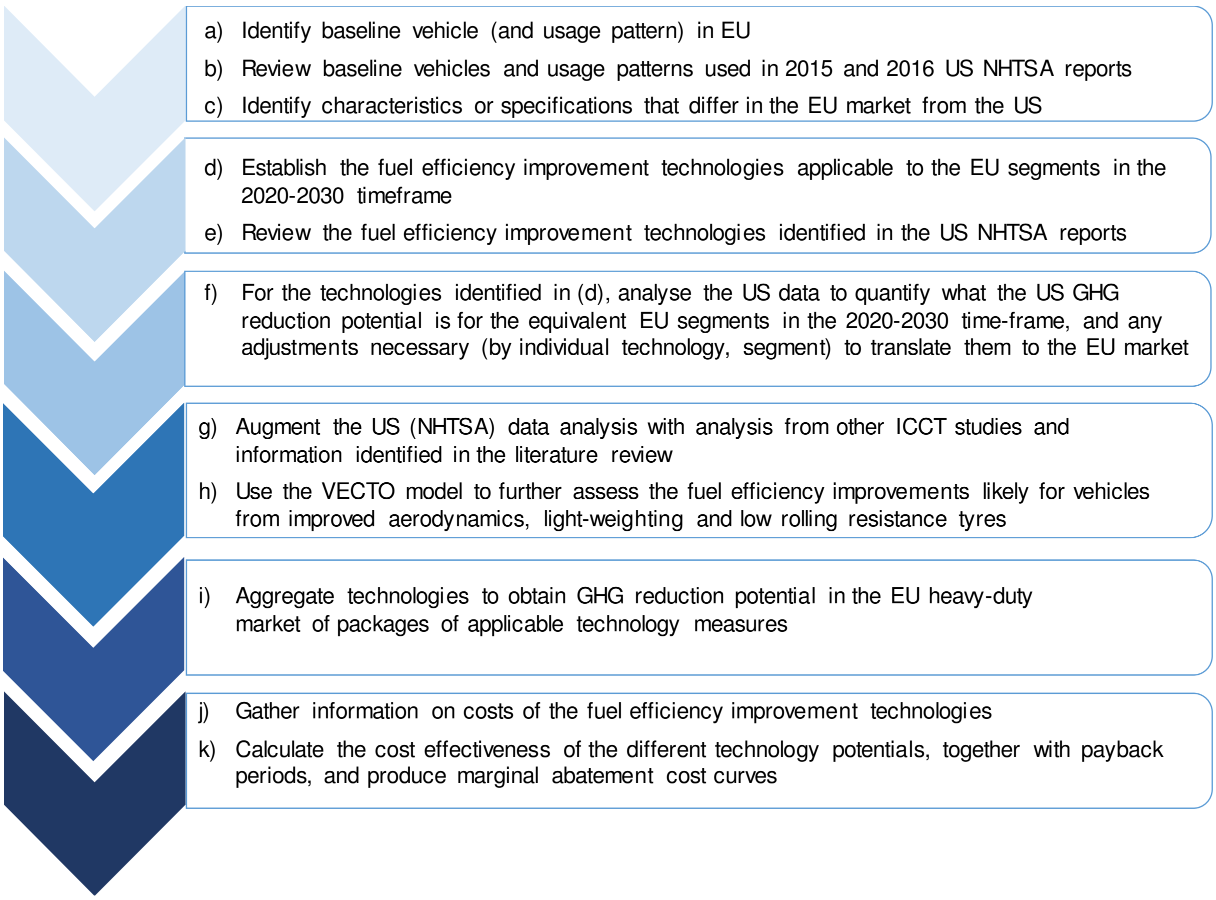


Figure 1.3: Further details on the methodological approach used for this study



This report provides a summary of the work completed for this project and the final results of the analysis. The report is structured as follows, with the information gathered from both the review of available literature and from consultations conducted during the study analysed and used to produce the contents of Chapters 3, 4 and 5:

- **Chapter 2:** Scope, assumptions and key information sources for the study;
- **Chapter 3:** Definition of baseline reference vehicles for US and European markets and their characteristics. (This describes activities (a) to (c) from Figure 1.3.);
- **Chapter 4:** Fuel consumption reduction technologies, and their potential for European segments. (This describes activities (d) to (i) from Figure 1.3.);
- **Chapter 5:** Cost-effectiveness of technologies for reducing the fuel consumption of HDVs (This describes activities (j) and (k) from Figure 1.3.);
- **Chapter 6:** A summary of the stakeholder consultation activities conducted during the project;
- **Chapter 7:** The report concludes by drawing together and summarising key findings, and identifying uncertainties.

2 Scope, assumptions and key information sources

This chapter provides a short summary of the scope of the work agreed with ICCT at the start of the project, and on some of the key assumptions and information sources used to inform the analysis performed, and the results provided in the remaining report sections.

2.1 Selection of HDV segments for inclusion in the study

A key aspect of the project's scope was defining the sub-set of HDV vehicles or activities that should be the focus of the project's investigation and analysis. This scope was agreed with the ICCT at the start of the study, based on the vehicle categories responsible for the consumption of the largest proportion of fuel in the EU. It was concluded that project should focus on three freight carrying segments, rather than any public service vehicle segments (e.g. buses).

Recent analyses (Hill et al. 2011) have tended to categorise HDV energy consumption by a number of different usage profiles (e.g. urban delivery, regional delivery, long-haul, construction, etc.) rather than specific vehicle type (e.g. rigid/articulated, weight category, axle configuration, etc.). Regional delivery trucks could be either rigid trucks or tractor/trailer combinations, but in Europe box-trucks are the principal vehicle type for this usage profile. In this study we examine in detail three HDV segments which are defined by a combination of their usage profile and the dominant European vehicle type employed.

The agreed scope to was to consider heavy duty technology potentials and costs with reference to the following usage profiles/ vehicle type HDV segments:

1. **Urban delivery using small rigid trucks** (this includes "service" activities and uses typically 7 tonne GVW panel vans in Europe)[7];
2. **Regional delivery using rigid trucks** (typically 12 tonne GVW rigid box-trucks in Europe);
3. **Long haul delivery using articulated vehicles** (typically 40 tonne GVW vehicles in Europe).

These three segments account for nearly two thirds of HDV energy consumption, and are the first three segments shown earlier in Figure 1.1.

Within the rest of this report the vehicle segment titles used to describe the three usage profiles/ vehicle type HDV segments listed above are as follows:

a) **Panel van**;
b) **Rigid box-truck;**
c) **Tractor-trailer combination.**

In addition, many of the subsequent sections of the report are also further subdivided to provide details for each of these three vehicle segments individually.

2.2 List of key information sources

A wide range of recent literature was reviewed as part of this project, with an overview provided in the following Table 2.1 of the key information sources, with further details (and web-links, where available) provided in the later references section of this report (in Chapter 8). A key aspect of the project was to take into account the significant amount of research on technology potential and associated costs for HDVs that has already been conducted by both the US EPA (Environmental Protection Agency) and NHTSA (National Highway Traffic Safety Administration) in support of the Phase 2 US HDV GHG/Fuel Economy proposal.

Three reports were first published by EPA and NHTSA in June 2015, and these are referred to /known as Report #1, Report #2 and the Cost Study. The original studies underlying these EPA NHTSA published reports were undertaken by Southwest Research Institute (SWRI), and were extensively peer

[7] The categorisation of Hill et al. (2011) sub-divided urban delivery activities into those using small vans up to 7.5 tonnes, labelled "Service/Delivery" in Figure 1.1, and those using larger trucks, "Urban Delivery > 7.5 t". These have been essentially aggregated in this study.

reviewed. Eastern Research Group (ERG) collated comments and published three peer Review Reports (ERG, 2015a; ERG, 2015b; ERG, 2015c). Post-publication changes and corrections were made to the original reports, and these amended reports were then issued and are used extensively in this study. (These are referred to as Reinhart T.E. (2015) and Reinhart T.E. (2016) for the updated Report #1 and Report #2, and Schubert R (2015) for the Cost Study. The US EPA/NHTSA analysed the data from the above reports and published the Draft Regulatory Impact Analysis which was later superseded by their final Regulatory Impact Analysis (RIA), published in August 2016. This is the key document referenced in this study, and is referenced as EPA and NHTSA (2016) in this report.

In addition, the ICCT has conducted technology potential and cost analysis on a US tractor-trailer and engine. These references were also included in the literature reviewed for this project.

Prior to this more recent analysis, two earlier projects were also completed for the European context in 2011. The first of these published studies was work conducted by experts from Ricardo Energy & Environment - this European study (Hill et al., 2011) was written to inform EU policy makers on the potential to reduce fuel consumption from HDVs in the EU. In 2011, the ICCT also commissioned TIAX LLC to conduct a study on the technology potential for EU HDVs (Law et al., 2011). This report was based both on technology potential studies undertaken in the US (NRC, 2010 and Kromer M et al., 2009), converted to the European context and a comparison with the earlier work by Hill et al. (2011).

The stated objective from ICCT for this new study was to conduct a new analysis of the potential heavy-duty vehicle technology for the European market that was similar to the 2011 TIAX study, but provided an updated analysis based on the latest information and results from recent studies in both the US and EU markets. The methodology that has been used for this new project was therefore similar to the TIAX 2011 study, and was described in earlier Section 1.2 of this report.

In addition to the review of key literature sources as part of this work, a range of consultation activities have also been performed to gather information and test draft results of the analysis for this project. These activities are further discussed in later Chapter 6 of this report.

Table 2.1: Key information sources reviewed

Author (date)	Publication title	Summary of content
Studies on behalf of US Department of Transportation/US Environmental Protection Agency as part of the Phase 2 rule making		
US-EPA and NHTSA (2016)	Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles - Phase 2 Regulatory Impact Analysis	This is the summary of the changes proposed by US-EPA and NHTSA (on behalf of the US Department of Transportation) to further reduce GHG emissions and increase fuel efficiency for on-road heavy-duty vehicles. The proposed standards are tailored to each of the three current regulatory categories of heavy-duty vehicles: (1) Combination Tractors; (2) Heavy-duty Pickup Trucks and Vans; and (3) Vocational Vehicles, as well as gasoline and diesel heavy-duty engines. In addition, new standards are proposed for combination trailers.
US-EPA and NHTSA (2015)	Proposed Rulemaking for Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles–Phase 2: Draft Regulatory Impact Analysis	This is the summary of the changes proposed by US-EPA and NHTSA (on behalf of the US Department of Transportation) to further reduce GHG emissions and increase fuel efficiency for on-road heavy-duty vehicles in their proposal stage. This document was superseded by the Regulatory Impact Analysis in August 2016
Reinhart (2015)	Commercial medium- and heavy-duty truck fuel efficiency technology study - Report #1	This SWRI research project was an important part of the evidence that fed into NHTSA and EPA's development of Phase 2 Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles (Class 2b – 8), the proposal above. It comprised • A literature review - to identify potential fuel saving technologies and review the state of the art. • The selection of a large number of engine and vehicle technologies for additional analysis; • Their fuel saving performance was simulated to project the fuel savings potential of each technology over a wide range of duty cycles. • Wherever possible, experimental data is used to inform and validate the simulation results. (All baseline engine and vehicle models are validated against experimental data.) Report #1 considered the individual technologies. The original report was updated taking into account the peer review.

Author (date)	Publication title	Summary of content
Reinhart (2016)	Commercial Medium- and Heavy- Duty Truck Fuel Efficiency Technology Study – Report #2	This was the second SWRI research project generating evidence that fed into NHTSA and EPA's development of Phase 2 Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles (Class 2b – 8). Whilst the preceding report (Report #1) evaluated individual potential engine and vehicle fuel savings technologies over a wide range of duty cycles, Report #2 evaluates the effectiveness of packages of those individual technologies as well as other related topics. The original report was updated taking into account the peer review.
Schubert et al. (2015	Commercial Medium- and Heavy-Duty Truck Fuel Efficiency Technology Cost	This SWRI research report accompanied the first two technical reports generating evidence that fed into NHTSA and EPA's development of Phase 2 Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles (Class 2b – 8). Based on the list of technologies and configurations identified by SWRI, this report examined the costs of implementation in constant 2011 U.S. dollars in the areas of incremental retail prices and life cycle cost elements.
ERG (2015)	Peer review of 'Commercial Medium and heavy Duty (MD/HD) truck fuel efficiency technology study – Report #3	This report, drawn together by ERG, collates the feedback from the peer review of the two technical reports. Its findings were incorporated into the revised, reissued SWRI reports #1 and #2.
Studies undertaken, or commissioned, by International Council on Clean Transportation		
Delgado et al. (2015)	Advanced tractor-trailer efficiency technology potential in the 2020–2030 timeframe	This research contributed to the dialogue on tractor-trailer efficiency. The work utilised a new 2010-emissions-compliant engine map input data to augment the state-of-the-art 'Autonomie' vehicle simulation model. It was used to assess how various efficiency technologies separately and cumulatively interact to impact tractor-trailer efficiency in line-haul applications. It included an evaluation of additional efficiency gains and interactions related to advanced vehicle load reduction technologies like aerodynamics, tyres, and weight reduction.
Meszler et al. (2015)	Cost effectiveness of advanced efficiency technologies for long-haul tractor trailers in the 2020–2030 timeframe	This report investigated the costs associated with tractor-trailer fuel efficiency technologies evaluated in a companion tractor-trailer simulation study, the Delgado 2015 reference above. The fundamental approach involved deriving technology costs from best-available data on heavy-duty vehicle and engine technologies to assess the cost-effectiveness of increasingly efficient tractor-trailer technology packages. Economic impact metrics including the payback period, lifetime savings, and marginal cost associated with various technology packages under a range of economic conditions, were investigated.

Author (date)	Publication title	Summary of content
Sharpe et al, (2015)	Literature review: Real world fuel consumption of heavy-duty vehicles in the United States, China and the European Union.	The primary objectives of the study were: • To provide a brief overview of the market and fleet characteristics of tractor-trailers in three geographic areas, and discuss the policy measures enacted in each region to promote increased HDV fuel efficiency; • To describe the various types of fuel consumption data and their respective usefulness in assessing the impacts of fuel efficiency and GHG regulations; • To synthesize all of the publically available real-world fuel consumption data in each region and illustrate the widespread lack of data across jurisdictions and underscore the need for further data collection and research in this area; • To lay the foundation for future research that can more thoroughly analyse how the rates of fuel-saving technology deployment differ from region to region and how this translates into differing rates of efficiency improvement over time
Thiruvengadam et al., (2014)	Heavy-duty vehicle diesel engine efficiency evaluation and energy audit	This study by West Virginia University for the ICCT sought to further understand the engine efficiency, energy losses, and prospects for improvement in diesel engines for heavy-duty vehicles. It involved laboratory engine testing and analysis of heavy-duty and medium-duty diesel engines (2010 US EPA compliant). The primary outputs were the characterisation of the engines' fuel consumption maps, and detailed energy audit analyses across varying engine speed-load conditions for the 12.8 litre and 6.7 litre engines tested (as representative engines for Class 8 tractor-trailers, and Class 4-6 trucks).
Law et al., (2011)	European Union greenhouse gas reduction potential for heavy-duty vehicles	This study by TIAX for the ICCT in many respects was the 2011 predecessor to this study. Its goal was to examine data and assumptions used in earlier studies to derive conclusions regarding the GHG reduction potential of HDVs in the EU. Its analysis was based on a comparison between HDV technologies offered in the US and those offered in the EU. It inputs included interviews with and data from the major US HDV and engine manufacturers

Author (date)	Publication title	Summary of content
Studies for European Union heavy duty vehicle CO_2 quantification and control		
Hill et al, (2011)	Reduction and Testing of Greenhouse Gas (GHG) Emissions from Heavy Duty Vehicles – Lot 1: Strategy	This study for the EC (DG CLIMA) was an initial step in the process of informing possible policy actions. It built up a comprehensive picture of: I. The heavy duty vehicle market and fleet; II. Technological options that could help to control CO_2 emissions from HDV; III. Current and likely future fuel use and CO_2 emissions from HDV; and IV. Policies and other measures that could be used as a means of controlling emissions from these types of vehicles. It is noted that the study is from the perspective of a 2010 analysis.
Hill et al, (2015)	Light weighting as a means of improving Heavy Duty Vehicles' energy efficiency and overall CO_2 emissions	This study by Ricardo Energy & Environment for EC (DG CLIMA) had as its objectives the identification of 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.
TU Graz, (2012)	Reduction and testing of Greenhouse gas emissions from heavy duty vehicles – LOT 2	Lot 2, a study undertaken by TU Graz for EC DG CLIMA was a successor to the Lot 1 study, Hill et al 2011. It considered the options for, and proposed a test procedure for fuel consumption or CO_2 emissions for heavy-duty vehicles to give standardised and neutral information to customers. The test procedure is based on component testing which is fed into a simulation tool. This was the birth of the EU VECTO simulation model approach to EU HDV regulation.
DG CLIMA (2014)	Working document for the methodology of the CO_2 determination of HD vehicles – draft proposal for discussion	This document is a working document for the methodology drafting for the CO_2 monitoring of HD vehicles. It is a draft proposal for discussion in the expert group. It describes, in draft regulatory language, the technical approach, vehicle selection and cycle allocation, constituent testing, conformity of production and the validation of process/ ex-post validation.

3 Selection of baseline reference vehicles and identification of their performance characteristics

3.1 European and US baseline vehicle characteristics

Because the overall objective of this analysis is to provide a new, evidenced-based and detailed authoritative analysis of the potential technologies that could reduce fuel consumption for HDVs within the EU market, relative to current vehicles, baseline vehicles were characterised for each of the three vehicle segments being studied (i.e. panel vans, rigid box-trucks and tractor-trailer combinations). The comparison with equivalent US vehicles is an important basis for quantifying the extent to which the different technologies that are important in the US market have the potential to improve fuel consumption of European baseline vehicles.

US baseline vehicles are defined in the Regulatory Impact Analysis (RIA) of the *"GHG Emissions and fuel efficiency standards for Medium- and Heavy-duty engines and vehicles Phase 2"* (EPA & NHTSA, 2016). However, prior to the publication of the proposed rulemaking (US EPA & NHTSA, 2015) SWRI undertook evidence gathering studies using a number of test vehicles, in consultation with EPA. The baseline vehicle categories defined in the SWRI work include similar categories to those previously defined as the "US Baseline vehicles" described in the earlier TIAX study, (Law et al., 2011). These studies provide important quantitative information regarding the fuel consumption potential of different technologies for different driving cycles, and their results are used in this new study.

One of the four test vehicles used in the SWRI studies was a tow truck (a US 'Class 6' truck). This is not comparable to any of the three European vehicle segments that are responsible for the most fuel consumption collectively. The remaining three test vehicles are summarised in Table 3.1 below.

Table 3.1 Test vehicles used in SWRI studies

Vehicle segment	Vehicle chosen in SWRI study[8]	Relevance to European comparison
Long haul delivery (Tractor trailer combination EU sector)	Kenworth T-700 / DD15 Class 8 Tractor-Trailer Vehicle, with a 14.6 litre, 362 kW engine and 36.3 tonne GVW.	Comparable to European long haul tractor-trailer.
Regional delivery (Rigid box-truck EU sector)	Kenworth T270 Class 6 box delivery truck, with a Cummins 6.7 litre 225 kW engine and 11.8 tonne GVW.	Comparable to European 12 t rigid box-truck.
Urban delivery (Panel van EU sector)	RAM Pickup with Cummins 6.7 litre, 287 kW diesel engine, and 4.54 tonne GVW. [*Note*: For the RIA, information was also available for a ~7 t panel van]	Not that comparable to a 7 t panel van, but the diesel engine variant is the closest match that exists. [*Note*: the panel van in the RIA is a closer match to the EU equivalent and such data, when given in RIA were used.]

The purpose of listing the vehicle characteristics for the European and US baseline vehicles for all three segments was to aid the translation of the fuel consumption reduction potential of different technologies between the two geographic regions. This translation depends on the baseline vehicles, and also on

[8] The vehicles listed are those relevant to this study. The tow truck and the pickup truck with the gasoline engine, some test vehicles used in the SWRI study, are not included.

their usage patterns. For example, it will be shown in Table 3.2 and Table 3.3 that the standard EU panel vans and rigid box-trucks use a manual gearbox, whereas in the US these vehicles use automatic transmissions. The fuel consumption reduction potential of going to an AMT gearbox therefore differs systematically between the two geographic regions.

In this study the list of vehicle characteristics given in the previous TIAX study (Law et al. 2011) was expanded and updated. Table 3.2, Table 3.3 and Table 3.4 give the baseline characteristics for the panel vans, rigid box-trucks and tractor-trailer combinations, respectively. The EU column defines the baseline vehicle that we used in this study and the US column defines the baseline vehicle from both the EPA Regulatory Impact Analysis (EPA & NHTSA, 2016), and some characteristics of the test vehicles used by the earlier SWRI report. Table 3.4 is sub-divided into characteristics for the tractor unit, trailer, and the combined tractor-trailer vehicle. For each table a series of explanatory notes, below the table, provides further details of the origins of the baseline values given.

Note: Although there are some significant differences (e.g. in the bodies, engine sizes) between EU vans and the US pick-up the work/operational profiles are similar and therefore they would benefit from many of the same technology packages.

Table 3.2: Characteristics of US and European vehicles for panel van segment

Panel van characteristic	EU	US*
Make/Model Example	New Iveco Daily van 4100	Generic HD pickup truck and Van: RAM 2500 pickup or Isuzu NPR
		
	Vehicle specifications	
Engine – power	132 kW @ 3,000 rpm (Note 1)	150 kW @1900-2100 rpm (Note 2)
Displacement	3.0 litres	7 litres (Note 2)
Torque	430 Nm (1,500 – 2,900 rpm)	750 Nm @1100-1900 rpm (Note 2)
Engine description	Fiat Chrysler 3.0 FCP F1C 4-cylider Euro VI, diesel engine with common rail and VGT	For Pickup truck: Diesel Cummins ISB 6-cylinder engine; single VGT; 4 valves per cylinder (Note 3)
Emissions control	EGR with DOC + DPF + SCR + ASC to comply with Euro VI regulations	EGR with DOC + DPF + SCR + ASC to comply with US 2010 regulations
Engine peak brake thermal efficiency	42% (Note 1)	40.0% (Note 4)
Transmission	6 speed MT (Note 5)	6 speed AT
Vehicle configuration	Rigid panel van	HD Pickup truck & van
Weights		
GVW kg (lb)	7,000 (15,432)	7,257 (16,000) (Note 6)
Kerb weight kg (lb)	2,900 (6,393)	4,672 (10,300) (Note 6)
Max payload kg (lb)	4,100 (9,039)	2,585 (5,700) (Note 6)

Panel van characteristic	EU	US*
Typical payload kg (lb)	1,448 (3,192) 35.3% loading	1,292 (2.850) 50% loading
Aerodynamic drag coefficient (C_D)	0.55	0.57 (implied from drag area below)
Average frontal area (m^2)	5.85	6.0 (Note 7)
Drag area	3.22 m^2 (from above 2 values)	3.40 m^2 (Note 7)
Steer tyres, dimensions, rolling resistance (kg/t)	215/75 R 17.5 7.1 (Note 8)	255/60 R 18 (Note 8) 7.7 (Note 9)
Drive tyres, dimensions, rolling resistance (kg/t)	215/75 R 17.5 7.1 (Note 8)	255/60 R 18 (Note 9) 7.7 (Note 9)
	Operational specifications	
Annual activity km (mi)	56,000 (35,000) (Note 10)	60,350 (37,500) (Note 11)
Typical duty cycle	From best available real world data, see Appendix 2	From 2015 Phase 1 requirement from MOVES model (see Note 12)
Fuel consumption[9]	15.8 L/100 km (Note 12)	15.3 L/100 km (Note 13)
CO_2 emissions	420 g CO_2/km	409 g CO_2/km

Notes to Table 3.2:

*** General:** The figures for US vehicles have in general been sourced from the EPA RIA study, where available, and from the SWRI study where appropriate figures were not available in the RIA.

Note 1: The engine specifications are taken from what is believed to be a representative vehicle (New Iveco Daily van 4100). However, there are few models available at this size category in the market, and model updates are infrequent. This vehicle is a relatively new model from 2015.

The information on engine peak brake thermal efficiency (42%) is an estimate using information from IVECO that suggested small improvement on ~41.7% calculated from the VECTO dataset.

Note 2: The engine details for the baseline US HD pickup truck and van diesel engine are taken from the EPA RIA Section 2.9.1.1 (Table 2-52). The engine speeds and torque given in the table come from Figure 2-21 of the RIA, which shows the baseline engine fuel map for this engine.

Note 3: There is little engine description in the RIA. Therefore the details provided are therefore an approximation based on the 285 kW Cummins ISB engine tested by SWRI in Report #1.

Note 4: The engine peak brake thermal efficiency is calculated from the minimum brake specific fuel consumption (BSFC) or 210 g/kWh given in the 2018 200 hp engine fuel map (Figure 2-21 of EPA RIA, August 2016) and the fuel net calorific value (CV) of 11.93 kWh/g (42.9 MJ/kg).

Note 5: the vehicle specifications (transmission, weights cross sectional area and wheel/tyre sizes are those for the representative vehicle (New Iveco Daily van 4100).

Note 6: The weights for the baseline HD pickup and van vehicle were taken from Table 3.23 of the EPA RIA (August 2016), and represent the average figures for Light Heavy (Class 2b-5) trucks.

[9] See Appendix 1 for the evidence for these values. Note, readers should be aware that the EU and US fuel consumption figures should not be compared directly, due to differences in duty cycles and environmental conditions.

Note 7: EPA RIA Table 4-15 gives a drag area of 3.4 m^2 for light heavy duty (LHD) vocational multi-purpose vehicle. Whilst this is not the same as HD pickup truck and van, for which no value is given, it is closer to that of the European panel van than the dimensions of the Dodge RAM pickup.

Note 8: Rolling resistance range used by Ricardo vehicle simulation modellers ranges from 6.6 to 7.7 kg/t. The value chosen is the mid-point of this range.

Note 9: Tyre rolling resistance for US baseline vehicle taken from the EPA RIA (See Table 2-59, for LHD diesel baseline modelling parameters for Multi-purpose vehicle, there being no data for the HD pickup truck and van). This specifies the “tire revs/mile” rather than tyre size and gives a value of 670. Using the calculator from: https://tiresize.com/calculator/ tyre sizes of 255/60 R 18 gave the correct number of revolutions per mile, and were available tyres. Similarly, the tyre rolling resistance was taken from Table 2-59 of EPA RIA.

Note 10: The annual activity is taken from 2010 Freight Transport Association’s (FTA’s) Manager’s Guide to Distribution Costs, Table 2.

Note 11: This figure is deduced from the mid-point of the data given in National Research Council. “Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles.” http://www.nap.edu/catalog/12845.html. 2010 for Class 2b, Class 3 and Class 4 vehicles.

Note 12: This is dependent on many factors. See discussion in Appendix 1 for details regarding the origins and variations (variability) of this 15.8 L/100 km figure.

Note 13: Table 5-18 of the EPA RIA gives the average required fuel consumption (6.32 gal/100 mi) from Phase 1 standards for HD Pickup and Van. This is further adjusted for 2015 baseline vehicles (i.e. a small increase in energy consumption from the 14.86 L/100km direct conversion). Note how for these vehicles fuel consumption metric is only in g/km not in g/t.km.

Overall, the best available real world data indicates that the European panel van has an average fuel consumption 3.2% higher than the EPA Phase 1 average required fuel consumption adjusted for 2015 vehicles. This comparison is believed to be more useful than comparing two completely different vehicles, e.g. the European panel van and either the Dodge RAM Pickup, described in the SWRI Report #1 (Reinhart T.E., 2015), or the Isuzu flat bed, used as the baseline vehicle in the TIAX study (Law K. et al, 2011). Nevertheless, care does need to be taken when comparing these two baseline vehicles, not least because in the US panel vans comprise a minority of this regulatory category.

Table 3.3: Characteristics of US and European vehicles for rigid box-truck segment

Rigid box-truck characteristic	EU	US*
Make/model Example	Mercedes Benz Atego 12 tonne rigid	KW T270 rigid truck
		
	Vehicle specifications	
Engine – power	203 kW@ 2,352 rpm (Note 1)	203 kW @2,5000 rpm
Displacement	7.08 L (Note 1)	7.0 litres (Note 2)
Torque	1,054 Nm@ 1,377 rpm (Note 1)	900+ Nm @1600-2350 rpm

Rigid box-truck characteristic	EU	US*
Engine description	Diesel MAN inline 6-cylinder engine; 4 valves per cylinder, common rail injection with two-stage turbo with intercooling at high power levels (Note 3)	Diesel Cummins ISB 6-cylinder engine; 4 valves per cylinder; single VGT (Note 4)
Emissions control	EGR + DOC + SCR + ASC + DPF; complies with Euro VI regulations	EGR + SCR + DPF; complies with 2014 GHG requirements
Engine peak brake thermal efficiency	41.7% (Note 5)	40.2% (Note 2)
Transmission	6 speed MT (Note 6)	6-speed AT (Note 7)
Vehicle configuration	Cargo box	Cargo box
Weights		
GVW kg (lb)	11,900 (26,235) (Note 5)	11,408 (25,150) (Note 8)
Kerb weight kg (lb)	7,750 (17,085) (Note 5)	6,328 (13,950)
Max payload kg (lb)	4,150 (9,149) (Note 5)	5,080 (11,200) (Note 8)
Typical payload kg (lb)	2,984 (6,579) 71.9% loading (Note 3)	2,540 (5,600) 50% loading (Note 8)
Vehicle's C_D	0.549 (implied from drag area below)	0.551 (implied from drag area below)
Vehicle's frontal area	8.80 m^2	9.8 m^2
Drag area	4.83 m^2 (from VECTO, see Note 5)	5.40 m^2 (EPA RIA Table 4-14)
Steer tyres, dimensions, rolling resistance (kg/t)	245/70 R 19.5 (See Note 9) 7.0 (Note 11)	275/75 R 20 (Note 10) 7.7 (Note 10)
Drive tyres, dimensions, rolling resistance (kg/t)	245/70 R 19.5 7.7	275/75 R 20 7.7 (Note 10)
	Operational specifications	
Annual activity km (mi)	88,000 (55,000) (Note 12)	80,000 (50,000) (Note 13)
Fuel consumption	24.9 L/100 km (Note 14) 8.33 litres /100 t.km	19.0 L/100 km (Note 15) 7.49 litres /100 t.km
Cycle and payload	VECTO Regional delivery at 3,000 kg payload	54% CARB HHDDT, 29% GEM 55 mph, 17% GEM 65 mph (see Table 4-14 of EPA RIA)
CO_2 emissions	654 g CO_2/km (Note 13) 219.2 g CO_2/km /t.km	500 g CO_2/ km (Note 14) 197 g CO_2/ t.km

Notes to Table 3.3:

* **General:** The figures for US vehicles have in general sourced from the EPA RIA study, where available, and from the SWRI study where appropriate figures were not available in the RIA.

Note 1: The engine specifications are taken from a database of 6 to 8 litre truck engines sold in 2015 that met Euro VI emissions regulations. Values are sales weighted averages, from a total of 56,649 engines. Consequently, the values given are not for any specific engine, but the average value rounded to the nearest integer (e.g. rpm at which maximum power or torque occurs).

Note 2: The engine details for the baseline US MHD vocational diesel engine are taken from the EPA RIA Section 2.9.1.1, (Table 2-52). The engine peak brake thermal efficiency is estimated based on data from EPA RIA Figure 2-20 of 209 g diesel/kWh max. Using assumed net calorific value for diesel fuel of 42.9 MJ/kg, this figure (equivalent to 0.209 kg fuel per 3.6 MJ) = 8.966 MJ fuel energy content to generate 3.6 MJ work from the engine = 40.2% efficiency.

Note 3: The engine description is taken from a representative model (MAN Truck and Bus AG D0836 LOH67 engine, which is a 6.87 litre, 186 kW @2,300 rpm, 1,000 N.m @ 1,200 rpm engine – close to the sales weighted average. It is noted that some 12 tonne rigid box-trucks use smaller, 4.8 l inline 4 cylinder, engines. However, these are a considerable distance from the sales weighted average engine specifications.

Note 4: The engine description for the baseline US MHD vocational diesel engine are taken from the EPA SWRI Study Report #1 Cummins ISB engine.

Note 5: Much of the remaining data for the "representative data" for the 12 tonne rigid box-truck are the characteristics for the baseline "declaration mode" 12t delivery mode truck within VECTO. Values obtained were compared with those for the Mercedes Benz Atego 12 tonne rigid example truck. No marked differences were noted. (For example, the engine peak brake thermal efficiency value is from the "12t Delivery Truck.vmap" VECTO file. Such data are not available from the databases that enable average engine displacement, power or torque to be found, and the VECTO values are peer reviewed representative values for Euro VI vehicles.) The details of the version of VECTO used for these data are given in Appendix 3.

With regards to kerb weight, VECTO provides only figures for the naked chassis value (i.e. without the body), so the kerb weight is instead calculated from the GVW and max payload in VECTO.

Note 6: The 6-speed MT gearbox is the "declaration mode" default gearbox used in VECTO for the 12t delivery truck. The Atego range is available with 6-, 8- and 9-speed manual transmissions, and an AMT transmission is also available.

Note 7: The 6-speed AT gearbox is that specified in the "Multi-purpose MHD diesel" baseline modelling parameters given in Table 2-57 of the EPA RIA (Aug 2016).

Note 8: Weights for the US box truck are taken from a (Class 6) Vocational MHD multipurpose vehicle, (Table 3-23 and 4-14 of EPA RIA). According to the EPA RIA *"The payloads were developed from Federal Highway statistics based on the averaging the* [maximum] *payloads for the weight classes of represented within each vehicle category"*. An average load factor of 50% is applied in the GEM modelling according to Table 4-14 of the EPA RIA.

Note 9: The tyre sizes quoted are those for the "Declaration mode" 12 t delivery truck specified in VECTO, whereas the rolling resistance values given are discussed in Note 11.

Note 10: Tyre rolling resistance taken directly from the EPA RIA (See Table 2-57, for MHD diesel baseline modelling parameters for multi-purpose vehicle. This specified the "tire revs/mile" rather than tyre size. Using the baseline value of 557, and the calculator from: https://tiresize.com/calculator/, indicated tyre sizes of 275/75 R 20 gave the correct number of revolutions per mile, and were available tyres.

Note 11: The rolling resistances used in the VECTO calculations were 8.345 kg/t for the steer tyres and 9.4 kg/t for the drive tyres. Discussions with experts concluded that these figures are anomalously high, corresponding to tyre rolling resistances values discontinued by the European tyre labelling directive. Therefore, the values given in Table 3.3 originate from the views of experts consulted, rather than VECTO.

Note 12: The annual activity is taken from 2010 Freight Transport Association's (FTA's) Manager's Guide to Distribution Costs, Table 3.

Note 13: Whereas the average annual mileage for a tractor-trailer combination is explicitly given in EPA RIA, see following table, this figure is deduced from the mid-point of the data given in National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." http://www.nap.edu/catalog/12845.html. 2010.

Note 14: The fuel consumption figure is taken directly from a VECTO simulation, using the "Declaration mode" 12 tonne rigid box-truck parameters, over the VECTO regional delivery cycle. Further discussion regarding alternative fuel consumption values is given in Appendix 1. The details of the version of VECTO used for these data are given in Appendix 3.

Note 15: Calculated from a fuel consumption figure of 28.88 gal/1000 ton-mile for the baseline emissions performance of Vocational MHD class multi-purpose given in Table 2-62 of the EPA RIA, (August 2016), and converted using the assumed 50% loading factor from Table 4-14 of the EPA RIA.

The table indicates there are differences between the US and European baseline rigid delivery trucks. Overall, the in-use fuel consumption for the European vehicle is modelled to be larger (around 31% higher than for its US counterpart per vehicle km (comparing the VECTO output with that from the EPA RIA, (Note 14). However, the lower typical payload described in the EPA RIA (15% lower than for the European baseline vehicle, as modelled in VECTO for the reference vehicle) means that per tonne-km, the European vehicle has around 11% higher than for its US counterpart per vehicle tonne-km.

the lower fuel consumption.

Table 3.4: Characteristics of US and European vehicles for tractor-trailer combination segment

Tractor-trailer characteristic	EU Average vehicle	US*
Make/model Example	Mercedes Benz Actros LS 4x2 Semi-trailer tractor	KW T-700 Tractor-trailer (with day cab and high roof)
		
Tractor unit		
Engine – power Displacement Torque	322 kW @ 1868 rpm (Note 1) 12.2 L (Note 1) 2,100 Nm @ 1291 rpm (Note 1)	376 kW @ 1800 rpm 14.8 L 2200 Nm @ 1240-1400 rpm
Engine description	Example: Diesel Mercedes OM471 engine, 6-cylinder, in-line, 4 valves per cylinder, waste-gated turbocharger (Note 2)	Diesel Detroit DD15 6-cylinder engine; single fixed geometry turbo-charger; auxiliary axial turbine (turbocompound); 4 valves /cylinder, 18.5 kPa exhaust backpressure
Emissions control	EGR + SCR + DOC + ASC + DPF to comply with Euro VI regulations	EGR + SCR + DPF; complies with 2014 GHG requirements with no margin
Engine peak brake thermal efficiency	44.80% (Note 3)	45.19%
Transmission	12 speed AMT (Note 4)	10-Speed MT (EPA RIA Table 2-25)
Tractor kerb weight kg (lb)	7,100 (15,653) (Note 3)	7,938 (17,500) (EPA RIA table 3-20)

Tractor-trailer characteristic	EU Average vehicle	US*
Steer tyres, dimensions, rolling resistance (kg/t)	315/55 R 22.5 (Note 3) 5.55	295/75 R 22.5 6.87 (EPA RIA Table 2-25)
Drive tyres, dimensions, rolling resistance (kg/t)	315/70 R 22.5 6.28	295/75 R 22.5 7.26 (EPA RIA Table 2-25)
Aerodynamics used	Roof fairing, controlling the cab-trailer gap and cab side extenders	Roof fairing, fuel tank/chassis fairings and cab side extenders (taken from RIA Section 2.4.1)
Trailer		
General description	Curtain-sider trailer (Note 5)	Box van trailer (Note 5)
Trailer kerb weight kg (lb)	7,500 (16,535)	6,124 (13,500) (RIA Section 3.5.2 for 53 ft box-trailer)
Tyres, dimensions, rolling resistance (kg/t)	385/65 R 22.5 5.55	295/75 R 22.5 6.0
Tractor – trailer combination vehicle configuration		
Weights		
Vehicle GVW kg (lb)	40,000 (88,000)	36,287 (80,000)
Kerb weight kg (lb)	14,600 (32,187)	14,061 (31,000) (From EPA RIA)
Max payload kg (lb)	25,400 (55,997)	22,226 (49,000)
Typical payload kg (lb)	19,300 (42,549) 76.0% loading	17,237 (38,000) 77.6% loading (From EPA RIA).
Light weighting	Virtually none	Virtually none
Vehicle's C_D	0.617	0.613 implied from drag area below
Vehicle's frontal area	10.2 m^2	10.4 m^2 (nominal value cited in EPA RIA)
Drag area	6.30 m^2 (from VECTO, see note 3)	6.38 m^2 (EPA RIA Table 2-25)
Annual activity km (mi)	130,000 (81,250)	201,168 (125,000) Note 6
Typical duty cycle	Long haul as exemplified by VECTO long haul cycle, see Appendix 2	Long haul as exemplified by NESCCAF driving cycle, see Appendix 2
Fuel Consumption	35.7 L/100 km (Note 7) 1.848 L/100 t-km (Note 7)	43.1 L/100 km (from value below) 2.501 L/100 t-km (Note 8)
CO_2 emissions	937.9 g CO_2/km (Note 7) 48.6 g CO_2/t.km (Note 7)	1,078 g CO_2/km 62.5 g CO_2/t.km (Note 8)

Notes to Table 3.4:

* **General:** The figures for US vehicles have in general sourced from the EPA RIA study, where available, and from the SWRI study where appropriate figures were not available in the RIA. The day

high-roof day cab was selected for the US comparison vehicle as this was more consistent with the EU equivalent. However, high roof sleeper cabs are more common in the US, especially for the long haul.

Note 1: The engine specifications are taken from a database of 10 to 13 litre diesel truck engines sold in 2015 that met Euro VI emissions regulations. Values are sales weighted averages, from a total of 336,053 engines. Consequently, the values given are not for any specific engine, but the average value rounded to the nearest integer (e.g. rpm at which maximum power or torque occurs).

Note 2: The engine description is taken from a representative model (Mercedes OM471 engine, which is a 12.8 litre, 335 kW @1,800 rpm, 2,200 N.m @ 1,100 rpm engine – close to the sales weighted average values.

Note 3: Much of the remaining “representative” data for the tractor unit of the baseline articulated truck are the characteristics for the baseline “declaration mode” long-haul combination truck within VECTO. Values obtained were compared with those for the Mercedes Benz Actros example tractor unit where possible. (For example, the engine peak brake thermal efficiency value is from the 40t Long_Haul Truck.vmap” VECTO file because such data are not available from the databases that enable average engine displacement, power or torque to be found. It is noted the VECTO values have been peer reviewed.) Where differences were noted, e.g. as for the gearbox, these are commented on.

Note 4: the 12-speed AMT gearbox is the “declaration mode” default gearbox used in VECTO for the tractor-trailer combination. The Atego range is available with 8-, 12- and 16-speed AMT or MT. However, consultation with Transmission Experts, has indicated that currently the median transmission for tractor-trailer combinations is around 10 speed AMT.

Note 5: The most common trailer in the EU is a curtain-sider, rather than a rigid trailer. This is taken as the “generic” trailer. The VECTO model does not specify the trailer type, rather its key characteristics. In the US the most common trailer type is a box van trailer, which accounts for around 67% of the market according to ICCT (2013).

Note 6: Figure taken directly from the EPA RIA (2016).

Note 7: VECTO Simulation results for “Declaration mode” tractor-trailer combination over the long haul cycle with 19.3 tonne reference load. The details of the version of VECTO used for these data are given in Appendix 3.

Note 8: This key value is derived from 9.64637 US gal/1,000 ton-mile and 98.2 gCO_2/ton-mile given in Table 2-26 of the EPA RIA for Class 8, day cab, high roof tractor-trailer for 2017 baseline. The fuel consumption per veh-km was derived from this assuming 19-ton payload, as specified by EPA.

Figure 1.1 shows how the long-haul segment (which is dominated by tractor-trailer combinations consumes the largest fraction of all fuel used by HDVs, and tractor-trailer combinations are the dominant vehicle type. Therefore, it is appropriate to undertake additional analysis into understanding the baseline for this vehicle segment. Therefore, two additional European long-haul tractor-trailer combinations were defined: A premium vehicle, representing close to the best currently available, i.e. with a reduced fuel consumption relative to the “average” vehicle, and an economy vehicle, representing a vehicle with an increased fuel consumption relative to the “average” (based on available evidence). Values of the same parameters are also given for ‘premium’ and ‘economy’ European tractors and trailers in Table 3.5.

Table 3.5: Characteristics of three types of European vehicles for tractor-trailer combinations

Tractor-trailer characteristic	EU average	EU Premium vehicle	EU Economy vehicle
Make/model Example	Combination of data from engines manufactured or data from VECTO (Note 1)	Mercedes Benz 1845 Actros with Tear-Drop aerodynamic trailer	MAN TGX Tractor with manual gearbox and a standard trailer
	Vehicle specifications		
Engine – power Displacement Torque	322 kW (Note 1) 12.2 L 2,100 Nm	336 kW (450 hp) 12.8 L 2,200 Nm	328 kW (440 hp) 12.4 L 2,350 Nm
Engine description	6-cylinder, in-line, diesel engine, 4 valves per cylinder (Note 2)	6-cylinder, in-line, 12.8 litre diesel engine, 4 valves / cylinder. Asymmetric turbocharger (Note 2)	6-cylinder, in-line, 12.4 litre diesel engine (Note 2)
Transmission	12 speed AMT	12 speed AMT	16 speed MT
Emissions control	EGR @ 0 - 25%, with DPF + SCR + (DOC + ASC) to comply with Euro VI regulations	EGR @ 0 - 25%, with DPF + SCR + (DOC + ASC) to comply with Euro VI regulations	EGR @ 0 - 25%, with DPF + SCR + (DOC + ASC) to comply with Euro VI regulations
Engine peak brake thermal efficiency	44.80%	46.00%	42.7% (Note 3)
Tractor kerb weight	7,100 kg	7,480 kg	7,460 kg
Steer tyres, dimensions, rolling resistance (kg/t)	315/55 R 22.5 5.55 kg/t	315/55 R 22.5 5.5 kg/t Energy Eff. Class C as defined in Reg EC 1222/2009	385/55 R 22.5 6.5 kg/t Energy Eff. Class D as defined in Reg EC 1222/2009
Drive tyres, dimensions, rolling resistance (kg/t)	315/70 R 22.5 6.28 kg/t	315/70 R 22.5 5.5 kg/t (Mostly Energy Eff. Class C, some Class B)	315/70 R 22.5 6.5 kg/t (Energy Eff. Class D)
Aerodynamics used	Roof fairing, and cab side extenders	Advanced roof fairing, and cab side extenders	Roof fairing, and cab side extenders
	Trailer specifications		
General description	Generic curtainsider trailer	Aerodynamic tear-drop curtain-sider trailer	Generic (curtainsider) trailer
Trailer kerb weight	7,500 kg	5,820 kg	7,500 kg
Tyres, dimensions, rolling resistance (kg/t)	385/65 R 22.5 5.55 kg/t	385/65 R 22.5 5.5 kg/t (Energy Eff. Class C)	385/65 R 22.5 6.5 kg/t (Energy Eff. Class D)

Tractor-trailer characteristic	EU average	EU Premium vehicle	EU Economy vehicle
Aerodynamics used	Standard curtainsider with little improvements applied	Aerodynamically designed trailer	Standard curtainsider with little improvements applied
	Tractor – trailer combination specifications		
Weights			
Vehicle GVW kg (lb)	40,000 (88,000)	40,000 (88,000)	40,000 (88,000)
Kerb weight kg (lb)	14,600 kg	13,300 kg	14,960 kg
Max payload kg (lb)	25,400 kg	26,700 kg	25,040 kg
Typical payload kg (lb)	19,300 (42,549)	19,300 (42,549)	19,300 (42,549)
Vehicle's Cd	0.617	0.473 (Note 4)	0.7 (estimated)
Vehicle's fontal area	10.2 m^2	9.5 m^2	9.5 m^2
Drag area	6.299 m^2	4.492 m^2 (Note 4)	6.650 m^2
Annual activity km (mi)	130,000 (81,250)	130,000 (81,250)	130,000 (81,250)
Fuel economy	35.66 L/100 km (Note 5) 1.848 L/100 t.km (Note 5)	31.61 L/100 km 1.638 L/100 t.km	38.72 L/100 km[10] 2.006 L/100 t.km
Cycle and payload	VECTO long haul cycle, see Appendix 2	VECTO long haul cycle, see Appendix 2	VECTO long haul cycle, see Appendix 2
CO_2 emissions	937.9 g CO_2/km (Note 5) 48.6 g CO_2/t.km (Note 5)	831.4 g CO_2/km 43.1 g CO_2/t.km	1,133 g CO_2/km 65.8 g CO_2/t.km

Notes to Table 3.5:

Note 1: Values taken for engines are based on a combination of data from manufactured engines, and from the VECTO declaration mode for 40 T with standard curtain-sider trailer.

The engine specifications are taken from a database of 10 to 13 litre truck engines sold in 2015 that met Euro VI emissions regulations. Values are sales weighted averages, from a total of 336,053 engines. Consequently, the values given are not for any specific engine, but the average value rounded to the nearest integer (e.g. rpm at which maximum power or torque occurs).

Note 2: The engine descriptions are taken from a publicity regarding the Mercedes OM471 engine, which is a 12.8 litre, 335 kW @1,800 rpm, 2,200 N.m @ 1,100 rpm engine[11].

Note 3: The engine peak brake thermal efficiency for a less efficient engine, came from analysis of real truck fuel consumption data from 18 Euro VI tractor units, extracted from many editions of LastAuto Omnibus magazine, collected by ICCT. It was assumed that the differences in fuel consumption for the "overall" test cycle are principally caused by changes in engine efficiency, particularly when averaged over several vehicles. The three tractor units with the highest overall fuel consumption, which were models from three different manufacturers were averaged, and their fuel consumption was compared with the average from the 18 vehicles. This led to the reduced efficiency given (42.7%) when compared to the efficiency for an average vehicle (44.8%). More details are given in Appendix 1.

[10] Assumes fuel consumption is 3.6% higher, due to poor rolling resistance tyres, and engine BTE is 42.7, from the assumptions detailed in Appendix 1.

[11] Consultation with Ricardo engine experts indicate this is representative of a modern "premium" engine. For publicity see, for example, http://media.daimler.com/marsMediaSite/en/instance/ko/Mercedes-Benz-OM-471-economical-powerful-and-reliable-Consum.xhtml?oid=9905489

Note 4: This value was found from vehicle simulations using the VECTO model (over the long haul cycle for the declaration mode tractor-trailer combination at its reference weight). The change in Drag Area required to generate a 9% reduction in fuel consumption was found (which is the estimated fuel consumption improvement for the aerodynamically designed trailer). It was then assumed the vehicle's frontal area was unchanged, and the difference was only in the vehicle's drag coefficient.

Note 5: VECTO Simulation results for "Declaration mode" tractor-trailer combination over the long haul cycle with 19.3 tonne reference load. The details of the version of VECTO used for these data are given in Appendix 3.

The principal differences between the three baseline vehicle types are:

- Changes in engine peak brake thermal efficiency;
- Changes in aerodynamic efficiency, ranging from the "standard" vehicle modelled in VECTO to a vehicle with an aerodynamic trailer, where an improvement in fuel consumption of 9% is assumed (from a series of on-the-road case studies) and for which C_D was calculated using the VECTO model;

Changes in rolling resistance, where the economy vehicle is assumed to be fitted with tyres of one tyre energy efficiency class worse than the standard (Class C, 5.1 ≤ Rolling resistance coefficient ≤ 6.0) low rolling resistance tyres fitted to the EU average and premium vehicles.

These three changes lead to the fuel consumption differences given, and the different average CO_2 emissions associated with this fuel consumption from these.

3.2 Differences between European and US market baseline vehicles

This section provides a summary discussion of the main differences between the European and US market baseline vehicles. Some comments on differences between the characteristics of the three vehicle segments for European and US baseline vehicles have already been provided below the corresponding tables describing their characteristics (i.e. Table 3.2, Table 3.3 and Table 3.4).

For the panel van (/pickup truck) segment, the "average" vehicles have some significant differences in typical body shape (mostly pick-ups in the US), and in the engine power, capacity and peak brake thermal efficiency (with the first two engine parameters being lower for EU vehicles, and the latter higher). There are also differences in the transmissions, with the US vehicle having an automatic gearbox, and the European vehicle being fitted with a manual transmission (MT). The US vehicle is also slightly larger with a greater drag coefficient. Typical tyre rolling resistance is also higher for US vehicles (i.e. 7.7 kg/t vs 7.1 kg/t for EU equivalents). Annual activity and typical load capacity and payload are similar. However, the fuel consumption for the EU vehicle is higher, which is likely to be due to differences in the average duty cycles between the two regions, given the above. These differences therefore need to be taken into account when undertaking comparisons.

For the rigid box-truck segment, the "average" vehicles are quite similar, both being rigid cargo box-vans. The principal differences are not so much in the engine, and its performance and efficiency, but in the transmission, i.e. with the US vehicle having an automatic gearbox, and the European vehicle fitted with a manual transmission (MT). The baseline US vehicle is also physically larger, but is more aerodynamic, such that its drag x area value is approximately 2% higher than for its European counterpart. Overall, the in-use fuel consumption for the European vehicle is modelled to be around 31% higher for the European vehicle (from a VECTO simulation) compared with the EPA/NHTSA RIA value. The 15% lower typical payload for the US vehicle means that fuel consumption per tonne-km is around 11% lower for the US vehicle. The differing assumptions that apply to the characteristic values for these two baseline vehicles need to be taken into account when undertaking any comparison.

The two baseline tractor-trailer combinations have distinctly different engines in terms of their displacement and peak power (US baseline engine being around 20% larger). Notwithstanding, their peak brake thermal efficiencies are similar (within 1%). In terms of the trailer and overall vehicle characteristics, the two baseline vehicles are quite similar regarding aerodynamic drag area (with the European average vehicle having a very slightly higher drag coefficient but a smaller frontal area).

There are differences in their GVW, and their kerb weights, which affects their payload capacities, and hence their weights when tested.

Overall, when the fuel consumption of the European baseline tractor-trailer combination over the VECTO long haul cycle (35.7 L/100 km) is directly compared with the value given in the EPA RIA for a Class 8, high roof day cab US baseline tractor-trailer combination, see Note 12 to Table 3.4 (43.1 L/100 km) the US truck has close to a 21% higher fuel consumption. Much of this difference can be accounted for because US trucks can, and on average do, travel at higher speeds where additional fuel is consumed to overcome increased wind resistance. This is clearly seen from the fuel consumption data reported in Table 3.14 SWRI Report #1. This shows that the fuel consumption increases by 20% (and 18%) between 55 mph and 65 mph for 50% (and 100% load) respectively.

There is a ~2 tonne difference in the assumed typical payload for the two vehicles; with the corresponding payloads being 17.2 tonnes for the US truck, and, 19.3 tonnes from the VECTO reference vehicle. (In terms of the loading factors these are 77.6% for the US truck and 76.0% for the European truck. Consequently, when expressed in terms of fuel consumption per 100 t-km, the 21% higher fuel consumption for each vehicle km for US truck increases to 35% for each t-km).

Although EU has a higher allowable payload, US has a larger trailer volume, therefore the freight efficiency will depend on the density of freight being moved. US will be more efficient moving lower freight density and the EU will be more efficient moving denser freight. The overall loading ratios (as a fraction of maximum payload) reflect these differences.

In the next chapter the fuel efficiency improvements of the individual technologies will be systematically assessed. For some technologies, the improvements described in the EPA reports ***do*** translate directly from US to European baseline vehicles (e.g. anticipated reductions in engine friction), because the vehicles are similar in many ways. But this does not apply for all technologies.

Key reasons why direct comparison does not translate directly include:

- When the European and US vehicles are fundamentally different, e.g. the rigid box-trucks have different transmissions to the baseline vehicles;
- When the European and US vehicles are subtly different, e.g. the average drag area for the tractor-trailer combinations;
- When vehicle usage patterns lead to adjustments being required when translating the technology potential found for US vehicles to the European market, e.g. the average speed of long haul operations leads to systematic differences in the potential of aerodynamic packages.

The comparison of the EU and US baseline vehicles provides an evidence base showing where direct comparison is appropriate.

4 Fuel efficiency improvement technologies

This chapter provides a summary of the fuel efficiency improvement technologies investigated for this project, and is structured to describe:

- The range of technologies included;
- The translation of improvements between the US and European markets;
- The fuel consumption reduction potentials of individual technologies, and packages of technologies translated into those appropriate for the European market, given the baseline vehicles' characteristics.

4.1 Technologies included

Technologies that improve fuel efficiency can be broadly put into the following two categories:

1. Those that increase the useable mechanical power delivered to the vehicles' wheels, i.e. improvements in the powertrain, such that less fuel is required to produce the same amount of work required by the vehicle; and
2. Those that decrease the external losses that occur when the vehicle is in motion, such that less fuel is consumed because less work is required to achieve the same utility.

The first category includes the broad technologies of:

a) Improved engine efficiency (Section 4.3.1), including:
   i) reduced frictional losses in the engine (Subsection 4.3.1.1);
   ii) reduction in auxiliary parasitic loads (Subsection 4.3.1.2);
   iii) improved air handling (turbo-charging and EGR) (subsection 4.3.1.3);
   iv) waste heat recovery & improved thermal management (subsection 4.3.1.4);

b) More efficient transmission & driveline (subsection 4.3.2);

c) Hybridisation to capture braking losses and reduce engine transients (subsection 4.3.3).

Whereas the second category includes:

d) Improved aerodynamics (subsection 4.3.4);

e) Light-weighting (subsection 4.3.5);

f) Reduced tyre & wheel losses (subsection 4.3.6);

g) Overnight hoteling loads (extended idle) reduction technologies (subsection 4.3.7);

h) Improved vehicle management technologies (subsection 4.3.8).

This broad categorisation defines also the structure provided in later Section 4.5 of this report, and in Chapter 5 on cost-effectiveness.

4.2 Translation of improvements between US and European markets

The improvements from different technologies described in the EPA reports do not translate directly from US to European baseline vehicles. The three key aspects to be considered here include:

- Any differences in technology fitted to the baseline vehicles. For example, US Service vehicles (HD pickup trucks and vans) tend to have automatic transmissions, whereas their European counterparts use manual gearboxes.
- The extent to which the technologies would benefit the US and European baseline vehicles. For example, for aerodynamic packages the smaller gap between the tractor and trailer for the EU baseline vehicle, relative to the US baseline vehicle, makes the reduced fuel consumption from this aspect of aerodynamic packages less for the European vehicles.
- The differences between US and European vehicles' usage patterns. For example, in Europe trucks are limited to 90 kph (56 mph) whereas in the US long haul speeds are higher and

consequently the impact of aerodynamic packages, or engine down-speeding will differ between the two markets.

The first two aspects above are generally summarised earlier in Table 3.2 to Table 3.5, which describe the baseline vehicles' characteristics, and considered further in Sub-section 4.3 of this report.

The aspect of average usage patterns is important because it both highlights differences that need to be taken into account in the technology potential translation between US and European vehicles, and defines the all-important speed-time profile over which improvements are estimated.

A further important issue is how well the driving cycles translate into real world benefits. The development process that led to the VECTO drive cycles was heavily dependent on the use of real world driving performance as a design criterion. Consequently, it is anticipated that fuel consumption reductions simulated (or measured) over these cycles are representative of the real world benefits.

The VECTO model has defined reference journeys for urban delivery, regional delivery and long-haul reference journeys, along with reference journeys for construction and municipal utility vehicles, and five representative usage patterns for buses and coaches. The principal journeys used for panel vans are presumed to be urban delivery, for box-trucks are presumed to be regional delivery, and for tractor-trailer combinations are presumed to be long-haul. These reference journeys are shown at 1 second resolution in Appendix 2, and some important parameters are given in Table 4.2.

Key assumptions:

For European usage patterns, the speed-time driving profile for urban delivery, regional delivery and long-haul vehicle segments are those agreed by detailed consideration within Europe and are embodied in the European Truck CO_2 certification model (VECTO).

The average payload for the regional delivery and long-haul vehicle segments are those agreed by detailed consideration within Europe and are embodied as the “reference” loadings in VECTO.

The supporting studies to the EPA Phase 2 rule making investigate technology potential for a range of different cycles, as indicated in Table 4.1. Equivalent data to that for the European cycles are given in the lower half of Table 4.2, with further details given in Appendix 2.

Table 4.1: Characteristics of drive cycles over which technology potential was assessed for US vehicles

Drive cycle characteristics	Urban delivery	Regional delivery	Long haul
Vehicle	RAM ICT 6.7 litre diesel engine	Kenworth T-270 box-van	Kenworth T-700 articulated truck
Drive cycles investigated	FTP City, FTP Highway, US06, SC03, WHVC, 65 MPH	CARB Stop-and-go cycle, 55 mph and 65 mph steady cruise, CILCC, Parcel Delivery Cycle, WHVC	CARB Stop-and-go cycle, 55 mph and 65 mph steady cruise, WHVC, NESCCAF Long Haul Cycle

Table 4.2: Characteristics for the US and European driving cycles

European Drive cycle characteristics	Urban delivery	Regional delivery	Long haul		
Distance (km)	27.81	25.84	108.18		
Average speed (kph/h)	29.8	57.1	73.59		
Average of second by second speed squared (kph)^2	1,444.5	4,108.7	5,934.1		
Number & duration of stops	25 stops, 593 s	10 stops, 236 s	5 stops, 239 s		
Percent of time at idle (%)	16.8	6.6	4.5		
Average driving speed (kph)	36.2	61.1	77.1		
US Drive cycle characteristics	**FTP City Light Duty**	**HHDDT (CARB)**	**NESCCAF**	**Steady speed**	
Distance (km)	12.07	4.57	166.32	Steady speed	
Average speed (kph)	31.35	24.65	87.28	88	104
Average of second by second speed squared (kph)^2	1,543.8	1,074.0	8,709	7,744	10,816
Number & duration of stops	17 stops, 265 s	5 stops, 115 s	3 stops, 0 s	0 stops	0 stops
Percent of time at idle (%)	19.4	16.3	0	0	0
Average driving speed (kph)	Not available	Not available	87.28	88	104

Based on the cycle characteristics, the US driving cycles (which were assessed in the EPA reports and SWRI studies) that are closest to the standard European usage patterns (the VECTO cycles) were identified. These are summarised in Table 4.3 below.

Table 4.3: US drive cycles that are relevant to the European driving patterns

European vehicle segment	European representative cycle	US representative cycle	Comparison to be made
Panel van	Urban delivery	FTP City	Directly comparable
Rigid box-truck	Regional delivery	CARB & steady speed 55 mph	Use mixture of 2 US cycles[12]
Tractor-trailer combination	Long haul	NESCCAF, steady speeds at 55 and 65 mph	Use combination of these 3 US cycles[13]

[12] Combination of a full CARB cycle around 207 seconds of 55 mph steady state driving, gives a “combined” cycle whose characteristics are quite close to the whole VECTO Regional cycle, as discussed in Appendix 2

[13] The European long haul cycle has characteristics similar to the NESCCAF cycle **minus** (difference between 55 mph & 65 mph steady speed cycles)

4.3 Improvements for individual technologies

The technologies that are included in this section are all the technologies that were considered in research leading up to the US regulation. These are augmented by some further technologies not considered in the research, but that are included in the final RIA for the Phase 2 rule.

The changes in fuel consumption for individual technologies are discussed in the order described in Section 4.1. For each technology, the discussion is structured to give the following:

- An overview of the technology and why it has the potential to reduce CO_2 emissions;
- Areas within the engine speed-load map for engine related technologies, or in the vehicle speed map range for vehicle related technologies, where the technology under consideration has the largest impact for the three vehicle segments considered;
- A qualitative description of use in baseline vehicles and prospects for future incorporation;
- Quantitative estimates of the change in fuel consumption per vehicle-km for each of the three vehicle segments considered.

A summary of the technologies considered, and the vehicle segments to which they apply, is given in Table 4.4.

Table 4.4: Summary of the technologies considered, and the vehicle segments to which they apply

Technology	Panel van	Rigid box-truck	Tractor trailer combination
Engine efficiency – friction, general and low viscosity oils	Yes	Yes	Yes
Vehicle accessories – Power steering, A/C, Cooling fan (not included in the US rule)	Yes	Yes	Yes
Engine efficiency - air handling (turbo-charging and EGR)	Yes	Yes	Yes
Waste heat recovery & thermal management	**No**	**No**	Yes
Thermal management	Yes	Yes	Yes
Transmission & driveline	Yes	Yes	Yes
Hybridisation	Yes	Yes	**No**
Aerodynamics	Yes	Yes	Yes
Lightweighting	Yes	Yes	Yes
Tyres & wheels	Yes	Yes	Yes
Tyre pressure monitoring and automatic inflation systems	Yes	Yes	Yes
Overnight hoteling loads (extended idle) reduction technologies	**No**	**No**	**No**
Vehicle management technologies	Yes*	Yes*	Yes*

Notes: * In general terms: For example PCC (predictive cruise control) might not be so useful for panel vans for urban delivery and platooning doesn't work for stop-start conditions. PCC is best in the middle range, and not so much at stop-start or steady speed driving conditions.

4.3.1 Engine efficiency technologies

4.3.1.1 Engines - Friction

Overview of technology and why it has the potential to reduce CO_2 emissions:

Engine frictional losses occur whenever two surfaces are in close contact, either directly, e.g. between the piston ring and the cylinder liner at top dead centre, or with a shearing oil film between the surfaces, e.g. between the piston ring and the cylinder liner during most of the stroke. Whole engine friction loss is often quantified as the difference between the mean power applied to the pistons over an engine cycle by the combusting mixture in the cylinders, and the mean power measured at the engine output shaft. Frictional losses are associated with a variety of energy transfers that occur between these two locations. Therefore, engine friction loses come from many sources[14].

Examples include the direct frictional losses from:

- Piston ring – cylinder liner friction;
- Cylinder valve – cam-shaft, particularly during the opening of the valve;
- Crank shaft – big end bearings;
- Connecting rod and little end bearings;
- Timing chain between crank shaft and the valve.

Mean powers are traditionally expressed in terms of mean effective pressures, and can be used to define a "friction mean effective pressure" (FMEP), given by:

$$FMEP = GMEP - PMEP - BMEP$$

Where:

FMEP = Friction mean effective pressure;

GMEP = Gross mean effective pressure, i.e. the power at the pistons;

PMEP = Pumping mean effective pressure;

BMEP = Brake mean effective pressure, i.e. the power at the engine's output shaft;

Friction analysis often refers to GMEP – PMEP as Net indicated mean effective pressure (NIMEP).

Engine modelling uses changes in FMEP, i.e. groups the friction and some other losses in FMEP. As noted above, direct frictional losses come from a number of origins. In addition to these direct frictional losses, other losses are also typically included in FMEP even though they are not strictly friction losses. Examples include:

- Energy required to drive loaded oil and coolant pumps;
- Crankcase pumping loss, windage and oil churning;
- Front end accessory drive (e.g. the frictional losses in alternators, compressors, etc.)

Reductions in both the direct and indirect frictional losses (e.g. through improved lubricants, materials and design) will lead to higher overall engine thermodynamic efficiency, and consequently, reduced fuel consumption for the same amount of mechanical work provided by the engine.

Note: The focus of the engine improvements identified in this report is primarily on hardware whereas significant improvements may also be achieved with 'soft' improvements to engine settings such as:

i. The optimisation opportunities that would be available if more capable NOx aftertreatment were used would allow the existing engine to be made more efficient with no impact on criteria emissions.

ii. Coupling i. with additional engine hardware optimisation offers further opportunity.

iii. Coupling either i. and/or ii. with focused optimisation for specific duty cycles offers further opportunity.

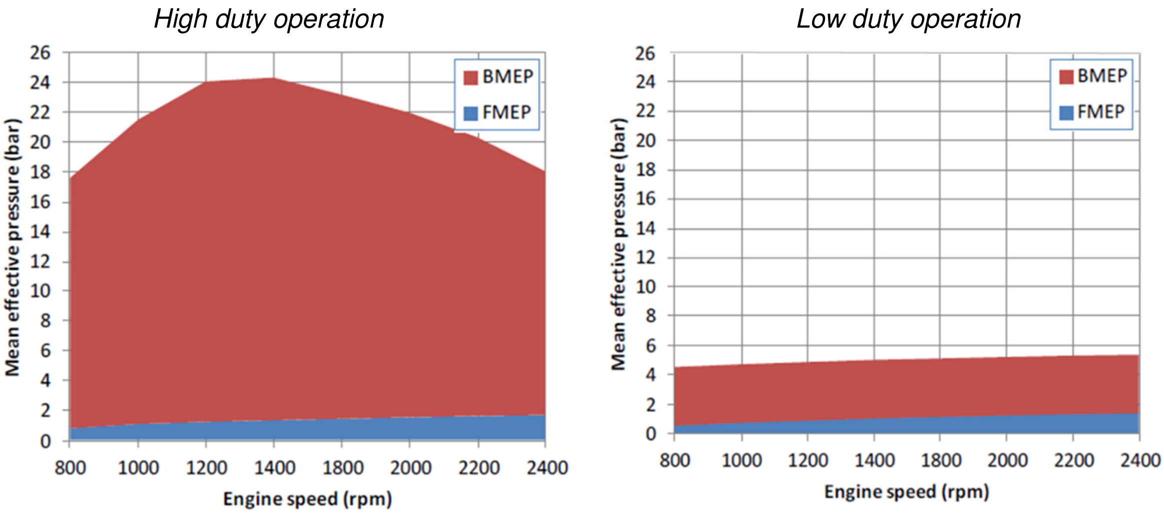
[14] For further details see, for example, "An introduction to heavy-duty diesel engine frictional losses and lubricant properties affecting fuel economy, Comfort A, SAE Paper 2003-01-3225, available from www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA460134

The potential these opportunities present is difficult to quantify (so these elements are not discussed further) because they depend on the baseline and duty cycle, however it may be higher than some of the other technologies mentioned.

Vehicle segments and usage patterns where the technology has largest impact:

The net indicated mean effective pressure (NIMEP) (after removing pumping losses) comprises BMEP (as indicated from the power at the engine's output shaft) + FMEP (the sum of the frictional losses). The figure below shows illustrative NIMEP disaggregated by its FMEP and BMEP components.

Figure 4.1: Illustrative breakdown of NIMEP into FMEP and BMEP at different engine speeds for high and low duty diesel engine operation



This leads to some important features of friction in terms of those parts of the engine speed-load map where it is more and less important:

- FMEP, generally, increases with engine speed, but is relatively load (NIMEP) independent;
- Therefore, at full load FMEP is small compared with BMEP, and at low load FMEP is of similar magnitude to BMEP;
- For engines that spend virtually all their time at relatively light loads, (e.g. smaller engines undertaking urban delivery duty cycles) the BMEP required from the engine is well below peak power and FMEP is relatively important. In contrast, for engines that spend virtually all their time at relatively high loads (e.g. engines undertaking long haul duty cycles) the BMEP required from the engine is closer to, or is at, peak power, and FMEP is relatively less important.
- Therefore, reducing friction in heavy-duty truck engines that spend most of their time at high load only leads to a smaller **relative** reduction in total fuel consumption (% reduction in fuel consumption) when compared to the same reduction in friction for engines that spend most of their time at low loads. However, absolute reduction in fuel consumption may be considerable (as measured by litres fuel consumed /100km). Further, some engine accessories, e.g. electrical or pneumatic systems, consume a large absolute amount of fuel at high loads, and particularly high engine speeds. Consequently, variable displacement pumps and improvements in auxiliaries' efficiencies are potentially important (see later).

FMEP reduction options that could be used by 2030 are many and include:

- Low viscosity oils*;
- Use of lower friction components, e.g. piston rings and/or liners, e.g. using diamond-like coatings and liner surface modifications and bearing surfaces;
- Reduction in energy required to drive loaded oil and water pumps, using variable displacement pumps*;

- Reduction in oil churning in the sump;
- Reduction in belt loses for timing and power belts;
- Improvement in auxiliary efficiencies, i.e. reducing loses in alternators, compressors, etc.

* *Measures explicitly included in the analysis.*

It is noted that some of the items above are not traditional friction reduction options, but would lead to a reduction in FMEP. Apart from improvements in auxiliary efficiencies, however, all are systems that are required as part of the engine's operation.

One item not on this list is roller bearings, i.e. replacing hydrodynamic shearing of the oil film between mating surfaces by roller bearings. Roller bearings are effective at low temperatures, and can make an important contribution to the cold-start light duty vehicle cycle test fuel consumption test. However, under normal operating conditions they only have the potential to lower friction slightly. Also, currently their durability is viewed as not proven, and so they are viewed as a less important technology for incorporation into HDV.

Another option not listed above would be full electrification of fluid pumps, which would result in zero actual FMEP but demand energy supply through another route; however, this is addressed in Section 4.3.1.2.

Future improvements in many of these items that reduce frictional losses are most likely to be from further small continuous incremental improvements.

Qualitative description of use in baseline vehicles and prospects for future incorporation:

Friction has been an area of continual attention and development. Since the beginning of internal combustion engine design friction reduction has occurred through a series of incremental improvements. However, attention has not been evenly spread across all engine sizes. This is because:

- The CO_2 regulations for light-duty cars and vans have incentivised the uptake of friction reduction engineering for light-duty vehicles, where, as noted above, reduction in FMEP generates a larger overall relative reduction in fuel consumption, for most light-duty vehicle usage patterns;
- The higher fuel costs in Europe relative to the US incentivises the uptake of friction reduction technologies (e.g. in engine design with low-friction coatings), and it is believed European baseline vehicles are slightly ahead of US baseline vehicles, i.e. have lower FMEP[15];
- The uptake of friction reduction engineering is also linked to taking risks. For heavy-duty vehicles, particularly the long-haul segment, but also for the regional delivery segment, the durability of engines is key. There is a perception (however unfounded) that technical improvements that reduce friction (e.g. engine design changes, use of alternative low friction materials /coatings) may compromise durability. Therefore, friction reduction options are incorporated less rapidly in heavy-duty engines[16].

Quantitative estimates of change in CO_2 per vehicle for the three vehicle segments considered:

The fuel consumption reduction benefits are duty cycle and payload dependent, with low speed, low average power demand cycles showing the biggest benefit. The SWRI study for EPA (Reinhart, 2016) gives the fuel consumption reduction modelled for a Detroit Diesel DD15 engine using the Kenworth T700 tractor trailer at 50% load, for the same "Reduced FMEP" technology, as ranging from 4.6% for an urban stop-and-go cycle developed by CARB, to 3.1% for steady 55 mph, and 2.1% for steady 65 mph[17]. For the smaller-engined box-truck, the fuel consumption reductions reported by SWRI were 6.8% for CARB cycle, to 2.6% for steady 55 mph, and 2.0% for steady 65 mph[18]. This is as expected from Figure 4.1.

[15] This was a view expressed by several of the Ricardo engineering experts during consultations
[16] This was a view expressed by a Ricardo expert in friction reduction technologies during consultation
[17] Data taken from Table 3-15 of Ref
[18] Data taken from Table 3-19 of Ref

Other consultants have provided the following generalisation: that a 10% reduction in FMEP leads to a 1% fuel consumption reduction for a truck at 2,000 rpm, and 2.5% for a light-duty car engine at 2,000 rpm.

The reductions in fuel consumption generated by changes FMEP reported in the SWRI Report #1 for the three different vehicle segments are summarised in the table below, taken from the dominant driving cycle for each vehicle segment.

Consultations with Ricardo experts did not give a clear indication regarding systematic differences between the technology potentials for US and European vehicles. It is anticipated that with regard to the baseline vehicles, similar technologies are used on both sides of the Atlantic. The one systematic difference considered was the higher (e.g. 104 kph, 65 mph) speeds in the US relative to Europe (90 kph) affecting long haul operations. The SWRI evidence is that reduced FMEP generates around 0.9% higher fuel consumption reduction potential at 55 mph relative to 65 mph. Therefore, the European potential, given in the final row of Table 4.5, is increased to account for this.

Table 4.5: Reductions in fuel consumption generated by changes in FMEP for both US (as indicated in EPA Report #1) and translated to European vehicles and driving patterns

Factor	Panel van for urban delivery cycle	Rigid box-truck for regional delivery	Tractor trailer combination for long haul
US research			
Fuel savings resulting from SWRI Report #1[19]	7.7%	5.1%	2.3%
Source in Ref	Table 3.23 for the urban stop-and-go cycle developed by CARB	Table 3.19 for the WHVC cycle	Table 3.15 for the long-haul (NESCCAF) cycle
European potential			
European technology potential by 2030 from 2015 baseline	7.7%	5.1%	3.1%

The SWRI study provides the above overall technology potentials for the different vehicle segments. It does not disaggregate the technologies.

However, consultations with Ricardo engine efficiency experts have generated some ancillary specific savings potentials. These were improvement in overall fuel consumption for:

- Variable displacement oil pumps where overall improvement could be 1 – 2%;
- Variable displacement coolant water pumps where overall improvement could be 0.5 – 1.2%;
- Bypass oil cooler where overall improvement could be 0.2% - 0.85%.

The "overall improvement in fuel consumption" is emphasised because these three technologies both reduce the parasitic ancillary losses through reducing the amount of mechanical work required, and improve energy efficiency through better thermal management. To avoid double counting, these technologies are not discussed again in the section on thermal management (Section 4.3.1.4). The European friction reduction potentials by 2030, from 2015 baseline vehicles, given in Table 4.5 were disaggregated into the three specific technologies highlighted, and "unspecified" FMEP improvements, as broken down in Table 4.6. In addition, the fuel consumption reduction potential from low viscosity oils is also included (values from Such et al, 2015 and McCarthy S., 2014).

These three measures generate a 4.0% fuel consumption reduction potential for the panel van with its urban delivery cycle. The benefit for the variable fluid pumps are reduced for the rigid box-truck for the regional delivery cycle and tractor-trailer combinations on long haul, by around 28% and 53%

[19] FMEP reductions assume a 10% reduction at high engine speed and load, to 35% at low speed and light load (See Section 3.3.1.12, Section 3.3.3.4 of SWRI Report #1)

respectively, in-line with the data given in Table 4.5. Similarly, the benefit of a low viscosity is reduced for the long haul segment.

After identifying some sources of the FMEP improvements, there remains generic, unpriced “further improvement in FMEP” of 3.7% for the panel van, 2.3% for the rigid box-truck and 1.4% for the tractor-trailer combination which are included in the cost-effectiveness analysis in Chapter 5.

These data provide the technology potential for a more detailed incremental cost analysis, described in Chapter 5 and are summarised in Table 4.6.

Table 4.6: Reductions in fuel consumption generated by changes FMEP for European vehicle segments disaggregated by technologies

Factor	Panel van for urban delivery cycle	Rigid box-truck for regional delivery	Tractor trailer combination for long haul
Overall European technology potential by 2030 from 2015 baseline*	**7.7%**	**5.1%**	**3.1%**
Unspecified FMEP improvements	3.70%	2.30%	1.40%
Variable oil pump	2.00%	1.50%	1.00%
Variable coolant pump	1.20%	0.80%	0.50%
Bypass oil cooler	0.80%	0.50%	0.20%
Low viscosity oil	2.0%	2.0%	1.0%

Note: This total is from the addition of all technologies but “low viscosity oil”. When considering cost effectiveness, e.g. in Table 5.10, low viscosity oils are always treated separately.

4.3.1.2 Engines - Reduction of auxiliary (parasitic) loads

Overview of technology and why it has the potential to reduce CO_2 emissions

An engine and vehicle has a number of accessories that are required for the engine’s operation or as aids for the driver. These include cooling fans, the engine’s water pump, oil pump and fuel injection pump (essential for engine operation) and power-steering pump, air conditioning, air compressor (aids for the driver/vehicle). (The latter group are referred to collectively as auxiliaries, and are not essential to the engine’s operation.) Traditionally these are gear or belt driven, and there is potential for improving their efficiencies, i.e. reducing losses and thereby reducing fuel consumption. One way this can be achieved is using electric systems that run only when required, rather than continually as for the mechanically connected systems. As an alternative to electrification, variable mechanical drives can also provide improvements (and avoid potential conversion losses from mechanical to electrical energy). This is the case for some of the options listed above, including water pumps and oil pump, which have also already been discussed in the previous section (4.3.1.1), so are not covered again here.

The EPA regulatory impact analysis indicated that for trucks the highest potential for fuel consumption reduction (for conversion from mechanical to electrical systems) is for power steering, cooling fans (0.5-1%), and air conditioning (0.5%).

Vehicle segments and usage patterns where the technology has largest impact

For auxiliaries, like power steering, cooling fans and air-conditioning (A/C), these loads are variable, depending on when and where a vehicle is driven (i.e. straightness of the road, temperature, gradient, light conditions, etc.). The mechanically coupled systems that the electrical systems replace (i.e. steering, fans and A/C) are often engine speed dependent, but relatively load independent. Consequently, the absolute fuel consumption of the mechanical accessories is both **time** and engine speed dependent. Therefore, the relative proportion of fuel consumption of these accessory loads is lower at higher speeds. (For buses and coaches the large passenger cabin with its electrical (e.g. lighting) needs and air conditioning requirements, and the pneumatic systems operating door opening and vehicle kneeling, make these three auxiliary systems also important.)

Qualitative description of use in baseline vehicles and prospects for future incorporation

The use of electrical systems (that can be switched on/off as needed) rather than continuously connected gear or belt driven auxiliaries has the potential to reduce fuel consumption. Considering key sub-systems individually:

a. **Cooling fans:** The potential fuel consumption benefits of using electric cooling fans, as well as other options to improve mechanically driven fans has been considered. However currently no production rigid or tractor trucks are supplied with electric cooling fans, there some potential for this technology.

b. **Power steering:** A recent SAE paper also outlined the advantages of electro-hydraulic power steering for heavy-duty trucks[20]. Currently the majority of heavy-duty trucks use conventional hydraulic systems. It has been estimated that "over 70% of the fuel consumed by conventional systems is unnecessary". Consequently, this technology does have significant potential up to 2030. However, electrohydraulic power steering does face challenges, especially the electric power limitations of the 24-V electrical systems.

c. **Air conditioning:** Virtually all trucks are fitted with air conditioning units. The EPA RIA includes higher efficiency air conditioning units, e.g. with the replacement of a belt or gear driven compressor A/C unit with an all-electric A/C unit to reduces direct parasitic losses. There are also potential benefits in reducing the impacts of direct GHG emissions from the refrigerant leakage covered in the EPA RIA (i.e. reducing leakage rates and moving to lower GWP refrigerants), but as these are not directly relevant to fuel consumption they are not considered in this report. (These options are also separately being addressed as part of other regulations in the EU.)

Quantitative estimates of change in CO_2 per vehicle for the three vehicle segments considered

Electrohydraulic power steering is a new technology with the potential to reduce fuel consumption, relative to baseline vehicles using mechanical-hydraulic systems. There are few data on the saving potential: the figure of 0.2 litres/ 100 km reduction in fuel consumption is given for a smaller truck (panel van) over an urban delivery cycle (see footnote 20). There are technology challenges to overcome before this technology can be applied to larger trucks. Notwithstanding, assuming that these can be successfully overcome it is assumed that the savings for a tractor-trailer combination undertaking long haul delivery is 0.1 litres/100 km. This estimate came from the cycle's higher average speed (which reduces the driving time per 100 km). Also, there is a lower demand on steering during long haul operation relative to urban delivery driving, meaning a switched electrical system would operate less than a continuously coupled mechanical system.

In the US Phase 2 rulemaking, the savings assumed for electrohydraulic power steering are included also together with the potential savings for electric cooling fans (see Table 4.7 below), with no further additional fuel consumption reduction potential included separately for the latter auxiliary compared to the case where only electrohydraulic power steering is included, suggesting that the savings are less than 0.5% alone for this accessory.

For air conditioning, establishing potential savings can be very complex and has been the subject of highly detailed studies for buses in the EU, where the impact is more significant. In the US Phase 2 Rule the identified potential fuel consumption savings are between 0.5% (for tractor-trailers and heavy vocational vehicles) and 1% (for other vocational vehicles), see Table 4.7 below. However, in the EU for the tractor-trailer baseline 40 tonne truck at its reference weight over the long haul, the VECTO model, in declaration mode, calculates A/C consumes around 7% of the total energy consumption of the auxiliaries, which is itself only 4.2% of the engine's output, i.e. the A/C consumption is 0.30% of the engine's output power. Consequently, improvements in air conditioning efficiency are likely to deliver < 0.1% reduction in fuel consumption (for < 33% A/C efficiency improvement); the potential improvements for the other vehicle types have also been reduced accordingly for the EU in Table 4.7.

To help identify which auxiliaries consume the most power, the VECTO model also calculates these. For the tractor-trailer baseline 40 tonne truck at its reference weight over the long haul, the energy consumptions calculated were:

Engine fan (a hydraulically driven constant displacement pump) 20.4% of all auxiliary power

[20] See SAE International paper on "Electrohydraulic power steering pursued for heavy duty vehicles, May 2015, http://articles.sae.org/14136/

Steering pump (a variable displacement pump)	8.8% of all auxiliary power
Air conditioning (using default A/C efficiency)	7.2% of all auxiliary power
Electrical system	27.4% of all auxiliary power
Pneumatic system	36.2% of all auxiliary power.

The 0.1 litre/100km fuel consumption reduction, given above, represents a 0.28% reduction from the 35.7 litre/100km baseline vehicle's fuel consumption, which from the VECTO analysis would be around a 70% reduction in the load from the steering pump.

For the engine fan, it is assumed that the savings potential for this accessory alone could be around double that for the steering pump for 40t tractor-trailer combinations based on the relative share of total energy consumptions above (i.e. around 0.5% saving). A similar saving is also assumed for the other EU vehicle types.

Table 4.7: Reductions in fuel consumption generated by technology changes for some auxiliaries for European vehicle segments

Factor	Panel van for urban delivery cycle	Rigid box-truck for regional delivery	Tractor trailer combination for long haul
US research			
Electro-hydraulic power steering AND cooling fans	1%	0.5%	1%
High efficiency air conditioning	1%	0.5%-1.0%	0.5%
Total for US accessory electrification	**2.0%**	**1.5%**	**1.5%**
European technology potential			
Electric cooling fans	0.5%	0.5%	0.5%
Electro-hydraulic power steering	1.27% (0.2 L/100 km)	0.80% (0.2 L/100 km)	0.28% (0.1 L/100 km)
High efficiency air conditioning	0.5%	0.25%	< 0.1%
Total for EU accessory electrification	**2.25%**	**1.54%**	**0.88%**

4.3.1.3 Air handling (Turbo charging and EGR)

Overview of technology and why it has the potential to reduce CO_2 emissions

Modern diesel engines (whether for passenger cars, or light- or heavy- commercial vehicles) all use turbo-charging to increase the charge air supplied to the engine. Most include an intercooler to reduce the compressed inlet air's temperature.

The principal current and possible turbo-charging technologies can be summarised as:

- Conventional turbocharging using a waste-gated turbocharger (WGT);
- Conventional turbocharging using a variable geometry turbine turbocharger (VGT);
- Asymmetric turbocharger (AST);
- Advanced boosting using two stage turbocharging (2ST);
- Advanced boosting using e-boosting;
- Energy recovery using turbo compounding[21].

[21] Turbo-compounding involves placing a second turbo-charger turbine downstream to extract further work from the remaining exhaust energy. It is not an engine turbo charging improvement, but is a waste energy recovery system. As it involves air handling, it is considered here in the "air handling" section 4.3.1.3 rather than in the "waste heat recovery" section 4.3.1.4.

The other gas exchange technology considered is exhaust gas recirculation, a technology used for reducing NOx emissions that is used alongside the turbo-charging technologies.

Vehicle segments and usage patterns where the technology has largest impact

It is somewhat artificial to consider turbocharging in isolation – turbochargers are matched to engines with their characteristics determined by the engines specifications, which vary with vehicle segments and usage patterns. In the future this would mean that engine downsizing, or down-speeding, may generally require higher efficiency turbochargers to deliver more charge air to the more slowly rotating or smaller combustion chamber (though benefits could potentially also be achieved by better matching against the down-speeded/downsized engine in some cases). In addition the turbo technology for an existing engine may also be improved/updated.

The two conventional turbocharging systems (Waste gated turbocharger - WGT and variable geometry turbine turbocharger - VGT) are fitted to baseline vehicles (predominantly it is WGT in Europe and VGT in the US). Waste-gated turbines are sophisticated systems, with most using an ECU controlled actuator to control the fraction of the exhaust gas that flows over the turbine blades. Many Euro VI engines already use 2-stage turbo charging (the placing of two turbochargers in series).

A variant on this uses an asymmetric turbine housing, developed by Daimler and BorgWarner (a turbocharger supplier) for use in vehicles with exhaust gas recirculation (EGR). Instead of all the exhaust flow going through a waste-gated single scroll housing, the AST has a split, asymmetric housing, with, for example, three cylinders feeding one side, and the remaining three (for a six-cylinder engine) feeding the other. The two housing sides, scrolls, are different sizes, EGR is taken from only one side (the smaller, more restrictive scroll to create the pressure differential required to drive EGR). This means in theory only one half of the engine sees the penalty of restricting the exhaust to drive EGR.

In the future, two stage turbo charging may occur to a greater extent than is currently the case. Its use is likely to be linked to downsized engines, retaining the power of the larger equivalent engine, but incurring penalties of poorer transient response and lower torque at lower engine speeds.

Rather than have a two stage turbocharger, the second boosting system can be powered electrically rather than using exhaust power (e-boosting). This can allow greater control over boost conditions, but at the penalty of higher costs. This technology also benefits from higher voltage infrastructure (which reduce losses in the distribution system in the vehicle, provide improvements to power for electrical components, and also allow for component down-sizing). Consequently, this currently relatively immature boosting approach is thought most likely to occur alongside hybridisation options. This would be most advantageous for panel vans (and buses) rather than in the rigid box-trucks and tractor-trailer combinations because of the highly transient and start-stop nature of their duty cycle.

Another variant of two stage turbocharging is to use the second turbine not to compress charge air, but to extract further work from the remaining exhaust gas energy (turbocompounding). In contrast to e-boosting, this is only potentially useful for long haul operations. For panel vans, its addition would probably lead to an overall increase in fuel consumption with the weight penalty reversing the smaller reduction from stop-start driving.

Qualitative description of use in baseline vehicles and prospects for future incorporation:

For the three vehicle segments the US and European baseline vehicle are as tabulated as in Table 4.8.

Table 4.8: Currently fitted turbocharging systems to US and European trucks for the three vehicle segments

Factor	Panel van	Rigid box-truck	Tractor-trailer
US Turbocharging	Single VGT	Single VGT	Single WGT
US EGR	EGR fitted	EGR fitted	EGR fitted
Europe Turbocharging	WGT*	WGT* (99%) or VGT (1%)	WGT* (83%) or VGT (17%)
Europe EGR	EGR fitted to most but not all (80%)	EGR fitted to most but not all (77%)	EGR fitted to most but not all (92%)

WGT includes both single stage and 2-stage WGT, with some manufacturers using 2-stage turbocharging extensively, whilst manufacturers use both strategies.

The estimates of the approximate share of WGT and VGT fitted to current vehicles was derived from analysis of engine database for Euro VI engines manufactured in 2015 for the rigid box-truck and tractor-trailer segments and noting that some DAF and Iveco and most Scania engines use VGT. This leads to very few rigid box-trucks being fitted with VGT but a much larger percentage (17%) of tractors having VGT rather than WGT. None of the engines known to use VGT were used in panel vans.

The percentage of vehicles not fitted with EGR was derived from analysis of engine database for Euro VI engines manufactured in 2015 for the rigid box-truck and tractor-trailer segments. It is noted that currently Iveco manufactured engines do not use EGR, and some Scania engines also do not use EGR. The percentage of panel vans that do not have EGR fitted was deduced from the percentage of 2014 registrations of trucks above or below 16t GVW in the EU that are manufactured by Iveco (ICCT, 2015) (22%) taking into account that 23% of the lighter than 16 t rigid box-truck engines were manufactured by Iveco.

Quantitative estimates of change in CO_2 per vehicle for the three vehicle segments considered

As noted earlier, it is sometimes difficult (and artificial) to try to separate the effects of changes in turbochargers from other engine changes, i.e. down-speeding and down-sizing. From SWRI Report #1 the benefits are given as the reduction in fuel consumption for a 5% improvement in turbo efficiency. These are summarised in Table 4.9.

The European technology potentials are derived from the SWRI reported values. For panel vans and rigid box-trucks US baseline vehicles have VGT, whereas European baseline vehicles have WGT. Conversations with Ricardo air handling experts indicate that changing from WGT to VGT would be expected to reduce fuel consumption by 1 – 2% for a single WGT. It is assumed that the introduction of VGT, relative to two-stage turbocharging, leads to an additional 1.0% improvement in turbocharging efficiency, and this figure is added to the US technology potentials for panel vans and rigid box-trucks. No similar difference in baseline vehicles exists for tractor-trailers. Here the principal difference is the lower average speed of the European long-haul cycle. The SWRI Report #1 indicates a 5% turbo efficiency improvement at 50% and 100% load leads to 0.4% smaller reduction in fuel consumption at 55 mph relative to 65 mph. Therefore, the European technology potential is reduced relative to the US value by 0.4%.

In addition, for long haul vehicle segment the EPA RIA gives the following improvements in fuel consumption over the NESCCAF cycle for changes in turbocharging, and the use of turbo-compounding:

- Use of an asymmetric turbo, Technology #7, 0.9% @ 100% payload;
- Removal of the EGR system, Technology #4, 0.7% @ 100% payload;
- Removal of both turbo compounding and EGR, Technology #6, 1.7% @ 50% and 100% payload;

- Using an optimised turbo-compound technology, Technology #2, 0.3% @ 100% payload.[22]
- Using turbo-compound to drive an alternator, Technology #3, 0.3% @ 100% payload;
- Removal of the turbo compounding from DD15 engine, Technology #5, 1.0% over NESCCAF @ 50% and 100% payload.

Note: Technology # are according to SWRI Report #1, Table 3.15 for tractor-trailer and 3.17 for regional trucks.

In terms of the single technology changes within the European context:

- Ricardo experts anticipate that EGR will continue to be used as part of the OEM's NOx control strategy, and therefore its removal was not believed to be a potential fuel consumption improvement option.
- Going from waste-gated, fixed geometry turbochargers to variable geometry turbine turbochargers, is expected to give fuel consumption reduction for tractor-trailer combinations of around 1%.
- Asymmetric turbocharging is likely to be preferred to VGT for Daimler, again giving a fuel consumption reduction for tractor-trailer combinations of around 1%. IP limitations (i.e. with Daimler ownership) probably preclude other manufacturers from using this technology, and it is not appropriate for engines that use no, or little, EGR.
- E-boosting is anticipated to only be attractive in conjunction with hybridisation for panel vans (or heavy duty vehicles with a very stop-start cycle, e.g. buses), and a separate fuel consumption improvement figure for e-boosting alone is not estimated.
- Using two-stage turbocharging relative to a waste-gated, fixed geometry turbocharger is anticipated to facilitate down-sizing, giving an indirect fuel consumption improvement over a wider operating range.

It was assumed that by 2030 changes in turbochargers lead to an overall improvement of air handling efficiency of around 6% for the European vehicle segments, probably by a combination of improved turbocharging and reduced EGR pressure penalties (as occurs for asymmetric turbochargers). The principal change anticipated by Ricardo engineering experts in the European market would be the replacement of WGT with VGT, although Cummins have noted that in some cases products have been reverting to WGT due to other considerations (e.g. cost). It is also assumed that by 2030 the vast majority of HDV will continue to use EGR as part of their NOx emissions control strategy.

Therefore, as guided by the air handling fitted to baseline European and US vehicles, and the impact of a 5% improvement in turbo-charging efficiency, data in Table 4.9, the following fuel consumption reduction potential exists from improvement in air handling by 2030, relative to the European 2015 baseline vehicles: 1.9% (panel van), 2.0% (rigid box-truck) and 2.5% (tractor-trailer combination). It could be argued these figures are pessimistic, but they are also intended to reflect that some 2015 baseline vehicles, specifically those from Daimler are already using asymmetric turbocharging, whilst other OEMs (DAF, IVECO and Scania) have some current models fitted with VGT.

To complement the use of improved turbocharging efficiency, using turbo-compounding to recover some exhaust energy, relative to a waste-gated, fixed geometry turbocharger, is anticipated to generate an additional 1 – 3% fuel consumption improvement for tractor-trailer combinations beyond the potential fuel consumption reduction from improved turbocharger efficiency. A technology potential of 2% (the mid-point of this range) is included in the assessment of technology fuel savings from air handling technologies.

[22] As noted earlier, this "air handling" technology does not help reducing the pumping losses of the engine system, but rather is an "energy recovery" technology similar to waste heat recovery.

Table 4.9: Fuel consumption reduction potential in US and Europe generated by improvements in air handling technologies

Technology	Panel van for urban delivery cycle	Rigid box-truck for regional delivery	Tractor trailer combination for long haul
US research			
+5% improvement in turbo-charging efficiency as modelled in SWRI Report #1	1.6%	1.7%	2.5%
Source in Ref	Table 3.23 for the urban stop-and-go cycle developed by CARB & WHVC	Table 3.19 for the WHVC cycle	Table 3.15 for the long-haul (NESCCAF) cycle
European technology potentials			
European technology potential by 2030 from 2015 baseline from improving turbo-charging	1.9%	2.0%	2.5%
European technology potential by 2030 from turbo-compounding	N/A	N/A	2%
Total European technology potential from improvement in air handling (from simple addition)	**1.9%**	**2.0%**	**4.5%**

4.3.1.4 Waste heat recovery and thermal management

Overview of technology and why it has the potential to reduce CO_2 emissions

The overall thermodynamic efficiency of a typical heavy duty engine (mechanical engine out torque relative to fuel energy content input) is around 42 – 46%. An illustrative breakdown as to how the energy is distributed is shown in Figure 4.2.

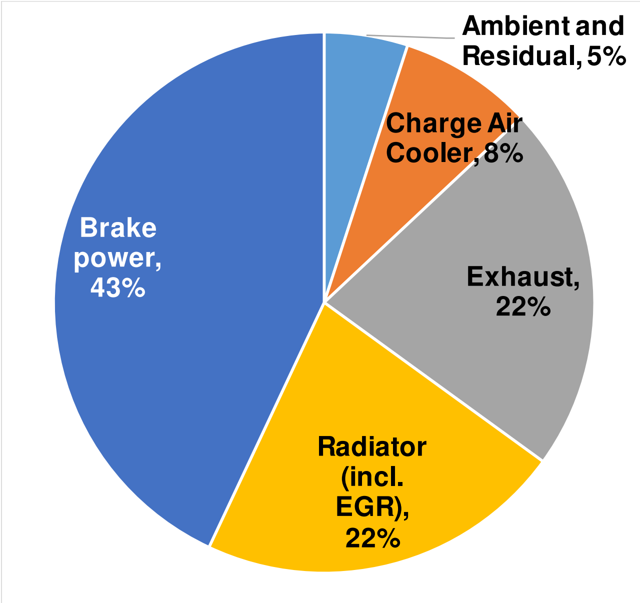
Much waste heat is produced, around 50% from Figure 4.2. This amounts to significant losses, especially for a vehicle with a high-load duty cycle such as a tractor-trailer combination. This waste heat is produced in components such as the exhaust gases, the EGR and oil coolers, the engine coolant etc. The waste heat in the exhaust gases can be partially utilised by turbochargers and turbo-compounding units, and heat in the coolant is often used to heat the driver's cab. However, there is still good potential to recover even more heat that is otherwise wasted by a diesel engine.

Three options for recovering this waste heat are:

- A heat engine (often referred to as the Rankine cycle or 'bottoming cycle'): this uses exhaust gas heat in an exchanger to drive an additional power turbine to generate energy. Various heat engines using various heat-exchange fluids are under investigation for such systems;
- Thermoelectric generation: this option converts some of the waste heat (either from the engine coolant or exhaust) into electricity using the Seebeck Effect;
- Fuel reforming: for this option, part of the engine exhaust gas reacts with small amounts of engine fuel in a mini-reactor fitted in the exhaust gas recirculation (EGR) loop to produce gaseous fuel that is fed back to the engine inlet.

However, only the first of these (i.e. a heat engine/bottoming cycle) is included in the EPA RIA for Phase 2. For reasons explained below, also this is the only waste heat recovery technology that is included in the cost-effectiveness analysis.

Figure 4.2: Illustrative breakdown as to how the original fuel energy becomes distributed in a truck



Source: DDC/Daimler (2011)

In addition to waste heat recovery, there are potential technologies that reduce the amount of waste heat generated, e.g. by reducing heat flow from the engine to its oil or coolant, so that it operates in a more adiabatic manner. These are collectively known as thermal management technologies.

Vehicle segments and usage patterns where the technology has largest impact

Waste heat recovery, and thermal management technologies, are based on there being waste heat to recover, or reduce. These technologies are best suited to engines operating at high-loads steady state conditions rather than transient operation. Therefore, these technologies are most beneficial for long haul operations, whilst for more transient driving, e.g. panel van activities, they have little direct benefit, and the additional weight of the technologies will generally lead to an overall (small) increase in fuel consumption.

Qualitative description of use in baseline vehicles and prospects for future incorporation;

The EPA considers waste heat recovery (WHR) as a technology for Phase 2 of the regulations. In the EPA Report #1 (Reinhart et al., 2015) the only WHR and thermal management technology described is heat engines (the water bottoming cycle, Technology #19, and R245 bottoming cycle, Technology #20). In EPA Report #2 (Reinhart et al., 2016) additional fluids, methanol and ethanol, are also considered, however. Data are presented in the EPA reports for the basic Rankine cycle, and when a recuperator is added. (This improves heat recovery through the use of a second heat exchanger, thereby increasing thermal efficiency further. However, this is at the expense of additional cost, weight and system complexity.)

Ricardo engine experts have indicated that neither water nor R245 are considered realistic potential technologies in Europe because:

- The water bottoming cycle, using water as the heat exchange fluid, is too big and too expensive to be commercially attractive. This uses a 100 bar water/steam evaporator.
- The R245 bottoming cycle, using the refrigerant R245 as the heat exchange fluid, is similarly not commercially attractive, because whilst the thermodynamic properties of R245 are practical, its greenhouse gas warming potential of around 900 (relative to carbon dioxide being 1.0) means R245 is being phased out within the next few years. However, there are alternatives to R245, which have a more favourable GHG potential, under investigation.

In Europe research has focused principally on the use of ethanol as the working fluid. The mechanical work harvested from the expander is added, via a gearbox, to the engine shaft, thereby reducing the power demand from the engine. Typical specifications are for a unit generating 15 kW mechanical power from a large heavy-duty engine.

Thermoelectric generation uses a temperature difference to directly generate electricity in a semi-conductor, known as the Seebeck effect. Such systems are smaller and lighter. However, currently they are relatively inefficient, with a heavy-duty vehicle demonstrator thermo-electric system generating 1 – 2 kW (c/f the 15kW from the heat engine). This technology is less mature than that of the heat engines.

Another waste heat recovery system being researched is the use of waste heat to provide the energy input required for fuel reforming (Megaritis et al, 2010). A system configuration might be converting some of the diesel fuel into hydrogen or other combustible gases which have a higher calorific value than the starting materials. The energy for the heat absorbing reactions comes from waste heat streams, e.g. the exhaust system.

There are, in addition, a number of thermal management approaches being researched, developed and added to engines. These range from engine encapsulation (Burgin T, 2011), which reduces cooldown (potentially useful for operations with frequent stops like delivery cycles) to the development towards an adiabatic engine, where no heat is lost to the environment in the ideal/extreme case (Kosaka H. et al, 2013). Intermediate active thermal management (coolant thermal management, variable speed water pumps and cooling air fans, and variable displacement oil pumps) are actively being researched.

Some of these technologies also contribute to FMEP reduction (see also Section 4.3.1.1), so when assessing the overall technology potential, care needs to be taken to avoid double counting the benefits. To mitigate for this risk, it is useful to define a generic “reduction in FMEP” benefit arising, in part, from the active thermal management technologies listed above[23]. These technology potential savings must not then be separately specified and double counted. This is controllable in this analysis since benefits and costs can be assigned appropriately, but care should be exercised in independent reviews.

Quantitative estimates of change in CO_2 per vehicle for the three vehicle segments considered

SWRI Report #1 only provides benefits from the two “bottoming cycles”, BC, and only gives fuel consumption reductions for the two steady speeds and the NESCCAF cycle, summarised in Table 4.10.

Table 4.10: Reductions in fuel consumption generated by use of heat recovery systems from US EPA Report #1

Heat recovery system	Steady speed 55 mph	Steady speed 65 mph	NESCCAF cycle
Water BC (Technology #19)	4.4%	4.8%	5.0%
R245 BC (Technology #20)	2.9%	2.8%	2.6%*

Notes: * Figures are from the US EPA Report #1; however, Cummins have noted savings can be up to 4%.

SWRI Report #2 indicates the net power/ engine power for a DD15 engine at 1,600 rpm and 60% load is around 6.5% for both water and ethanol with the recuperation adding a further 0.5%. (Typical net power/engine power ratios are reduced at lower speeds, falling to around 5% at 1,000 rpm.)

Research in Europe is not pursuing either the Water BC or R245 approaches. Data for using the bottoming (Rankine) cycle with ethanol as the working fluid indicates fuel consumption reductions of 3 – 5% for exhaust heat only to exhaust heat + EGR recovery systems[24]. This is comparable to the water BC reduction in fuel consumption quoted in SWRI Report #1.

It is not anticipated that for the vehicle segments of interest either thermoelectric or fuel reforming will occur in any significant percentage of new vehicles by 2030 and would not give a potential fuel consumption reduction potential greater than a bottoming cycle.

However, a variety of thermal management technologies are likely to be fitted to new models by 2030, and are anticipated to provide 2.5% - 5% reduction in fuel consumption. These include some/all of:

- Lubricant thermal management;
- Coolant thermal management;
- Engine encapsulation;

[23] For example, such as that specified as “Technology 11” in Table 3.15 of the SWRI Report 1 (Reinhart T.E. (2015)

[24] Value from Ricardo thermal management engineering expert

- Advanced materials, including the use of ceramics within engines, principally as coatings on, for example:
    - Piston crowns;
    - Top section of cylinder liner;
    - Intake/exhaust valves;
    - Exhaust port liner.

As noted earlier, care needs to be taken not to double count these as "FMEP reductions" also.

In the next chapter on cost-effectiveness, waste heat recovery systems are only considered explicitly for the long haul cycle. It is assumed that the bottoming cycle, alongside other thermal management technologies, gives an overall fuel consumption reduction of 4.5% for tractor-trailer combinations. For the other vehicle segments, there is an amalgamated "FMEP reduction" item that would include thermal management technologies within the 2% overall fuel consumption reduction potential.

Engine encapsulation, which is being used in some passenger cars and is of benefit for vehicles with a stop-start duty cycle, is only considered for panel vans. This is assumed to have an overall fuel consumption reduction potential of 1.5%.

Other thermal management techniques are to manage the temperature of the lubricating oil or water coolant. This can be by using variable displacement oil pumps or active bypass oil coolers. Standard oil pumps are specified to provide the required oil flow at low engine speeds, and are therefore oversized for higher engine speeds. Variable displacement pumps optimise the oil flow for different engine speeds. Coolant thermal management includes speeding up engine warm-up (of little benefit to truck engines) and maintaining the optimal engine temperature when fully warm. Ricardo engine experts indicate that these techniques together have the potential to reduce fuel consumption by several percent, being more beneficial for larger engines undertaking long haul cycles.

A summary of the fuel consumption reduction potential from waste heat recovery and thermal management technologies is given in Table 4.11. The conclusions regarding the technology potentials in Europe for the three vehicle segments are given in the lower half of the table.

Table 4.11: Fuel consumption reduction potential in US and Europe generated by improvements in thermal management technologies

Factor	Panel van for urban delivery cycle	Rigid box-truck for regional delivery	Tractor trailer combination for long haul
US research			
Water BC (Technology #19)	N/A	N/A	4.1%
Source in Ref			Table 3.15 for the steady 55 mph
Other thermal management technologies (not included in FMEP reduction)	No data given in SWRI Report #1	No data given in SWRI Report #1	No data given in SWRI Report #1
European technology potential			
By 2030 from 2015 baseline for waste heat recovery	N/A	N/A	4.5% (see footnote 24)
For other thermal management technologies (not included in FMEP reduction) in 2030 from 2015 baseline	1.5% for engine encapsulation 0.5% for other technologies	0% for engine encapsulation 1% for other technologies	0% for engine encapsulation 2% for other technologies

4.3.2 Transmission and driveline technologies

Overview of technology and why it has the potential to reduce CO_2 emissions

The transmission of power from the engine to the tyres and wheels involves changing the rotational speed from the engine, including enabling the engine to idle when the vehicle is stationary. It is noted that the overall efficiency depends on a range of components, including the gearbox, clutch and the rear axle. Further, the deep integration of the engine and transmission to optimise vehicle gearing to engine performance, and enhanced communications between the engine ECU and the transmission controller to optimize operation, provides potential for reductions in fuel consumption. For example, in Europe the baseline transmission of a rigid box-truck is a 6-speed manual transmission. Replacing a 6 speed manual transmission with an 8-speed AMT with a closer gear-ratio spread, would enable engine downspeeding, and keeping the engine more at is most efficient speeds. Replacing with an 8-speed MT would, it is generally viewed, decrease driveability, and even with driver training would not generate the same reduction in fuel consumption.

The principal current and possible future transmission technologies can be summarised as:

- Manual transmissions (MT);
- Automatic transmissions (AT);
- Automated manual transmissions (AMT);
- Dual clutch transmissions (DCT);
- Continuously variable transmissions (CVT).

There are a few DCT used in European commercial vehicles (by Volvo and Fuso) but currently these are a small fraction of the whole. The Ricardo experts consulted are of the opinion that there would be no significant potential improvements to be gained by adopting this technology into European commercial trucks. DCT are more expensive than AMT, heavier, and, in the view of the experts, of little benefit to vehicle operators providing few savings but increased maintenance complexity. Therefore, according to Ricardo's analysis there does not appear to be a strong cost-benefit driver. However, it is noted that others[25] have reported benefits for DCTs in the medium-duty space. The non-cost issue of driver comfort, favouring DCT over AMT in passenger cars, is much less of an issue in the slower accelerating trucks. In the EPA RIA, the Phase 2 technology inputs for tractors gives the same benefit for AMT and DCT (Table 2-30 of EPA, 2016). There are not tabulated data for rigid box-trucks or vans. Consequently, in this analysis we do not consider DCT separately but assume the widespread adoption of AMT, replacing MT in Europe, will include a small contribution from trucks fitted with DCT. No potential savings were identified for CVT in the US Phase 2 rule, therefore no savings potentials have been applied to the EU fleet either.

Note: there are potentially also possible benefits to be achieved from the closer integration of the engine and the gearbox, however these benefits are difficult to quantify are not considered further in this report.

Vehicle segments and usage patterns where the technology has largest impact

In terms of engine speed and torque, there is little change in the transmission loss contribution to fuel consumption with engine speed, but the frictional transmission losses become a smaller fraction of the overall torque with increasing torque. One example gives losses reducing from 2.5% to 1.7% with a five-fold increase in torque.

More pertinent is the drive cycle, through the number of gear changes expected per km; this increases from Long haul delivery to Regional Delivery, with Urban delivery having the greatest number of changes.

Qualitative description of use in baseline vehicles and prospects for future incorporation

For the panel vans and rigid box-trucks, the baseline vehicle transmissions are 5-speed AT for the US and 6 – 9 speed MT for Europe. The anticipated dominant transmission of the future is AMT. In Europe current long haul tractor units have 9 – 12 speed AMT, whilst the EPA baseline vehicle described in the EPA and NHTSA RIA (EPA & NHTSA, 2015) has a 10-speed MT transmission. In the future it is anticipated AMT will dominate but the number of gears will increase.

[25] From discussions with ICCT

Quantitative estimates of change in CO_2 per vehicle for the three vehicle segments considered

In terms of transmitted torque efficiency values typically found are:

- Automatic transmissions are the least efficient in terms of torque transmission efficiency because of higher fluid energy losses. Changing to an AMT can improve efficiency by 20% - 30% relative to a fluid coupling, but improvements are significantly smaller for modern gearboxes where the gears become "locked" soon after a gear change[26]. If the average overall efficiency of an MT is 98% the increase transmission loses alone would produce an increase in fuel consumption by up to 0.6%.
- Manual transmissions have comparable torque transmission efficiency to an AMT, but the driver controls the selection of the gear. Studies have indicated that despite the similar torque transmission efficiencies, changing from manual transmissions to an AMT leads to a 5 – 7% **reduction** in fuel consumption due to the AMT's consistency of operation[27]. (This factor will be driver and driving style dependant over the same route.)

In addition to the types of transmissions, there is also the complicating factor of the number of gears within the gearbox. This affects the average engine speed, and is linked to strategies for down-speeding where optimisation requires different gear ratios and intervals.

The data below for the panel van and rigid box-truck are taken from Table 2-66 of the EPA RIA, respectively based on a combination of increased number of gears and an advanced shift strategy. For the US tractor-trailer combination the improvement in fuel consumption predicted for the gearbox due to gearbox improvements are 2.0%, (see Table 2-30 from the EPA RIA). However, co-benefits from the deep engine-transmission integration also arise from the downspeeding B option (see Table 3.15 SWRI Report #1, and Transmission Efficiency Improvements in EPA RIA Table 2-30) where at a steady 55 mph around a 1.0% improvement in fuel consumption is predicted (the mean between 50% & 100% load). These two figures are combined to give the tabulated value of 3.0%, in Table 4.12.

Table 4.12: Fuel consumption reduction potential in US and Europe generated by improvements in transmission and driveline technologies

Vehicle segment	Panel van	Rigid box-truck	Tractor-trailer combination
US			
2015 baseline	5-speed AT	5-speed AT	10-speed MT
2030 potential	8-speed AT	6-speed AMT	18-speed AMT
US FC reduction potential by 2030 from improved transmission (see text above)	5.9%	4.7%	3.0%
Europe			
2015 baseline transmission technology	6-9 speed MT	6-9 speed MT	10-speed AMT
2030 potential transmission technology	9-speed AMT	9-speed AMT	18-speed AMT
European FC reduction potential by 2030 from improved transmission	7.0%	5.0%	1.67%

The potential improvements in the table above are those assumed in the cost-effectiveness analysis. It is acknowledged that some lighter HDV, i.e. in the panel van segment, do use DCT, e.g. the Fuso Duonic system, and that Eaton has recently (2015) launched the "Procision 7" DCT for medium duty vehicles. However, the opinion of Ricardo's technology experts is that for the European panel van and rigid box-truck segments there will be little to no benefit for DCT in European vehicles on average, and

[26] Information from Ricardo Transmission experts.
[27] 5 – 7% improvement was a figure provided by Ricardo transmission experts

the principal improvement will be from moving away from MT to, predominantly, AMT, and this is what is assumed in the cost-effectiveness analysis.

4.3.3 Hybridisation

Overview of technology and why it has the potential to reduce CO_2 emissions

Hybrid vehicles have more than one source of power. Most commonly this is a combination of an internal combustion engine and one or more electrical machines. (Alternatives to the electric machines are flywheels and hydraulic energy storage.) The principles by which they improve the fuel economy of the vehicle are by:

- Turning off the engine when it is not required;
- Harvest kinetic energy lost on braking (rather than it being dissipated as heat in the brakes);
- Downsizing the fossil fuel burning engine through load averaging.

A number of hybrid and fully electric "solutions" have been proposed and demonstrated, each appealing to different applications and sectors, and having a range of timeframes when they are expected to be mature. These include:

- Start-stop;
- Mild hybrid and full hybrid*;
- Electric vehicle;
- Fuel cell vehicle;
- Energy storage in a battery, flywheel or hydraulic system.

* The difference between mild and full hybrids is that for the former less than 20% of the total power sent to the wheels is produced by the electric machine(s) whereas for the latter the proportion is more than 20%.

Vehicle segments and usage patterns where the technology has largest impact

The implementation of stop-start technology alone in heavy duty vehicles is complex requiring high torque and durability requirements. This may mean that it is preferable to implement a mild or full hybrid concept. The EPA RIA considers stop start with enhancements, which include control systems and additional battery capacity. Consultation with Ricardo hybrid technology experts indicated that a theoretical start-stop system may achieve 2 – 5% fuel consumption reduction, although it is very dependent on the duty cycle. For the urban delivery cycle for a panel van, we have interpreted this as a potential fuel consumption reduction of 4.5%.

Hybrid solutions have been developed principally for light-duty vehicles. In Europe this has been driven by the CO_2 regulations, and the need for manufacturers to reduce their fleet CO_2 emissions.

In contrast, only a relatively small fraction of the overall energy requirements are lost during braking for a tractor-trailer combinations undertaking long haul operations. Whilst this could be potentially harvested when the vehicle reduces its speed, the additional complexity is usually judged to outweigh the benefit for European operations. This makes the use of hybridisation currently unattractive for this vehicle segment.

Hybrid vehicles are likely to be most advantageous for stop/start type driving pattern, e.g. urban buses, or smaller freight carrying vehicles that similarly undertake urban delivery type activities, i.e. the panel van segment.

It is notable that developments in the area of fully electric vehicles (including using fuel cells) are currently progressing rapidly – for example, Daimler's development of an electric urban articulated truck whose GVW is 26 tonnes[28], and development of electric and hydrogen fuel cell heavy trucks by Tesla[29] and Nicola Motor Company[30], as well as others. However, it seems likely that these technologies will

[28] https://www.daimler.com/products/trucks/mercedes-benz/urban-etruck.html
[29] https://electrek.co/2016/07/20/tesla-semi-truck-business-cargo/
[30] https://nikolamotor.com/one

only be available to fulfil niche roles in the 2030 time-horizon, so they are not considered in greater detail here.

Qualitative description of use in baseline vehicles and prospects for future incorporation

Currently none of the 2015 baseline vehicles in any of the three vehicle segments in the US or Europe contain any hybrid features.

Looking to the future, the US DOE Super Truck 2 programme is funding four companies to improve their freight efficiency relative to a 2010 baseline vehicle. One of the four companies, Navistar, will have a dual mode/hybrid transmission system.

The EPA RIA does include consideration of hybrid technologies (at different levels) for the vehicle segments it addresses (vocational vehicles and pick-ups and vans). It also gives some fuel consumption reduction estimates. For vocational vehicles (i.e. including the 12 t rigid box-truck these are summarised in Table 2-66 of the EPA RIA, and indicate a technology potential of 4-5% fuel consumption reduction over the “regional composite cycle” for non-integrated mild hybridisation. SWRI Report #2 (which evaluates the effectiveness of packages of those individual technologies, described in Report #1, as well as other related topics) does include some estimates of the impacts of hybridisation. For the US pick-up truck and van segment data are given only for the case of the Dodge RAM Pickup truck. Both belt and crank driven integrated starter/generator (BISG & CISG) within a 50 kW parallel hybrid system are considered.

From a number of unpublished technology potential studies Ricardo experts have concluded that for the long haul (40 t GVW) and regional delivery (12 t GVW) vehicle segments, they anticipate negligible impact of hybridisation by 2025. However, it is appreciated that possibilities exist, and are being considered. For example, using smart alternators to power auxiliaries when a large truck is coasting, thereby enabling the engine to stop rather than coast. It is also recognised that batteries are not the only way of storing harvested energy, with ultra-capacitors also being a possibility. Notwithstanding these research activities, the feedback from the European consultants is that the technology readiness level is too low for these to be included in this study considering realisable potential by 2030.

Quantitative estimates of change in CO_2 per vehicle for the three vehicle segments considered

The EPA RIA indicated that for a multi-purpose vocational vehicle the projected reduction in fuel consumption (not modelled in GEM) over the multi-purpose composite cycle is 14 – 19% (in Table 2.66 of EPA and NHTSA, 2016). It also reports a study by Argonne National Laboratory, considering strong hybrid technology, using a 50 kW starter/generator with a 70 kWh Li-ion battery pack. It quotes a fuel consumption reduction of 18 – 22%.

Some NREL studies comparing the fuel consumption of Class 6 hybrid electric and conventional diesel trucks (both fitted with Cummins ISB 6.7 220 hp diesel engines) found differences as summarised in Table 4.13 below.

Table 4.13: Reductions in fuel consumption generated by the use of hybrid systems on a Class 6 truck over various driving cycles (from NREL study)

Driving cycle	Fuel consumption reduction
Hybrid truck users forum Class 6 cycle (HTUF 6)	25%
New York composite cycle (NY Comp)	31%
CARB heavy heavy-duty diesel truck cycle (HHDDT)	-4% (i.e. increase in consumption)

The average improvement was 17.3%, but there is a wide variation, as seen above. These data are consistent with those reported in the EPA Report #2.

Overall, it is seen that for the delivery vehicle segment considerable improvements in fuel economy can be anticipated if hybridisation were to be implemented.

The potential fuel consumption reduction from full hybridisation is only included for the panel van segment. It is assumed this potential is 28.0% (the average of the two higher savings noted in Table 4.13, which compares with a lower figure of 23-26% for *Integrated Mild Hybrid with Stop-Start* from the EPA RIA Table 2-36 for the ARB transient cycle for vocational vehicles. The actual value, as noted, is very sensitive to driving pattern and is relatively poorly defined. Also, relative to the baseline vehicle with its manual transmission, the change to a full hybrid potential replaces the change to an AMT. Therefore, to prevent double counting, the 7% potential fuel savings for transmission improvements are retained, and an additional 22.58% savings potential for the full hybrid is included (see Table 5.10 and Table 5.10). In addition, a separate incremental cost analysis was generated including stop-start technology (which is only included in this section on hybridisation) only. However, because the project seeks to define the **maximum fuel consumption reduction potential** and full hybrids also include stop-start technology, start-stop is not considered separately within the cost-potential savings analysis. (However, the lower capital cost and yet moderate fuel consumption reduction potential of start-stop technology mean it is a potentially attractive option for the service segment, ahead of the implementation of full hybridisation.)

For HD trucks heavier than the HD pick-up truck and van, the principal information regarding its potential for US Phase 2 is given in the EPA RIA. Table 2-66 of the EPA RIA gives projected vocational transmission improvements over the GEM baseline. Fuel consumption reductions are, as anticipated, very cycle dependent, being zero for steady speeds. For an integrated mild hybrid with stop-start over the regional composite cycle (a GEM cycle for vocational vehicles) the saving is 4 – 5%. This is the saving assumed for the European rigid box-trucks.

Table 4.14 Use of hybrid systems currently, and potentially in 2030 for US and European trucks for the three vehicle segments

Vehicle segment	Panel van	Rigid box-truck	Tractor-trailer
US research			
2015 baseline	No hybrid fitted	No hybrid fitted	No hybrid fitted
2030 potential	Fully integrated hybrid with start-stop	Integrated mild hybrid with stop-start	N/A
US FC reduction potential by 2030 from hybridisation	28%	4.5% (From EPA RIA for vocational vehicle – regional)	N/A
European technology potential			
2015 baseline	No hybrid fitted	No hybrid fitted	No hybrid fitted
2030 potential	Fully integrated hybrid with start-stop	Enhanced stop-start system	
European FC reduction potential by 2030 from hybridisation	22.58% together with 7% from change in transmission	4.5%	N/A

4.3.4 Aerodynamics

Overview of technology and why it has the potential to reduce CO_2 emissions

The power required at the wheels of a vehicle to propel it along a flat road is used principally to overcome rolling and aerodynamic resistance and braking and inertia losses. The drag equation gives the drag force, F_D, as:

$$F_D = \frac{1}{2} \rho V^2 C_D A$$

Where

- F_D = the drag force
- ρ = the fluid (air) density (a parameter that cannot be changed for a vehicle)
- V = the speed of the vehicle relative to the air
- C_D = a dimensionless coefficient, the drag coefficient
- A is the frontal area of the vehicle.

Changes in vehicle design impact C_D and A, whereas the usage pattern determines the vehicle's speed profile. Aerodynamic treatments are designed to reduce the drag coefficient, and include a range of mainly passive measures including aerodynamic farings, side skirts, aerodynamic body/trailer shapes, tailgates and similar features. A number of active aerodynamic features have also been developed, and have seen implementation in light-duty vehicles (e.g. active grill shutters), whilst some models have these, they are not yet commonly applied in the heavy duty vehicle market.

Vehicle segments and usage patterns where the technology has largest impact

Fuel consumption, expressed in terms of volume of fuel used per 100 km, is directly proportional to the drag force. (However, the power use, which is proportional to fuel consumption rate, scales with the cube of speed. But when normalised to speed, to express fuel consumption as volume of fuel used per 100 km this scales with speed squared.) The drag equation indicates that the drag force scales with the square of the vehicle's speed. The average speeds for the three vehicle segments, for representative European and US driving cycles are tabulated below (in Table 4.15), together with the ratio of their squares relative to the VECTO urban delivery cycle (in Table 4.16).

Table 4.15: Key characteristics of representative European and US driving cycles

	European			US		
Segment	Average speed (km/hr)	Average speed squared $(km/h)^2$	VECTO Cycle	Average speed (km/hr)	Average speed squared $(km/h)^2$	Cycle
Panel van	29.8	1444.5	Urban delivery	31.35	1543.8	FTP-City (for light-duty)
Rigid box-truck	39.8	4108.7	Regional delivery	24.7	1074.0	CARB
Tractor-trailer combination	73.6	5934.1	Long haul	88.0	7834.7	Steady speed 55 mph
				87.4	8769.4	NESCCAF

The data indicate that for the three vehicle segments being considered the aerodynamic drag from the long haul cycle is 4 – 6 times greater than that for the slower speed cycles, and that the drag from the higher average speed US long haul cycles are 32-48% higher than the equivalent European long haul cycle.

Table 4.16: Ratio of averaged speed squared relative to the VECTO urban delivery cycle

	European		US	
Segment	Relative average speed squared	VECTO Cycle	Relative average speed squared	Cycle
Panel van	1.00	Urban delivery	1.07	FTP-City (for light-duty)
Rigid box-truck	2.84	Regional delivery	2.15 §	CARB & SS 55 mph
Tractor-trailer combination	4.11	Long haul	6.07	NESCCAF

Notes: § Calculated from 70% of CARB cycle + 30% (by time) of steady speed 55 mph

Qualitative description of use in baseline vehicles and prospects for future incorporation

There is a general challenge in obtaining quantitative data on drag factors and forces because, unlike for light-duty vehicles where drag coefficients are published for specific models, neither drag coefficients nor the product of the coefficient and frontal area are generally published for heavy duty vehicles. For tractor – trailer combinations there is the added complication that the drag factor changes for each different trailer type attached.

General qualitative feedback from a number of consultations has indicated some systematic trends and differences between the two "typical" aerodynamic properties of tractor trailer combinations in the two geographic areas:

1. US trucks are larger;
2. European trucks have a more advanced aerodynamic starting point that in the US.

As a result, it might be expected that European long haul trucks have reduced baseline drag profile than their US counterparts. However, in Table 2-25 of the EPA RIA, the drag area given for the baseline US tractor-trailer combination is only slightly higher (1.3% higher) than that for the European baseline vehicle. US trucks also tend to travel at higher speed, amplifying the importance of drag reduction.

Further examination of these generalisations revealed:

- The larger size of US trucks is principally concerned with length and weight, not necessarily frontal area.
- Another difference between the two markets is that Europe tends to use the cab-over engine configuration. This is principally caused by regulatory limits on vehicle length and the cab over engine configuration gives more space for payload. However, it can lead to poorer aerodynamic drag coefficients than for the US equivalents. In a 2007 study[31] a reduction in C_D (ΔC_D) of 0.05 was quoted from comparison of a Volvo cab-over and Volvo US conventional design. However, in the past decade the cab-over design has become more rounded, and less bluff body shaped. Therefore, this ΔC_D is now anticipated to be less than 0.05.
- While the restrictions on trailer length lead to the generalisation that US trailers have a better clearly visible aerodynamic shape than their European counterparts, it is believed subtle rounding of the rear of European trailers, and the notable filling of the gap between the tractor and trailer units in Europe, relative to the US, support a better baseline aerodynamic profile for European long haul tractor-trailer combinations.
- The important comparator is the vehicle's drag area. For the tractor-trailer baseline vehicles this is found to be similar, with the US value being 101.9% of the European values, see Table 3.4.
- In Europe trucks are limited to a maximum speed of 90 kph and the analysis of the "typical" drive cycles does support lower average European long haul speeds.

Box 1: Background on trailer length

In Europe max length of tractor + trailer is 15.50 m, or 16.50 m if it has a tighter turning circle – see ITF Vehicle dimensions.PDF, from:
http://www.internationaltransportforum.org/IntOrg/road/pdf/dimensions.pdf

Typical European trailer dimensions are 13.6-13.7 metres, which is shorter than US (see below).

In US truck lengths vary between states. For "semitrailer", i.e. equivalent to a European trailer, minimum length is 48 feet (14.63 m) (with the most common being 53 feet / 16.15 m), file FHWA Truck size_regs_final_rpt.PDF, from:
http://ops.fhwa.dot.gov/FREIGHT/publications/size_regs_final_rpt/size_regs_final_rpt.pdf

Quantitative estimates of change in CO_2 per vehicle for the three vehicle segments considered

The EPA Report #1 reports that improvements in aerodynamics give some of the largest reductions in fuel consumption of all the potential technologies. The data from EPA Report #1 is summarised in Table 4.17. Translation into the European context is challenging, with the scaling of the US modelled reduction potential by relative average squared speed predicting savings for the tractor-trailer combination of around 6.3%. (The influence of different test cycle speeds on going from the US driving

[31] Hjelm, L. and Bergqvist, B. (2007) "European truck aerodynamics - a comparison between conventional and cab-over-engine truck aerodynamics and a look into future trends and possibilities" The Aerodynamics of Heavy Vehicles II: Trucks, Buses and Trains.

cycles to the equivalent European cycles, estimated from the ratio of the average squared speed, is given as a multiplying factor in the third row of the US data of Table 4.17.)

However, because aerodynamic drag is such an important single factor for this key vehicle segment, further assessments were undertaken. The VECTO model (full version and vehicle details are given in Appendix 3) was run using the declaration mode for the same drag area changes that were modelled by SWRI. The data are shown in the lower portion of Table 4.17. For the tractor-trailer combination a 25% reduction in aerodynamic drag over the long haul driving cycle gave a 7.84% reduction in fuel consumption relative to the baseline configuration. This is a significantly larger saving than that predicted by scaling the US data for the slower speed of the European long haul cycle (6.3% reduction). But both these figures are less of a reduction than that reported for the tear-drop aerodynamic trailer case studies for curtainsider trailers (11.2% ± 5.9% fuel consumption reduction). From the VECTO model simulation it was found that a 28.7% reduction in aerodynamic drag was required to generate a 9.0% reduction in fuel consumption relative to the baseline configuration.

Equivalent VECTO simulations for the 12 t rigid box-truck over the regional delivery cycle gave a reduction in fuel consumption, relative to the baseline configuration, of 6.3% for a 15% reduction in aerodynamic drag. These data are also included in the lower portion of Table 4.17.

A complementary analysis reported by Don-Bur (a maker of aerodynamic trailers) reports actual (verified) savings from case studies of fleets, principally undertaking long haul activities in the UK. It reports average fuel consumption reductions of 11.3% ± 4.9% for panelled tear-drop trailers (24 trials) and 11.2% ± 5.9% for curtain-sider tear-drop trailers (8 trials). However, in both cases the spread of the data was large (as indicated by the variability of the data shown in Figure 4.3).

Figure 4.3: Fuel savings reported from Don-Bur trailers

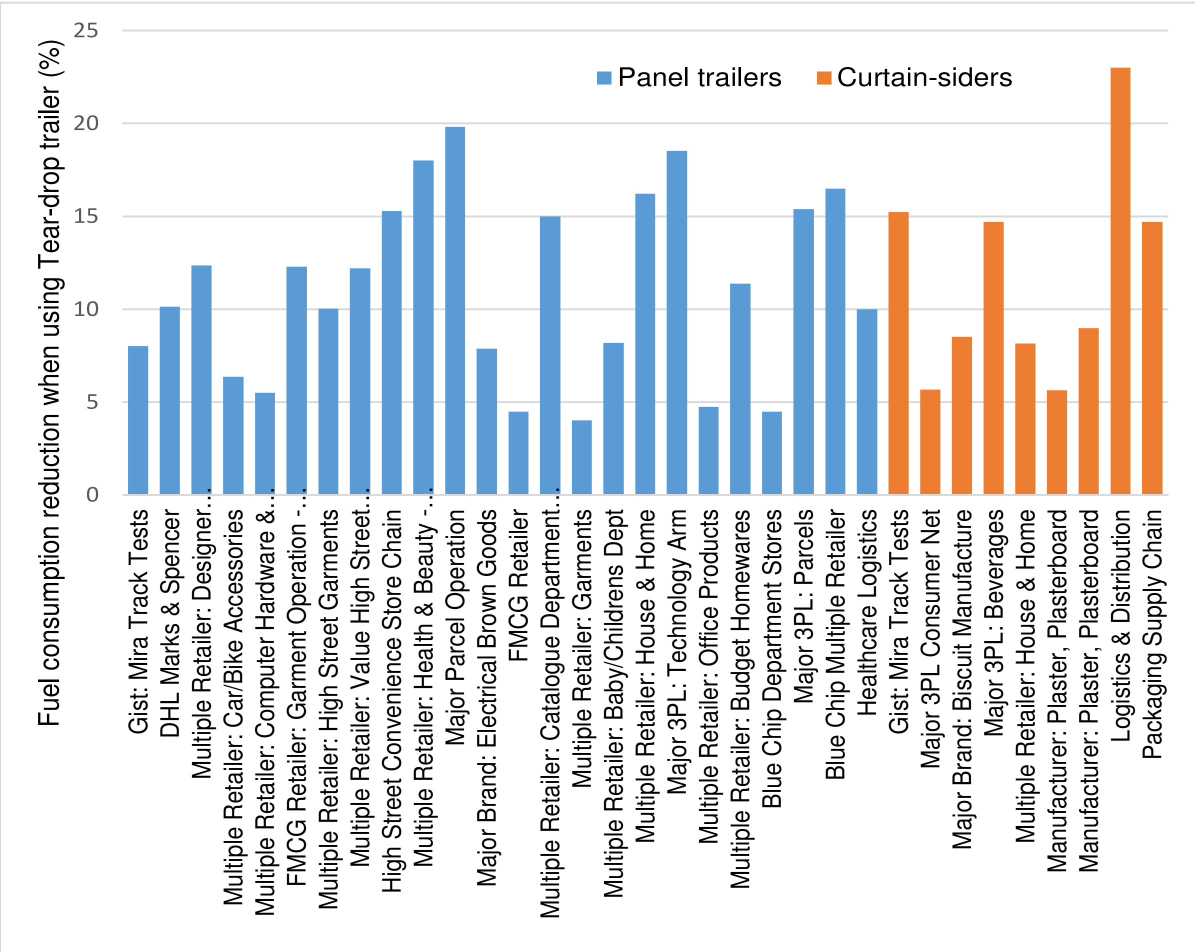


Table 4.17: Reductions in fuel consumption generated by changes in aerodynamic treatments from US EPA Report #1 model, VECTO modelling and case studies, and overall technology potential

Vehicle segment	Panel van	Rigid box-truck	Tractor-trailer
US			
Drag reduction modelled by SWRI	Reduction in C_D of 10%	Reduction in C_D of 15%	Reduction in C_D of 25%
Reduction in fuel consumption	0.60%	3.11%	9.25%
Speed influence Europe/US	0.935	1.32	0.677
Europe			
Drag reduction modelled in VECTO	N/A	Reduction in C_D of 15%	Reduction in C_D of 25% *
Reduction in fuel consumption resulting from C_D reduction above	N/A	6.3%	7.84%
Technology potential assumed for improved aerodynamics	**0.60%**	**6.3%**	**10.6%**

Note: C_D is estimated to reduce further to ~30% total reduction when also an aerodynamic trailer is added.

Therefore, although the translation of the US studies suggests a more modest fuel consumption reduction potential (6.26% from Table 4.17) the on-the road evidence indicates close to twice this reduction can be achieved. In conclusion, based on the evidence given in Table 4.17 it is assumed that improved aerodynamic trailers (alone) can reduce the fuel consumption for tractor-trailer combinations by 9.0% relative to an average tractor-trailer combination. (From VECTO simulations this 9.0% fuel consumption reduction is modelled by a 28.7% reduction in drag coefficient (C_D). It is also further assumed that the improvements reported do not represent the ultimate potential savings from aerodynamics. From Table 4.17 it is seen how VECTO calculates a 25% reduction in C_D leads to a 7.84% reduction in fuel consumption. It is assumed that a further 5% reduction in C_D is possible (i.e. to for a total of 33.7% reduction in C_D) for vehicles using the current aerodynamic trailers by 2030. This leads to an additional 1.6% reduction in fuel consumption, such that an overall savings potential of 10.6%, relative to a baseline tractor-trailer combination.

For rigid box-trucks it is assumed relative to 2015 baseline vehicles, a fuel consumption reduction potential of 6.3% over the regional delivery cycle exists by 2030 (as modelled in VECTO and indicated in Table 4.17). For panel vans a fuel consumption reduction potential of 0.6% over the urban delivery cycle exists by 2030 (the figure modelled by SWRI).

4.3.5 Light-weighting

Overview of technology and why it has the potential to reduce CO_2 emissions

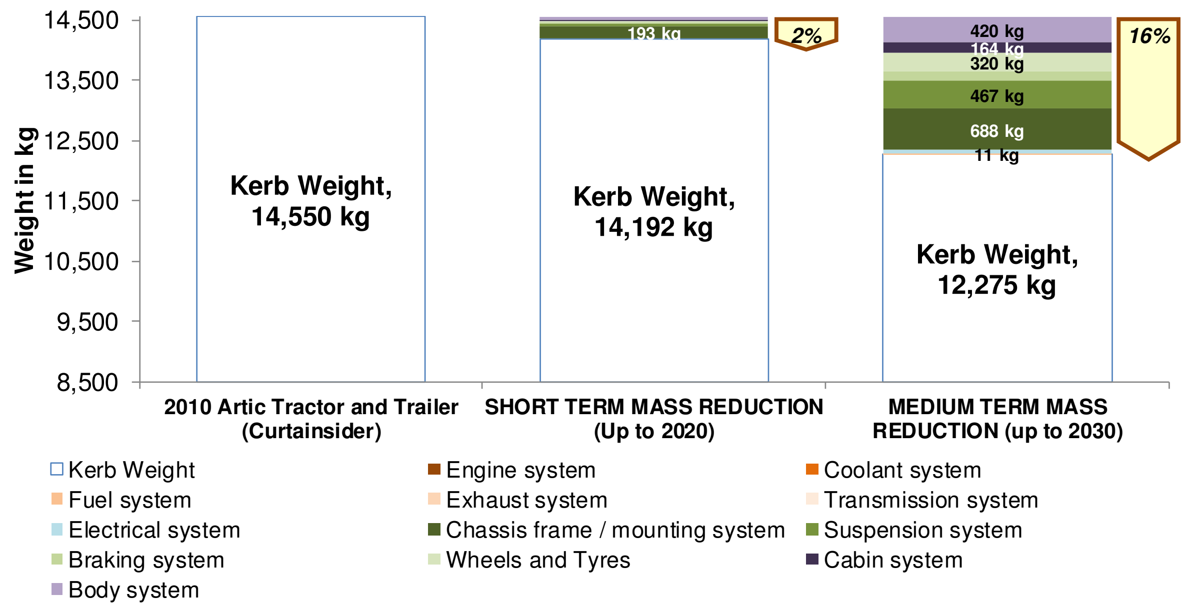
Reducing vehicle mass can reduce CO_2 emissions by two distinct routes:

- It reduces the tractive force required to accelerate the same payload (volume limited operation) and the rolling resistance when travelling at constant speed; or
- It enables more payload to be carried within the vehicle's GVW limit (weight limited operation), thereby reducing the number of vehicle – km that need to be driven to move the same quantity of freight t-km.

It should be noted that the single term "light-weighting" includes a wide variety of technologies. Ricardo Energy & Environment undertook a detailed study of HDV light-weighting for DG CLIMA in 2015 (Hill et al, 2015). This considered around 40 light-weighting measures, each with its own light-weighting potential and costs. The following analysis draws heavily from that study.

For a tractor – trailer combination, the following scenarios might occur, summarised in Figure 4.4 and Table 4.18 which is taken directly from Figure 2.8 of Hill et al., 2015.

Figure 4.4: Estimated mass reduction potential by system for an articulated truck



This figure above describes anticipated contributions from 12 different light-weighting areas. Table 4.18 below also provides the corresponding numerical values of the data shown in Figure 4.4.

Table 4.18: Estimated mass reduction potential by system for an articulated truck

Area for light-weighting	Mass reductions (kg)			% of savings
	Articulated Tractor	Artic Trailer (Curtain-sider)	Whole vehicle (40t GVW)	
Engine system	0.0	0	0.0	0.00%
Coolant system	0.0	0	0.0	0.00%
Fuel system	9.6	0	9.6	0.42%
Exhaust system	0.0	0	0.0	0.00%
Transmission system	11.2	0	11.2	0.49%
Electrical system	49.9	1.05	51.0	2.24%
Chassis frame / mounting system	191.8	496	687.8	30.23%
Suspension system	227.9	239.5	467.4	20.55%
Braking system	63.4	81.1	144.5	6.35%
Wheels and Tyres	158.5	161.46	320.0	14.06%
Cabin system	163.5	0	163.5	7.19%
Body system	0.0	420	420.0	18.46%
2030 kerb weight	**6,624.3**	**5,650.49**	**12,274.8**	
Sum of mass savings	**875.8**	**1,399.11**	**2,274.9**	**100.00%**

In practice, yet further reductions might be possible, but at what is deemed to be unacceptable cost.

It is emphasised that the data in Table 4.18 are from the EC study reported in Hill et al, 2015, and are for slightly different baseline vehicles relative to that described in Tables 3.2 to 3.5. Therefore the actual savings potential used in this study, in kg, taken by applying the percentage changes possible by 2030 as reported in Hill et al., 2015, to the kerb weight baseline vehicles described in Tables 3.2 to 3.5.

In addition, rather than focus on the areas where the light-weighting might occur, as in Hill et al., 2015, in this study, where light-weighting is one of twelve technology categories, it would be disproportionate to include the level of detail provided in the light-weighting study. Key data are the maximum savings potential by 2030, and the cost of achieving this. The individual light-weighting options are aggregated according to the cost per kg saved, reported in the light-weighting study. Cumulatively they provide an overall fuel consumption reduction potential, and individually they position groups of light-weighting measures alongside the other eight technology categories.

In terms of a percentage change in vehicle kerb weight, the Hill et al., 2015, study predicts a maximum potential 2.5% mass reduction by 2020 and a 15.6% mass reduction by 2030 for the European articulated tractor and curtain-sided trailer. It is also noted that the vast majority of the light-weighting occurs due to material substitution, replacing steel components with aluminium based components.

Similar analysis for panel vans and rigid box-trucks give weight reduction potentials as indicated below for all three vehicle segments (in Table 4.19). It is noted that the truncating of weight-reducing options at particular costs per kg saved, does mean that the "weight reduction potential" described in this study is slightly less than the extended series summarised in Figure 4.4 and Table 4.18. However, addition of further light-weighting potential would generate small potential CO_2 reductions, but at high costs.

Table 4.19: Reductions in vehicle weight resulting from light-weighting for European vehicles and driving patterns

Vehicle segment	Weight reduction potential by 2020	Weight reduction potential by 2030
Panel van	3.2%	11.7%
Rigid box-truck	4.9%	16.6%
Tractor-trailer combination	2.5%	15.6%

Vehicle segments and usage patterns where the technology has largest impact

Reductions in the vehicle's inertia reduces the energy required to accelerate the vehicle, but leads to little change for steady speed driving (the rolling resistance, expressed per tonne of vehicle weight, would be slightly reduced). Consequently, the larger savings occur for the more transient driving, rather than steady speed driving. Furthermore, at higher speed, steady state driving, more energy is required to overcome the aerodynamic resistance, which is independent of vehicle mass. Therefore, proportionately the reduction in rolling resistance from light-weighting leads to even less reduction with increasing speed. However, for weight limited operations, light-weighting can improve freight carrying efficiency and does result in proportional fuel consumption benefits regardless of driving cycle characteristics.

These effects were illustrated by a VECTO simulation of a 12 tonne rigid box-truck over the three freight cycles (using the VECTO declaration mode parameters and vehicle at its reference weight). The reductions in fuel consumptions from a 1,400 kg lightweighting (18% reduction to kerb weight) were 7.1% reduction for the urban delivery cycle, 4.8% for the regional delivery cycle and 2.7% for the long haul cycle. These reductions are based on the identified potential from Hill et al, (2015).

Qualitative description of use in baseline vehicles and prospects for future incorporation

The whole analysis is founded on the evidence supported assumption that fuel consumption reduction is both proportional to the amount of light-weighting, and that it is independent of where the weight is lost from. The relationships used (fuel consumption reduction per kg, or tonne, of light-weighting) were those modelled using VECTO for the rigid-box truck and the tractor trailer combination. This approach is consistent with that used for determining the fuel consumption reduction from improvements in aerodynamics, or reductions in rolling resistance.

In the medium term material substitution appears to be the best option for light-weighting. Details of the sum of weight reductions potentials are given in Table 4.19. This generates the potential savings by 2030 given in Table 4.20.

Generally, it is considered that light-weighting for the panel van and rigid box-truck segments would lead to lighter vehicles on the roads, because for these segments vehicles tend to be operated in the "volume limited" regime. In contrast, for tractor-trailer combinations, these vehicles can be operated in the "weight limited" regime, and each unit of light-weighting could lead to an increase in payload, and an overall reduction in vehicle km driven.

Quantitative estimates of change in CO_2 per vehicle for the three vehicle segments considered

The data in SWRI Report #1 gives:

- Vehicles' empty weights and gross vehicle weights;
- The change in CO_2 emissions for various driving cycles for stated weight reductions (effects for a given cycle are proportional, such that doubling the light-weighting doubles the CO_2 emissions reduction).

These data, which were then incorporated into the EPA RIA, are given in the upper half of Table 4.20, and were derived form a more detailed underlying assessment of weight reduction opportunities for individual components (e.g. in a similar way as was implemented in the study by Hill et al, 2015).

The potential weight loss from the Ricardo studies (Hill et al, 2015) similarly gives potential weight reductions and the associated fuel consumption reductions for the European context from an independent analysis. (An important aspect of the conversion between the weight reduction possible and the fuel savings generated came from modelling using a 2014, very early, version of VECTO. Changes in the VECTO model, and its driving cycles, vehicle definitions, etc., have changed the modelled efficacy of weight reductions.) These are shown in the lower half of Table 4.20.

The SWRI report gave data for light-weighting for the heavy-duty pick-up truck (Table 3.27 of reference Rheinhart, 2016). For a 7.3% lightweighting of the pickup (a reduction in weight of 500 lbs), around a 1.9% reduction in fuel consumption was found over the FTP-City and FTP-Highway driving cycles. For the panel van the Ricardo study indicated the potential light-weighting was more than double this (16.7%) and its assessment of the associated reduction in fuel consumption was 3.73% (close to double that from the US study for double the light-weighting).

Table 4.20: Reductions in fuel consumption generated by changes in potential light-weighting translated to European vehicles and driving patterns

Vehicle segment	Panel van	Rigid box-truck	Tractor-trailer combination
US		From EPA Report #1	
Degree of lightweighting (lb, % relative to baseline kerb weight)	227 kg, (500 lb) 7.3%	455 kg, (1,000 lb) 7.2%	2,000 kg (4,400 lb) 14.2%
FC reduction potential for this degree of lightweighting (Drive cycle for reduction)	1.9% FTP-City & FTP-Highway	2.0% CARB & 55 mph SS	2.2% (3.6%) NESCCAF, (WHTC)
Europe			
Degree of lightweighting kg, Note 1 % relative to baseline vehicle kerb weight (Note 2)	339 kg 11.7%	1,285 kg 16.6%	2,280 kg 15.6%
VECTO simulation FC reduction modelled for the above weight reduction	Note 3	4.4%	3.38%
FC reduction potential (From Hill et al, 2015)	3.48% (volume limited) Urban delivery	3.73% (volume limited) Regional delivery	3.08% (volume limited) Long haul
FC reduction potential assumed in this study for this degree of lightweighting	**4.7% (volume limited) See Note 3**	**4.4% (volume limited)**	**3.38% (volume limited) 8.23% (weight limited)**

Notes to Table 4.20:

Note 1: The degree of lightweighting is the percentage reductions specified in the lightweighting study (Hill et al, 2015) **applied to the baseline vehicles**, i.e. to the kerb weights given in Table 3.2 to Table 3.4.

Note 2: The percentage reductions in the baseline vehicles' kerb weight are those specified in the lightweighting study (Hill et al, 2015).

Note 3: The VECTO model does not include a panel van, and so no direct comparison can be made. However, the change in fuel consumption for the rigid box-truck from a 16.6% weight reduction over the urban delivery cycle was 7.1% (it being 4.4% for the regional delivery cycle) at the reference weight. For the empty rigid box-truck the fuel consumptions are lower, and the reduction over the urban delivery cycle increases to 7.4%. On this basis for the 11.7% lightweighting potential estimated by Hill et al, 2015, the fuel consumption reduction potential is taken as 4.7%.

Table 3.4 indicates the kerb weight of European baseline vehicles is 14.6 tonnes, which enables the vehicle to carry a maximum payload of 25.4 tonnes (for 40.0 t GVW vehicle). A reduction in vehicle kerb weight of 2,280 kg (15.6%) enables a further 2.28 t of payload to be carried. This is an increase, relative to the baseline payload, of 8.98%. If this was used, such that the vehicle continued to operate at its GVW, for a fleet the additional payload capacity would reduce the number of journeys by 8.24%, generating this savings potential for weight limited operation.

4.3.6 Tyres and wheels

Overview of technology and why it has the potential to reduce CO_2 emissions

The power required at the wheels of a vehicle to propel it along a flat road at a constant speed is used principally to overcome rolling and aerodynamic resistance. The issue of aerodynamic resistance was discussed in Section 4.3.4. The rolling resistance equation gives the rolling resistance force, F_{RR}, as

$$F_{RR} = C_{RR}\, N$$

Where

- F_{RR} = the rolling resistance force
- C_{RR} = the dimensionless rolling resistance coefficient
- N = the force perpendicular to the surface on which the vehicle is rolling.

C_{RR} is usually expressed in units of kg force per tonne of vehicle weight. Its influence on fuel consumption, expressed in terms of volume of fuel used per 100 km, is directly proportional to the rolling resistance and is independent of the vehicle's speed. (However, the energy use, which is proportional to fuel consumption rate, scales with the vehicle's speed. But when normalised to speed, to express fuel consumption as volume of fuel used per 100 km, this leads to the speed independence of fuel used per 100 km and speed. This, in turn, makes losses from tyres and wheels virtually drive cycle independent, very different from the situation with aerodynamics.) Rolling resistance is not a consequence of a single factor, but several including:

- The physical properties of the tyre, which determines the tyres rolling resistance under standard test conditions, and for new tyres is displayed according to the tyre labelling regulations Reg 1222/2009;
- The inflation pressure of the tyre;
- The temperature during testing as tyre flexibility is temperature dependent;
- The characteristics of the surface the tyre is in contact with.

The technologies that can lower rolling resistance are, principally:

- Low rolling resistance tyres (including single wide tyres);
- Tyre pressure monitoring systems;
- Automatic tyre inflation systems.

Low rolling resistance tyres use different tyre materials, tread patterns, or a single wider tyre replacing a pair of tyres to safely carry the same load as the tyre it replaces. Consequently, a truck fitted with low rolling resistance tyres uses less fuel than a comparable vehicle whose tyres have a higher rolling resistance for each mile travelled. However, tyres wear out, and the continued reduction in fuel consumption requires the replacement tyres also to have a low rolling resistance.

Tyre pressure monitoring systems (TPMSs) constantly measure the tyre pressures, **advising** the driver when a tyre is under inflated. It then requires driver intervention, after notification, to rectify. Automatic tyre inflation systems both measure tyre pressures and when an under-inflated tyre is detected, it automatically re-inflates to the correct pressure.

Vehicle segments and usage patterns where the technology has largest impact

The rolling resistance equation indicates that the rolling resistance force is independent of the vehicle's speed, and only dependent on its weight. The average weights for the three vehicle segments, for baseline European and US trucks are tabulated in Table 4.21, using the data from Table 3.2 to Table 3.4.

Table 4.21: Average rolling resistances and vehicle weights for the baseline European and US trucks for the three vehicle segments

Vehicle Segment	European vehicle average	US vehicle average	Ratio of European to US average
	Average tyre rolling resistances		
Panel vans	7.1 kg/t	7.7 kg/t	92%
Rigid box-truck	7.4 kg/t	7.7 kg/t	95%
Tractor-trailer combinations	5.8 kg/t	6.38 kg/t	86%
	Average weights		
Panel vans	4.35 tonnes	5.96 tonnes	73%
Rigid box-truck	10.7 tonnes	11.8 tonnes	108%
Tractor-trailer combinations	33.9 tonnes	32.6 tonnes	101%

Notes to Table 4.21:

The figures in the above table represent an approximate weighted average. For a tractor trailer there are 3 rolling resistances (RR) for, (i) steer tyres (X), (ii) driving tyres (Y), (iii) trailer tyres (Z). If the loads on the axles are A tonnes for the steer axle, B tonnes for the driving axle(s) and C tonnes for the trailer axles, then total resistance is:

$$\text{Total RR} = A.X + B.Y + C.Z$$

And the weighted average resistance is:

$$\text{Total RR} / (A + B + C) \text{ kg/tonne}$$

However, loads for each axle were only identified for a few tractor trailer cases. Analysis of the available information showed that that the arithmetic mean of the three rolling resistances was close to the axle weighted mean. In most cases the arithmetic mean of the rolling resistances has been used, as the error was judged within the uncertainties in knowing the rolling resistances of the tyres.

The ratios of the European to US average weights are given in lower half of Table 4.21. The principal differences in weight arise for panel vans and rigid box-trucks where the European average vehicles are 73% and 108%, respectively, of the equivalent US average vehicle. This leads to a change in the technology potential between the two baseline vehicles.

Qualitative description of use in baseline vehicles and prospects for future incorporation

As for aerodynamics, there is a general challenge in obtaining quantitative data on vehicle rolling resistance because these characteristics are not published and it depends on a number of factors. General qualitative feedback from a number of consultations has indicated few systematic trends and differences between the "typical" rolling resistance properties of trucks in the two geographic areas.

One measure to reduce rolling resistance is the replacing of two tyres with a single wide tyre. Modern tri-axle trailers have each axle fitted with two tyres, rather than four as was the case a decade ago[32]. This leads to both reductions in rolling resistance and some light-weighting, and are the standard tyres assumed for European baseline trailers.

The European tyre labelling directive is also encouraging the uptake of low rolling resistance tyres in Europe. For 385/65 R 22.5 trailer tyres these Class 3 tyres are available with efficiency ratings of Class B ($4.1 < C_{RR} < 5.0$ kg/t) to Class E ($7.1 < C_{RR} < 8.0$ kg/t), found from reviewing the tyre specifications from the principal tyre manufacturers. At present this regulation does not apply to re-treaded tyres an important portion of the replacement tyre market, and these tyres are generally thought to have a higher rolling resistance.

It is generally believed that new trucks are fitted with low rolling resistance. It is assumed that new trailers are fitted with Class C fuel efficiency tyres, and an average rolling resistance of 5.5 kg/t applies. This is the value assumed in the VECTO model declaration mode.

In addition, tyre pressure is also an important parameter, with an under-inflation of 20% being reported to lead to an 18% change in rolling efficiency. Continuous in-use tyre pressure monitoring systems (TPMSs) are being developed and fitted, but currently not generally used[33]. Such systems advise the driver if a tyre is under-inflated. However, it then requires intervention to pump up the tyre to its correct pressure to reduce fuel consumption. It is assumed that modern trailers do not have any automated TPMS fitted. Yet more sophisticated are automatic tyre inflation systems. These, like TPMS, continuously monitor tyre pressure, but automatically inflate to the correct pressure.

Quantitative estimates of change in CO_2 per vehicle for the three vehicle segments considered

Improvements in rolling resistance, like aerodynamics, are one of the more important of the fuel consumption reduction technologies, especially for the tractor-trailer combinations.

It is generally reported that tyre development is continuous, and figures for improvements in C_{RR} range from a 5 – 10 % reduction by 2030, with some experts predicting larger improvements. The principal cause of the improvement is the use of new materials. However, average improvements in tyre rolling resistance are expected to be larger than that from improvements in the tyre properties because of:

- Extension of the European tyre labelling directive to include re-treaded tyres;
- The potential banning of the sale of tyres at the high rolling resistance end of the spectrum, e.g. Energy Efficiency Class F (CRR > 8.1) being the first to be withdrawn;
- The uptake of "intelligent tyres[34]", leading to both improved tyre lifetime and fuel economy;
- Measures taken to reduce vehicle (tyre) noise, including improvements in road surfaces.

Together it is assumed that the expected technology potential between 2015 and 2030 is for a reduction in the rolling resistance coefficients by 15 – 20% relative to their current value. This change in C_{RR} can be modelled in a vehicle simulator to predict the fuel consumption reduction **per truck km driven**.

Much more difficult to estimate are the savings to be obtained from TPMS and ATIS. The challenge arises because these technologies generate no savings for "a correctly maintained" vehicle/trailer. Rather, savings arise when a tyre, or tyres, are under-inflated, and the TPMS or ATIS leads to correction. The savings therefore depend on the fraction of the fleet that have under-inflated tyres, the extent to which they are under-inflated, the impact of the under-inflation on fuel consumption (following corrective action). For TPMS, savings are therefore further diluted by the diligence of the driver to act on the warnings given.

The methodology used to estimate the potential of low rolling resistance tyres to reduce fuel consumption is to start with the assumption, from Ricardo and industry experts, that for tractor-trailer long haul operations in Europe the potential reduction in rolling resistance relative to baseline vehicles is 20%. (I.e. two thirds that modelled by SWRI which is summarised in the upper third of Table 4.22.)

---

[32] Modern tyres would typically be two 385/65 R 22.5 rather than four 110 R 20 tyres.
[33] See UK Low Carbon Vehicle Partnership press release: http://www.lowcvp.org.uk/news,michelin-introducing-intelligent-tyres-to-provide-easy-tyre-pressure-monitoring-for-large-commercial-vehicles_1837.htm
[34] "Intelligent tyres" is the phrase used by Michelin to describe their tyres fitted with integral TPMS combined with RFID system : http://www.lowcvp.org.uk/news,michelin-introducing-intelligent-tyres-to-provide-easy-tyre-pressure-monitoring-for-large-commercial-vehicles_1837.htm

On this basis, the reduction in fuel consumption implied by the US studies would be 66.7% of that simulated by SWRI over the most appropriate driving cycle for European vehicle segments, scaled by the ratio of the baseline rolling resistance in Europe (relative to the US) and the ratio of the baseline vehicle weights, both given in Table 4.21. This is summarised in the middle (Europe) section of Table 4.22.

In addition, the impact of a 20% reduction in rolling resistance was calculated using the VECTO tool, for the 12 t truck and 40 t articulated tractor-trailer combination (using the declaration mode parameters and these with 80% of the original rolling resistance). The reductions in fuel consumption are given below the reductions inferred from the US studies in the middle (Europe) section of Table 4.22.

As noted in the previous sub-section, whilst it is relatively straightforward to estimate the reduction in fuel consumption caused by replacing tyres with lower rolling resistance tyres, it is more complex for TPMS and ATIS. This is because it depends on the fraction of the fleet that have under-inflated tyres, the extent to which they are under-inflated. For TPMS, savings are therefore further diluted by the diligence of the driver to act on the warnings given. (It is assumed that the impact of the under-inflation on fuel consumption is relatively well characterised. In their truck tyre technical book, Michelin indicate the non-linear influence of inflation pressure on tyre mileage leads to around a 4% and 18% deterioration for 10% and 20% under inflation, respectively.[35]). The EPA RIA, referencing Docket EPA-HQ-OAR-2014-0827, reports that ICCT found in their workshop that opportunities exist for ATIS that could lead to a 0.5 – 2 percent reduction in fuel consumption. After considering this evidence, the input values to the Phase 2 GEM are set to 1.2 percent reduction in CO_2 emissions and fuel consumption for ATIS and 1.0 percent reduction for TPMS.

In a recent study for EC DG CLIMA, TNO and TU Graz concluded the reduction potential of TPMS was considerably lower than this. They explored low and high “savings potential” scenarios. For N2 commercial vehicles they concluded the fuel consumption reduction potentials were between 0.22% - 0.43%. For N3 vehicles when both the tractor and trailer were fitted with TPMS, the potential was 0.18% - 0.35% (van Zyl, et al. 2013), whereas if TPMS was only fitted to the tractor, the savings were two thirds of this.

The values given in Table 4.22 for TPMS are those for the “high savings potential” scenario. For ATIS (which was not mentioned in the TNO TU Graz study, the savings are taken to be 120% of the TPMS values, following the ratio used by EPA in their RIA.

[35] Micheline technical information on truck and bus tyres, Edition 24

Table 4.22: Reductions in fuel consumption generated by changes in rolling resistance from US SWRI Report #1 and applied to European vehicles and driving patterns

Factor	Panel van	Rigid box-truck	Tractor-trailer combination (average of steer drive and trailer tyres)
US			
Average truck weight	5.96 tonnes	11.8 tonnes	32.6 tonnes
Rolling resistance of SWRI's baseline vehicle[36] (and the value in EPA RIA)	7.8 (7.7)	10.967 (Note 1) (7.7)	5.608 (6.38)
Reduced rolling resistance (reduction%) [and the value in EPA RIA]	5.46 (30%) [6.38 (17%)]	7.68 (30%)	3.926 (30%) [6.38 (22%)]
Drive cycle	FTP City,	CARB urban truck cycle & 55 mph	NESCCAF
Load & Table in SWRI Report #1	ALVW, Table 3.27	50%, Table 3.20	75%, Table 3.16
Reduction in fuel consumption for above 30% reduction in rolling resistance	2.7%	7.1%	7.65% (Table 3.16 of SWRI #1) at 75% load
Europe			
Impact of 20% reduction in C_{RR} from European baseline, calculated from SWRI findings	1.15%	4.15%	5.1%
Impact of 20% reduction in C_{RR} from VECTO simulation	< 3.0% Note 2	4.8%	5.1%
Fuel consumption reduction assumed for 20% reduction in C_{RR}	**2.5%**	**4.8%**	**5.1%**
Impact of TPMSs	**0.43%**	**0.43%**	**0.42%**
Impact of ATIS	**0.52%**	**0.52%**	**0.50%**

Notes to Table 4.22:

Note 1: The baseline rolling resistance used by SWRI in their assessment, and the baseline figure given in the EPA RIA differ markedly for the rigid box-truck, with the former appearing anomalously high. However, these were the values used by SWRI to generate the savings reported in the table.

Note 2: The VECTO model does not include a panel van, and so no direct calculation was undertaken. However, the change in fuel consumption for the empty rigid box-truck from a 20% reduction in tyre rolling resistance over the urban delivery cycle was 3.0% (it being 4.0% for the regional delivery cycle when empty and 4.8% for the regional delivery cycle at the reference weight).

The analysis concludes the potential of low rolling resistance tyres for reducing fuel consumption from tractor-trailer combinations is 5.1%, two thirds of the value from the SWRI Report #1 studies and the reduction calculated using the VECTO model for the baseline European vehicle. The additional impact of TPMS is estimated to be 0.42% reduction in fuel consumption, or if this was replaced by ATIS a further 0.08%. Reductions in fuel consumption caused by the lower rolling resistance are slightly less for the rigid box-truck, and around half for the panel van. All the fuel consumption reduction potentials

[36] Data taken from Table C.9 of SWRI Report #1 (Reinhart T.E. (2016)

used in the cost-effectiveness analysis in the next chapter are summarised in the lower third of Table 4.22.

4.3.7 Overnight hoteling loads (extended Idle) reduction technologies

Overview of technology and why it has the potential to reduce CO_2 emissions

During long haul operation the tractor trailer combinations can spend extended periods stationary but with their engine running (known as hoteling or extended idle). This can use significant quantities of fuel. The US EPA RIA quotes a fuel consumption rate of 3 litres (0.8 US gallons) per hour. For a ten hour overnight stop this would amount to 30 litres of diesel being used, but no distance (t-km freight) travelled. There are a number of idling reduction technologies available to reduce this. These include[37]:

- Auxiliary Power Unit (APU) replacing the truck engine to power the truck's systems. The EPA RIA estimates the fuel use of an APU is typically a quarter that of the main truck engine.
- Fuel Operated Heater (FOH) to provide heating services to the truck through small diesel fired heaters. The EPA RIA estimates these typically use around 5% the fuel (0.04 gallons per hour) of the main truck engine.
- Battery Air Conditioning Systems (BAC) to provide cooling to the truck.
- Automatic Stop/Start Systems which power the truck systems through the battery and starts the engine to recharge the battery after it reaches a threshold level.
- Thermal Storage Systems to provide cooling to trucks.

In addition, parking spaces with electrical power provision could be used to power the truck's systems independently of the truck's engine, enabling the latter to be shut down over night.

Vehicle segments and usage patterns where the technology has largest impact

Extended idle reduction technologies only apply to tractor-trailer units when they are stationary for long periods.

Qualitative description of use in baseline vehicles and prospects for future incorporation

Currently few tractor units use extended idle reduction technologies. However, because they are generally additional to the engines powertrain system, they could be incorporated in future vehicles. The optimum system will be application specific. For example, a tractor-trailer combination undertaking long haul deliveries in Northern Europe will be principally concerned with heating, and a fuel operated heater (the current default in the EU) could be optimum. However, the same vehicle undertaking long haul deliveries in Southern Europe will be principally concerned with air conditioning, and an APU or BAC system could be optimum.

Quantitative estimates of change in CO_2 per vehicle for the three vehicle segments considered

The EPA RIA considered extended idle reduction technologies, for example Table 2-25 of GEM inputs for the Baseline Class 7 and 8 tractors, and Tables 2-40 and 2-42 consider the GEM inputs for the 2021, and 2027 Class 7 and 8 tractor standard setting. In all these tables fuel consumption reduction figures are only given for the sleeper cabs. From Table 3-4 of this study, we consider the baseline tractors as being day cabs. Furthermore, the fuel consumption estimates over the typical European driving cycles do not include any component from overnight hoteling. Therefore, in this analysis the introduction of fuel reduction potential of extended idle reduction technologies for day cabs is taken a zero in this project's cost-effectiveness analysis. However, overnight hoteling load reduction technologies are noted as potential fuel consumption reduction technologies.

4.3.8 Vehicle management technologies

Overview of technology and why it has the potential to reduce CO_2 emissions

In addition to the engine and vehicle engineering technologies discussed in the previous report sections, there are some vehicle management changes that too can reduce CO_2 emissions from freight vehicles. These include:

- Predictive (and adaptive) cruise control;

[37] List taken from Section 2.4.8 of EPA RIA

- Vehicle platooning;
- Driver aids such as route management.

Predictive cruise control, also known as E-horizon and powertrain control refers to technologies which enable the vehicle to anticipate the route ahead, and adapt its behaviour accordingly. Importantly, relative to platooning, it delivers fuel savings for individual vehicles, and is not a "co-operative inter-vehicle" technology like vehicle platooning.

Vehicle platooning involves having vehicles in electronic communication with each other sharing data about speed, relative position and drivers' intentions. These would enable vehicles to travel very close behind one another safely, gaining aerodynamic benefit.

Driver aids including route management have been used for many years. However, recent advances in traffic speed monitoring on the road network and vehicle to infra-structure communications, mean that its sophistication is increasing, and proactive route management, rather than simply pre-journey route planning, is increasingly being used. The gain is to reduce overall fuel consumption for the task by optimising total distance travelled, congestion delays, and the constraints on drivers' hours.

Vehicle segments and usage patterns where the technology has largest impact

Both predictive cruise controls and vehicle platooning are most advantageous for tractor-trailer combinations. The slower speed for urban delivery, and their stop start duty cycle means that neither technology is very beneficial for panel vans undertaking urban delivery activities. Again it is noted that predictive cruise control applies to individual vehicles, whereas platooning applies to groups of vehicles.

Active route management is potentially useful for all vehicle segments, warning of emergency incidents restricting, or closing, a route in urban and rural (long haul) environments.

Qualitative description of use in baseline vehicles and prospects for future incorporation;

Currently neither predictive cruise controls nor vehicle platooning are part of either the US or European baseline vehicle usage. Route management planning is part of nearly all delivery operations, and active route management is being increasingly used. It is more mature for operations using a repetitive route, e.g. bus or coach operations, where the experience of one driver can warn and aid those who would follow shortly.

Quantitative estimates of change in CO_2 per vehicle for the three vehicle segments considered

In EPA Report #1 vehicle testing and simulation approaches were evaluated to identify whether the GEM model accurately accounts for all technologies with CO_2 reduction potential. The report concluded that not every technology that affects the vehicle's demand for power can be effectively evaluated. Some of these non-evaluated technologies are:

- Smart cruise control (using optimal BSFC load);
- GPS based cruise control;
- Driver reward systems.

Whilst these management measures are acknowledged as potential CO_2 reduction technologies, and are qualitatively considered, no quantification of their CO_2 reduction potential is given, except for predictive cruise control which is estimated as 2% improvement for tractor-trailer long-haul operation in the EPA RIA (August 2016), Table 2-30. Studies in Europe regarding E-horizon and powertrain control, have led to claims by Volvo and Daimler that savings can reach as much as 5%. However, a more conservative estimate (e.g. in-line with the EPA RIA) is more appropriate for typical operation.

The Ricardo-led Safe Road Trains for the Environment (SARTRE) project has indicated for a platoon where the vehicle – vehicle separation is 10 metres, fuel savings for the lead truck are around 5%, and for following trucks are around 10% for 90 km/h steady speeds. This falls to around 1.5% for the lead truck and 8% for the following truck if the gap extends to 15 metres.[38]

Note that there is the potential element of double counting, because improved aerodynamics would reduce aerodynamic drag, and savings from the platooning of aerodynamically efficient trucks would be lower than the figures quoted above.

[38] http://www.sartre-project.eu/en/publications/Documents/ITSWC_2012_control_pres.pdf

For estimates of the impact of driver training, in the past the UK operated a scheme entitled: Safe and fuel efficient driving. Two case studies involving regional distribution quote fuel savings of around 12% for Bibby Distributions and around 7% for Tesco[39]. No estimates of changes in CO_2 emissions caused by active route management are offered. These will be highly variable, being negligible when the network is running freely. When problems occur, there would be an immediate benefit for panel vans operating in a network or interconnected roads, who can avoid congestions or road closures. For long haul operation, where there may be little alternative, the savings are more due to the driver being aware of problems, and managing time, e.g. taking a break, rather than rerouting.

Except for predictive cruise control, vehicle management technologies are not included in the cost-effectiveness analyses because they correspond to potential reductions in fuel consumption generated by more behavioural, and co-operative actions rather than deterministic single vehicle technology changes. These overall potential improvements are not included in the mixture of measures included in the overall fuel reduction potential of technologies.

Table 4.23: Reductions in fuel consumption generated by vehicle management technologies from the EPA RIA (August 2016) and applied to European vehicles and driving patterns

Vehicle segment	Panel van	Rigid box-truck	Tractor-trailer
US			
Predictive cruise control	N/A	N/A	2.0%
Europe			
Predictive cruise control	N/A	N/A	2.0%

4.4 Improvements for packages of technologies

4.4.1 Overview

The Section 4.3 considered the potential of the individual technologies. However, for tractor-trailer combinations a vehicle comprises two separate entities: an engine, within a tractor unit, and its trailer. For the other two segments, the trailer (i.e. body) is an integral part of the rigid truck. For all segments, the individual technologies are fitted to the whole vehicle, and they interact. This section considers how packages of technology might perform in combination, based on the available evidence.

This is potentially a complex analysis, and was approached by the EPA by using engine and vehicle simulations. An alternative approach is to break-down the use of the energy into broad areas:

- Engine losses which affect the mechanical power provided by the engine;
- Other losses before the wheels, including on-vehicle auxiliaries, transmission losses, etc.;
- Driving losses caused by aerodynamic drag;
- Driving losses caused by rolling resistance;
- Braking/inertia losses (which are most significant for stop-start driving, and of much smaller importance for long haul operations).

This approach is shown schematically in Figure 4.5 below, with illustrative figures more typical for tractor trailer combinations undertaking long haul operations rather than a panel van undertaking urban deliveries, or a rigid box-truck undertaking regional deliveries. Whilst this schematic is a gross simplification, it does show the principal sources of energy consumption. These can be characterised by five key parameters, see Figure 4.5. (Whilst the relative sizes of the losses vary for the three different vehicle segments, the apportioning of losses to these five areas remains a useful overview as to where the vehicle's energy is consumed.)

[39] See http://www.system-training.com/training/case-studies/

Figure 4.5: Illustrative schematic of the energy loss components from vehicle fuel use

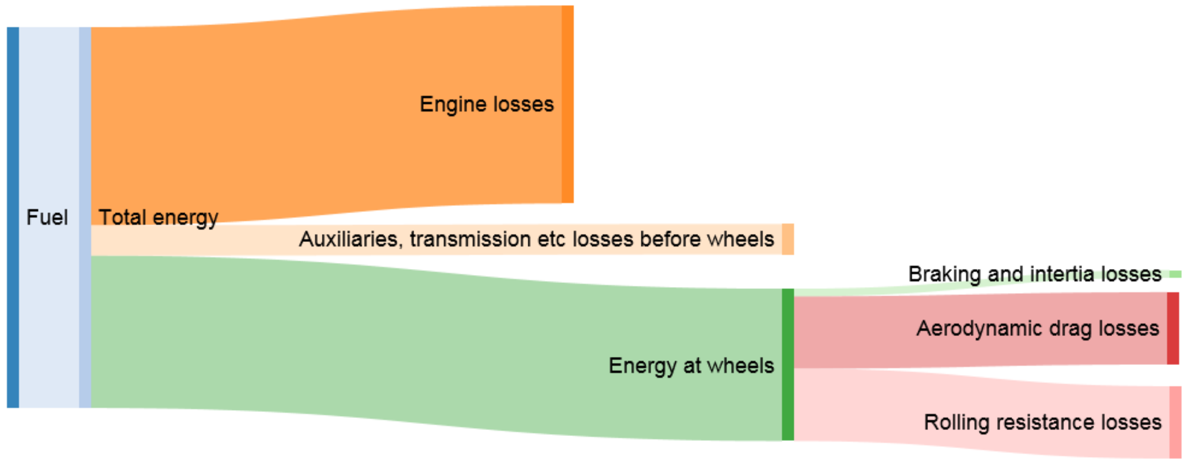


Table 4.24: Key parameters impacting on vehicle energy consumption

Energy loss source	Key parameters
Engine losses	Brake thermal efficiency
Other losses before the wheels	Auxiliaries, transmission efficiency and driveline losses
Aerodynamic drag	Drag coefficient
Rolling resistance	Coefficient of rolling resistance
Vehicle inertia	Vehicle weight

In addition to the above parameters, vehicle management technologies (e.g. predictive cruise control) also reduce the energy requirement at the wheels to undertake the same vehicle-km journeys.

The next subsection (4.4.2) provides a summary of the available evidence on the combined reduction potential for technology packages for tractor-trailer combinations.

This vehicle segment is chosen because it is the HDV vehicle segment that consumes the most fuel (see Figure 1.1) and it is also the most complex because of the tractor and trailer components, as opposed to a single unit for rigid vehicles. It also illustrates how the potential fuel consumption reduction potential for packages of measures related to the potential fuel consumption reduction potential for the technologies singly. The subsequent Section 4.5 provides an assessment of the overall fuel consumption reduction potential.

4.4.2 Reduction potential from technology packages for tractor-trailer combinations

4.4.2.1 Data on technology packages from this study's analysis

For the long haul tractor trailer combinations, the baseline values for these aggregated parameters, and their potential value by 2030 are given in Table 4.25. The impact of improved aerodynamics is not expressed in terms of C_D for the average vehicle, but in terms of reduction in fuel consumption for the premium and 2030 vehicles.

Table 4.25: Potential fuel consumption reductions for groups of technologies for tractor-trailer combinations

	EU average	EU Premium	EU Economy	2030 potential value	2030 FC reduction potential relative to EU average
Brake thermal efficiency	44.8%	46.00%	42.6%	52.6% (Note 1)	**14.9%**
Driveline efficiency	95.5%	95.5%	95.5%	97.1%	**1.67%**
Drag coefficient (Drag area, m^2)	0.663 6.3 m^2	0.473 (Note 2) 4.49 m^2	0.70 6.65 m^2	0.439 (Note 2) 4.17 m^2	**10.6%**
Coefficient of rolling resistance (-20% C_{RR})	5.8 kg/t	5.5 kg/t	6.5 kg/t	4.64 kg/t	**5.50% (Note 3)**
Vehicle weight (kg)	14,600	14,820	14,690	12,633	**3.38%**

Notes to Table 4.25

Note 1: Including improvements in air handling and waste heat recovery

Note 2: Drag coefficients and drag area calculated using VECTO to find what reduction in C_D is required to generate a 9% (for EU premium vehicle) and 10.6% (for 2030 potential vehicle) fuel reduction.

Note 3: Fuel consumption reduction for changes in rolling resistance calculated using VECTO. They are the combination of reduction from rolling resistance improvements and also TPMS from Table 4.22.

4.4.2.2 Comparison of estimated reduction potentials with other available data

Inevitably for future technologies there are few to no measurement data, because vehicles containing many of the technologies do not exist. However, there are some indications of what the potential of technology combinations might be. For example, in the June 2016 issue of LastAuto Omnibus, a German trucking magazine, there are data from back to back road testing of a 2013 Euro VI MB truck, and a more recent 2016 version. The changes are due to changes in the engine only. These comprise:

- Improved Common-Rail-System X-Pulse with an injection pressure of 2,700 bar (in the previous model it was 2,100 bar);
- 8-hole injection nozzle;
- Asymmetric turbocharger, developed and manufactured in-house at the manufacturing site in Mannheim rather than WGT;
- A reduced exhaust gas recirculation rate;
- The compression ratio was increased from 17.3 to 18.3:1.

Overall, the MB publicity suggests a fuel efficiency improvement of 3%. The LastAuto Omnibus on-the-road overall fuel consumption change is 2.27% +/- 0.27 (the error range coming from simple uncertainty from the numerical precision). However, this measured improvement is not exactly directly comparable, and is systematically slightly low because the average speed of the vehicles for the different cycles was higher for the 2016 model, albeit only by 0.3 km/h (0.36%) overall.

These measurements are consistent with the EPA reported single technology assessments where using an asymmetric turbo (0.9% fuel efficiency improvement over NESCCAF cycle) and total removal of the EGR system (0.7% fuel efficiency improvement over NESCCAF cycle). The text of EPA Report #1 indicates that higher compression ratios increase BMEP, thereby improving efficiency, but does not provide a quantification of this in the technologies simulated (Table 3.15 of reference Eastern Research Group, 2015a).

Another overall engine fuel efficiency measure comes from the engine's thermodynamic efficiency, i.e. the ratio of the mechanical energy provided at its driveshaft relative to the net energy content of the fuel consumed. It is believed this is close to 46% for the Mercedes Benz OM 471 2016 Euro VI engine[40]. For the "Generic engine" used in the EC 40 t GVW Long Haul VECTO truck simulation this has an average efficiency of 43.7% over the engine speed/torque values where power > 100 kW, and 44.8% when averaged over the engine speed range 1,200 – 1,600 rpm and torque range 1,400 – 2,300 Nm ranges. These are the ranges where the engine spends most of its time for the long haul cycle. Relative to this generic engine, an engine whose efficiency is 46.0% would show a fuel efficiency improvement of 2.68% - very close to that reported in the Mercedes Benz press release.

SWRI Report #2 (Reinhart, 2015) reports: "Based on the technologies studied in this project, it appears that there is the potential to improve tractor truck engine fuel consumption by 2-5% without a waste heat recovery system, and by 6% to 9% with a waste heat recovery system. These improvements are achieved compared to the 2019 baseline on cruise speed cycles."

In their regulatory impact analysis, the EPA assumes a 2027 MY tractor has an engine whose improved efficiency leads to a fuel consumption reduction of 5.4% relative to the 2017 MY baseline tractor unit (data from Table 2.37 of the EPA RIA).

The target within Europe is to obtain 50.0% overall engine efficiency, which would include waste heat recovery. This would be a 10.4% improvement relative to the "Generic long haul engine" modelled in VECTO and an 8.0% improvement relative to the "premium long haul engine".

It is also noted that the US Supertruck programme is also seeking to achieve 50% brake thermal efficiency, relative to an approximately 42% 2010 baseline figure. This corresponds to a 16% reduction in fuel consumption relative to the baseline engine. This programme also seeks to show a technical pathway to achieve 55% BTE, through modelling and analysis. There is a new DOE-Cummins program that is going to demonstrate a 55%BTE on the engine dynamometer in two years[41].

For the overall efficiency of tractor-trailer combination vehicles, in addition to the engine efficiency, the EPA Report #2 reports that an aggressive reduction in C_D (25%) and C_{RR} (30%) provides a 20% fuel consumption reduction on the long haul NESCCAF cycle. These are two of the technologies that reduce whole vehicle retarding forces, the others being light-weighting and vehicle management measures. However, differences in the average speeds of long haul cycles in US and Europe mean that the equivalent aerodynamic and rolling resistance improvements for European vehicles would not generate such high fuel consumption reductions.

The studies for individual technologies show that improvements in fuel efficiency caused by reductions in C_D, C_{RR} or weight (through light-weighting) are linearly dependent on the degree of reduction within the range of improvements being considered. (Hence reductions of C_D of 12.5% or C_{RR} of 15% lead to exactly half the reductions from 25% and 30% respectively.)

The data in EPA Report #2 show that from whole vehicle simulations of combinations of technology measures, the overall change in fuel efficiency is not simply the compounded change of the individual components. The difference occurs because the impact of the individual technologies averaged over the whole cycle, when compounded may not be the same as their combined impact on a second by second basis. It is the whole vehicle simulation involving several technologies simultaneously that leads to the more accurate assessment.

4.5 Summary of fuel consumption reduction potential for all technologies

The previous report sections have provided the assessment of the potential for fuel consumption reduction from individual technologies (Section 4.3), as well as information on reductions from technology packages (illustrated for tractor-trailer combinations in Section 4.4). This section provides a summary of the overall potential from all technological options for the three vehicle segments.

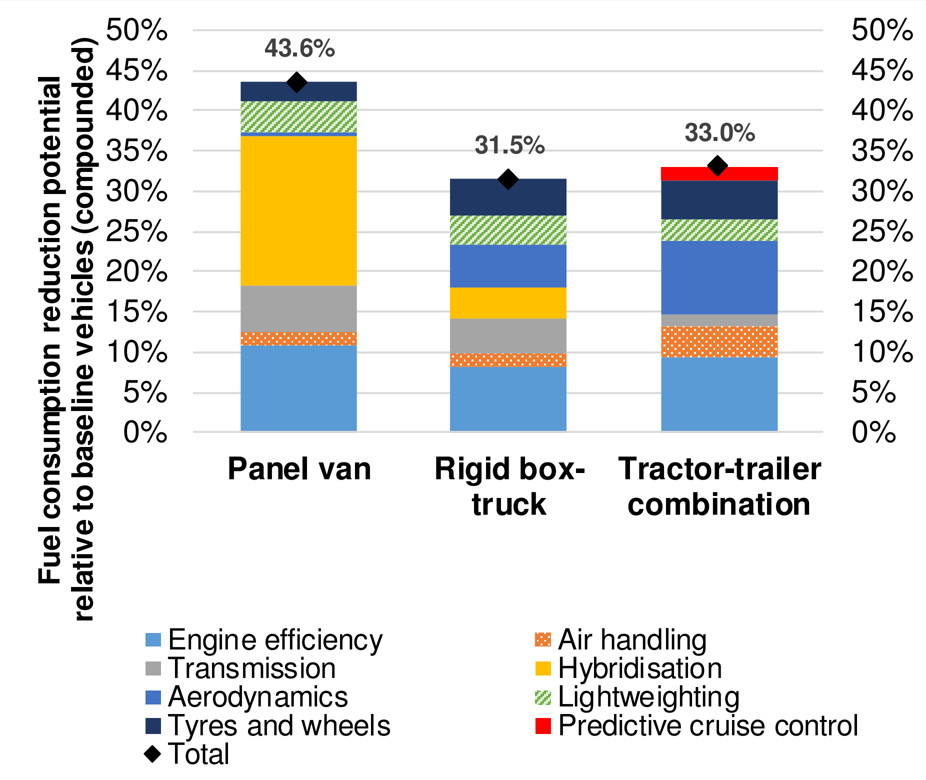
---

[40] Engine efficiency improvement approaching 46% comes from both Mercedes Benz media releases, see http://media.daimler.com/marsMediaSite/en/instance/ko/Mercedes-Benz-OM-471-economical-powerful-and-reliable-Consum.xhtml?oid=9905489 and vies of Ricardo heavy duty engine experts

[41] See, for example, Cummins press release dated 1st September 2016 http://investor.cummins.com/phoenix.zhtml?c=112916&p=irol-newsArticle&ID=2198980

The fuel consumption reduction for all the individual technologies discussed in this chapter are summarised in Table 4.26, with the compounded fuel consumption reduction potentials shown as a stacked bar chart in Figure 4.6.

Figure 4.6: Potential 2030 EU vehicle fuel consumption reductions relative to 2015 baseline vehicles



Notes: Includes accounting for technological overlap/mutual exclusivity between AT and Full Hybrids.

The data in Table 4.26 gathers together the conclusions reached and tabulated at the end of each of the sub-sections for individual technologies within Section 4.3. The final row in the table, shaded blue, is their compounded effect (i.e. reflecting that savings from two 50% reduction technologies cannot be simply added mathematically as they would not lead to zero emissions but a 75% overall reduction).

Table 4.26: Potential 2030 EU vehicle fuel consumption reductions relative to 2015 baseline vehicles from all technologies

Technology	Panel van	Rigid box-truck	Tractor-trailer combination
Unspecified FMEP improvement (En)	3.70%	2.30%	1.40%
Variable oil pump (En)	2.00%	1.50%	1.00%
Variable coolant pump (En)	1.20%	0.80%	0.50%
Bypass oil cooler (En)	0.80%	0.50%	0.20%
Low viscosity oils (En)	2.00%	2.00%	1.00%
Electric cooling fan (En)	0.5%	0.5%	0.5%
Electric steering pump (En)	1.27%	0.80%	0.28%
High efficiency electric air conditioning (En)	0.5%	0.25%	0.1%
Improved air handling (Ai)	1.90%	2.00%	2.50%
Turbo compounding (Ai)	0.00%	0.00%	2.00%
Engine encapsulation or waste heat recovery (En)	1.50%	0.00%	4.50%
Other thermal management technologies (En)	0.50%	1.00%	2.00%
Improvements in transmission (Tr)	7.00%	5.00%	1.67%
Hybridisation or enhanced stop-start (Hy)	22.58%	4.50%	0.00%
Futuristic aerodynamics (Ae)	0.60%	6.30%	10.60%
Lightweighting (Li)	4.70%	4.40%	3.38%
Low-rolling resistance tyres (Ty)	2.50%	4.80%	5.10%
TPMS (Ty)	0.43%	0.43%	0.42%
Overnight hoteling and vehicle management technologies	0.00%	0.00%	2.00%
Compounded sum of the above	**43.6%**	**31.5%**	**33.01%**

Notes: If the fuel consumption reductions from all technologies are simply added together, then, for example for the panel van, this would give a total of potential reductions of 53.18%. However, this neglects that when combining reductions, each subsequent reduction is on a reduced total. For example, two 50% reductions would not lead to an overall 100% reduction, but a 75% reduction. It is this combined, or compounded, sum that is given in the final column of the table and that is less than the reduction obtained from simply adding together all the individual reductions.

5 Cost effectiveness of technologies for improving the fuel efficiencies of HDVs

5.1 Sources of information on costs

Previous chapters have focussed on identifying the different technologies that could contribute to reduced fuel consumption from HDVs by 2030, relative to 2015 baseline vehicles. They focused on the potential savings that might be achieved for three vehicle segments operating in the European context.

This chapter considers the incremental costs of incorporating the technologies to the current baseline vehicles. This enables the incremental cost-effectiveness of the technologies to be calculated and compared. This, in turn, enables both the extent of the potential carbon savings to both be evaluated and ranked in terms of their incremental cost relative to the other technologies.

The estimated 2030 cost information that has been used in the development of this incremental cost analysis has been taken from a variety of sources, including:

- 2011 TIAX study (Law et al., 2011);
- EPA Regulatory Impact Analysis (EPA & NHTSA, 2016);
- SWRI Cost-effectiveness study, Report #3 for EPA (Schubert et al., 2015);
- Cost-effectiveness study of advanced efficiency technologies for long haul tractor-trailers study (Meszler et al, 2015);
- Consultations with Ricardo experts;
- Additional research and consultations.

In general, it is worth highlighting that since the number of HDVs produced annually is orders of magnitude lower than that for passenger cars, the rate of cost reduction for new technologies due to volume production is generally anticipated to be significantly lower than for light duty vehicles (LDVs). However, at least some of the technical measures proposed for application may benefit to an extent from learning/cost reductions in LDVs (e.g. in particular those relating to battery costs).

The following report sections provide a summary of the cost analysis in this area, including an outline of individual cost assumptions (Section 5.2), and the result of their combination into overall incremental cost curves (Section 5.3). An overall summary of the results of this analysis is presented in the final Section 5.4.

The values of the capital investments, or operational costs over the vehicle's lifetime, are prices to the truck buyers/operators (expressed in €(2015) currency). For many of the technologies, the prices look forward to a time of relatively mature production: the prices quoted assume that initial learning has occurred and they are the prices for high volume production. The values used in the calculations are the €(2015) values.

5.2 Cost for single technologies

5.2.1 Engine efficiency technologies

5.2.1.1 Engines - Friction

The incremental development of engines is confidently expected to lead to reduced friction technologies being incorporated in new engines (Ricardo engine experts). These are not added after an engine has been manufactured, but are an integral part of an engine build. It was also viewed that it was very difficult to assign an incremental cost to many individual engine friction reduction technologies. Consequently, for each vehicle segment there is an "unspecified FMEP improvement" item, which is not assigned any capital cost. The reduction in fuel consumption varies for the different vehicle segments, as described in the previous chapter and summarised in Table 4.26. These data provide the technology potential for a detailed cost effectiveness analysis, as described in Chapter 4.

The technologies where both reductions in fuel consumption and incremental costs can be estimated (from Ricardo engine efficiency experts) are as follows (with fuel consumption impacts as summarized in Table 4.25 and incremental costs as listed here):

- Variable coolant pump €90
- Variable oil pump €90
- Bypass oil cooler €25
- Low viscosity oils see below.

Lubrication oils are a consumable, changed routinely as part of the service and maintenance regime of a vehicle. Low viscosity oils are more expensive than the baseline 5W-30 oil. Average sump oil capacities were found for the three vehicle segments, and the average number oil changes per year (from their recommended service interval and average annual mileage). From these the additional price for low viscosity oil for each year of the vehicle's life was calculated (discounted back to 2015). These were €41 per year for the panel van, €155 per year for the rigid box-truck and €330 per year for the tractor-trailer combination.

5.2.1.2 Engines – Reduction of auxiliary parasitic loads

As discussed in Section 4.3.1.2, cooling fans, improved steering pumps and air conditioning all have the potential to reduce fuel consumption. However, for the reasons discussed in that same section, electric hydraulic steering pumps exhibited the greatest practical potential to reduce fuel consumption significantly over typical European driving cycles. However, no authoritative data were found for the incremental cost of adding an electric hydraulic steering pump or other electrical accessories individually. The additional complexity of the system, relative to replacing a mechanically driven oil or coolant pump with a variable switchable electric pump, leads to an estimated price twice that given for upgrading these pumps. This is €180 per vehicle; however, there is high uncertainty in this figure. Cost estimates are only available from the EPA RIA (in Section 2.11.10.2) for the electrification of all accessories (ranging from $369 for lighter trucks, to $697 for regional/vocational, and $1393 for heavy tractor-trailers for MY 2027). Estimates for individual measures have therefore been made assuming similar scaling between vehicle segments for the different options.

5.2.1.3 Engines – Air handling

It was assumed that by 2030, changes in turbochargers lead to an overall improvement of air handling efficiency of around 6%, through a combination of improved turbocharging and reduced EGR pressure penalties (as occurs for asymmetric turbochargers). The principal anticipated change in the European market would be the replacement of WGT with VGT. It is also assumed that by 2030 the vast majority of HDV will continue to use EGR as part of their NOx emissions control strategy.

In terms of incremental cost, moving from WGT was estimated to be around €875 – €1,165[42] by the Ricardo experts. The figure given in the NHTSA Cost study (Schubert et al., 2015) for 300,000 units was €1,055[43]. This applied to both Class 2b & 3, and to Class 6 trucks. (No analysis for Class 8 trucks was performed.)

For the cost-effectiveness analysis, it was assumed the incremental capital cost was €1,050 (2015 euros) for improved air handling for all vehicle segments.

Turbocompounding, included in this air handling section rather than as an energy recovery technology, was estimated to have an incremental cost around €1,900[44] when added to a Class 8 tractor unit (Schubert et al., 2015) and between €1,500 – €1,750[45] by Ricardo engine experts. The incremental cost assumed for this study is between these two estimates, namely €1,800.

5.2.1.4 Engines – Waste heat recovery and thermal management

Waste heat recovery: The Ricardo experts estimated a price of €3,000 - €5,000 for a 15 kW organic Rankine cycle waste heat recovery system for a tractor unit. This is less than the €10,500 estimate ($12,500) given in the NHTSA Cost study (Schubert et al., 2015) for 300,000 units for a heat recovery system for a Class 8 truck[46].

---

[42] £750 - £1,000 from Ricardo experts
[43] $1,277 from Schubert et al., 2015
[44] $2,300 for Turbocompounding, from Figure 41 of reference Schubert et al., 2015
[45] £1,250 and £1,500 for Turbocompounding from Ricardo experts
[46] This difference comes from differing views of the experts in projecting future system costs

For the cost-effectiveness analysis, it was assumed the incremental capital cost was €5,000 for a waste heat recovery system for Class 8 tractor units.

Engine encapsulation: No authoritative data were found for the incremental cost of encapsulating the small engines used in panel vans. It was assumed the addition of thermal insulation, bespoke for an engine but used in a wide variety of other applications for thermal management, would be €25 per engine when mass produced.

5.2.1.5 Summary of Engine technology costs

Table 5.1 provides a summary of the assumed individual technology costs for the different engine-based measures for the different vehicle segments used in the cost-effectiveness analysis.

Table 5.1: Summary of estimated 2030 EU engine technology costs relative to 2015 baseline vehicles (in 2015 €)

Technology	Panel van	Rigid box-truck	Tractor-trailer combination
Unspecified FMEP improvement (En)	€0	€0	€0
Variable oil pump (En)	€90	€90	€90
Variable coolant pump (En)	€90	€90	€90
Bypass oil cooler (En)	€25	€25	€25
Low viscosity oils (En)	€40.95 per year	€155.32 per year	€331.36 per year
Electric cooling fan (En)	€50	€90	€180
Electric steering pump (En)	€95	€180	€360
High efficiency electric air conditioning (En)	€55	€105	€210
Improved air handling	€1,050	€1,050	€1,050
Turbo-compounding	-	-	€1,800
Waste heat recovery	-	-	€5,000
Engine encapsulation	€25	-	-

5.2.2 Transmission and driveline

Section 4.3.2 indicates that the predominant transmission technology change for European panel vans and rigid box-trucks that would generate potential fuel consumption reductions is to replace their predominantly manual transmissions with automated manual transmissions (AMT).

For the Class 2b & 3, and vocational vehicles, the NHTSA Cost study (Schubert et al., 2015) considers the incremental cost of replacing **automatic** transmissions with AMT. It gives incremental costs of €680 for Class 2b & 3 trucks, €1,025 for Class 4 – 6 trucks and €1,400 for Class 8 trucks.

These data are not directly relevant to the European market, where manual gearboxes dominate the transmissions for the panel vans and rigid box-trucks. Ricardo experts commented that it is hard to obtain incremental costs, as they are usually subsumed within the overall vehicle cost. They quote figures around €1,150 to €3,450 for the incremental costs of AMT relative to MT. This appears consistent with the US cost study because of the higher costs of AT relative to MT.

For the cost-effectiveness analysis, it was therefore assumed the incremental capital cost of replacing MT with AMT transmissions for panel vans and rigid box-trucks was the middle of the range given above, €2,300. AMT transmission technology is the dominant baseline technology for long haul tractors, but future fuel consumption reduction is expected due to increases in the number of available gear ratios. The incremental capital cost of increasing the number of gears in the AMT transmission for tractor units is assumed to be €1,500 based on consultation with Ricardo experts.

Table 5.2: Summary of estimated 2030 EU transmission and driveline technology costs relative to 2015 baseline vehicles (in 2015 €)

Technology	Panel van	Rigid box-truck	Tractor-trailer combination
Replacing MT with AMT	€2,300	€2,300	-
Going from 12 speed AMT to 18 speed AMT			€1,500

5.2.3 Hybridisation

The cost of full hybridisation for panel vans from different sources has varied widely: figures as high as €30,000 have been suggested. However, these are dependent on the time period to which the estimate applies, and are strongly dependant on the cost of battery packs, the principal component cost for pure EVs also. A study for the European Commission in 2009, gave the cost of Li-ion battery systems as $900 - $1,800 /kWh[47]. More recent, peer reviewed articles have noted how this has fallen to below US $400 by 2014[48], and media reports that Tesla Model S battery packs cost around $190 /kWh[49]. Recent research by Ricardo Energy & Environment for the European Commission has shown that the costs of future batteries is anticipated to reduce dramatically over the next 10-15 years.

In their cost study for NHTSA, Schubert et al., 2015 give a price of €14,000 as the incremental cost for Class 2b & 3 strong hybrids. This is similar to the figure of €15,000 - €16,500 for the low and high range for long haul tractors given in Meszler et al, 2015. However, the Ricardo hybrid vehicle experts were of the opinion that this is probably too high, and an incremental cost of €13,000 by 2030 (expressed in 2015 €) might be a better projection. In part this is caused by the rapid reduction that has occurred in battery prices, as discussed above. This is the value used in this study.

The value for enhanced stop/start systems, is more determined by hardware modifications, and relatively unaffected by the rapid fall in Li-ion battery prices. In their cost study for NHTSA, Schubert et al., 2015 give a price of €1,160 ($1,378) for this technology applied to Class 4-6 diesel trucks. Recent analysis by FEV/ICCT on CO_2 reduction technologies for the European car and van fleet reported the cost of an advanced start/stop system for a 3.0 L diesel engine is €92[50]. However, the choice of exact value does not impact the “technology potential and cost analysis” reported in Table 5.10 because the higher technology potential arises from changing the powertrain to a full hybrid system.

For this cost-effectiveness analysis, it was assumed the incremental capital cost of adding strong hybridisation to a panel van is €13,000, and of adding stop/start technology to a Class 4-6 diesel truck is €1,160 (both expressed as 2015 € prices).

Table 5.3: Summary of estimated 2030 EU hybridisation technology costs relative to 2015 baseline vehicles (in 2015 €)

Technology	Panel van	Rigid box-truck	Tractor-trailer combination
Enhanced stop-start systems	€100 - 1,160	€1,160	-
Full hybrid	€13,000	-	-

[47] EC JRC. (2009). Plug-in Hybrid and Battery-Electric Vehicles: State of the research and development and comparative analysis of energy and cost efficiency, http://ipts.jrc.ec.europa.eu/publications/pub.cfm?id=2759
[48] Nykvist, B. and Nilsson, M., 2015, “Rapidly falling costs of battery packs for electric vehicles”, Nature Climate Change Letter, http://www.nature.com/nclimate/journal/v5/n4/full/nclimate2564.html
[49] Article in “Green Car Reports” April 2016, http://www.greencarreports.com/news/1103667_electric-car-battery-costs-tesla-190-per-kwh-for-pack-gm-145-for-cells
[50] CO_2 reduction technologies for the European car and van fleet, a 2025-2030 assessment, ICCT, November 2016, http://www.theicct.org/sites/default/files/publications/EU-Cost-Curves_ICCT_nov2016.pdf

5.2.4 Aerodynamics

The incremental cost of going from a baseline tractor-trailer combination to the best available trailers with advanced roof fairing and cab side-extenders on the tractor unit, was estimated to be €1,000 (from consultation with a manufacturer of aerodynamic trailers). To progress beyond the best currently available to further futuristic reduced tractor-trailer combinations is assumed to cost a further €1,000.

For panel vans the incremental cost of reducing their drag coefficient is taken from the EPA Supporting Cost Analysis (Shubert et al, 2015) where a figure of $267.37 is given. This is not for retrofit aerodynamic styling, but is integral to the whole panel van design. The incremental cost assumed for European panel vans is €250.

Neither the EPA Supporting Cost Analysis nor the EPA RIA include data on the cost of improved aerodynamics for the rigid box-truck (vocational vehicle) segment. Therefore, the incremental cost assumed for this vehicle segment was 150% that for the panel vans, because the rigid box-trucks are larger vehicles and because more extensive engineering is anticipated. Consequently, the incremental cost is assumed to be €375 for improved aerodynamics for this vehicle segment.

Table 5.4: Summary of estimated 2030 EU aerodynamic improvement technology costs relative to 2015 baseline vehicles (in 2015 €)

Technology	Panel van	Rigid box-truck	Tractor-trailer combination
Aerodynamic trailer	N/A	N/A	€1,000
Other future aerodynamic improvements	€250	€375	€1,000

5.2.5 Light-weighting

The recent study on lightweighting of heavy duty vehicles for EC DG CLIMA (Hill et al., 2015) considered a whole range of lightweighting options, their potential mass reductions and their costs. This is illustrated in Table 4.18. The cost data used in this analysis is taken directly from the EC study.

Rather than treat each of the potential 40 lightweighting measures separately, or amalgamating them all into a single value, for the cost-effectiveness reduction measures were grouped according to their cost per kg potential mass reduction they could produce. The overall fuel consumption reduction potential for each cost group is calculated, and used in the analysis. The sum of all the fuel consumption reduction potentials are those totals given in the third column of earlier Table 4.19. This forms the basis for the lightweighting data within the analysis of cumulative incremental fuel consumption reduction against incremental costs for the technologies, which are summarised in Table 5.5.

Table 5.5: Summary of estimated 2030 EU lightweighting technology costs relative to 2015 baseline vehicles (in 2015 €)

Technology	**Panel van**		**Rigid box-truck**		**Tractor-trailer combination**	
	Cost (€)	Fuel saving (%)	Cost (€)	Fuel saving (%)	Cost (€)	Fuel saving (%)
Total when Euro/kg saved = €0	€ 0	0.50%	€ 0	0.22%	€ 0	0.33%
Total when Euro/kg saved >€0 - €1	€ 1	0.03%	€ 0	0.00%	€ 53	0.09%
Total when Euro/kg saved €1 -€2	€ 91	0.66%	€ 300	0.71%	€ 300	0.33%
Total when Euro/kg saved €2 - €3	€ 111	0.64%	€ 295	0.44%	€ 40	0.02%
Total when Euro/kg saved €3 - €4	€ 3	0.01%	€ 7	0.01%	€ 0	0.00%
Total when Euro/kg saved €4 - €5	€ 202	0.59%	€ 1,423	1.11%	€ 2,032	0.65%
Total when Euro/kg saved €5 - €10	€ 601	1.33%	€ 989	0.46%	€ 8,751	1.96%
Total when Euro/kg saved > €10	€ 1,455	0.94%	€ 6,622	1.47%	€ 0	0.00%
Total for all weight options	**€ 2,464**	**4.70%**	**€ 9,635**	**4.43%**	**€ 11,176**	**3.38%**
Total weight reduction (%)	**11.7%**		**16.6%**		**15.6%**	

5.2.6 Tyres and wheels

Unlike many fuel consumption reduction technologies (improved turbo-charging, waste heat recovery systems or hybridisation) low rolling resistance tyres are not a single purchase, rather they are a vehicle consumable. The cost of applying low rolling resistance tyres was estimated from estimating the number of miles the vehicle would travel in its lifetime of 10 years and the number of tyres that would be originally fitted and replaced during this time (and discounted backwards to the starting year).

The incremental cost per tyre relative to a higher rolling resistance, was found by comparing various tyre prices for a higher energy efficiency class tyres, and was taken as 10% more than the baseline tyre price[51]. For tractor-trailer combinations this was estimated as an incremental cost of €41.30 per tyre, and an annual cost of €420 for the tractor and its trailer. This is somewhat higher than the cost of €33 per tyre given in NHTSA, Schubert et al., 2015 cost study, and the incremental cost of €23 per tyre given in the EPA RIA.

Costs are lower for the panel van and rigid box-truck segments because their tyres cost less, because vehicles have fewer tyres and because these vehicle segments travel fewer km per year, and need fewer sets of new tyres. The annual incremental cost for these vehicle segments were taken €46 / vehicle /year for panel vans and €130 / vehicle /year for rigid box-trucks.

The EPA RIA report estimates the cost of fitting TPMS to all vehicle segments (see Section 2.9.3.7.1) as being $583 in 2021 falling to $507 by 2027 for the tractor-trailer combination, and $307 in 2021 falling to $267 by 2027 for the two smaller vehicle segments. On this basis the incremental costs of fitting TPMS to European vehicles were taken as €475 for the tractor-trailer combination, and €250 for panel vans and rigid box-trucks.

The incremental costs for ATIS were given in Section 2.9.3.7.2 of the EPA RIA. These were consistently 157% of the costs of TPMS for the tractor-trailer combination for different years. The costs assumed for this study's cost-effectiveness analysis were therefore assumed to be 157% of those for TPMS, i.e. €746 for the tractor-trailer combination, and €400 for the two smaller segments.

[51] Note: there the alternative to higher technology material or higher technology architecture is a simple lowering of original Tread Depth, which leads to lower mileage and higher annual cost. In combination with technical improvements, this could lead to further reduction in net fuel consumption.

Table 5.6: Summary of estimated 2030 EU tyre and wheel technology costs relative to 2015 baseline vehicles (in 2015 €)

Technology	Panel van	Rigid box-truck	Tractor-trailer combination
Improved tyre tolling resistance	€46 per year	€130 per year	€420 per year
TPMS	€250	€250	€475

5.2.7 Overnight hoteling loads reduction and vehicle management technologies

Sections 4.3.7 and 4.3.8 explain that although overnight hoteling loads reduction and vehicle management technologies are maturing technologies that are confidently expected to reduce overall CO_2 emissions from vehicles, especially tractor-trailer combinations on long haul (overnight) operations, these technologies are not expected to generate any reduction in fuel consumption for the baseline vehicles and operations analysed in this study, with the exception of predictive cruise control. The incremental costs for the latter technology is based in the EPA RIA (2016) and is presented in Table 5.7.

Table 5.7: Summary of estimated 2030 vehicle management technology costs relative to 2015 baseline vehicles (in 2015 €)

Technology	Panel van	Rigid box-truck	Tractor-trailer combination
Predictive cruise controls	-	-	€640

5.3 Cost-effectiveness, incremental cost analysis and payback periods for single technologies

5.3.1 Overview of methodology

This section provides a summary of the methodology used in the analysis of cost-effectiveness, incremental costs and payback periods. The information presented here is based on the maximum potential fuel consumption reduction for technologies, both individually and in combination (Chapter 4) and associated **incremental costs** (from Section 5.2). Together these data can be used to generate incremental cost – maximum potential abatement graphs, which are sorted in order of the technologies that cost least for the potential fuel consumption reduction they generate. After making some assumptions regarding the financial savings from reduced fuel costs, pay-back periods can also be calculated.

It is noted that the analysis presented here, a cumulative incremental analysis allows substantially more technology to be added as the incremental cost-effectiveness “buffer” created by very cost-effective early technologies is carried over to offset the less-cost-effectiveness of some fraction of later technologies. This is distinctly different from the related marginal cost (MAC) analysis, which will tell you exactly at what point the “next” Euro of technology investment is not cost-effective given assumed technology and fuel prices. However, it is worth noting that the previous work conducted in this area for HDVs (e.g. by Schroten et al., 2012, and Hill, et al. 2015) has used the MAC terminology in this context.

The first step for this approach is to consider the costs and fuel consumption reduction potentials of technologies individually. In this context, the following important aspects are highlighted:

- **Light-weighting options where there is assumed to be no capital cost.** Rather they are a consequence of improvement by design and evolution. The experts consulted did not ascribe an incremental cost to these improvements, although their fuel consumption reduction potential was known. Light-weighting options are not presumed to be retrofitted to existing vehicles but become part of some baseline trucks in 2030.

- **Technologies that are mutually exclusive:** Trucks will continue to have turbo-compressors. However, moving from a waste gated turbo, a truck might have a VGT, asymmetric turbo-charger or two stage turbocharging, but not all three. From the consultations 2ST technology is seen to have the highest potential. Therefore, in the summary the technology potential given is the maximum possible improvement generated by going to the technology offering the highest potential benefit. (In practice manufacturers might choose other options, for a range of reasons, and these would need to be included in a "technology uptake" analysis, which is outside the scope of this study defining the "technology potential".)
- **Some technologies do involve capital cost, but are not included because of uncertainties in both their costs and benefits.** This occurs particularly in the realm of friction reduction. New materials, and coatings, are anticipated to be developed and possible by 2030, but are not included in the single technology analysis.
- **There are technologies that are not part of the vehicle build** (i.e. do not incur a direct build cost) but are more operational costs, e.g. low rolling resistance tyres, and low viscosity oils, both of which are vehicle consumables. These are included by considering their incremental costs (and savings) during the assumed 10 year lifetime of the vehicle.
- **Technologies where there is a barrier to general take up**, e.g. caused by IPR ownership and restricting patents. Technologies where this was found include trailer aerodynamic styling, and asymmetric turbo-charging. However, these are not seen as barriers to the technologies potential, merely to the commercial prospects of rate of uptake. However, assigned incremental costs do not include potential costs of accessing IPR.

The estimates on technologies' incremental cost and generated CO_2 savings were used to evaluate their cost-effectiveness. For these analysis, cumulative incremental fuel consumption reduction against incremental costs for the technologies were developed, showing the compounded carbon savings of all technologies and their relevant incremental abatement cost[52]. The effectiveness (in €/tCO_2) was calculated as the ratio of the single measure's Net Present Value (NPV) to the achieved lifetime CO_2 savings. The technologies were ordered starting from the most cost-effective and proceeding by increasing costs of abatement.

The values of the capital investments, or operational costs over the vehicle's lifetime, are prices to the truck buyers/operators expressed in €(2015) currency. For many of the technologies, the prices look forward to a time of relatively mature production: the prices quoted therefore assume that initial learning has occurred and they are the prices for high volume production. The values used in the calculations are the €(2015) values for 2030 expenditures.

The cost analysis starts with year 2030, assuming all capital expenses are made at that time. A discount rate of 4% was assumed for economic costs and savings occurring in the following years. This is the "Social discount rate" used by regulators, e.g. the EC, to assess the benefit to society, and excludes the influence of taxes and duties. The impact of choosing a different discount rate, e.g. 8% generally used as the private discount rate, to assess cost-effectiveness from an end user perspective, is to reduce the value of fuel savings, and to increase the time it takes for the investment to show a positive return. However, this is counter-balanced by the additional savings accrued when including fuel taxes when analysing from a private perspective.

Most technologies were considered to be purchased only once, at the beginning of the vehicle's lifetime; however, tyres and lubricant oil are changed periodically and were, therefore, treated as operational expenses. The prices from 2030, over the vehicle's lifetime, were kept constant. The tyre life (km) was taken from the UK Freight Transport Association's "Managers' Guide" which provides guidance for the three vehicle segments (FTA, 2010). The operational cost of lube oil changes was calculated from analysing oil change frequencies and lube oil capacities from a number of representative trucks.

Fuel savings were translated into economic benefits by making assumptions regarding fuel prices. These are notoriously difficult to predict with high confidence.

Further complexity arises because the volatile commodity price is given in $ per barrel, whereas what is important for the EU market depends on the Euro/$ exchange rate for many countries, but not all. Further, for policy assessments (i.e. 'social perspective' analysis), e.g. as undertaken by the European

[52] Consultation with economists experts have indicated that the analysis undertaken is of incremental costs and the benefit they potentially deliver, not "marginal" costs.

Commission it is net cost that is important to the policy makers, they see taxes as merely a moving of money between organisations/government. Whereas for an operator, it is the cost that they see that determines their behaviour. However, this too is not simple. For many organisations, where they buy and sell "goods or services" the VAT costs incurred are off-set by the VAT receipts they earn. Consequently, their costs include the fuel duty but not the VAT.

For this study, we follow the approach that would be followed by the policy makers, quoting costs net of VAT and taxes. However, to aid the conversion between different analytical approaches EU average duty and tax levels are explicitly given.

The fuel price projections used in some recent European Commission studies come from the PRIMES-TREMOVE model, using the reference scenario data[53],[54]. This is the scenario used for the EC DG CLIMA Lightweighting study, (Hill et al, 2015). The fuel price (€ /litre excluding excise duty and VAT) for this reference scenario is summarised in Table 5.8.

Table 5.8: Fuel price (€/l) - Excl. excise duty and VAT for the reference price scenario from PRIMES-TREMOVE model

	2010	2015	2020	2030	2040	2050
Reference price scenario (excl. taxes)	0.652	0.869	0.889	0.924	0.997	1.055
Reference price (incl. taxes)	1.103	1.147	1.190	1.234	1.277	1.320

The EU average fuel duty and VAT can be obtained from other sources[55]. From the analysis of these data it is found the fuel price with excise and VAT is 225% of the base fuel cost (declining over time as is assumed fuel duty remains constant). This immediately shows a challenge with the EU Reference Scenario, because the reference prices went from 1.47 €/litre in 2010, (actual average was €1.17, 80% of this EU Reference Scenario) to 1.96 €/litre in 2015, (actual average was €1.24, 63% of this EU Reference Scenario). However, after this abrupt rise in 2015, 33% increase in 5 years, the EU reference Scenario predicts only a 21% rise in the 35 years between 2015 and 2050 (in €2015). Other fuel price scenarios could be devised and analysed. The principal impact of changes in fuel price, in particular on going from the EU Reference Scenario to the real average 2015 price, is to increase the payback period.

In order to evaluate the compounded fuel savings, each technology was considered independently from the others. Where some technologies were mutually exclusive, the ones generating the maximum savings potential were taken into account (i.e. Two-stage Turbocharging among the air handling technologies, the futuristic aerodynamic configuration and full hybridisation for panel vans).

The cumulative incremental fuel consumption reduction against incremental costs for the technologies is given in Table 5.10 to Table 5.12 for the panel vans, rigid box-trucks and tractor-trailer combination segments for the individual technologies. (For tractor-trailer combinations the data are relative to the standard baseline vehicle, not the premium or economy baselines.) Taking account of the factors above, the cumulative incremental fuel consumption reduction against incremental costs for the technologies are shown in Figure 5.1 to Figure 5.3. The technologies are arranged into nine groups, each given a separate colour, to simplify the figure legend but without losing any detail. The groups are:

- Light-weighting;
- Engine, including friction reduction and the use of low viscosity oils;
- Aerodynamic drag improvement;
- Air handling and EGR;
- Low rolling resistance tyres;

[53] The PRIMES-TREMOVE model was developed by E3MLab, Athens, under contract to the European Commission. It projects the evolution of demand for passengers and freight transport by transport mode and transport mean, based on economic, utility and technology choices of transportation consumers, and projects the derived fuel consumption and emissions of pollutants. Operation costs, investment costs, emission costs, taxes and other public policies, utility and congestion influence the choice of transportation modes and means. A more detailed description is available from: http://ec.europa.eu/clima/policies/strategies/analysis/models/docs/primes_tremove_en.pdf

[54] A description of the 2013 Reference Scenario, relevant to Energy, Transport and GHG emissions out to 2050 is given in http://ec.europa.eu/transport/media/publications/doc/trends-to-2050-update-2013.pdf

[55] Fuel prices over the past 11 years with and without taxes are given in http://ec.europa.eu/energy/observatory/reports/Oil_Bulletin_Prices_History.xls

- Waste heat recovery;
- Transmission improvements;
- Management.

The other assumptions, such as on activity and lifetime, are also summarised in Table 5.9 below.

Table 5.9: Other input assumptions used in the incremental cost calculations

Mode	Service truck	Regional delivery truck	Long haul tractor-trailer (Average)
Baseline fuel consumption (L/100 km)	15.8	24.9	35.7
Annual mileage (km)	35,000	60,000	130,000
Vehicle lifetime (years)	12	12	10
CO_2 EF (kgCO_2/L fuel)	2.67	2.67	2.67
Annual fuel consumption (L)	6,335	14,400	47,320
Annual CO_2 emissions (kg)	16,914	38,448	126,344

5.3.2 Analysis for panel van (urban delivery) segment

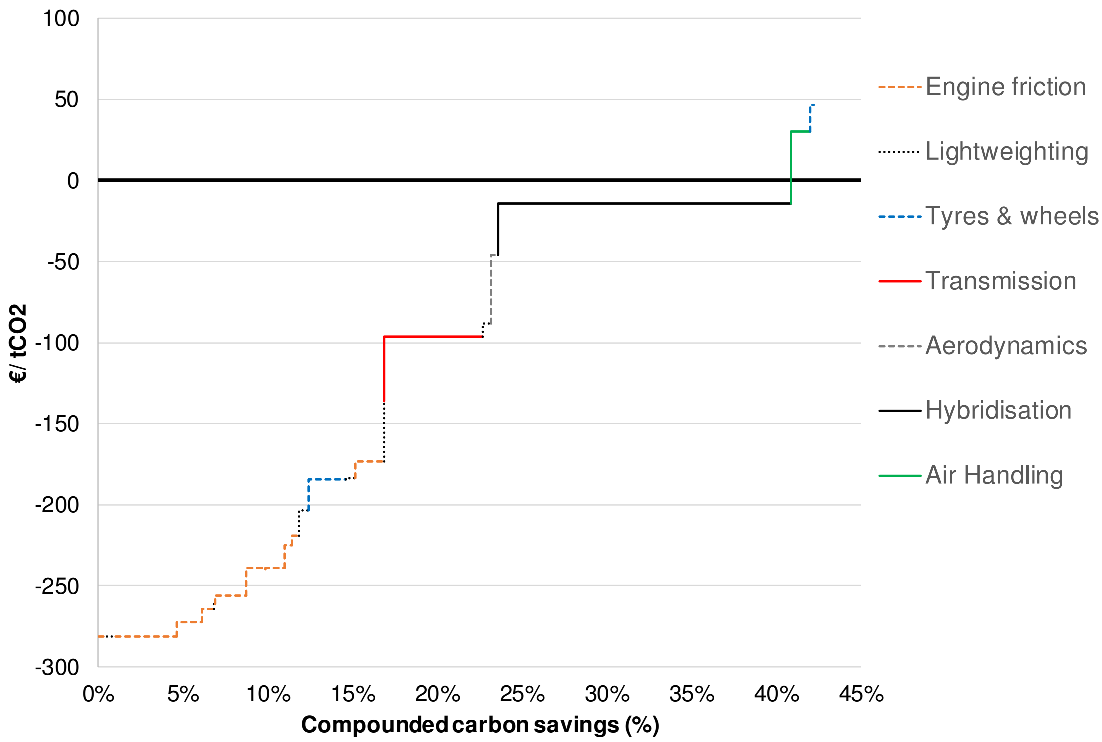
Table 5.10 contains the incremental cost-fuel consumption reduction potential curve for the 7.0 t GVW panel van. This segment differs from the tractor-trailer combinations in the following aspects:

- This vehicle segment uniquely includes the full hybrid technology;
- The transmission upgrade is from a manual (MT) to automated manual transmission (AT), rather than merely increasing the number of gears available*;
- Because light-weighting is more important, light-weighting of seats, glazing and fuel is added;
- Also engine encapsulation is included whereas waste heat recovery is excluded.

* *Note*: AMT is mutually exclusive with the hybrid system, and this is accounted for in the cost-curves.

The data are shown as a "simplified" graph in Figure 5.1. This is plotted with the most cost-effective aspect on the left, and the least cost-effective on the right. However, it is seen in Table 5.10 there are 20 different categories of technologies, making the resulting graph difficult to read. Therefore, the 20 different technology categories were grouped (e.g. with six technologies being labelled "Engine technologies") for better clarity. The greater detail is provided in the corresponding tabulated data.

Figure 5.1: Incremental cost-fuel consumption reduction potential curve for panel van for 2030



From the data it is seen the largest potential savings come from full hybrid technology (28.0% minus the saving for AMT), going to an automated manual transmission (AMT, 7%), from some engine friction reduction technologies (3.7%) and from the use of low viscosity oils (2.5%). The use of stop-start technology in place of full hybridization (i.e. the use of mild hybridisation) would replace the hybrid savings with 4%[56].

The compounded effect of all the measures are calculated to be a fuel consumption reduction potential of 43.3%, relative to the baseline vehicle, whose characteristics are given in Table 3.2. This would improve the fuel economy from 15.8 litres/100 km to 8.96 litres/100 km for the urban delivery cycle.

In terms of the 2030 cost-effectiveness, Figure 5.1 shows that all measures except improved air handling, TPMS and light-weighting options costing more than €5 per kg weight saved generate a net benefit over the twelve-year lifetime of the vehicle with the financial assumptions used for the base-case analysis. However, if the maximum acceptable payback period was set at 5 years, then the compounded fuel consumption reduction potential would be restricted to 16.5% and many measures would not be deemed cost-effective, including upgrading the gear box, and the introduction of a full hybrid.

These cost calculations do not assign a monetary value to the CO_2 emitted. Ascribing a value to the CO_2 emitted would increase technology cost effectiveness and reduce the payback period of all scenarios evaluated in this study. Cost effectiveness and payback as defined in this study are strictly based on consumer expenditures and reflect the point at which such expenditures are either negative (consumer savings), zero (no net change in consumer costs), or positive (increased consumer cost).

These "payback" calculations are sensitive to the financial assumptions made in the analysis. If the discount rate was increased from 4% to 8%, then the introduction of a full hybrid system would not generate a payback within 12 years. However, if the fuel price was increased at the same time, to include tax and duty which would need to be paid by a vehicle operator, then the payback occurs after 7.28 years rather than the 9.61 years found for the financial base-case analysis.

[56] Consultation with Ricardo hybrid technology experts indicated that a theoretical start-stop system may achieve 2 – 5% fuel consumption reduction, although it is very dependent on the duty cycle. For the urban delivery cycle for a panel van, we have interpreted this as a potential fuel consumption reduction of 4%.

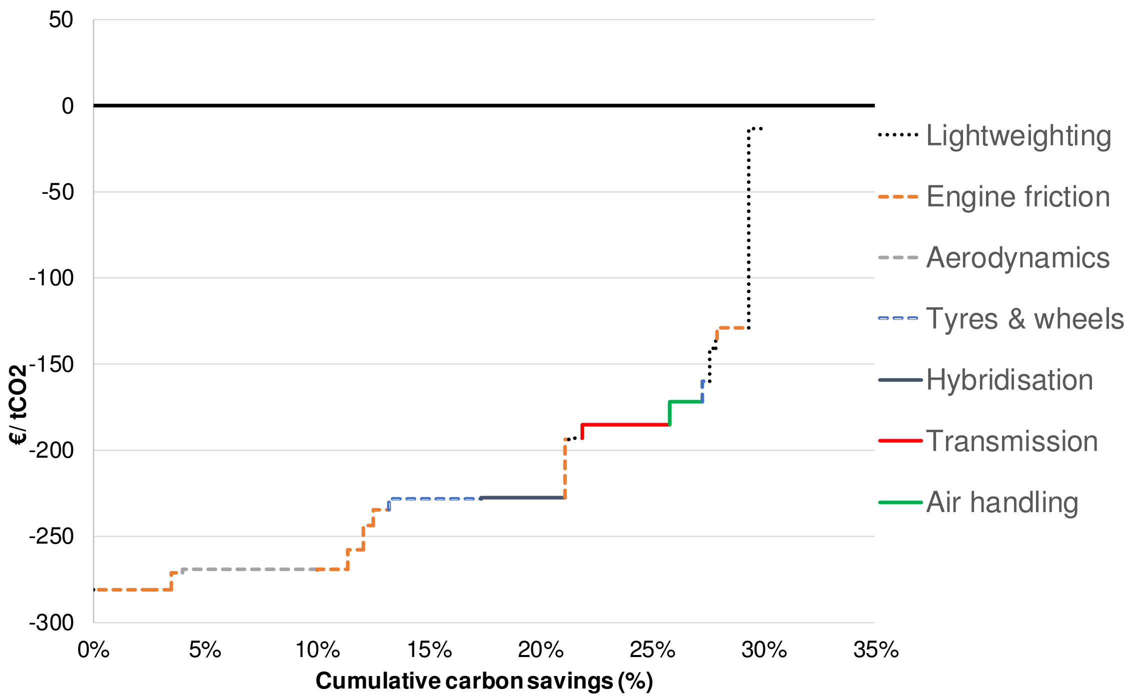
5.3.3 Analysis for rigid box-van vehicle segment

Table 5.11 contains the incremental cost-fuel consumption reduction potential analysis for the rigid box-truck. This segment differs from the tractor-trailer combination segment in the following aspects:

- The transmission upgrade is from a manual to automated gearbox, rather than merely increasing the number of gears available;
- The light-weighting of seats and glazing is added, whereas engine light-weighting is omitted;
- Waste heat recovery is excluded.

The data are shown as an incremental cost-fuel consumption reduction potential graph in Figure 5.2.

Figure 5.2: Incremental cost-fuel consumption reduction potential curve for the rigid box-truck for 2030



From the data it is seen the largest potential savings come from improved aerodynamics (6.3%), the fitting of AMT, rather than a manual gearbox (5.0%), low rolling resistance tyres (4.8%), the fitting of non-integrated mild hybridisation, with start-stop (4.8%) and some engine friction reduction technologies (2.3%). The compounded effect of all the measures are calculated to be a fuel consumption reduction potential of 31.5%, relative to the baseline vehicle, whose characteristics are given in Table 3.3. This would improve the fuel economy from 24.9 litres/100 km to 17.1 litres/100 km for the European rigid box-truck segment.

In terms of the 2030 cost-effectiveness, Figure 5.2 shows that all but light-weighting options costing more than €5 /kg weight saved generate a net benefit over the ten-year lifetime of the vehicle. However, if the maximum acceptable payback period was set at 5 years, then the compounded fuel consumption reduction potential would be little affected (27.6%) for this financial base-case. If a payback period of 2 years was demanded, the compounded fuel consumption reduction potential would be restricted to 23.2% because for this pay-back cut off even upgrading from AT to AMT, improved air handling and the use of low viscosity lube oil would not occur, and the 5.0%, 2.0% and 2.0% fuel consumption reduction potentials associated with these technologies are lost.

Table 5.10: Incremental cost-fuel consumption reduction potential data for the panel van for 2030

Technology	Cumulative CAPX (€)	Fuel savings per technology (%)	Compounded savings (%)	Incremental cost (€/tCO₂)	NPV (€)	Payback (years)	Cumulative lifetime emission savings (tCO₂)
Other thermal management technologies (En)	0	0.50%	0.50%	-281.5	249.35	0.0	0.9
Euro/kg saved = 0 (Li)	0	0.50%	0.99%	-281.5	247.68	0.0	1.8
Unspecified FMEP improvement (En)	0	3.70%	4.66%	-281.5	1845.17	0.0	8.3
Engine encapsulation (En)	25	1.50%	6.09%	-272.1	723.04	0.3	11.0
Bypass oil cooler (En)	50	0.80%	6.84%	-263.8	373.96	0.6	12.4
Euro/kg saved >0 - 1 (Li)	51	0.03%	6.87%	-261.5	13.26	0.7	12.4
Variable oil pump (En)	141	2.00%	8.73%	-256.1	907.39	0.9	16.0
Electric steering pump (En)	236	1.27%	9.89%	-239.2	538.34	1.5	18.2
Variable coolant pump (En)	326	1.20%	10.97%	-239.1	508.43	1.5	20.4
Electric cooling fan (En)	376	0.50%	11.41%	-225.0	199.35	2.1	21.3
High efficiency electric air conditioning (En)	431	0.50%	11.86%	-219.4	194.35	2.3	22.1
Euro/kg saved 1 - 2 (Li)	522	0.66%	12.44%	-203.5	238.83	2.9	23.3
Euro/kg saved 2 - 3 (Li)	633	0.64%	13.00%	-184.2	209.79	3.7	24.5
Low-rolling resistance tyres (Ty)	633	2.50%	15.18%	-184.0	815.02	Note 1	27.9
Low viscosity oils (En)	633	2.00%	16.87%	-173.0	613.07	Note 1	31.5
Euro/kg saved 3 - 4 (Li)	636	0.01%	16.88%	-150.1	2.94	5.0	31.5
AT (Tr)	2,936	7.00%	22.70%	-96.0	1190.86	7.4	43.9
Euro/kg saved 4 - 5 (Li)	3,138	0.59%	23.16%	-89.0	93.38	7.7	44.9
Futuristic (Ae)	3,388	0.60%	23.62%	-46.3	49.22	9.7	46.0
Full hybrid (Hy)	14,088	22.58%	40.87%	-14.0	560.85	11.3	86.0
Improved air handling (Ai)	15,138	1.90%	41.99%	30.4	-102.48	>12 years	89.4
TPMS (Ty)	15,388	0.43%	42.24%	46.7	-35.56	>12 years	90.1
Euro/kg saved 5 - 10 (Li)	17,444	2.27%	43.55%	229.7266	-923.96	>12 years	94.2

Note 1: For low viscosity oils and low-rolling resistance tyres rather than an up-front capital cost, there is an operational cost, which is dependent on mileage, and cost for each service, or replacement set of tyres. This is summed over the vehicle's lifetime, generating an equivalent lifetime CAPX cost, from which an NPV and payback period is calculated.

Table 5.11: Incremental cost-fuel consumption reduction potential data for the rigid box-truck for 2030

Technology	Cumulative CAPX (€)	Fuel savings per technology (%)	Compounded savings (%)	Incremental cost (€/tCO_2)	NPV (€)	Payback (years)	Cumulative lifetime emission savings (tCO_2)
Euro/kg saved = 0 (Li)	0	0.22%	0.22%	-281.5	296.4	0.0	1.1
Unspecified FMEP improvement (En)	0	2.30%	2.51%	-281.5	3098.8	0.0	12.1
Other thermal management technologies (En)	0	1.00%	3.49%	-281.5	1347.3	0.0	16.8
Bypass oil cooler (En)	25	0.50%	3.97%	-271.0	648.6	0.4	19.2
Futuristic (Ae)	400	6.30%	10.02%	-269.0	8112.9	0.45	49.4
Variable oil pump (En)	490	1.50%	11.37%	-268.9	1930.9	0.5	56.6
Variable coolant pump (En)	580	0.80%	12.08%	-258.0	987.8	0.8	60.4
Electric cooling fan (En)	670	0.50%	12.52%	-243.9	583.6	1.4	62.8
Electric steering pump (En)	850	0.80%	13.22%	-234.5	897.8	1.7	66.6
Low-rolling resistance tyres (Ty)	850	4.80%	17.39%	-228.4	5246.9	Note 1	89.6
Mild hybrid (Hy)	2010	4.50%	21.10%	-227.6	4902.8	2.0	111.1
High efficiency electric air conditioning (En)	2115	0.25%	21.30%	-193.7	231.8	3.3	112.3
Euro/kg saved 1 - 2 (Li)	2415	0.71%	21.86%	-193.2	656.6	3.3	115.7
AT (Tr)	4715	5.00%	25.77%	-185.4	4436.4	3.6	139.7
Improved air handling (Ai)	5765	2.00%	27.25%	-171.8	1644.6	4.2	149.3
TPMS (Ty)	6015	0.43%	27.56%	-160.0	329.3	4.6	151.3
Euro/kg saved 2 - 3 (Li)	6310	0.44%	27.88%	-141.4	297.8	5.4	153.4
Euro/kg saved 3 - 4 (Li)	6317	0.01%	27.89%	-135.2	6.5	5.7	153.5
Low viscosity oils (En)	6317	2.00%	29.33%	-129.2	1236.9	Note 1	163.0
Euro/kg saved 4 - 5 (Li)	7740	1.11%	30.12%	-13.6	72.5	11.3	168.4
Euro/kg saved 5 - 15 (Li)	15350.0	1.93%	31.47%	823.7	-7610.0	>12 years	177.6

Note 1: For low viscosity oils and low-rolling resistance tyres see the footnote to Table 5.10.

Table 5.12: Incremental cost-fuel consumption reduction potential data for the tractor-trailer combinations for 2030

Technology	Cumulative CAPX (€)	Fuel savings per technology (%)	Compounded savings (%)	Incremental cost (€/tCO_2)	NPV (€)	Payback (years)	Cumulative lifetime emission savings (tCO_2)
Unspecified FMEP improvement (En)	0	1.40%	1.40%	-290.0	5025.6	0.00	17.3
Other thermal management technologies (En)	0	2.00%	3.37%	-290.0	7179.5	0.00	42.1
Euro/kg saved = 0 (Li)	0	0.33%	3.69%	-290.0	1184.6	0.00	46.2
Variable oil pump (En)	90	1.00%	4.65%	-282.7	3499.7	0.22	58.5
Bypass oil cooler (En)	115	0.20%	4.84%	-279.9	692.9	0.30	61.0
Variable coolant pump (En)	205	0.50%	5.32%	-275.5	1704.9	0.44	67.2
Futuristic (Ae)	2,205	10.60%	15.36%	-274.8	36051.3	0.46	198.4
Predictive cruise control (Ma)	2,845	2.00%	17.05%	-264.2	6539.5	0.78	223.2
Electric cooling fan (En)	3,025	0.50%	17.46%	-260.9	1614.9	0.87	229.4
Improved air handling (Ai)	4,075	2.50%	19.53%	-256.1	7924.4	1.02	260.3
Euro/kg saved >0 - 1 (Li)	4,128	0.09%	19.60%	-242.4	270.1	1.44	261.4
Low-rolling resistance tyres (Ty)	4,128	5.10%	23.70%	-236.1	14901.1	Note 1	324.5
Increase # gears in AMT (Tr)	5,628	1.67%	24.97%	-217.5	4494.9	2.23	345.2
Turbocompounding (Ai)	7,428	2.00%	26.48%	-217.3	5379.5	2.23	370.0
Euro/kg saved 1 - 2 (Li)	7,728	0.33%	26.72%	-216.6	884.6	2.25	374.1
Organic Rankine cycle (Wa)	12,728	4.50%	30.02%	-200.3	11153.9	2.78	429.7
TPMS (Ty)	13,203	0.42%	30.31%	-198.6	1032.7	2.83	434.9
Electric steering pump (En)	13,563	0.28%	30.50%	-186.1	645.1	3.23	438.4
Euro/kg saved 2 - 3 (Li)	13,603	0.02%	30.52%	-128.4	31.8	5.18	438.7
High efficiency electric air conditioning (En)	13,813	0.10%	30.59%	-120.4	149.0	5.47	439.9
Low viscosity oils (En)	13,813	1.00%	31.28%	-72.9	902.1	Note 1	452.3
Euro/kg saved 4 - 5 (Li)	15,845	0.65%	31.73%	-37.5	301.3	8.52	460.3
Euro/kg saved 5 - 10 (Li)	24,596	1.88%	33.01%	86.0	-2002.3	>10 years	483.6

Note 1: For low viscosity oils and low-rolling resistance tyres see the footnote to Table 5.10.

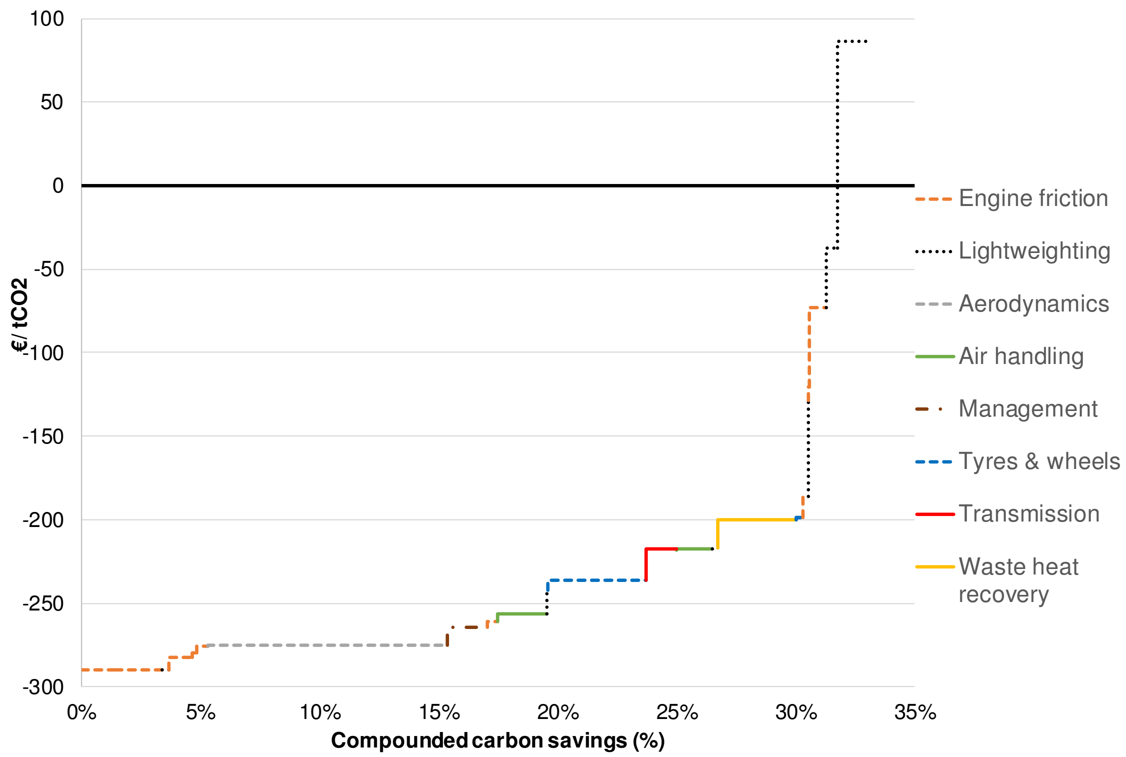
5.3.4 Analysis for tractor-trailer combinations

Table 5.12 contains the incremental cost-fuel consumption reduction potential analysis for the long-haul tractor trailer relative to the baseline 2015 European vehicle. This segment differs from the panel van and rigid box-trucks in the following key aspects:

- Waste heat recovery is included;
- Hybridisation options are excluded.

The data are shown graphically in Figure 5.3.

Figure 5.3: Incremental cost-fuel consumption reduction potential curve for long haul tractor-trailer (relative to average European 2015 truck)



From the data it is seen the largest potential savings come from aerodynamics (10.6%), low rolling resistance tyres (5.1%) waste heat recovery (4.5%), and using improved air handling (2.5%).

The compounded effect of all the measures are calculated to be a fuel consumption reduction potential of 33.0%, relative to the baseline vehicle, whose characteristics are given in Table 3.4. However, this does not include vehicle management opportunities like vehicle platooning, with the exception of for predictive cruise control.

In terms of cost-effectiveness Figure 5.3 shows that all options generate a net benefit over the ten-year lifetime of the vehicle except for light weighing options costing more than €5 /kg weight saved. However, if the maximum acceptable payback period was set at 5 years, then the compounded fuel consumption reduction potential would be slightly lower, 30.52% with only some further light-weighting options not being deemed cost-effective. For a payback period of 2 years, the compounded fuel consumption reduction potential would be restricted to 23.70% because other technologies, most notably turbo-compounding and waste heat recovery would cease to be included. (As noted in Section 5.3.2 the "payback" calculations are sensitive to the financial assumptions made in the analysis.)

A fuel consumption reduction potential of 33.1%, relative to the baseline vehicle would improve the fuel economy from 35.66 litres/100 km to 23.89 litres/100 km.

5.4 Summary of cost-effectiveness and pay back periods

A summary table for the full fuel saving potential for different technologies for the three vehicle segments is given in Table 5.13. The cost-effectiveness potential under various payback period assumptions are summarised in Table 5.14.

Table 5.13: Summary of 2030 fuel saving potential for different technologies for the three vehicle segments

Individual technologies	Panel van	Rigid box-truck	Tractor-trailer combination
Unspecified FMEP improvement (En)	3.70%	2.30%	1.40%
Variable oil pump (En)	2.00%	1.50%	1.00%
Variable coolant pump (En)	1.20%	0.80%	0.50%
Bypass oil cooler (En)	0.80%	0.50%	0.20%
Low viscosity oils (En)	2.00%	2.00%	1.00%
Electric cooling fan (En)	0.5%	0.5%	0.5%
Electric steering pump (En)	1.27%	0.80%	0.28%
High efficiency electric air conditioning (En)	0.50%	0.25%	0.10%
Improved air handling (Ai)	1.90%	2.00%	2.50%
Engine encapsulation, or waste heat recovery (En)	1.50% (EC)	0%	4.50% (WHR)
Other thermal management technologies (En)	0.5%	1.0%	2.0%
Transmissions (Tr)	7.00%	5.00%	1.67%
Hybridisation: Full hybrid or integrated mild hybrid with stop-start (Hy)	22.58% (FH) Note 1	4.50% (IMH+SS)	N/A
Futuristic (Ae)	0.60%	6.30%	10.60%
Lightweighting - Euro/kg saved 0 - 1 (Li)	0.53%	0.22%	0.42%
Lightweighting - Euro/kg saved 1 - 2 (Li)	0.66%	0.71%	0.33%
Lightweighting - Euro/kg saved 2 - 3 (Li)	0.64%	0.44%	0.02%
Lightweighting - Euro/kg saved 3 - 4 (Li)	0.01%	0.01%	
Lightweighting - Euro/kg saved 4 - 5 (Li)	0.59%	1.11%	0.65%
Lightweighting - Euro/kg saved 5 - 15 (Li)	2.27%	1.93%	1.88%
Low-rolling resistance tyres (Ty)	2.50%	4.80%	5.10%
TPMS (& ATIS) (Ty)	0.43% (0.52%)	0.43% (0.52%)	0.42% (0.50%)
Overnight hoteling and vehicle management technologies	0%	0%	2.0%
Overall compounded savings potential	**43.55%**	**31.47%**	**33.01%**

Note 1: Reduce to avoid double counting with the fuel savings potential from the change in transmission from MT to AMT

Table 5.14: Summary of the 2030 cost-effectiveness potential under various payback period assumptions for different technologies for the three vehicle segments

Individual technologies	Panel van		Rigid box-truck		Tractor-trailer combination	
Discount rate	**4%**	**8%**	**4%**	**8%**	**4%**	**8%**
Total of compounded potential savings from all technologies	43.6%	43.6%	31.5%	31.5%	33.0%	33.0%
Total of compounded potential savings from all technologies with payback period of 5 years	16.9%	16.1%	27.6%	26.5%	30.5%	30.5%
Total of compounded potential savings from all technologies with payback period of 2 years	11.4%	11.0%	21.1%	17.4%	23.6%	23.6%

Figure 5.4: Summary of the 2030 cost-effectiveness potential under various payback period assumptions for different technologies for the three vehicle segments

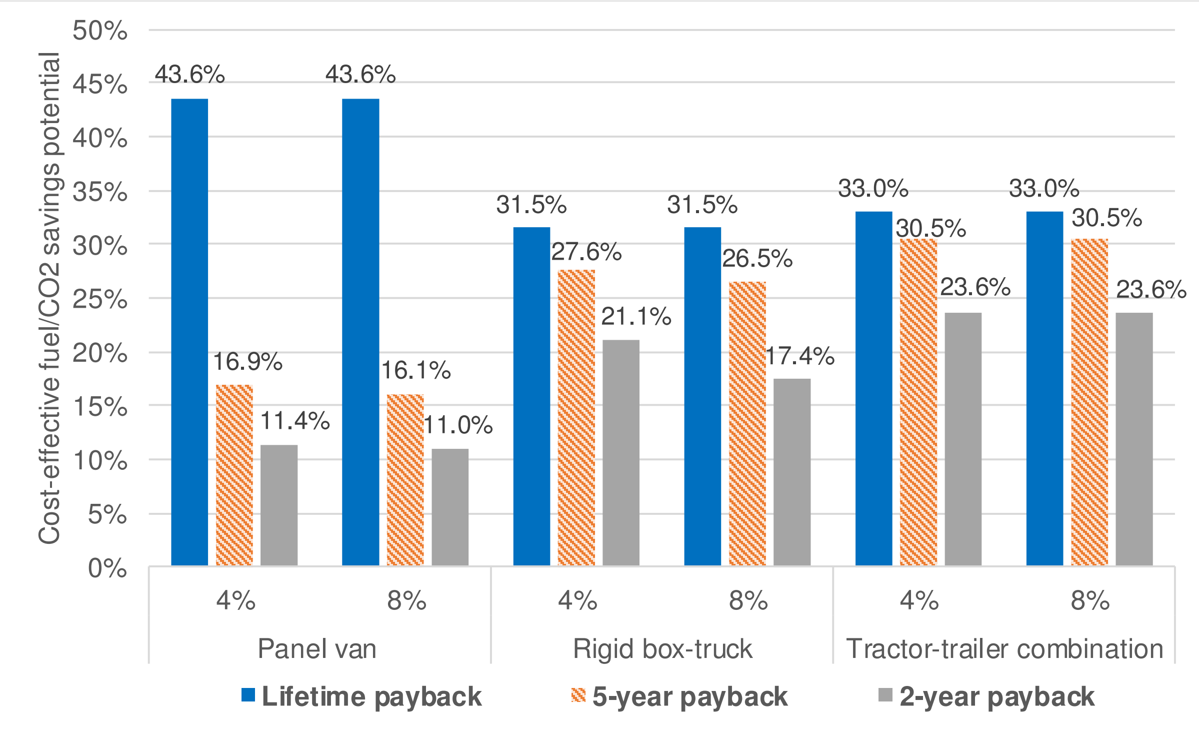


Table 5.14 and Figure 5.4 indicates the extent to which the payback calculations are sensitive to the financial assumptions made in the analysis. One aspect where the payback period changes from within, to outside, the expected life of the vehicle is for full hybridisation of the panel van. If the discount rate was increased from 4% (for the social perspective) to 8% (the typical rate for private/end-user investments), then the introduction of a full hybrid system would not generate a payback within 12 years.

It is also the case that the discount rate is not the only financial assumption that markedly affects the perceived economics of potential fuel reduction technologies. Their financial viability is also very sensitive to fuel price. If the fuel price was effectively doubled at the same time as the discount rate was increased from 4% to 8%, to include tax and duty which would need to be paid by a vehicle operator, then the payback period for the fitting of a full hybrid system to a panel van would occur after 4.88 years rather than the 9.38 years found for the financial base-case analysis.

6 Stakeholder consultation

Consultation, and also later peer-review, with engineering experts and some selected stakeholders were used to complement the review of previous studies, and the analysis of the data obtained. The primary purpose of these was to explore the full potential that future technologies in engine, transmission, aerodynamics, tyre, etc. have to enter the market within the 2020-2030 timeframe. The views generated are complementary to the information obtained from the literature review.

Many of the experts consulted were experienced engineering consultants within Ricardo, who have worked with OEMs and Tier 1 suppliers addressing challenges, and improving the efficiency, of aspects of the heavy-duty trucks. This was a deliberate strategy because these experts have an oversight often of several or many companies' perspective. A list of the consultations is given in Table 6.1, organised by technical area following the structure of Chapter 4 on individual technologies.

Table 6.1: Consultations undertaken as part of this study

Technical area	Extent of consultation	Organisation
Engine efficiency: Overall characteristics	Two experts One expert	Ricardo Cummins
Engine efficiency: Friction (Note 1)	Two experts One expert	Ricardo Cummins
Engine efficiency: air handling (turbo-charging and EGR)	Two experts One expert	Ricardo Cummins
Engine efficiency: waste heat recovery & thermal management	One expert	Ricardo
Engine efficiency: Overall	Two experts One expert	Ricardo Cummins
Transmission & driveline	One expert	Ricardo
Hybridisation	Two experts One expert	Ricardo Eaton
Aerodynamics (Note 2)	Two experts One expert One expert	Ricardo Don-Bur Trailers WABCO
Lightweighting	One expert	Ricardo
Tyres & wheels	One expert Two experts	Ricardo Michelin
Vehicle management technologies	Reports prepared for SARTRE EU project	Ricardo
Overall fleet efficiency	One expert One expert	UK Freight Transport Association NA Council for Freight Efficiency

Notes to Table 6.1:

Note 1 Because friction is cross technology, changes in FMEP were covered in a number of other consultations

Note 2 Consultations on aerodynamics comprised both overall, qualitative discussions and quantitative discussions regarding the range of drag factors and cross-sectional areas for the various vehicle segments that Ricardo have used relatively recently when undertaking whole vehicle simulation modelling.

In addition to the experts with detailed knowledge in a relatively narrow field, the project benefitted from ongoing discussions with O Delgado, R Muncrief and F Rodriguez of the ICCT.

7 Conclusions and discussion

7.1 Conclusions of the fuel consumption reduction potential and its cost-effectiveness from this study

7.1.1 Purpose of project and role of consultation

The work programme has found the technology potential, and costs, of fuel consumption reduction technologies suitable for heavy duty vehicles by 2030, relative to European 2015 baseline vehicles. This was from a combination of published studies, in particular United States (US) research that underpins the US Phase 2 rulemaking, new European and US studies, and consultations with technology and vehicle experts. A list of the consultations in terms of the experts and area(s) of technology expertise are given in Chapter 6.

7.1.2 Definition of vehicle segments

The technology potentials and costs were detailed for three vehicle segments:

- **Rigid panel vans** between 3.5 and 7.5 tonnes gross vehicle weight (GVW), which undertake urban delivery (or service) activities;
- **Rigid box-trucks** around 12 tonnes GVW, which undertake regional delivery activities;
- **Tractor-trailer combinations** typically of 40 tonnes GVW, which undertake long haul journeys.

7.1.3 Baseline vehicles

Baseline vehicles were defined for the three vehicle segments for both the US and European markets. The detailed characteristics of the US vehicles were taken principally from the EPA studies. For Europe an iterative process was used, starting with literature information which was then refined with views of experts. The refined information was then checked further with additional literature searching and consultations. This enabled many parameters to be characterised, but not fuel consumption, for which little European data is given in standard databases and references. Appendix 1 details the information that was reviewed to obtain the baseline values given for fuel consumption. Much of this is expressed in terms of CO_2 emissions per km, and this has been translated, as detailed in Appendix 1, into corresponding fuel consumption data (litres per 100 km).

Key differences between US and EU baseline vehicles include:

- **Panel vans**: Fundamentally different vehicles with the European vehicle being a panel van, whereas US “service” vehicle investigated by SWRI was a heavy-duty pickup truck or a van.
- **Rigid box-trucks:** Superficially quite similar vehicles, both being rigid box cargo trucks. However, there are differences, as highlighted in Table 3.3, which lead to marked differences for their in-use fuel consumption per vehicle km. This is calculated to be around 31% higher for the European vehicle (from a VECTO simulation) compared with the EPA/NHTSA RIA value. The 15% lower typical payload for the US vehicle means that fuel consumption per tonne-km is around 11% lower for the US vehicle.
- **Long haul tractor trailer combination vehicles:** Table 3.4 details some marked differences between the European and US baseline vehicles, but overall the vehicles are moderately similar. However, the fuel economy for tractor-trailer combinations for the European segment (35.7 litres/100km) was around 21% lower than for its US equivalent (43.1 litres/100 km). This was principally caused by different average speeds over long-haul operations rather than any major differences between the two baseline vehicles.

  However, there is a major difference in the load carrying capacity of the two vehicles, it being 3,713 kg (8,000 lb) greater for the European vehicle. This is reflected in the typical payloads, 19.3 t for the European tractor-trailer combination, around 2 tonnes more than for the US truck. This increases the difference in the fuel consumption per 100 km per tonne of payload to 35%, (it being 1.848 litres /100 tonne km for Europe, and 2.50 litres /100 tonne km for US.

It was also noted that there is considerable diversity in the characteristics of long haul tractor trailer combinations. Therefore, in addition to an “average” European tractor-trailer combination, characteristics for “premium” and “economy” vehicles were also given. For these vehicles, fuel consumption was 31.6 and 38.7 litres/100 km, respectively, straddling the 35.7 litres/100km figure for the “average” vehicle (all three vehicles have similar payload capacities and fuel consumption per tonne of payload follow the patterns for the whole vehicle).

7.1.4 Fuel efficiency improvement technologies

The potential of fuel consumption reduction technologies was considered, for the technologies separately, and in combinations (i.e. considering potential overall engine, transmission and vehicle technology improvements). When considering the improvement potential reported in the EPA Phase 2 studies, allowance was made for translation from US to European markets. Two key influences were considered:

a. Differences between the baseline vehicles, (covered above); and
b. Differences in usage patterns/driving characteristics for the two geographic areas – which for tractor-trailer combinations undertaking long-haul journeys are principally caused by the higher permitted speeds in the US relative to Europe (where HDVs are limited to 90 km/h).

In addition to the fuel consumption reduction potentials of the technologies, their capital costs, or operational costs for tyres and low viscosity lube-oils, were collected.

7.1.5 Technology applicability

Overall it was found that nearly all of the technologies that the US studies included in the regulatory impact analysis (EPA RIA, 2016) could be applied to European baseline trucks and the fuel-consumption reduction potentials that they bring are substantial. Notwithstanding there are some marked differences in the reduction potentials. These arise principally for the following reasons:

- For some technologies, e.g. transmissions, the differences between the baseline vehicle technologies mean that the European technology potential (for two panel vans and rigid-box trucks) are larger than for the US potentials.
- For other technologies, e.g. aerodynamics and rolling resistance, the slightly more advanced European baseline vehicles, mean that the European technology potential (for tractor-trailer combinations) are smaller than for the US potentials.
- For vehicle usage patterns vary systematically between the US and Europe, with the principal difference being the 90 kph upper speed limit in Europe, where as in the US truck maximum speed limits for the interstate roads (which are set by individual states) are generally 112 kph (70 mph) for most of the US but 120 – 128 kph (76 – 80 mph) for the central and west US area except California and Oregon[57]. This leads to systematically different technology needs, especially for tractor-trailer combinations undertaking long haul operations, and systematically different technology potentials, especially for improved aerodynamics.

7.1.6 Impact of fuel price

The cost of fuel to users/operators is significantly higher in Europe than the US, principally because of the duties and taxes levied on fuels. Practically this has encouraged the uptake of some fuel consumption reduction technologies relative to the US, driven by their commercial attractiveness. This is seen by some systematic differences in the baseline vehicle data.

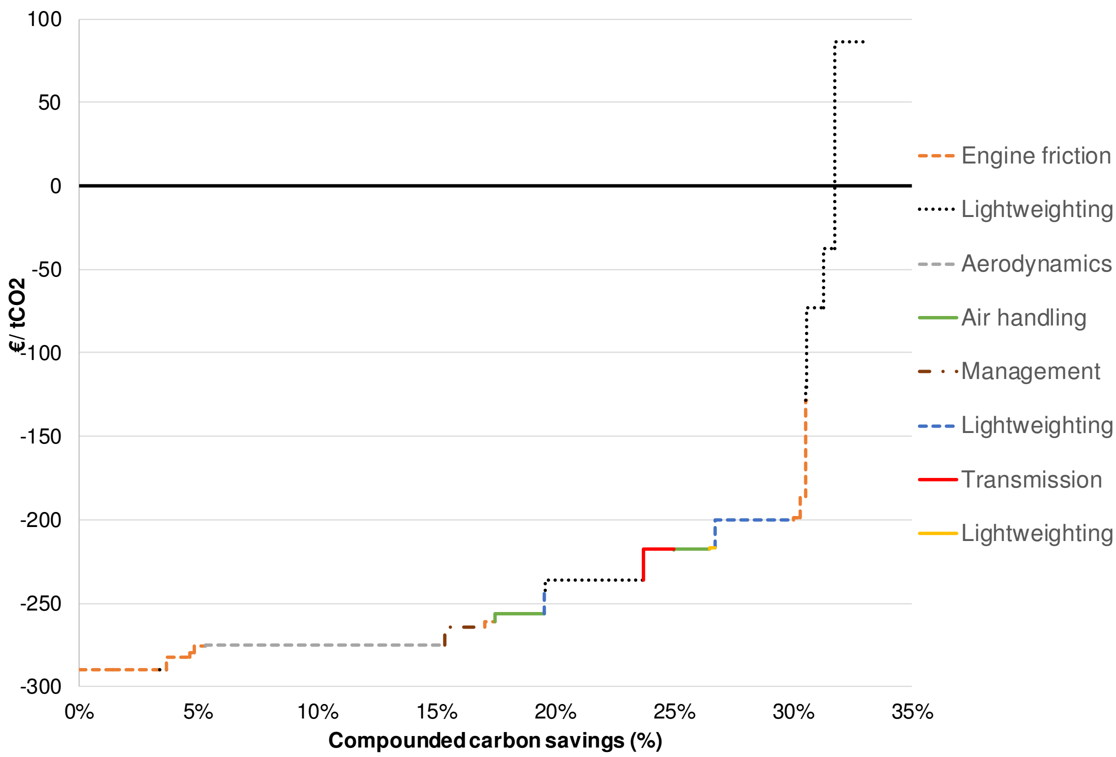
When assessing the cost-effectiveness of technologies, the cost of fuel is a key component, since the capital (or operational) costs are offset by the cost of the fuel not used. However, the incremental cost-fuel consumption reduction potential analysis undertaken uses the Social Discount Rate, i.e. the lower rate (typically ~4% at the European level) applied when considering investments at the society level (i.e. vs private) with the fuel price also excluding taxes and duties. Because of the high levels of fuel duty and taxes, this will systematically overestimate the time required for a technology to produce a net positive return on the capital investment of new technologies when considering the end-user perspective, though the higher discount rates (e.g. 8%) seen by private companies will counteract this.

[57] State truck speed limits on their interstate taken from http://www.iihs.org/iihs/topics/laws/speedlimits/mapmaxspeedonruralinterstates?topicName=Speed

7.1.7 Results from incremental cost-fuel consumption reduction potential analysis

The incremental costs and fuel consumption reduction potentials of individual technologies were assessed. This enabled the development of incremental costs/fuel consumption reduction curves for each vehicle segment. The figure below (identical to Figure 5.3) shows the incremental cost-potential fuel reduction curve for the tractor-trailer combination (with the component data being given in Table 5.12). This shows that overall the compounded savings potential, relative to the 2015 baseline vehicle, is 33% on a social cost perspective (at 4% discount rate and excluding fuel taxes).

Figure 7.1: Incremental cost-fuel consumption reduction potential curve for long haul tractor-trailer for 2030 (relative to average European 2015 truck)

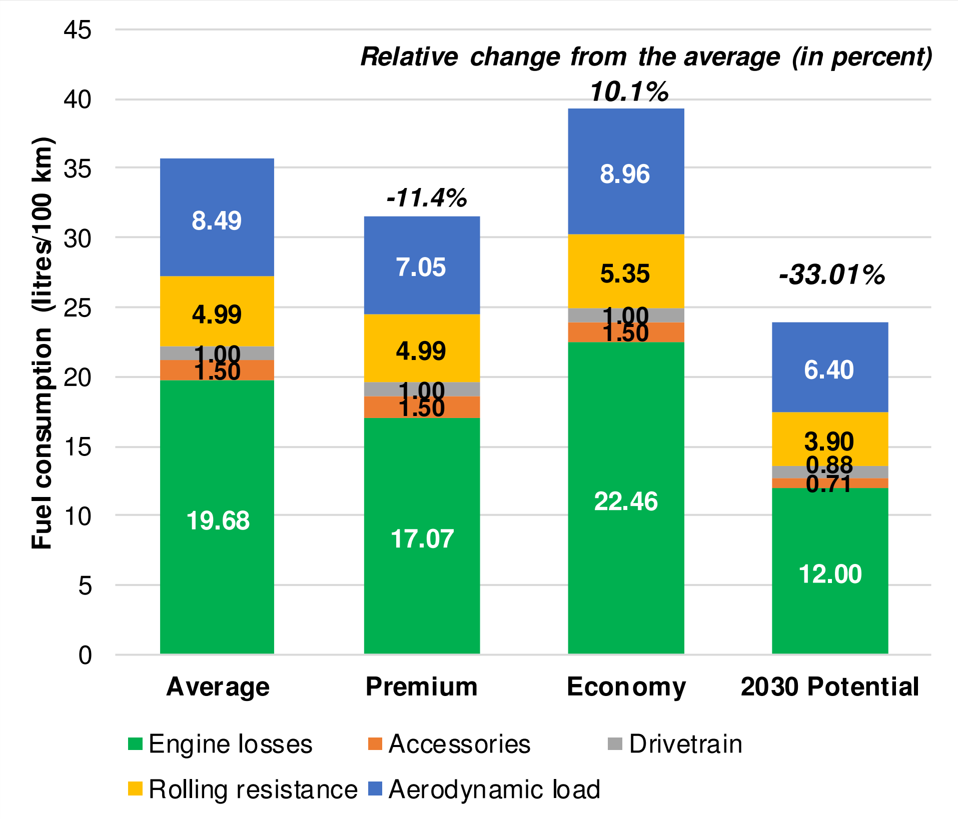


Around 30.3% of the 33% figure occurs for technologies where the return is > €200 /tCO_2 saved over the vehicle's lifetime. (This corresponds to a payback period of less than 3 years.) In terms of the technologies, the largest CO_2 savings (fuel consumption reductions) come from aerodynamic improvements (~10.6%), low rolling resistance tyres (5.1%) waste heat recovery (4.5%), and using improved air handling (2.5%) in order of their cost-effectiveness.

If these potentials were realised the fuel consumption from the average European tractor-trailer combination would reduce from 35.7 litres/100 km to 23.9 litres/100 km with an assumed payload of 19.3 tonnes (including vehicle management fuel consumption reduction technologies like predictive cruise control, but excluding vehicle platooning).

These fuel consumption values can be broken down in terms of how the fuel is used (e.g. due to engine losses, rolling resistance, aerodynamic drag etc.). This is shown in Figure 7.2 for the "average" European tractor-trailer combination, and the 2030 potential vehicle. A similar breakdown is provided for the "premium" and "economy" baseline trucks also. This figure illustrates the inter-relatedness of the losses, i.e. reducing aerodynamic losses means the engine has to produce less useable mechanical work, and consequently engine losses also reduce, in addition to any engine efficiency improvements that have been made also. However, vehicle road load improvement reduces the torque demands and shift the operational points of the engine to lower efficiency areas, so engine losses increase (engine efficiency is reduced) with aerodynamic improvements unless an appropriate AMT adjusts the gearing back to the point of high engine efficiency.

Figure 7.2: Schematic breakdown regarding where fuel is consumed (litres/100km) for long haul tractor trailer combinations (2015 baseline vehicles versus 2030 potential)



Incremental costs-fuel consumption reduction potential curves for the panel van and rigid box-truck segments are given in Figure 5.1 and Figure 5.2. Overall these give the maximum saving potential of all technologies of 44.7% for the panel van undertaking urban deliveries and 31.7% for the rigid box-truck undertaking regional deliveries.

A summary of the largest fuel savings technologies, and their approximate marginal pay-back period is provided in Table 7.1 below for the two vehicle segments.

Table 7.1: Summary of technologies with the largest fuel savings potential for panel vans

Panel van	Saving potential	Payback period (years)
Overall saving potential of all technologies	43.6%	
Full hybrid from MT gearbox	28%	11.3
Automated manual transmission from MT	7%	7.4
Various engine improvements	8.5%	~ 1 year (Note 2)
Low viscosity oil	2.5%	~ 4 years (Note 1)

Notes for Table 7.1:

Note 1 – for low viscosity oils and lower rolling resistance tyres costs occur during the lifetime of the vehicle, operational costs, and are not simply capital costs. The payback period quoted is the equivalent figure that would occur when all the additional operational costs are summed over the lifetime of the vehicle.

Note 2 – Some engine improvements will be incremental, incorporated into new engines, and will not incur additional capital expenditure costs. Therefore, these payback periods are somewhat reduced.

For the panel van segment savings are dominated by the possibility of full hybridisation. Addition of a stop/start system rather than full hybrid would replace the 28% potential saving with a much reduced 7% saving potential, but at a much improved payback period (3.5 rather than 11.3 years). It is also noted that for these low speed vehicles aerodynamic improvements make only a small (0.6%) reduction in fuel consumption.

Table 7.2: Summary of technologies with the largest fuel savings potential for rigid box-trucks

Rigid box-truck	Saving potential	Payback period (years)
Overall saving potential of all technologies	31.5%	
Futuristic aerodynamics	6.3%	0.45 years
Automated manual transmission from MT	5%	3.6 years
Various engine improvements	7.4%	2.0 (Note 2)
Low rolling resistance tyres	4.7%	~ 2 years (Note 1)
Mild hybridisation	4.5%	~ 2 years

Notes for Table 7.2:

Note 1 – for low viscosity oils and lower rolling resistance tyres, costs occur during the lifetime of the vehicle, operational costs, and are not simply capital costs. The payback period quoted is the equivalent figure that would occur when all the additional operational costs are summed over the lifetime of the vehicle.

Note 2 – Some engine improvements will be evolutionary, incorporated into new engines, and will not incur additional capital expenditure costs. Therefore, these payback periods are somewhat reduced.

For rigid box-trucks there are five technologies that offer 3 – 7% reductions in fuel consumption, but no technology that dominates unlike for panel vans (where full hybridisation has the potential to deliver a 28% fuel consumption reduction) and for tractor-trailer combinations (where advanced aerodynamics applied to both the tractor and the trailer units has the potential to deliver a 10.6% fuel consumption reduction).

Table 7.3: Summary of technologies with the largest fuel savings potential for tractor-trailer combinations

Tractor trailer combination	Saving potential	Payback period (years)
Overall saving potential of all technologies	33.0%	
Futuristic aerodynamics	10.6%	0.46 years
Various engine improvements	5.4%	< 2 (Note 1)
Low rolling resistance tyres	5.1%	~ 2 years (Note 2)
Waste heat recovery	4.5%	2.8 years
Improved air handling and energy recovery through turbo-compounding	4.5%	~ 2.2 years

Notes for Table 7.3*:*

Note 1 – Some engine improvements will be evolutionary, incorporated into new engines, and will not incur additional capital expenditure costs. Therefore, these payback periods are somewhat reduced.

Note 2 – for low viscosity oils and lower rolling resistance tyres, costs occur during the lifetime of the vehicle, operational costs, and are not simply capital costs. The payback period quoted is the equivalent figure that would occur when all the additional operational costs are summed over the lifetime of the vehicle.

What is also noticeable from Table 7.1 to Table 7.3 is how different technologies are more important for the different vehicle segments. Based on the technology list provided in earlier Table 4.4 the relative rankings of different technologies for the three vehicle segments are given in Table 7.4, with technologies that were of only minor importance for vehicles excluded for a simpler illustrative comparison. This illustrates the variety of dominant technologies.

However, it must not be assumed that smaller savings, e.g. due to lightweighting or other engine improvements are not important, because the overall fuel saving reduction potential is a consequence of the sum of all the contributions listed.

Table 7.4: Summary of the rankings, in terms of fuel consumption reduction, from the technologies considered for the three vehicle segments

Technology	Panel van	Rigid box-truck	Tractor trailer combination
Engine efficiency – friction, including some vehicle accessories but excluding low viscosity oils	2	1	2
Air handling (turbo-charging and EGR)			4 =
Low viscosity oils	4		
Waste heat recovery & thermal management			4 =
Transmission & driveline	3	3	5
Hybridisation	1 (Full hybrid)	5 (non-integral mild)	
Aerodynamics		2	1
Tyres & wheels		4	3

7.2 Uncertainties

This investigation is on the fuel consumption reduction potential, and costs of new technologies applied to heavy duty trucks. During the course of the study a number of assumptions have been made, and these have uncertainties associated with them. They are qualitatively systematically considered in this section.

7.2.1 Completeness of the list of technologies

There have been a number of previous studies considering the technologies that have fuel consumption reduction potential for heavy duty trucks, in particular the detailed Regulatory Impact Analysis recently published by EPA and NHTSA (Ref) see the bibliography. In addition, this study has been peer reviewed by a number of experts in a range of organisations all actively engaged in advancing heavy duty truck technologies. Consequently, it is believed that all the important technologies have either been explicitly included in the study, or the principles of how they reduce fuel consumption has been discussed, e.g. through friction reduction or thermal management.

7.2.2 Size of the potential savings for the individual technologies

The maximum potential fuel reduction potential against baseline European vehicles have been quantitatively estimated for the list of technologies. However, uncertainties regarding these savings potentials arise from:

- Uncertainties in the correct definition of baseline vehicles, their key components or the parameterisation of these key components;
- Uncertainties in the savings potential that could be produced by the full application of new technologies to these baseline vehicles.

It is believed the characteristics of baseline vehicles summarised in Chapter 3 of the report are generally well defined, but with some key areas of uncertainty. These include the engine peak brake thermal efficiency (and its average of the engine speed-load points used for a cycle) and the aerodynamic drag coefficient. The former arises because, unlike for light duty vehicles, the engine peak brake thermal efficiency is not required to be measured and reported during engine certification. European heavy duty engine certification requires that the pollutant emissions over the WHTC (and other cycles) has to be below specified limit values, but the fuel consumption over this cycle, although routinely measured, is not reported or in the public domain. The uncertainties in the aerodynamic drag coefficient arise because this is not a directly measureable quantity, but has to be inferred from whole vehicle performance, using, for example, a vehicle simulation model, to separate out the impacts of rolling resistance from coast down data. Such data are not currently required to be reported. In contrast to the uncertainties in the aerodynamic drag coefficient, the frontal area of vehicles (the other factor in determining the drag area) is well characterised, it being relatively easily measured physically.

The savings potential that could be produced by individual technologies also vary in terms of their uncertainty. For some technologies, e.g. the replacement of a mechanical steering pump with an electrical hydraulic system, the addition of a waste recovery system for a tractor-trailer combination for long haul operations, or the adding of full hybrid technology to a panel van, there is considerable evidence and experience regarding their savings potentials. However, there is not a single answer because it does depend on the driving cycle. But for a well characterised given driving cycle the savings potential can be moderately well characterised.

For other technologies it is anticipated many incremental improvements will occur leading to reductions in engine friction, or the lowering of rolling resistance from wheels. For these the uncertainty in the savings potential by 2030, relative to 2015 baseline vehicles, is higher, with the figures given being more of expert judgement on the cumulative effect of the incremental, rather than it being the case that adding a single unit saves X% in fuel consumption.

The savings from improvements in aerodynamics is more enigmatic, principally because of lack of hard data on its value for baseline vehicles, and how changes in bodywork quantitatively changes the drag coefficient. The EPA RIA uses a relatively theoretical approach in its assessment of the savings potential. This study uses a combination of average savings from field studies combined with a projection of future savings. However, there are large systematic differences between the situation in the US and Europe, with the latter having more severe vehicle length restrictions (which limit the addition of aerodynamic trailer tails) and a lower maximum speed limit. However, EU Directive 2015/719 grants derogations on the maximum lengths to allow for improved aerodynamic performance. Consequently, although improvements in aerodynamics are the single most important technology change for tractor-trailer combinations, there is considerable uncertainty in its quantification.

Additional uncertainty regarding the potential savings for the individual technologies arises from technologies that are not fully commercially developed (i.e. technology readiness level is less than 9[58]). All of the technologies described in this report have been at least technology readiness level 6 (prototype systems tested and anticipated to perform close to that for commercial system). For such pre-full commercial application stages, uncertainties arise from both the potential fuel savings that might be possible, and the limited quantity of fuel saving test data available.

The final uncertainty to be considered in the quantification of size of the potential savings for the individual technologies arises from operational factors. For some technologies this has been included in the assessment – most notably for the replacing of manual transmissions for European panel vans and rigid box-trucks with automated manual transmissions. Research has indicated that for MT using exactly the same gear changing points as an AMT transmission the savings potential is small. However, the research has also shown that most drivers do not use exactly the same gear changing points as an AMT transmission generally changing gears in a less optimised manner. Consequently, the savings potential is much higher. The other operational factor that affects most fuel reduction technologies is the difference between "real world driving" profiles and the test cycles, in terms of speeds, stops, loadings, ambient conditions, drivers' style and many other parameters. Together, these can markedly affect the fuel savings potential of different technologies. However, if the test cycles are a true "average" pattern of gradients and speeds, then some operational styles should generate improved potential savings relative to the average, whilst other operational styles would generate reduced potential savings. (This is unlike the situation that has arisen for the pre-2017 testing of light duty vehicles in Europe where the "test cycle" (NEDC) was systematically at the advantageously low fuel consumption end of the spectrum and real world driving virtually always gave poorer fuel consumption.)

[58] Technology readiness level is a widely used scale of 1 – 9 to describe the maturity of a technology. An overview of the descriptions of the 9 levels is given in https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

7.2.3 Potential costs

A further aspect of the study has been to estimate the incremental costs associated with the innovative technologies. These have uncertainties associated with them for a range of reasons:

Some improvements will involve future changes to production methods, and for some of these it has been assumed that the future production method, and materials, are unchanged from current practice. This may not be the case.

For other systems, e.g. the replacement of a mechanical steering pump with an electrical hydraulic system, or the addition of a waste recovery system, these relatively well defined, discrete engineered hardware have had their prices moderately well characterised.

For a number of technologies, however, there are already market precedents, e.g. for low rolling resistance truck tyres, or low viscosity oil, these technologies are already currently available, although are also being developed further. In these cases, it was assumed that whilst the performance of the technology might change, e.g. the rolling resistance of tyres decreases further with advances in materials and tyre technology, the incremental price (which is set somewhat by market forces) remains unaltered.

For some technologies that are currently at a lower technology readiness level, their detailed design and manufacturing processes have yet to be determined, and consequently this generates uncertainty in the incremental costs ascribed to them has a high uncertainty.

In addition to the above uncertainties, there is also a general uncertainty on the transferability of cost data from the US-based sources to the European context (i.e. beyond currency conversion issues) in particular because of scales or production.

7.2.4 The use of potential costs in the incremental cost – potential fuel consumption reductions analysis

Preceding discussions have noted how there are varying uncertainties in both the potential fuel reductions and the incremental costs of the technologies considered. When attempting to calculate the financial implications of fuel savings over the lifetime of a vehicle, uncertainties in the values used, and assumptions made, in the analysis arise. These include:

- Assumptions about the future price of diesel fuel;
- Assumptions about the Euro, or UK pound, US dollar exchange rate (the basis of the oil commodity price);
- Assumptions about the discount rate used to amortise the upfront incremental technology costs.

In this study, the assumptions made and values adopted are clearly given. However, at the end of the analysis the “attractiveness” of technologies will be affected by these values, and the choice of different values would affect the attractiveness of technologies, both in relative and absolute terms.

8 References

Burgin, T. (2011), (Rieter Automotive). “CO_2 And Emission Reduction By Means Of Heat Storage In The Powertrain”. IMechE, VTMS 10, Paper C1305/042/2011

DDC/Daimler (2011), Exhaust Heat Driven Rankine Cycle for a Heavy Duty Diesel Engine, a presentation by Rakesh Aneja, Sandeep Singh, Kevin Sisken (Detroit Diesel Corporation) and Roland Dold, Heijo Oelschlegel (Daimler AG), October 2011. Available from: https://www1.eere.energy.gov/vehiclesandfuels/pdfs/deer_2011/wednesday/presentations/deer11_singh.pdf

Delgado, O., Lutsey, N. (2015) Advanced tractor-trailer efficiency technology potential in the 2020-2030 timeframe. International Council on Clean Transportation. April 2015. http://www.theicct.org/us-tractor-trailer-efficiency-technology

Delgado, O., Muncrief R. (2016) New study on technology potential for EU Tractor-Trailers, Presentation given at Road to Efficiency Workshop, June 2016, Brussels, available from: https://www.transportenvironment.org/sites/te/files/2016_06_ICCT_tech_potential_EU_Tractor-Trailer_FINAL.pdf

Eastern Research Group (ERG) (2015a) Peer Review of “Commercial medium- and heavy-duty (MD/HD) truck fuel efficiency study – Report #1”. February 20.

Eastern Research Group (ERG) (2015b) Peer Review of “Commercial medium- and heavy-duty (MD/HD) truck fuel efficiency study – Report #2”. June 18, Available from: https://acquia-stage-nhtsa.dot.gov/sites/nhtsa.dot.gov/files/draft-swri-mdhd-fe-tech-report2_docket-version_peer-review-report.pdf

Eastern Research Group (ERG) (2015c) Peer Review of “Costs of medium- and heavy-duty vehicle fuel efficiency and emission reduction technologies for MY 2019-2022”. April 21.

EC DG CLIMA (2014) Working document for the methodology drafting for the CO_2 monitoring of HD vehicles, May 15th 2014. http://ec.europa.eu/clima/policies/transport/vehicles/heavy/docs/technical_annex_en.pdf

EPA and NHTSA (2016) Greenhouse Gas Emissions and fuel efficiency standards for Medium- and Heavy-duty engines and vehicles Phase 2 – Regulatory Impact Analysis, August 16 2016, https://www3.epa.gov/otaq/climate/documents/420r16900.pdf

EPA and NHTSA (2015) Proposed Rulemaking for Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles–Phase 2: Draft Regulatory Impact Analysis, June 2015,

FTA (2010) Freight Transport Association (FTA) Manager’s Guide to Distribution Costs 2010, available from: http://www.fta.co.uk/export/sites/fta/_galleries/downloads/cost_information_service/managers_guide_sample.pdf

FTA (2016) Logistics Carbon Review, Incorporating the sixth annual report of the LCRS (covering 2005 – 2014), May 2016, available from: http://www.fta.co.uk/export/sites/fta/_galleries/downloads/logistics_carbon_reduction_scheme/logistics-carbon-review-2016.pdf

Hill, N., Norris, J., Kirsch, F., Dun, C., McGregor, N., Pastori, E., Skinner, I. (2015) Light weighting as a means of improving Heavy Duty Vehicles’ energy efficiency and overall CO_2 emissions. Report for DG Climate Action. Ricardo-AEA. March 27 2015. http://ec.europa.eu/clima/policies/transport/vehicles/heavy/docs/hdv_lightweighting_en.pdf

Hill, N., Finnegan, S., Norris, J., Brannigan, C., Wynn, D., Baker, H., Skinner, I. (2011) Reduction and testing of greenhouse gas (GHG) emissions from Heavy Duty Vehicles – Lot 1: Strategy. Report for DG Climate Action. Ricardo-AEA. February 22 2011. http://ec.europa.eu/clima/policies/transport/vehicles/docs/ec_hdv_ghg_strategy_en.pdf

ICCT (2013) Trailer technologies for increased heavy-duty vehicle efficiency - Technical, market, and policy considerations, June 2013, available from http://www.theicct.org/sites/default/files/publications/ICCT_HDVtrailertechs_20130702.pdf

ICCT (2015) European vehicle market statistics – Pocketbook 2015/16, available from http://www.theicct.org/european-vehicle-market-statistics-2015-2016

Kosaka, H., Wakisaka, Y., Nomura, Y., Hotta, Y. et al., (2013) "Concept Of 'Temperature Swing Heat Insulation' In Combustion Chamber Walls, An Appropriate Thermo-Physical Properties For Heat Insulation Coat". SAE Int. J. Engines 6(1):2013, doi10.4271/2013-01-0274

Kromer, M., W. Bockholt, M. Jackson. "Assessment of Fuel Economy Technologies for Medium- and Heavy-Duty Vehicles.", Prepared by TIAX LLC for National Academy of Sciences. November 19, 2009

Law, K., Jackson, M. D., Chan, M. (2011) European Union Greenhouse Gas Reduction Potential for Heavy-Duty Vehicles. TIAX LLC. December 23, 2011. http://ec.europa.eu/clima/policies/transport/vehicles/heavy/docs/icct_ghg_reduction_potential_en.pdf

McCarthy, S.A., (2014), The future of heavy-duty engine oils, Tribology and Lubrication Technology, Oct 2014, (p 38 – 48)

Megaritis, A., Tsolakis, A., Wyszynski, M. L., Golunski, S. E. "Fuel Reforming For Diesel Engines" Paper 13, 2010: Advanced Direct Injection Combustion Engine Technologies And Development. Volume 2: Diesel Engines, Woodhead Publishing In Mechanical Engineering

Meszler, D., Lutsey, N. (2015) Cost effectiveness of advanced efficiency technologies for long-haul tractor-trailers in the 2020-2030 time frame. International Council on Clean Transportation. April 2015. http://www.theicct.org/us-tractor-trailertech-cost-effectiveness

Muncrief R, and Sharpe B. (2015) Overview of the heavy duty vehicle market and CO_2 emissions in the European Union, (Report: Working paper 2015-6) ICCT, December 2015, available from: http://www.theicct.org/overview-heavy-duty-vehicle-market-and-co2-emissions-european-union

National Research Council, 2010. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." http://www.nap.edu/catalog/12845.html

Reinhart T.E. (2016) Commercial medium- and heavy-duty truck fuel efficiency study – (Revised) Report #1. (Report No. DOT HS 812 146). National Highway Traffic Safety Administration. March 2016. https://www.regulations.gov/#!documentDetail;D=EPA-HQ-OAR-2014-0827-1760

Reinhart T.E. (2015) Commercial medium- and heavy-duty truck fuel efficiency study – (Revised) Report #2. (Report No. DOT HS 812 194). National Highway Traffic Safety Administration. October 2015. https://www.regulations.gov/#!documentDetail;D=EPA-HQ-OAR-2014-0827-1623

Schubert, R., Chan, M., and Law, K. (2015) Commercial medium- and heavy-duty truck fuel efficiency cost study. (Report No. DOT HS 812 177). National Highway Traffic Safety Administration. June: https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/812177-commedhdtruckfueleffictechcoststudy.pdf

Sharpe, B. and Muncrief, R., (2015) Literature review: Real world fuel consumption of heavy-duty vehicles in the United States, China, and the European Union, ICCT White paper funded by ClimateWorks Foundation. January 2015, available from: http://www.theicct.org/sites/default/files/publications/ICCT_HDV_FC_lit-review_20150209.pdf

Schroten, A., Warringa, G. and Bles, M. (2012) Marginal abatement cost curves for Heavy Duty Vehicles, A report for the European Commission, DG Climate Action by CE Delft, http://www.cedelft.eu/publicatie/marginal_abatement_cost_curves_for_heavy_duty_vehicles_/1318

Such, C. and Noble, A., (2015) Developments to reduce CO_2 emissions from heavy-duty diesel engines and gas engines, Delphi Commercial Vehicle Powertrain Conference, Gillingham, UK, April 2015

Thiruvengadam, A., Pradhan, S., Thiruvengadam, P., Besch, M., Carder, D., Delgado, O. (2014) Heavy-duty vehicle diesel engine efficiency evaluation and energy audit. West Virginia University. Oct 2014. http://www.theicct.org/heavy-duty-vehicle-diesel-engine-efficiency-evaluationand-energy-audit

TU Graz (2012) Reduction and Testing of Greenhouse Gas Emissions from Heavy Duty Vehicles - LOT 2 Development and testing of a certification procedure for CO_2 emissions and fuel consumption of HDV. June 2012. http://ec.europa.eu/clima/policies/transport/vehicles/heavy/docs/hdv_2011_01_09_en.pdf

Van Zyl, S., van Goethem, S., Kanarachos, S., Rexeis, M., Hausberger, S. and Smokers, R., 2013, Study on tyre pressure monitoring systems (TPMS) as a means of reducing light-commercial and heavy-duty vehicles fuel consumption and CO_2 emissions. TNO and TU Graz (Report no TNO-060-DTM-2013-02025) for EC DG CLIMA. Available from http://ec.europa.eu/clima/policies/transport/vehicles/heavy/docs/tno_2013_final_report_en.pdf

Appendices

Appendix 1: Fuel efficiency of European baseline vehicles
Appendix 2: Driving patterns of baseline vehicles in US and Europe
Appendix 3: VECTO model version and files used for vehicle simulations

Appendix 1 – Fuel efficiency of European baseline vehicles

Overview

The project requires evidence based, authoritative fuel efficiency data for the baseline vehicles. Also, such absolute values will enable the translation of fuel consumption reductions, expressed as percentage relative changes, to be converted into absolute values.

From the literature, the following is noted:

- There is no requirement to report CO_2 values for HDV in Europe, and therefore they are not generally reported;
- HDV engine homologation relies on an **engine test**, performed using an engine dynamometer, over the WHTC. This duty cycle comprises three 600 second components, specifying engine speed – load points that are intended to emulate urban, sub-urban and highway driving. It is not directly comparable to on-the-road driving for any of the three vehicle segments considered in this study.

Consequently, there is very little truck fuel consumption data published that is of high provenance.

Data that are available include:

- The data from Ricardo AEA Lot 1 study for EC CLIMA, referred to in the TIAX report
- VECTO simulation
- EMEP EEA speed related emission factors (for average speed of a cycle)
- Emission factors from the German Hand Book of Emission Factors, HB EFA (v 3.2)
- Some average fuel consumption figures from UK DfT Statistics
- Other ad hoc data, from recent Ricardo HGV testing
- ICCT Lit Review Jan 2015 (Sharpe & Muncrief)

The relevance of these fuel efficiency data to the three segments of interest is summarised below:

	Panel van	Rigid box-truck	Tractor-trailer combination
DG CLIMA Lot 1, TIAX	Yes	Yes	Yes
VECTO	No	Yes	Yes
EMEP EEA Average speed emission factors	Yes	Yes	Yes
UK DfT truck average fuel consumption for different weight ranges	Yes	Yes	Yes
German HB EFA	Yes	Yes	Yes
Others ad hoc data	No	No	Very little
ICCT Lit Review Jan 2015	No	No	Yes, several

Colour Key:

- Red: No relevant data from this source,
- Light green: Light green results use the metric of CO_2 emissions /km of drive cycle,
- Dark green: Darker green results expressed as fuel consumption data (litres per 100 km).
- Yellow: Yellow – despite searching, no reliable data found that we report.

Conversion between fuel consumption and CO_2 emissions

The study has considered the fuel consumption of trucks (which can be expressed in terms of mass or volume of fuel used), and the resulting CO_2 emissions. This requires the conversion between fuel mass or volume consumed and the CO_2 emissions produced by the fuel. The study also considers the peak brake thermal efficiency of engines. This requires the conversion between fuel mass or volume consumed and its energy content. This section details the assumptions made, and origins of values used in these conversions.

Density of diesel

The European Fuel Directive, EN590, sets wide limits for the density of diesel, between 820.0 and 845.0 kg/m^3 – this is not a sufficiently precise conversion factor.

The Digest of UK Energy Statistics (DUKES)[59] uses the figure of 1,192 litres per tonne, which corresponds to a density of 838.9 kg/m^3.

Datasheets from Birmingham University[60] suggests the density of Diesel is 837 +/- 8 kg/m^3.

In this study the figure used is the DUKES figure, **838.9 kg/m^3.**

CO_2 emissions from diesel

DUKES also contains fuel conversion factors[61], giving values of 3,164 g CO_2 per kg of diesel, and 2,654 g CO_2 per litre of diesel.

There is an inconsistency between the conversion factors used in DUKES, and those implicit within VECTO. The latter uses a CO_2 to fuel ratio of 3,160 g CO_2 per kg of diesel, rather than the slightly higher precision value of 3,164 used here. VECTO also assumes a fuel density of 832 kg m^3, rather than the 838.9 figure assumed here. This is a significant difference, and means for the same mass of diesel used by an engine the VECTO quoted CO_2 volume is 0.83% larger than that from other sources, which, when compounded with the small change in the CO_2 to fuel conversion factor, leads to a net difference of 0.96%.

Because VECTO is focused on producing a CO_2 emissions value, it is presumed this is the more correct, and it is the fuel consumption, in litres /100km that is generally reported in this study.

Energy content of diesel

In Table A.1 of DUKES the lower calorific values given are 42.9 MJ /kg of diesel, and 35.99 MJ /litre of diesel. (The lower calorific value is the energy content from the complete combustion of diesel to produce CO_2 and steam, rather than liquid water. This is what flows down the exhaust pipe from a diesel engine.)

[59] Digest of UK Energy Statistics available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/483877/energy-and-environment-notes.pdf

[60] Fuel data sheets from Birmingham University from (http://www.claverton-energy.com/wordpress/wp-content/uploads/2012/08/the_energy_and_fuel_data_sheet1.pdf)

[61] See page 234 of 2015 publication

Details of HDV fuel efficiency from the various sources

EC HDV Lot 1 study (AEA) reported in TIAX study

The data given in Table 2-1 in the report on: "Reduction and Testing of Greenhouse Gas (GHG) Emissions from Heavy Duty Vehicles – Lot 1: Strategy." is reproduced below:

Vehicle Segment		EU Fuel Economy	As g/km
Service	mi/gal	14.7	
	L/100 km	16.0	427.2
Urban Delivery	mi/gal	11.2	
	L/100 km	21.0	560.7
Regional Delivery	mi/gal	9.3	
	L/100 km	25.3	675.5
Long Haul	mi/gal	7.7	
	L/100 km	30.6	817.0

VECTO fuel consumption data

VECTO calculates fuel consumption in units of litres of fuel used per 100 km driven, and in units of fuel used per 100 t.km driven.

As noted in the previous section, the VECTO the conversion factor used in VECTO gives slightly lower CO_2 emissions per unit of fuel consumed than the conversion factors from DUKES. It is the latter that are reported here.

Panel vans – VECTO currently has no vehicle of this type set up within it, and hence provides no guidance.

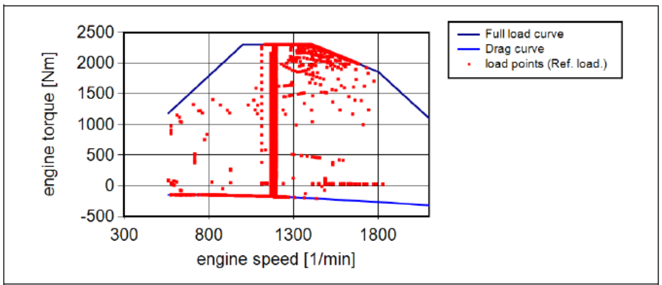
Rigid box-trucks - Declaration mode, reference weight (3.0 tonnes loading), regional delivery cycle gives the following outputs:

Fuel consumption 24.9 litres /100 km with 3.0 t load, i.e. 8.30 litres /100 t.km

CO_2 emissions 654.2 CO_2/km with 3.0 t load, i.e. 219.2 g CO_2/ t.km

Tractor-trailer combinations, undertaking long haul journeys **-** Declaration mode, reference weight, long haul cycle gives the outputs below (providing both fuel consumption and CO_2 emissions, both per km and per t.km)[62]:

Loading		Empty	Reference	Full
		0.0 t	19.3 t	25.4 t
Ø Speed	km/h	79.9	79.2	78.7
FC	l / 100 km	26.4	35.7	38.7
	l / 100 t.km	-	1.8	1.5
CO2	g / km	693.6	937.9	1017.7
	g / t.km	-	48.6	40.1



40t_Long_Haul_Truck | 09/19/2016 17:09:12 | **VECTO Declaration Results** | Page 2 of 3

[62] The version of VECTO used to generate this output is specified in Appendix 3

These data give the following outputs:

Fuel consumption 35.7 litres /100 km with 19.3 t load, i.e. 1.85 litres /100 t.km

CO_2 emissions 937.9 g CO_2/km with 19.3 t load, i.e. 48.6 g CO_2/ t.km

EMEP / EEA Speed related emission factors

The Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP) is a special programme under the United Nations Economic Commission for Europe (UNECE). It has a long established tradition of publishing authoritative air pollutant emission inventory guidebooks. The most recent, 2013, version published by the European Environment Agency (EEA), contains data for heavy-duty trucks as an appendix[63]. These give emissions of a range of species**, including CO_2**, for complex driving cycles dependent on their average speed. The data are in units of g CO_2/km and are given for different truck weight ranges.

Panel van (urban delivery) @ 30 kph & with 50% of the maximum payload

For 3.5 – 7.5 tonne rigid truck value – 331.5 g/km

For 7.5 – 12 tonne rigid truck value – 534 .0 g/km

For 12 – 14 tonne rigid truck value – 590.0 g/km

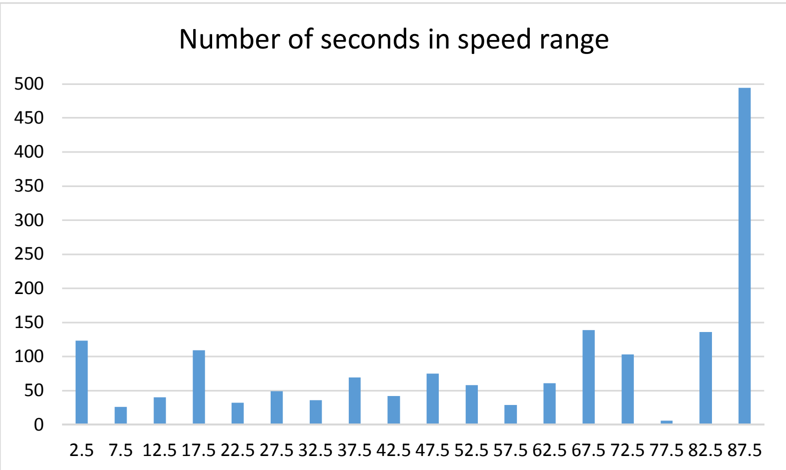
From plotting emissions against midpoint weight of vehicle, and evaluating for a 7.0 tonnes GVW truck, at 35% load, the emissions are estimated to be **385 g/km**. This corresponds to a fuel consumption of 14.50 litres fuel/ 100 km. This is the figure is that used in the “Summary table” at the end of this note.

Rigid box-truck @ 58 km/h & with 50% of the maximum payload

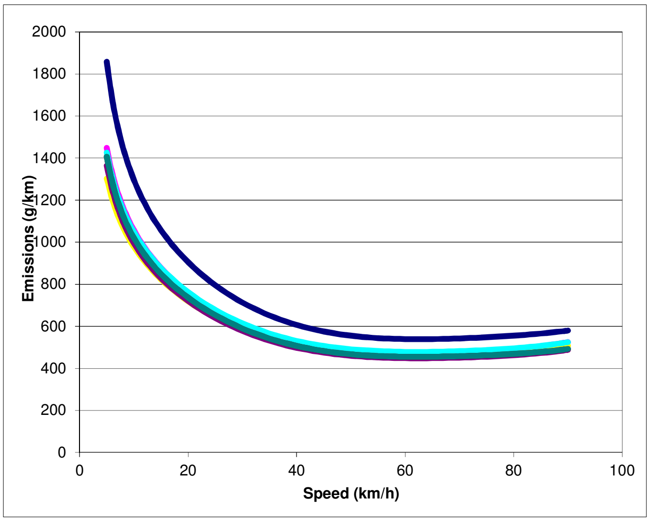
For 7.5 – 12 tonne rigid truck value – 424.7 g/km

For 12 – 14 tonne rigid truck value – 456.1 g/km

Both these values appear inappropriately low. It believed this arises because the time spent at different speeds (from analysis of the drive cycle) and the CO_2 emissions for different speeds are as shown in the following two figures:



[63] For Exhaust emissions from road transport HDV see http://www.eea.europa.eu/publications/emep-eea-guidebook-2013/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-b-road-transport-annex-hdv-files.zip



Therefore, undertaking a weighted average for 0 – 20 km/h, 20 – 40 km/h etc gives emissions of: **565 g/km** over the cycle, rather than the 456 g/km obtained from using only the cycle's average speed. The 565 g/km corresponds to a fuel consumption figure of 21.3 litres/100 km, which is the figure quoted in the "Summary table" at the end of this note.

Tractor-trailer combinations

From baseline table at an average speed of 74 km/h, the average speed of VECTO long haul cycle, for the average of 30 – 40 t GVW and 40 – 50 t GVW the emissions are: **884 g CO_2/km.**

Again this is expected to be at the low emission end of the range of values when compared with the VECTO long haul cycle, because it underestimates emissions from the slower portions of the driving cycle. This corresponds to a fuel consumption figure of 33.3 litres/100 km

DfT UK average fuel consumption data

Data on average heavy goods vehicle fuel consumption are taken from the UK Department for Transport website[64]. The relevant table is included in Table 8.1.

[64] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/482687/env0104.xls

Table 8.1: Average heavy goods vehicle fuel consumption: Great Britain, 1999-2004 (UK DfT)

Average heavy goods vehicle fuel consumption: Great Britain, 1999-2014[1,2,3]

Miles per gallon

	Net weight (tonnes)	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Rigid vehicles	Over 3.5t to 7.5t	13.4	12.3	13.2	12.6	13.3	13.7	13.7	13.7	13.2	12.8	12.8	14.2	13.2	13.4	13.6
	Over 7.5t to 14t	11.6	11.0	11.3	10.9	11.0	11.6	10.8	11.4	10.6	10.5	11.1	11.1	11.9	11.5	11.3
	Over 14t to 17t	9.6	9.8	9.7	9.7	10.0	10.1	9.6	9.1	9.3	9.7	9.7	10.0	9.5	10.4	9.8
	Over 17t to 25t	8.6	9.0	8.9	9.1	9.6	10.0	10.0	9.5	9.1	9.4	9.4	9.2	9.4	9.4	9.4
	Over 25t	6.7	6.6	6.8	6.6	6.6	6.9	6.7	6.7	6.4	6.4	6.5	6.8	6.3	6.2	6.5
	All rigid vehicles	**10.1**	**9.7**	**9.8**	**9.5**	**9.8**	**10.0**	**9.7**	**9.4**	**9.0**	**9.2**	**9.1**	**9.5**	**9.0**	**8.9**	**8.9**
Artic vehicles	Over 3.5t to 33t	8.8	8.6	8.6	8.6	9.0	9.3	9.0	8.9	8.8	8.8	8.5	8.8	8.9	9.0	9.0
	Over 33t	7.8	7.6	7.7	7.6	7.9	8.0	8.0	7.9	7.6	7.6	7.6	7.9	7.7	7.7	7.8
	All artic vehicles	**8.0**	**7.8**	**7.8**	**7.8**	**8.0**	**8.2**	**8.1**	**8.0**	**7.7**	**7.7**	**7.6**	**7.9**	**7.8**	**7.8**	**7.9**

1. These figures are for heavy goods vehicles registered as goods vehicles in Great Britain, carrying freight within the United Kingdom. The figures exclude non-freight carrying HGVs such as recovery vehicles or fire engines.
2. These figures are based on the gallons of fuel purchased by hauliers or taken from their own supplies for a surveyed vehicle, together with their records of miles travelled during a given survey week (see notes and definitions).
3. There are breaks in this series in 2011 and 2012 due to breaks in the underlying road goods survey.

Source: Continuing Survey of Roads Goods Transport, DfT
Last updated: November 2015
Next update: November 2016
Telephone: 020 7944 4129
E-mail: environment.stats@dft.gsi.gov.uk
The figures in this table are not National Statistics

Using standard conversion factors between UK gallons and litres, and miles and km, the equation below was used to convert UK DfT miles per gallon figures into litres /100 km fuel consumption.

$$\text{litres per 100 km} = \frac{282.81}{\text{miles per gallon}}$$

Panel van

For 3.5 – 7.5 tonne rigid truck value – 20.79 litres/100 km   from 13.6 mpg

For 7.5 – 14 tonne rigid truck value – 24.7 litres/100 km   from 11.45 mpg, the average 2011-14

Rigid box-truck

For 7.5 – 14 tonne rigid truck value – 24.7 litres/100 km   from 11.45 mpg, the average 2011-14

Tractor-trailer combination

For > 33 t articulated truck – 36.35 litres/100 km   from 7.78 mpg, the average 2011-14

.

As an aside - These data indicate little to no improvement in the average fuel consumption between 2000 and 2014. However, as noted in the main report, these are aggregated data, of only moderate provenance. It may be, for example, that increases in loading, consequently, on-the-road weights, and reduced numbers of empty journeys resulted in a situation where an improvement in vehicle efficiency has been off-set by increased vehicle weights, and the lack of improvement in the average fuel consumption between 2000 and 2014.

German HB EFA

These data were taken from HB EFA v 3.2, which became available from INFRAS in July 2014, and is the current version.

Panel van - For rigid trucks 3.5 – 7.5 t GVW on flat roads, with 50% load

Average of 19 stop/go driving patterns over different road types, gave average fuel consumption of 153 g fuel/km, and hence CO_2 emissions of 448 g/km. This is equivalent to 16.88 litres/100 km.

Rigid box-truck - For 12 – 14 rigid truck

69 Cycles of stop/go characteristics, mean is 867 g/km, average speed 14 kph

69 Cycles of freeflow characteristics, mean is 470 g/km, average speed 63 kph

Weighted average of 1 stop/go to 2 freeflow gives average speed of 47 kph, and emissions of 602 g/km, which is equivalent to a fuel consumption of 22.68 litres per 100 km

Tractor-trailer combination - For > 40 t artic truck

For URB/MW-Nat/>=90 /freeflow – 931 g/km @ av speed of 81.94 kph

For RUR/MW/>=90 / Freeflow – 750 g/km @ av speed of 86.3 kph

It is assumed that the latter is very close to a constant speed cycle, whereas the former includes some accelerations and decelerations. These two CO_2 emission rates are equivalent to fuel consumptions of 35.1 and 28.3 litres /100 km. The first figure is used in the table at the end of this appendix.

Others data considered

Tractor-trailer combination

Some experimental data for a 40 t GVW articulated truck loaded to 30 tonnes, driven on a test-track in dual fuel diesel/methane fuelling mode was considered. Its CO_2 emissions as measured using PEMS were 1,030 g CO_2/km. This is equivalent to a fuel consumption of 38.8 litres /100 km.

However, this was a modified Euro V truck, assessed over Part 3 of the world harmonised vehicle cycle.

Therefore, whilst it is not recommended its data is used, this is consistent with the around 950 g CO_2/km figure ultimately recommended.

ICCT – Literature review

The data is taken from Section 4.3 (EU) of the study: "Real world fuel consumption of heavy-duty vehicles in the US, China and the EU, B Sharpe & R Muncrief, Jan 2015.

Table 8: EU tractor-trailer fuel consumption data

Source	Data type	Year	Data collection methodology	Fuel economy (mpg)	Fuel consumption (L/100 km)
AEA-Ricardo	Fleet-wide	2011	Estimate based on attributing total fuel consumption and vehicle kilometers traveled to 8 HDV vocations (see Table 4.19 in the Lot-1 report)	7.6	30.9
Lastauto Omnibus	14 tractor-trailers	2012-2013	Test values reported in magazine issues from March 2012 to July 2013*	6.3	37.1 (EEV and Euro V)
				6.5	36.4 (Euro VI)
Trucking Magazine	4 tractor-trailers	2013	Test values reported in July 2013**	6.2	38.1

* Fuel economy and consumption values derived by taking an average of the "average" figures reported for each full vehicle road test.

** Fuel economy and consumption values derived by taking an average of the "overall" figures reported for each full vehicle road test.

The average figures were noted, by ICCT, lie in the range 36 – 38 litres fuel / 100 km. Summarising these data, and converting fuel consumption to g CO_2/km gives:

Source	Fuel economy mpg	Fuel consumption litres/100 km	CO_2 emissions g/km
AEA-Ricardo	7.6	30.9	820.2
	6.3	37.1 (EEV and Euro V)	984.7
Lastauto Omnibus:	6.5	36.4 (Euro VI)	966.2
	6.2	38.1	1,011.3
Trucking Magazine	Bottom of range	36.0	955.5
	Top of range	38.0	1,008.6

US EPA data – for comparison within this document

Tractor-trailer combination

From baseline table:

Cycle	L/100 km	g CO_2/km
Fuel economy expressed (L/100km) - CARB	61.01	1619.4
Fuel economy expressed (L/100km) - 55 MPH	34.79	923.4
Fuel economy expressed (L/100km) - 65 MPH	41.85	1110.8

Summary and conclusions

A summary of the above data sources is tabulated below. For studies where the reported fuel consumption was expressed in g CO_2/vehicle km, these have been converted into the standardised unit of litres diesel /100 km.

Summary of the fuel consumption data from different sources, all expressed in units of litres fuel/100 km

Study	Panel van	Rigid box-truck	Tractor-trailer combination
EC LOT 1, TIAX	16.0	21.0	30.6
VECTO		23.6	35.9
EMEP EEA	14.50	21.29	33.30
UK DfT Averages	13.60	24.70	36.03
German HB EFA	16.88	22.68	35.08
ICCT Review Lastauto Omnibus min			36.00
ICCT Review Lastauto Omnibus max			38.00

Panel van segment

Recommend a baseline CO_2 emissions figure of 15.8 litres/100 km (420 g CO_2/km) as the average for three of the four values above. (The DfT average figure for 3.5 – 7.5 t GVW vehicles is believed to be for a vehicle that is, on average, lighter than the 7.0 t GVW baseline vehicle considered here.) The mean and standard deviation for the remaining three studies are 15.8 ± 1.2 litres /100 km.

For the rigid box-truck segment

The mean and standard deviation of the five values given is 22.7 ± 1.56 litres /100 km. It is recommended that the reference value selected for European regional delivery baseline vehicles is 24.9 litres /100 km, i.e. the value from the VECTO simulation. This value is within the 60% of the standard deviation of the data (and the mean and standard deviation of the other four data points are within 1 and 9 percent of the five point statistics respectively), but importantly, its origins, assumptions, payload, drive cycle etc. are all defined, and known, from examination of the parameters used within the model.

For the tractor-trailer combination – Average vehicle

The mean and standard deviation of the seven values given is 35.0 ± 2.38 litres /100km. It is noted that the EC LOT1 data, which originated from a 2010 Ricardo-AEA review and was reported in the 2011 TIAX study is something of an outlier. The mean and standard deviation of the remaining six values is 35.7 ± 1.53 litres /100km.

It is recommended that the reference value selected for European long haul **standard** baseline vehicle is 35.7 litres /100km, i.e. the value from the VECTO simulation. This is both close to the mean figure of the other five values, being less than 1.0% **higher**, and has the advantage that its origins assumptions etc are all known, as noted for the regional delivery segment.

For the tractor-trailer combination – Premium vehicle

This vehicle derived from the “average” (VECTO) vehicle but with the following two key differences:

- A more efficient engine, and
- A more aerodynamic trailer.

Considering what is meant by a **more efficient engine**: Examination of the engine map in the VECTO model gave the following engine efficiencies – in terms of the mechanical work generated divided by net calorific value of the diesel fuel required to produce it:

For 59 points where mechanical power produced > 100 kW, Average efficiency = 43.2%

For the sub-set of 17 points where the engine speed is 1,200 to 1,600 rpm, and the torque is >1,399 Nm (this is the portion of the engine load that dominates for this cycle, see figure under "VECTO fuel consumption data" section of this appendix) the average efficiency = 44.35%. This is the efficiency assumed for the "average" vehicle.

It is assumed that the most efficient engine currently available has an average efficiency of 46.0%. In terms of fuel consumption relative to an average efficiency of 44.35%, fuel consumption would become 96.4% of original value.

Considering what is meant by a **more aerodynamic trailer**: Research has indicated Don Bur currently produce the most aerodynamic "tear-drop" trailers[65]. In their brochure they quote a whole series of "trials" where for 23 trials with box-van rigid trailers the average fuel savings were 11.26%, whereas for 8 curtain-sider trials the average was 11.18%. However, there is something of an alarming spread in the data with some trials reporting savings of only around 4%, and others reporting nearly 20% savings. (See Figure 4.3 in the main report.)

More recent designs (http://www.donbur.co.uk/news/donbur-3000th-teardrop-trailer) quote a CD of 0.402, relative to the value used in VECTO of 0.663, a 39.4% reduction in C_D.

Web based feedback from operators reporting what "they" found suggests an 8 – 10 % reduction in fuel consumption was actually achieved.

Therefore, it is recommended that for the premium long haul truck, for this project we assume that the improved trailer aerodynamics lead to fuel consumption becoming 91% of its original value.

Combining the more efficient engine and the aerodynamic trailer leads to the "best currently available tractor trailer combination" having a fuel consumption of 87.7% of the average vehicle, i.e. 31.5 litres /100 km for the European long haul driving cycle.

For the tractor-trailer combination segment – Economy vehicle

This was assumed to be a tractor – trailer combination, similar to the "average" vehicle but with the following two differences:

- The engine efficiency is poorer than for the average vehicle;
- The vehicle is fitted with cheaper remoulded tyres, i.e. has a higher rolling resistance than the average vehicle.

Consideration of what constitutes a less efficient engine, used real truck fuel consumption data from many editions of LastAuto Omnibus magazine, collected by ICCT. The data was filtered to extract data from 2014 onwards, for tractor and trailer combinations, only Euro VI vehicles, and considering the fuel consumption reported only for the "overall" test cycle. It was assumed that the differences in "overall" fuel consumption are principally caused by changes in engine efficiency, particularly when averaged over several vehicles. The absolute values are a fuel consumption of around 35 litres /100 km. The three tractor units with the highest overall fuel consumption, which were models from three different manufacturers were averaged. The analysis gave:

Average fuel consumption figure: 100% ± 4.2% (from sample size of 16 vehicles)

Average fuel consumption for three highest: 104.8% ± 0.54% (from sample size of 3 vehicles)

This would be equivalent to the engines peak brake thermal efficiency dropping from 44.8% for the "average" long-haul truck to 42.7% for the "economy" vehicle.

For the tyre rolling resistance, it has been assumed that the moderately low rolling resistance, Class C fuel economy tyres (CRR = 5.55 kg/t for the steer and trailer tyres) are replaced with re-treaded tyres whose rolling resistance is 6.5 kg/t. This amounts to a 17% increase in rolling resistance. From the data in table 4-19, this would lead to a 3.62% increase in fuel consumption.

[65] Feedback from experts – brochure taken from http://www.donbur.co.uk/gb-en/docs/150320-Don-Bur-Teardrop-Brochure.pdf

Together these two changes, when compounded, lead to the “economy” tractor trailer having a fuel consumption 8.6% higher than for the “average”. These are the data used to derive the “economy” long-haul vehicle characteristics given in Table 4-5.

Appendix 2 – Driving patterns of baseline vehicles in US and Europe

Objectives

The data translation process between US and European potential fuel consumption reductions need to take into consideration both differences in baseline vehicle characteristics, and also the way the vehicles are used. In part, this includes differences in average loading and mileage, but it also includes "typical driving cycles". This Appendix describes these "typical driving cycles" for the European long haul, regional delivery and urban delivery usage patterns, the driving cycles over which the US vehicles were tested, and reaches some conclusions as to how the US data on CO_2 reduction potential for different technologies, as reported in the EPA studies, can be "translated" into those appropriate for European driving patterns.

Some key assumptions

For Europe:

The European Commission has invested a considerable amount of resources in trying to define representative driving cycles for long haul, regional delivery and urban delivery driving cycles within its VECTO vehicle simulation CO_2 quantification tool. (In total the EC has defined 10 driving cycles, four for buses, one for coaches and five for "trucks". These five are: long haul, regional delivery, urban delivery, construction and municipal utility cycles.)

For the US:

The NHTSA studies to support Phase 2 of the US HDV greenhouse gas (GHG) regulation, published by the EPA, describe the CO_2 reduction potential on four different vehicles, tested, and simulated, over a range of different driving cycles. These are summarised in Table 3-12 of the report: Report #1 (Eastern Research Group, 2015a), reproduced below.

EPA Report #1 TABLE 3.12 VEHICLES AND DRIVE CYCLES USED IN STUDY

Vehicle	Drive cycles
RAM Pickup	FTP City, FTP Highway, US06, SC03, WHVC, 65 MPH
T270 Box-Truck	GEM Cycles, CILCC, Parcel Delivery Cycle, WHVC
F-650 Tow Truck	GEM Cycles, CILCC, Parcel Delivery Cycle, WHVC
T-700 Tractor	GEM Cycles, WHVC, NESCCAF Long Haul Cycle

Typical driving patterns used in EU studies

The long haul, regional delivery, urban delivery VECTO truck cycles are taken as the representative European cycles for tractor-trailer combinations, rigid box-trucks and panel vans, respectively.

VECTO does not use traditional drive cycles, specifying time and speed. Rather, it defines missions, in terms of the journey to be undertaken on a metre by metre basis, together with target speeds and the road's gradient. It uses the vehicle simulation model to define how quickly the vehicle can accelerate to the target speed. The fuel consumption and CO_2 emissions from the simulation are the key outputs from the model, but the resulting time-speed profile is also an output. Currently VECTO does not have a model 3.5 – 7.5 tonne truck, and therefore the urban delivery cycle was run using the 12 t GVW declaration mode vehicle with no load, i.e. an empty 12 tonne rigid box-truck, to obtain an approximate speed time profile for this cycle. The origins of the time-speed and time-gradient graphs shown later are tabulated below.

Vehicle category	Drive cycles	Cycle run
Tractor-trailer combination	VECTO Long haul cycle	40 t truck at around 75% load
Rigid box-truck	VECTO Regional delivery cycle	12 tonne truck at around 75% load
Panel van	VECTO Urban delivery cycle	12 tonne truck with no load

As noted in the Objectives section, we are trying to define "typical driving cycles" for the European long haul, regional delivery and service vehicles, particularly in the context of cycles for which CO_2 emissions reduction potential has been characterised in the EPA studies.

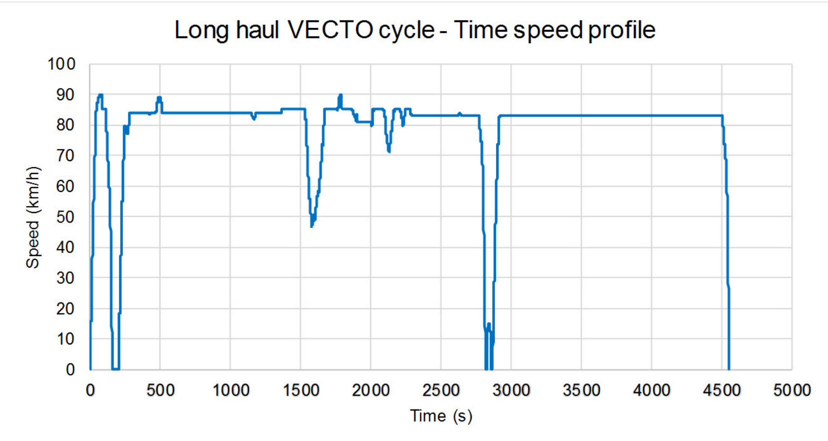
The time duration or distance of the cycle is, in essence a scaling factor and of secondary importance. However, it is important for cold start cycles because it determines the ratio cold running/hot running.

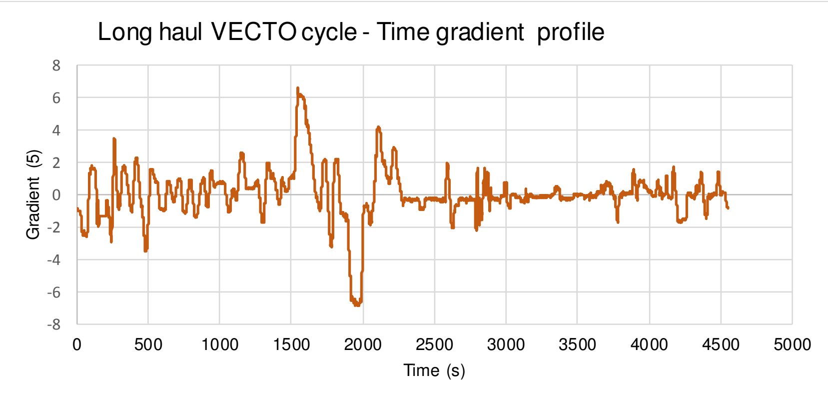
More important features of a drive cycle are:

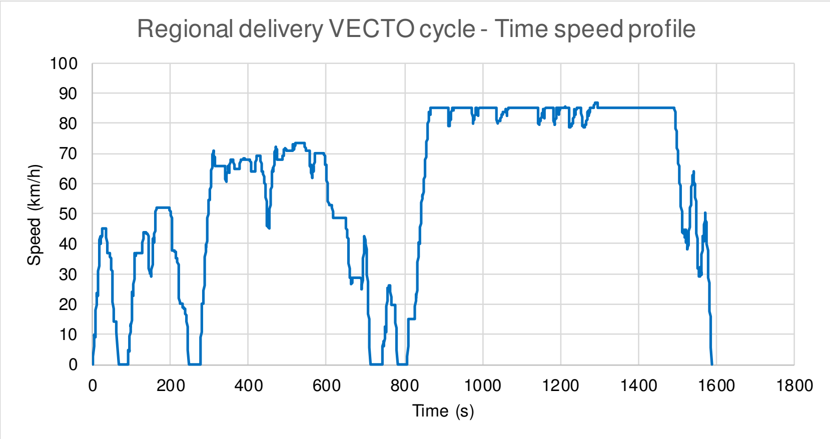
- Average speed
- The average square of speed
- Percentage of time spent accelerating, and rates of acceleration,
- Numbers of times the vehicle stops /km
- Percentage of time vehicle spends stationary.

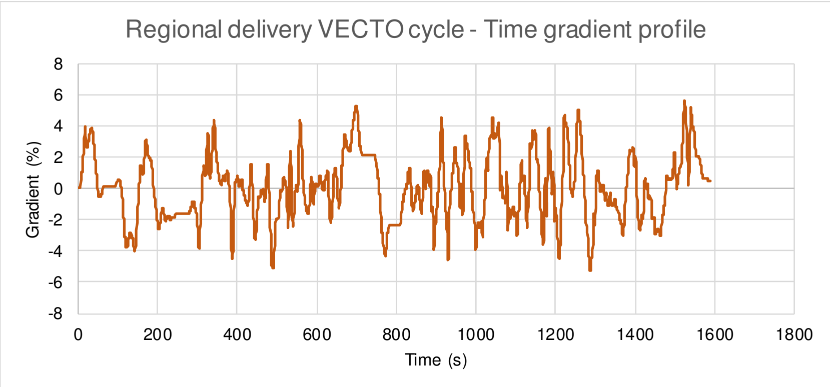
The average square of speed is important because the aerodynamic drag force scales with speed squared, and consequently so too does fuel consumption expressed in units of litres fuel per 100 km driven.

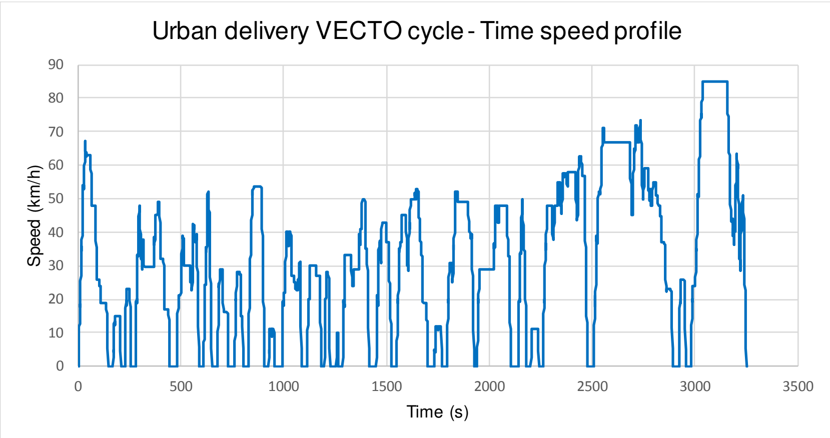
The time/speed profile for the three EU vehicle categories, defined in the VECTO model (from the VECTO version described in Appendix 3) are shown below:

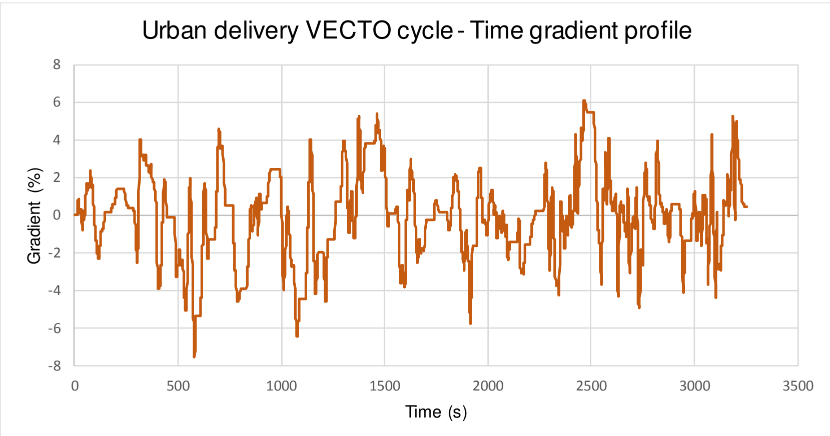





Regional delivery VECTO cycle - Time speed profile
Speed (km/h)
100
90
80
70
60
50
40
30
20
10
0
0
200
400
600
800
1000
1200
1400
1600
1800
Time (s)


Regional delivery VECTO cycle - Time gradient profile
Gradient (%)
8
6
4
2
0
-2
-4
-6
-8
0
200
400
600
800
1000
1200
1400
1600
1800
Time (s)


Urban delivery VECTO cycle - Time speed profile
Speed (km/h)
90
80
70
60
50
40
30
20
10
0
0
500
1000
1500
2000
2500
3000
3500
Time (s)


Urban delivery VECTO cycle - Time gradient profile
Gradient (%)
8
6
4
2
0
-2
-4
-6
-8
0
500
1000
1500
2000
2500
3000
3500
Time (s)

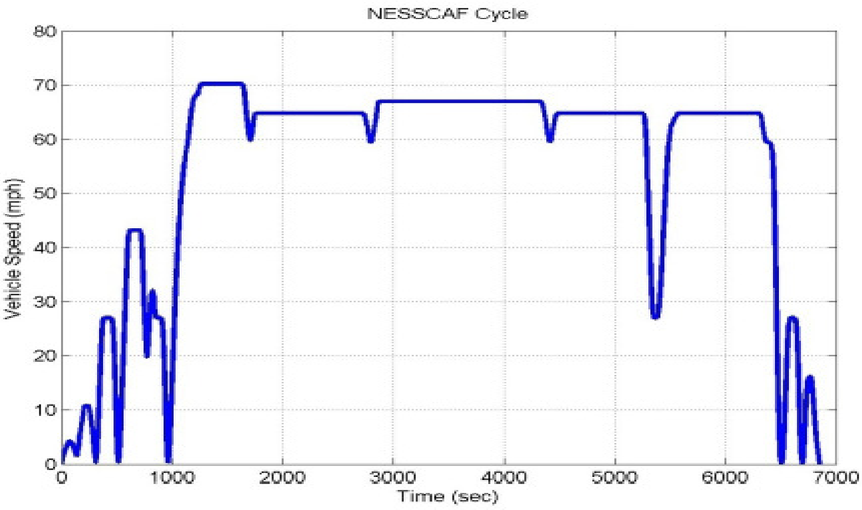
Typical driving patterns used in US studies

Long haul cycle:

From Table 3.12 (Vehicles and drive cycles used in study) of SWRI Report #1 five cycles were used to examine the CO_2 emissions from the Class 8 truck: 3 GEM cycles plus two others. Together the cycles over which the vehicle was tested comprise:

- A low speed urban cycle developed by CARB (Heavy heavy duty diesel truck – transient section),
- A constant 55 MPH with no grade or wind,
- A 65 MPH constant speed with no grade or wind,
- The world harmonised vehicle cycle (for heavy duty vehicles), WHVC
- NESCCAF Long Haul Cycle.

The speed time profile of the NESCCAF Long haul cycle is:



This looks moderately similar to the VECTO long haul cycle except for clear difference that the upper speed for the US cycle is around 104 – 112 km/h (65 – 70 mph) whereas trucks in Europe have a 90 kph speed limiter. More quantitatively, the comparison between the two cycles is tabulated below:

		VECTO Long haul	NESCCAF
Duration	h	1.47	1.90
Distance	km	108.18	166.32
Average Speed	km/h	73.59	87.41
Average driving speed	km/h	77.07	87.45
Max. Speed	km/h	90.00	112.98
Max. Acceleration	m/s2	1.00	0.24
Max. Deceleration	m/s2	-1.00	-0.48
Time in acceleration	s	642.00	806.00
Time in deceleration	s	591.00	655.00
Avg Acceleration	m/s2	0.25	0.14
Avg Deceleration	m/s2	-0.27	-0.17
Percent Idle	%	4.5%	0.0%
Number of stops		5	6
Stops	#/km	0.05	0.04[66]

[66] Number of stops for NESCCAF includes those in the first 1,000 seconds where the vehicle's speed falls to below 0.5 mph even if it does not reach zero.

Implications for translation of US EPA data - Long haul cycle:

The CO_2 reduction potential reported in the EPA studies for different technologies can be "translated" into those appropriate for European driving patterns by using the relationship below:

Potential fuel consumption change for European long haul driving =

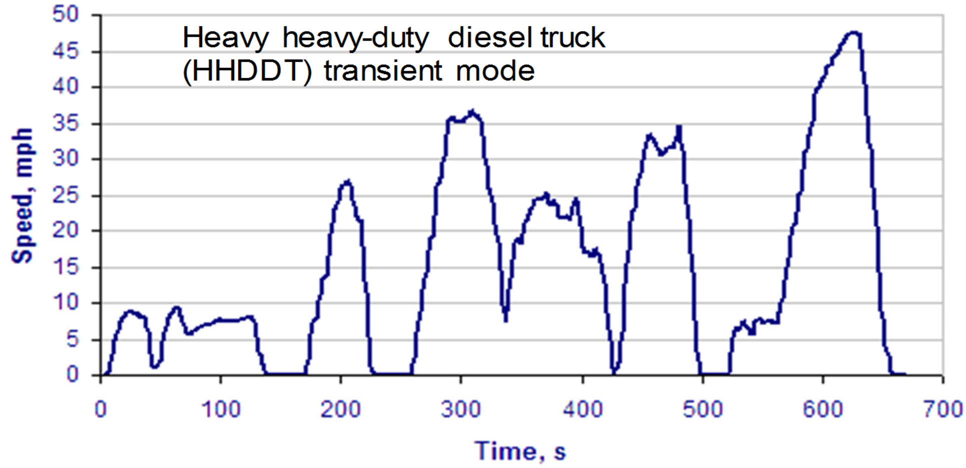
Potential over US NESCCAF cycle **minus** (difference between 55 mph & 65 mph steady speed cycles)

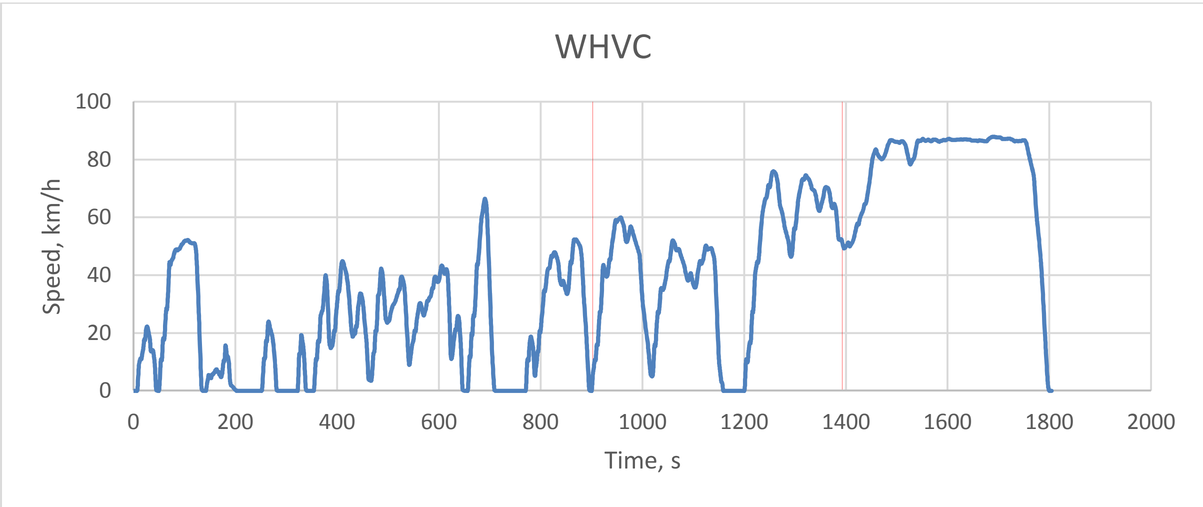
Regional delivery cycle

From Table 3.12 (Vehicles and drive cycles used in study) of SWRI Report #1 there are six cycles used to examine the CO_2 emissions from the Regional delivery Kenworthy T270 box-truck: These were:

- A low speed urban cycle developed by CARB (HHDDT – transient section),
- A constant 55 MPH with no grade or wind,
- A 65 MPH constant speed with no grade or wind,
- Combined International Local and Commuter Cycle (CILCC),
- Parcel Delivery Cycle,
- The world harmonised vehicle cycle (for heavy duty vehicles), WHVC.

Examination of the time - speed profiles suggest the Steady 65 mph, CILCC and Parcel Delivery Cycle are poor comparisons with the EU VECTO Regional delivery cycle. This leaves two transient cycle possibilities: the HHDDT – transient section and the world harmonised vehicle cycle. Their speed-time profiles are shown below:





Detailed examination of the time - speed profiles suggests two possibilities are closest to emulating the VECTO Regional delivery cycle:

1. A combining of the results from CARB and 55 MPH cycles, using appropriate weights; or
2. Using the results from the WHVC cycle.

Further analysis indicates that although taking different weightings for the three separate time - speed profiles, for different segments of WHVC, would be appropriate, the EPA studies only report the CO_2 emissions from the **whole cycle**. Therefore, option 1 is the most practical.

Characterisation of the cycles gives:

		VECTO Regional			**CARB**	**55 mph**
		Whole	Section 1	Section 1a		
Duration	h	0.45	0.24	0.08	0.19 (668 s)	
Distance	km	25.84	9.25	2.05	4.57	
Average Speed	km/h	57.08	39.20	25.23	24.65	88 kph
Average driving speed	km/h	61.09	44.85	27.80	29.61	88 kph
Max. Speed	km/h	88.51	73.65	51.90	76.51	88 kph
Max. Acceleration	m/s2	1.00	1.00	1.00	1.32	0
Max. Deceleration	m/s2	-1.00	-1.00	-1.00	-2.43	0
Time in acceleration	s	349.00	218.00	85.00	261.00	0
Time in deceleration	s	352.00	232.00	89.00	187.00	0
Avg Acceleration	m/s2	0.37	0.40	0.43	0.34	0
Avg Deceleration	m/s2	-0.36	-0.37	-0.41	-0.47	0
Percent Idle	%	6.6%	12.6%	9.2%	16.8%	0
Stops	#/km	0.15	0.43	0.98	1.09	0

In terms of a time weighting, a full CARB cycle + 31% of the cycle time, i.e. around 207 seconds of 55 mph steady state driving, gives a “combined” cycle whose characteristics are quite close to the whole VECTO Regional cycle.

Implications for translation of US EPA data – Regional delivery cycle:

In terms of the driving patterns, the CO_2 reduction potential reported in the EPA studies for different technologies for the T270 box-van can be “translated” into those appropriate for European driving patterns by using the algorithm below:

Potential for European regional driving =

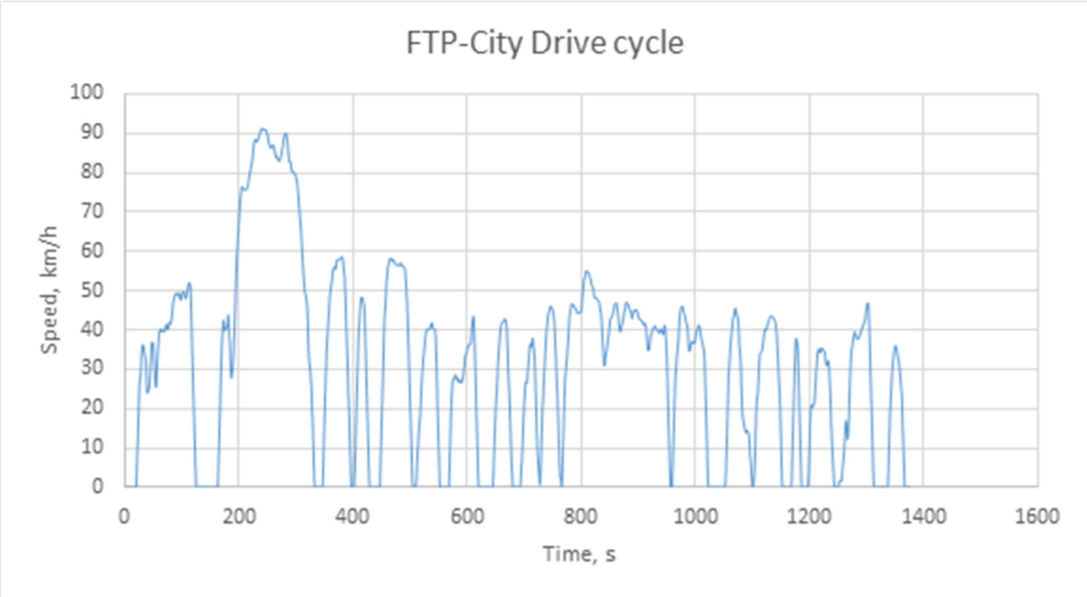
> Potential over CARB (HHDDT – transient section) + 55 mph steady speed cycle, with appropriate weightings.

Urban delivery cycle

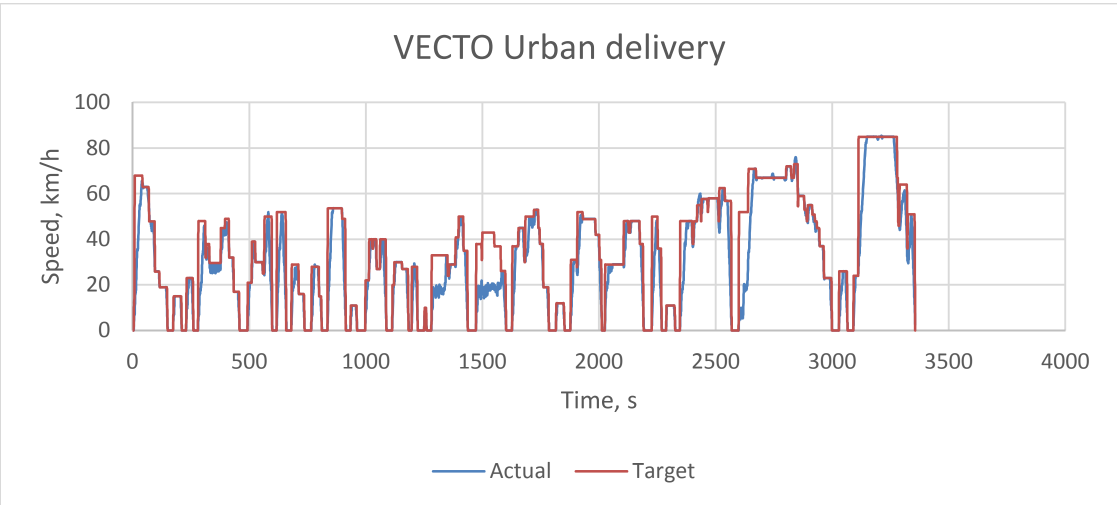
From Table 3.12 (Vehicles and drive cycles used in study) of SWRI Report #1 there are six cycles used to examine the CO_2 emissions from the RAM Pick-up truck. These are:

- FTP City cycle
- FTP Highway cycle
- US06 and SC03
- WHVC
- A 65 MPH constant speed with no grade or wind.

Examination of the time - speed profiles suggest the FTP Highway cycle, the US06 and SC03 cycles, the WHVC and the 65 MPH constant speed with no grade or wind, are all poor matches with the EU VECTO Urban delivery cycle. This leaves the single possibility in terms of the time - speed profiles: the FTP City cycle.



This compares moderately well with the VECTO Urban delivery cycle shown earlier



In terms of the key characteristics of the two cycles, these are:

		FTP-City (for light-duty)	VECTO Urban delivery		HHDDT Transient (CARB)
Duration	h	0.38	0.93		0.19
Distance	km	12.07	27.81		4.57
Average Speed	km/h	31.35	29.84		24.65
Average driving speed	km/h	38.89	36.24		29.61
Max. Speed	km/h	91.25	85.34		76.51
Max. Acceleration	m/s2	1.48	1.00		1.32
Max. Deceleration	m/s2	-1.48	-1.00		-2.43
Time in acceleration	s	532.00	826.00		261.00
Time in deceleration	s	463.00	849.00		187.00
Avg Acceleration	m/s2	0.51	0.48		0.34
Avg Deceleration	m/s2	-0.59	-0.47		-0.47
Percent Idle	%	19.4%	17.7%		16.8%
Stops	#/km	1.42	0.90		1.09

Whilst the characteristics of the CARB HHDDT Transient cycle are given in the column on the far right of the table, this does not help that much because the RAM Pickup was not tested over this (more heavy-duty vehicle) cycle.

Implications for translation of US EPA data – Urban delivery cycle (service vehicles):

In terms of the driving patterns, the CO_2 reduction potential reported in the EPA studies for different technologies can be "translated" into those appropriate for the European service vehicle driving pattern by evaluating the savings over the FTP-City cycle.

Final comments on the technology potential translation between US and European vehicles and usage.

This paper has focussed on prioritising which driving cycles are most relevant to the European context from the CO_2 reduction potential reported in the NHTSA studies to support Phase 2 of the US HDV greenhouse gas (GHG) regulation. This arises because different driving patterns in the two continents affect the CO_2 reduction potential of different technologies differently.

However, for the data translation further factors need to be considered. Most notably:

- Differences in baseline vehicle characteristics, and
- Differences in the extent to which the technologies that can deliver reductions in CO_2 emissions are already fitted to baseline vehicles.

Appendix 3 – VECTO model version and files used for simulations

General Declaration mode files

Model version: 2016_07_19-VECTO-**3.0.4.565**

Drive cycles	Regional_Delivery.vdri	Creation date for compressed file we used	16/6/2016
	Long_Haul.vdri	Creation date for compressed file we used	16/6/2016

Vehicle files

The files used came from the sub-folders

2016_07_19-VECTO-3.0.4.565\Generic Vehicles\Declaration Mode\12t Delivery Truck

And

2016_07_19-VECTO-3.0.4.565\Generic Vehicles\Declaration Mode\40t Long Haul Truck

Vehicle files	.vveh	Creation date for compressed file we used	19/7/2016

Similarly files specifying engine, gear box, full load power curve were all compressed on 19/7/2016

For both the 12 tonne delivery truck and the 40 tonne long haul truck

Note how these files were the declaration mode files, and the VECTO model was run using “Declaration mode”.

Ricardo
Energy & Environment

The Gemini Building
Fermi Avenue
Harwell
Didcot
Oxfordshire
OX11 0QR
United Kingdom

t: +44 (0)1235 753000
e: enquiry@ricardo.com

ee.ricardo.com