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# FUEL EFFICIENCY TECHNOLOGY IN EUROPEAN HEAVY-DUTY VEHICLES: BASELINE AND POTENTIAL FOR THE 2020–2030 TIME FRAME

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# TABLE OF CONTENTS

# EXECUTIVE SUMMARY

In December 2015, 195 countries adopted the first-ever binding climate deal at the United Nations Climate Change Conference in Paris (COP 21). The pledge includes reducing EU-wide $CO_2$ emissions by 40% from 1990 levels by 2030 and reducing $CO_2$ from all sectors not covered by the Emissions Trading Scheme (ETS) by 30% from 2005 to 2030. Transport is one of the largest sectors not covered by the ETS. There is significant pressure on the European Commission, as well as on the individual member states, to consider a range of measures for reducing $CO_2$ from all sectors. To guide this process for the transport sector, the European Commission (EC) issued a communication in July 2016 to major European stakeholders entitled "A European Strategy for Low-Emission Mobility." The strategy outlines the EC's plans for upcoming work and regulations aimed at reducing EU-wide transport-related $CO_2$ emissions. The document specifically addresses heavy-duty vehicle (HDV) $CO_2$ emissions, which currently represent around a quarter of road transport $CO_2$ emissions, and states the EC's intent to move toward regulating $CO_2$ from HDVs.

The technical research described in this report is aimed at informing stakeholders on the technological potential for improving the efficiency of new heavy-duty freight-hauling vehicles in the EU in the 2020–2030 time frame, thereby reducing $CO_2$ emissions and fuel consumption from these vehicles. The analysis focuses on two vehicle segments on either end of the freight hauling operational spectrum: long-haul tractor-trailers and urban rigid delivery trucks. These segments represent approximately 85% of HDV $CO_2$ emissions. Given that the effectiveness of a technology is strongly influenced by the characteristic driving cycle of the vehicle, the selection of these two HDV classes is aligned with the study's objective of analyzing a wide range of fuel-saving technologies. The first step is to define two baseline vehicles representing the average of the corresponding HDV segment. The second step is to determine how much fuel consumption could be reduced from these vehicles by applying technologies that are either already commercially available or that are estimated to become commercially available within the next decade. The study uses vehicle simulation modeling software to determine the fuel consumption of the two baseline vehicles as well as the potential improvement from a stepwise addition of successively more advanced technology packages. The accuracy of the modeling depends heavily on the accuracy of the model inputs that are used. For that reason, a key component of the study is comprehensive literature research to obtain and validate the inputs, such as the engine fueling map, aerodynamic drag coefficient, and the rolling resistance of the vehicle for both the baseline and the technologically advanced vehicles.

The findings from the study show that there is significant potential to reduce fuel consumption from the current average EU freight truck. The key results of this study, which have implications for the first phase of EU HDV $CO_2$ standards, are highlighted below and summarized in Figure ES 1 and Figure ES 2.

### » 1. Baseline determination

To determine the $CO_2$ value for the baseline tractor-trailer and rigid delivery truck used in this study, we employed vehicle simulation modeling using fixed payloads and duty cycles. The aim was to create a baseline tractor-trailer and rigid truck that would represent the sales-weighted average of that entire vehicle segment. The legitimacy of this methodology completely relies on the accuracy of the simulation model's inputs. To ensure accurate fuel consumption information, we focused on acquiring representative values for the aerodynamic drag, rolling resistance, and engine fuel consumption maps in order to determine which tractor-trailer and rigid truck specifications would best represent fleetwide average composites for their respective segment. The aerodynamic drag baseline numbers are based on 14 sources, covering 21 different vehicles. The baseline rolling resistance value is the result of analyzing 13 sources, covering 16 different vehicles and over 2,500 tire models. Lastly, the engine fuel maps used for our baseline analysis were provided by a recognized engineering service provider (AVL), and are the result of their expertise in engine benchmarking. The baseline tractor-trailer used in our study has a fuel consumption value of 33.1 L/100km when tested over the VECTO Long Haul cycle. The baseline urban delivery truck used in our study has a fuel consumption value of 21.4 L/100km when tested over the VECTO Urban Delivery cycle.

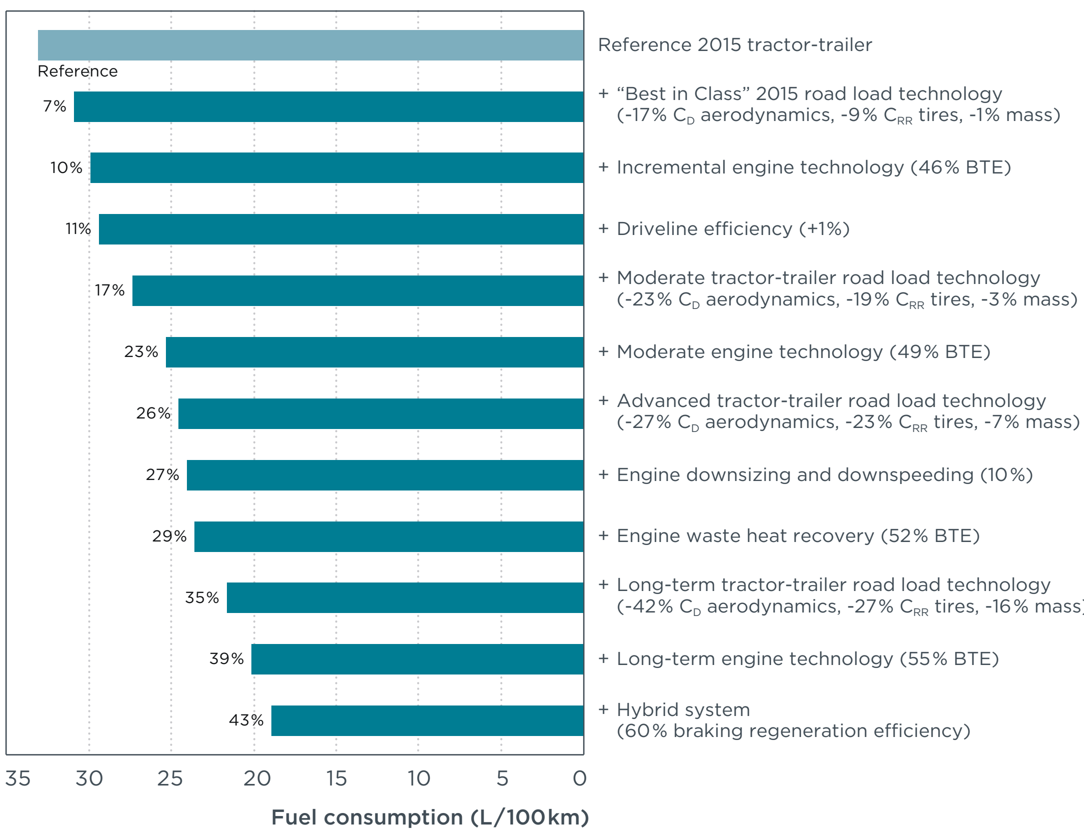


**Figure ES 1.** Potential fuel consumption reduction from selected tractor-trailer efficiency technologies in the 2020–2030 time frame over the VECTO Long Haul cycle.
Per VECTO's defined protocols, the payload modeled for the Long Haul cycle is 19.3 tonnes.

### » 2. Tractor-trailer potential in the mid-term and long-term

Figure ES 1 illustrates the potential fuel consumption reduction from the baseline tractor-trailer through the sequential application of technology packages primarily focusing on tires, aerodynamics, trailer, and engine efficiency improvements. Our mid-term analysis focused on technologies that are already commercially available, including engine turbocompounding, low friction accessories, downsped drivelines, low rolling resistance tires, and trailer aerodynamic devices. Applying these technologies to our baseline vehicle, which represents the fleet average vehicle in 2015, would achieve 27% fuel consumption and $CO_2$ reduction over the VECTO Long Haul cycle. This amounts to a reduction in fuel consumption from the tractor-trailer baseline of 33.1 L/100km to 24.0 L/100km. The corresponding average annual reduction is 3.1% per year from 2015 to 2025. For comparison, under the U.S. HDV standards, the average long-haul tractor-trailer fuel consumption reduction was 3.1% per year for Phase 1 (from 2010–2017) and 2.8% per year for Phase 2 (from 2017 to 2027). Further reductions could be attained by utilizing well-known but not yet widely commercialized technologies that are predicted to be available in the market within 10 years. These technologies include a 55% brake thermal efficiency engine with waste heat recovery, heavy-duty hybridization for long-haul, and advanced aerodynamics. The use of such a technology package results in a 43% reduction from the 2015 baseline by 2030. This would require an average annual reduction from 2015 to 2030 of 3.6%, reducing the fuel consumption of new tractor-trailers to 18.9 L/100km by 2030.

### » 3. Rigid truck potential in the mid-term and long-term

The technologies incorporated in the analysis of the urban rigid delivery truck include some overlap with the long-haul tractor-trailer technologies as well as some technologies not considered for the tractor-trailer. In general, the technologies that are the most relevant for both vehicle segments are the low rolling resistance tires, mass reduction, and engine efficiency technologies. For tractor-trailers, the aerodynamic and waste heat recovery technologies are significant, but they are less so for trucks that follow an urban driving cycle. For urban delivery trucks, improved accessories, improved transmissions, and hybrid technologies are very pertinent. Figure ES 2 shows the potential fuel consumption reduction for the rigid truck, with a mid-term technology package representing commercialized technologies and a long-term technology package representing well-known but not necessarily widely commercialized technologies. Applying the mid-term technology package to our baseline 12-tonne delivery truck results in a 23% reduction in fuel consumption over the Urban Delivery cycle. Starting from a baseline fuel consumption of 21.4 L/100km over the Urban Delivery cycle, mid-term technology would reduce fuel consumption to 16.5 L/100km. An analysis of technologies that are not yet commercialized but are predicted to be available in the 2025–2030 time frame was also performed. Note that although full hybrid delivery trucks are currently available on the market, we opted to analyze this technology as part of our longer-term package. This is because as more advanced road load reduction technologies (e.g., low rolling resistance tires, aerodynamic devices, and mass reduction) are applied, the braking losses increase, providing higher fuel consumption reduction potential for hybrid systems. The long-term package for the rigid delivery truck over the Urban Delivery cycle results in a 43% reduction in fuel consumption from the 2015 baseline, an annual improvement of around 3.6% per year from 2015–2030. This would mean a reduction from a baseline fuel consumption of

21.4 L/100km to 12.1 L/100km by 2030. As shown in Figure ES 2, the total fuel consumption reduction values for the same truck are lower under the Regional Delivery and Long Haul cycles, respectively, due in large part to lower effectiveness of the full hybrid system under less transient driving.

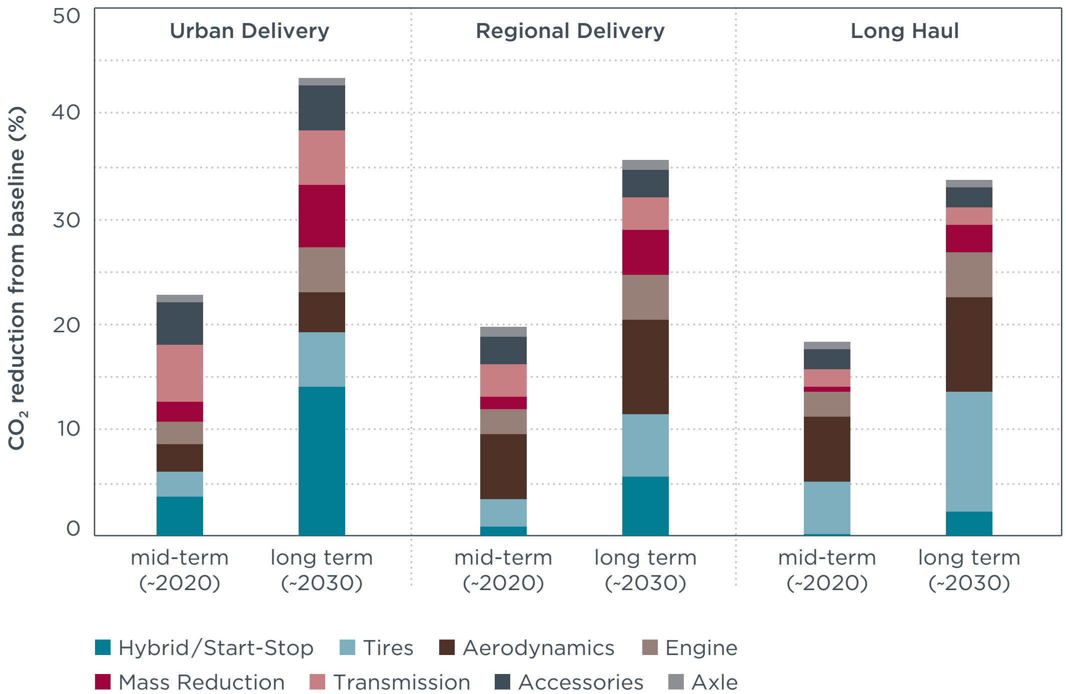


**Figure ES 2.** Potential fuel consumption reduction from selected rigid truck efficiency technologies in the 2020–2030 time frame over the VECTO Urban Delivery, Regional Delivery, and Long Haul cycles. Per VECTO's defined protocols, the payload modeled for the Urban Delivery and Regional Delivery cycle was 3 tonnes, while the payload modeled for the Long Haul cycle was 9.8 tonnes.

There are additional questions that were not covered within the scope of the research conducted for this report. First, because this research was focused on technologies that would be applied to freight hauling HDVs in the EU, it specifically looked at a tractor-trailer and an urban delivery truck. Other types of HDVs, such as construction equipment, service vehicles, and buses, were not covered in this research. We note that these types represent less than 10% of HDV $CO_2$ emissions. Second, this report did not assess the cost, payback, and cost-effectiveness of the individual technologies and technology packages that were analyzed for this project. Such topics are the subject of an upcoming ICCT publication.

# 1. INTRODUCTION

The European Union has historically been a leader in vehicle environmental policy, as demonstrated by the adoption of Euro-like emissions standards in many non-European countries. Despite this traditional leadership role, European policymakers have not addressed the fuel efficiency of freight transportation for decades. Fuel efficiency standards for heavy-duty vehicles (HDVs), which set mandated fuel consumption targets for new vehicle sales, are a key element to counteract the negative impacts of freight demand increase on climate change and energy security.

In the time frame 1990 to 2014, on-road transportation was the only carbon dioxide ($CO_2$) source that did not achieve any emissions reductions (European Environment Agency [EEA], 2016a). In the 24-year period, on-road transportation $CO_2$ emissions increased by 17%, and accounted for 24% of Europe's total $CO_2$ emissions in 2014 (EEA, 2016b). Furthermore, the growth of $CO_2$ emissions from commercial vehicles has significantly outpaced those of passenger vehicles; from 1990 to 2014 $CO_2$ emissions of commercial vehicles increased by 25%, while the passenger car emissions did so by 12% (EEA, 2016c). Diesel-powered HDVs account for about one-quarter of the total on-road $CO_2$ emissions in the European Union (EEA, 2016c) and their share is expected to increase to around 45% by 2030 under a business-as-usual scenario (Façanha, Miller, & Shao, 2014). This growing trend is incompatible with European targets aiming for a 60% reduction of greenhouse gas (GHG) emissions by 2050 compared with 1990 levels (European Commission [EC], 2011).

Previous experience shows that non-binding fuel consumption targets and market forces alone are not sufficient to drive the GHG reductions necessary to meet the European Union's objectives. In 1998, automakers signed a nonbinding agreement to reduce the average $CO_2$ emissions from new light-duty vehicles (LDVs) sold to 140 g/km by 2008. As it became evident the target was not going to be met in 2006, the European Commission (EC) announced it would be implementing mandatory $CO_2$ standards. The difference in performance of the voluntary and mandatory approaches is evident; until 2007, the $CO_2$ emissions reduction averaged 1% per year, while the annual decrease has averaged 3.5% since 2008 (Díaz, Tietge, & Mock, 2016). Although mandatory $CO_2$ standards have been in place for LDVs since 2009, no specific regulatory targets have yet been defined for heavy-duty vehicles. A recent analysis shows that the fuel efficiency of tractor-trailers in the European Union was stagnant from 2002 to 2014 (Muncrief & Sharpe, 2015).

European original equipment manufacturers (OEMs) are global players in the HDV market, accounting for 40% of the global production of HDVs above 3.5 tonnes (Hill et al., 2011). The United States, Canada, China, and Japan, markets in which European HDV OEMs sell their products, have already introduced GHG standards for HDVs, mandating efficiency improvements of up to 44% in the 2020–2030 time frame compared with a 2010 baseline (Sharpe, Lutsey, Delgado, & Muncrief, 2016). The lack of action at the EU level to address the fuel consumption and $CO_2$ emissions of HDVs can result in the European Union falling behind the United States and other countries in HDV efficiency technology research, development, and deployment, negatively affecting the competitiveness of European OEMs in these markets. Well-designed and implemented standards incentivize research and development on new fuel efficiency technologies, overcome market barriers to efficiency improvements, and increase the market penetration of commercially available technologies at a faster rate than would occur from relying on market forces alone. Furthermore, EU policymakers have a demonstrated influence on the international arena as exemplified by the wide adoption of pollutant emissions standards in line with the EU legislation by several key markets, such as China, India, Brazil, Russia, and Indonesia. As such, the development and implementation of $CO_2$ emissions standards is a crucial step in maintaining the European Union's leadership and competitiveness in the global arena.

In light of increasing freight demand, the ineffectiveness of market forces to improve the fuel efficiency of HDVs, and the competitiveness and global leadership challenges resulting from other world regions moving forward with HDV GHG standards, the EC started work on developing a policy pathway for reducing GHG emissions from HDVs. The first step toward this goal is closing the knowledge gap and increasing market transparency by measuring the fuel consumption of HDVs. To this end, the EC commissioned in 2009 the development of a standardized testing procedure. The resulting methodology[1] for determining vehicle $CO_2$ emissions (EC, 2017c) consists of component testing combined with a simulation tool, named VECTO (Vehicle Energy Consumption Calculation Tool). The development of the testing methodology provided the necessary groundwork for the EC to propose the introduction of a monitoring and reporting scheme for HDV $CO_2$ emissions (EC, 2017b). Additionally, the EU bindingly committed during the 21st session of the Conference of the Parties (COP 21) to cut emissions to at least 40% below 1990 levels by 2030 as part of the Paris Agreement. Following this commitment, the EC indicated in July 2016 that it will start working on the development of mandatory efficiency standards for HDVs during the current mandate (EC, 2016). On May 31, 2017, as part of its most recent package of regulatory initiatives related to transportation called "Europe on the Move," the European Commission communicates that a proposal for $CO_2$ standards for HDVs in the EU is envisaged for the first half of 2018 (EC, 2017a).

The evaluation of the fuel-saving potential of different HDV technologies is a fundamental step in the development of the HDV $CO_2$ standards. Using state-of-the-art vehicle simulation modeling, this study provides an independent analysis on the current status of fuel consumption reduction technology and the potential of available and in-development technologies to deliver future efficiency gains.

## PREVIOUS WORK

The HDV technology potential question has been addressed by several studies in the past few years for both the U.S. and EU markets. (Breemersch & Akkermans, 2015). Relevant studies for the United States include those by NESCCAF (Cooper et al., 2009), TIAX (Kromer, Bockholt, & Jackson, 2009), National Research Council (National Academies of Sciences [NAS], 2010), SwRI (Reinhart, 2015, 2016) and the International Council on Clean Transportation (ICCT) (Delgado & Lutsey, 2015). Of particular relevance for the European market are the reports by Ricardo-AEA (Hill et al., 2011), TIAX (Law, Jackson, & Chan, 2011), the Institute for Energy and Environmental Research (IFEU) (Dünnebeil et al., 2015) and T&M Leuven Tractor-trailers are responsible for the majority of fuel use and GHG emissions of the on-road freight sector in the European Union (see Figure 1), as well as in most other markets (Sharpe & Muncrief, 2015). Furthermore, the aforementioned studies agree that long-haul tractor-trailers have the largest potential for substantial and cost-effective fuel efficiency improvement. A summary of the technology potential of long-haul tractor-trailers for the studies conducted for the EU market is shown in Table 1.

1 The regulation outlining the $CO_2$ certification methodology was adopted by on May 11, 2017 by the Technical Committee – Motor Vehicles. At the time of writing of this paper, the regulation had not been published in the *Official Journal of the European Union*.

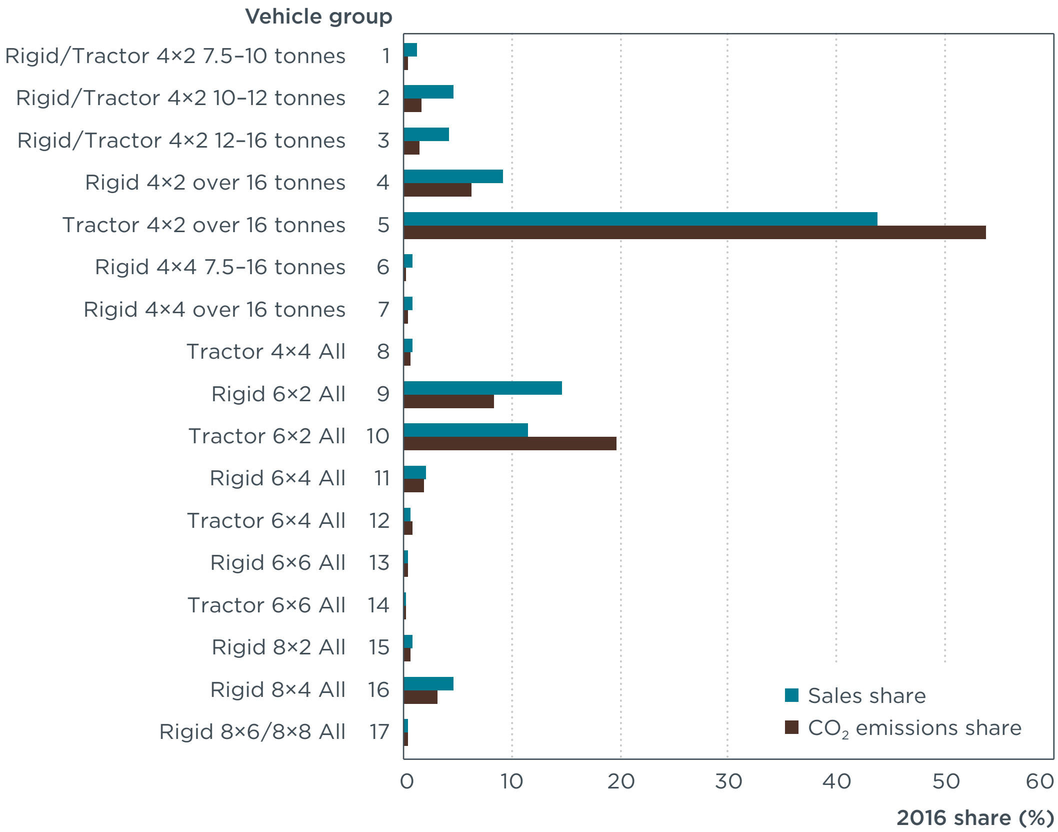


**Figure 1.** Distribution of new HDV registrations and $CO_2$ emissions in the European Union in 2016

**Table 1.** Technology potential for long-haul HDVs from four previous EU studies

| | Studies | | | |
|---|---|---|---|---|
| **Author** | Ricardo-AEA, 2011 | TIAX, 2011 | T&M Leuven, 2015 | IFEU, 2015 |
| **Baseline vehicle** | 2010 Euro V | 2014 Euro VI | 2014 Euro VI | 2014 Euro VI |
| **Methodology** | Expert consultation | Literature review | OEM survey | Vehicle simulation |
| **Analysis' time frame** | 2010–2030 | 2014–2030 | 2014–2020 | 2015–2025 |
| | **Potential for fuel consumption reduction** | | | |
| **Engine** | 6% | 14.6–17.9%* | 5.0% | 2.3% |
| **Accessories** | 0–8% | – | 1.5% | 1.0% |
| **Bottoming cycle** | 1–6% | – | – | 3.0% |
| **Transmission** | 0–10% | 1–1.5% | 0.5% | 0.5% |
| **Axles** | – | – | 0.5% | 1.0% |
| **Tires** | 6–10% | 9–12% | 4.0% | 5.9% |
| **Aerodynamics** | 10–18% | 5–9% | 4.0% | 5.8% |
| **Lightweighting** | 1–4% | 2.2% | 0.5% | 0.7% |
| **Hybridization** | 4–10% | 8–12% | – | 3.7% |
| **Driver assistance** | 2–10% | 2–7% | 2.5% | 3.4% |
| **Total** | Up to 50% | 41–52% | 15–17% | 24% |

**Includes accessories and bottoming cycle*

The estimates for the technology potential are strongly dependent on the baseline vehicle selected, the assumed technology availability in the analysis time frame, the vehicle payload, duty cycle, the effectiveness of the individual technologies, and the assessment methodology. Of the four EU studies presented in Table 1, only one uses vehicle simulation to quantify technology potential; the other three rely on expert consultation and literature review. Given the complex interaction among technologies and vehicle systems, the potential of different technology packages may not be accurately estimated by multiplicative aggregation of the individual technologies' effectiveness. Physics-based vehicle simulations are able to capture these interactions and improve the estimation confidence of future technology packages.

## STUDY OBJECTIVES AND OUTLINE

The primary objective of this report is to establish through simulation modeling the current efficiency baseline levels of European trucks and to estimate the potential for fuel consumption reduction through different technology packages in the 2020–2030 time frame. By evaluating different levels of technology integration, this study shows some possible stepping stones for a technological pathway leading to significant improvements in fuel efficiency in the mid- and long-term.

Figure 1 shows the distribution of HDV registrations and $CO_2$ emissions for different vehicle configurations for 2016, using vehicle sales statistics[2] and fuel consumption and vehicle mileage assumptions by Ricardo-AEA (Hill et al., 2011). Tractor-trailers account for 57% of new HDV registrations and 75% of the $CO_2$ emissions; tractor-trailers with a 4×2 axle configuration are the single highest contributor. The 4×2 rigid trucks represent 19% of new HDV registrations and 10% of the $CO_2$ emissions. To cover the most ground in terms of fuel-saving technologies, this study focuses on two vehicle configurations covering the two ends of the operation spectrum: a 40-tonne 4×2 tractor-trailer for the long-haul segment and a 12-tonne 4×2 rigid truck for the urban freight segment.

## STUDY LIMITATIONS

This study aims to provide a robust assessment on the emerging technologies that are expected to be commercially available to increase HDV efficiency in the new 2020–2030 fleet. As such, the scope of the current work is limited to engine, transmission, and vehicle technology, and excludes strategies that target driver behavior, operations, and logistics improvements. Furthermore, this study does not include any assessment on the cost-effectiveness of the technologies and technology packages considered. The cost-effectiveness of the technologies considered in this report will be addressed separately in a future study.

Following this introductory section, Section II describes the study methodology. Section III describes in detail the determination of the baseline vehicles, the relevant data inputs, the model validation, and the baseline fuel consumption results. Section IV builds from the developed baselines to analyze the applicable available and emerging technologies, their individual fuel consumption reduction effectiveness, and their integrated potential when assembled in technology packages. Closing this report, Section V concludes with a summary of the findings, their implications, and a policy discussion.

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2 Content supplied by IHS Global SA; Copyright © IHS Global SA, 2016. All rights reserved.

# 2. METHODOLOGY

The baseline vehicle model development and technology potential evaluation is done via a state-of-the-art vehicle simulation modeling software tool called Autonomie. The software, developed by Argonne National Laboratory (ANL, 2015) in the United States, is used to assess diverse vehicle configurations and to estimate the effects of vehicle specifications on fuel consumption in a manner similar to Europe's Vehicle Energy Consumption Calculation Tool (VECTO). University and industry groups use Autonomie as a research and development tool. It was chosen for this study because it offers greater flexibility, enhanced analysis capabilities, and higher results transparency than VECTO. Delgado and Lutsey present additional details on ICCT's simulation capabilities using Autonomie (Delgado & Lutsey, 2015). As a first step, a comparison of both vehicle simulation tools was performed. Although Autonomie and VECTO use the same set of underlying physics-based models for estimating fuel consumption, the driver model programmed into each tool is different. Using the same set of vehicle input data, both tools were used to simulate the fuel consumption over different driving cycles. The results from the two vehicle simulation tools showed good agreement; further details on this comparison are presented at the end of Section III.

Autonomie was then used to create baseline models for a tractor-trailer and a rigid truck, based on typical model year 2015 key vehicle specifications obtained from a combination of sources including sales databases, market penetration databases, publicly available literature sources, technical brochures, ICCT consultants' analyses, and personal communications with industry experts. The inputs required to accurately model a vehicle include engine parameters (e.g., displacement, maximum power, engine fuel map, maximum torque curve, and engine friction curve), driveline parameters (e.g., transmission type, transmission gear ratios, transmission efficiency maps, rear axle ratio, rear axle efficiency, tire radius), and vehicle road-load-related parameters (e.g., curb weight, payload, frontal area, aerodynamic drag coefficient, rolling resistance coefficient, rotational inertia of rotating parts). The simulation software is capable of accounting for the non-linear interactions among the vehicle's systems that could result from modifying a single vehicle characteristic. For example, improving the aerodynamic performance of the trailer results in a shifting of the engine's speed and torque and impacts the amount of energy dissipated as braking in a given driving cycle. Other key inputs in determining baseline fuel consumption are the driving cycle speed and grade profile. The European Union has developed mission-specific duty cycles based on HDV operations in Europe (Luz et al., 2014). After specifying the characteristics of the baseline vehicles, this study models their fuel consumption behavior over such specific duty cycles. The ICCT has previously conducted a similar analysis on a U.S. tractor-trailer (Delgado & Lutsey, 2015).

For the assessment of the fuel consumption reduction potential, a literature review was performed to identify individual fuel-saving technologies that are currently available or are expected to become available during the 2020–2030 time frame. Each technology's individual potential was estimated by a combination of literature review and vehicle simulation over representative duty cycles and payloads. After the individual technology analysis, the combined technology potential of technology packages was assessed.

# 3. BASELINE VEHICLES MODEL DEVELOPMENT

Determining the baseline vehicles' characteristics and their respective fuel consumption is an important step in establishing the potential to reduce $CO_2$ emissions. However, due to the lack of reliable and publicly available fuel consumption figures, no official baseline currently exists in Europe. Making use of an extensive literature review and best available data, this section defines the key vehicle characteristics of representative tractor-trailers and rigid trucks in the European market, and estimates their fuel consumption through vehicle simulation. These vehicle models provide the foundation for the technology potential analysis presented in Section IV of this report.

## TRACTOR-TRAILER BASELINE DEVELOPMENT

Long-haul tractor-trailers emit approximately 75% of the $CO_2$ emissions of the heavy-duty truck fleet (see Figure 1). The most common tractor-trailer configuration, with a 4×2 drivetrain and a gross combined weight (GCW) of 40 tonnes, was selected for this analysis. A wide range of recent literature was reviewed to gather the input parameters necessary for the creation of a tractor-trailer baseline vehicle model. There is a wide range of values for some of the technical parameters relevant for the tractor-trailer baseline fuel consumption. This study is transparent on the range of variability found for such parameters and on the methodology used to select the baseline values that are deemed representative of an average vehicle. The following sections describe the details of the selection of engine, driveline, and road load baseline parameters.

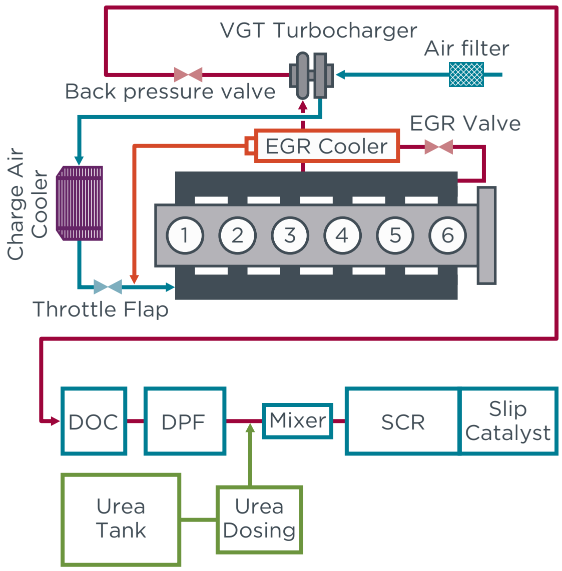
### Engine

Analysis of recent sales and registration data from IHS Automotive shows that typical European tractor-trailer engines have displacements ranging between 10 L and 13 L, power ratings between 250 kW and 380 kW, and maximum torque values between 1,500 Nm and 2,500 Nm. The most commonly sold engine on the market[3] has a 12.8 L engine displacement and a power rating of 340 kW.

ICCT commissioned AVL List GmbH, an engineering service provider company with extensive experience in powertrain benchmarking, to provide a representative engine fuel map for this study. The Euro VI engine selected for this analysis has a displacement of 12.8 L, equipped with a common rail system with fuel injection pressures between 2,000 and 2,500 bar and a single-stage variable geometry turbocharger (VGT). The engine uses cooled exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) for nitrogen oxides ($NO_x$) emissions control, and a diesel particulate filter (DPF) for particulate matter (PM) control.

Figure 2 shows the key engine characteristics and engine layout of the baseline tractor-trailer engine used in this study. The engine fuel consumption map accounts for the power consumed by the oil, coolant, and fuel pumps. The fuel map does not account for the power consumed by other vehicle accessories such as cooling fan, air compressor, power steering, and alternator; these were included in the vehicle simulation model as constant power demands.

3 2015 sales data supplied by IHS Global SA show that engines with a displacement between 12.7 and 12.9 liters have a 45% market share in the 4×2 tractor-trailer segment. Similarly, engines with a power rating between 330 kW and 350 kW have a 39% market share in the 4×2 tractor-trailer segment.




| Engine Data | |
|---|---|
| **Swept Volume** | 12.8 L |
| **Max. Torque** | 2,400 Nm (1,000–1,400 rpm) |
| **Max. BMEP** | 23.6 bar (1,000–1,400 rpm) |
| **Max. Power** | 350 kW (1,500–1,900 rpm) |
| **Emission Legislation** | Euro VI |
| **$NO_x$ Engine Out Emissions** | 5–6 g/kWh (Low $CO_2$ Mode) |
| **Fuel Injection Equipment** | Common Rail (2,000–2,500 bar) |
| **Turbocharger** | Single stage VGT |
| **Engine $NO_x$ Reduction** | Cooled HP EGR |
| **Peak Cylinder Pressure** | -205 bar |

**Figure 2.** Tractor-trailer engine layout and technical characteristics

Because engine efficiency is a key characteristic affecting vehicle fuel consumption, a validation exercise was performed that consisted of comparing this study's engine map efficiency values against values reported elsewhere. Table 2 shows cycle-averaged and peak brake thermal efficiency (BTE) values found in the literature (Dünnebeil et al., 2015; Engström, 2015; Mercedes-Benz [MB], 2016) and in-service conformity testing reports (Kraftfahrt-Bundesamt [KBA], 2015) using a portable emissions measurement system (PEMS). The engine peak BTE used in this study is within 2.4% (1.1 absolute percentage points) of the peak efficiency values for the 12.8 L Mercedes-Benz OM 471 engine, and the state-of-the-art Euro VI engine used by Dünnebeil et al. (2015). A better measure of engine efficiency (i.e., cycle-averaged) is obtained through testing or simulation over a representative duty cycle. Data available for four representative tractors (all with 12.8 L engines with power ratings between 310 kW and 350 kW) shows in-use testing[4] BTE of 38.3% on average. The same engines were tested over the world harmonized transient cycle (WHTC) engine dynamometer test resulting in an average of 41.4% BTE. This study's engine was exercised in the simulation tool over the WHTC, resulting in a cycle-averaged BTE value of 42.1%, about 0.7 percentage points higher than the WHTC results of the engine used for in-use PEMS testing mentioned previously. In addition, vehicle simulation using steady-state engine fuel maps typically underestimates fuel consumption because transient phenomena such as turbocharger boost pressure buildup, aftertreatment thermal management, and transient EGR flow rates and temperatures are not accounted for during the steady-state engine mapping process. Transient correction factors (Hausberger, Rexeis, Kies, Weller, & Silberholz, 2016; Luz et al., 2014) or alternative "cycle-averaged maps" (U.S. Environmental Protection Agency [U.S. EPA] & U.S. Department of Transportation [U.S. DOT], 2016a) might be used to account for transient engine behavior. Furthermore, we also note that cycle-averaged engine efficiency depends heavily on how well the engine is integrated with the vehicle components (e.g., engine-transmission matching) and the desired application (i.e., duty cycle and payload). The results of this validation exercise show that the engine map efficiency values used in this study are in line with the typical values of engines available in the EU market.

4 Euro VI regulation introduced in-use testing requirements that involve field measurements using PEMS. The testing is conducted over a mix of urban (0–50 km/h), rural (50–75 km/h) and motorway (> 75 km/h) conditions, with exact percentages of these conditions depending on vehicle category.

**Table 2.** Engine efficiency comparison

| Engine Brake Thermal Efficiency | Notes | Source |
|---|---|---|
| 38.3% | Cycle-averaged BTE, in-use testing | KBA, 2015 |
| 42.4% | Cycle-averaged BTE, over Volvo's fuel cycle (BLB) | Engström, 2015 |
| **41.9%** | **Cycle-averaged BTE, Long Haul cycle simulation** | **This study** |
| 41.4% | Cycle-averaged BTE, WHTC engine dynamometer test | KBA, 2015 |
| 42.2% | Cycle-averaged BTE, WHTC simulation, Volvo engine | Engström, 2015 |
| **42.1%** | **Cycle-averaged BTE, WHTC cycle simulation** | **This study** |
| 45.0% | Peak BTE, MB 12.8 L OM471 engine | MB, 2016 |
| 45.9% | Peak BTE, state of the art 12.8 L Euro VI truck | Dünnebeil et al., 2015 |
| 46.0% | Peak BTE, Volvo $CO_2$RE base engine | Engström, 2015 |
| **44.8%** | **Peak BTE, generic Euro VI 12.8 L engine** | **This study** |

## Driveline

The transmission of power from the engine to the tires involves speed reduction (i.e., torque multiplication) steps at the transmission and the rear drive axle. The dominant driveline configuration in western, central, and southern Europe is a 2-axle (4×2) tractor with a 3-axle semi-trailer; longer combination tractor-trailers (with lengths up to 25 m, gross vehicle weight (GVW) up to 60 tonnes, and trailers with four or more axles) are more common in northern Europe (i.e., Sweden, Finland, Netherlands, Denmark, and Norway).

Europe, with about 70% market penetration (Rodriguez, Muncrief, Delgado, & Baldino, 2017), leads other markets in the adoption of automated manual transmissions (AMTs). The most common AMTs have 12 gears and operate in direct drive (i.e., 1:1 gear ratio) at top gear. Table 3 summarizes typical driveline characteristics of European 40-tonne tractor-trailers based on IHS Automotive sales data, technical brochures, and consultation with experts. For a given vehicle speed, the transmission gear ratios, rear axle ratio, and tire diameter directly influence the operating speed of the engine; lower engine speeds increase fuel efficiency through lower friction losses.

**Table 3.** Tractor-trailer driveline parameters

| | |
|---|---|
| **Axle configuration** | 4×2 |
| **Transmission type** | Automated manual transmission |
| **Transmission gears** | 12 |
| **Transmission gear ratios** | 14.9, 11.6, 9.0, 7.0, 5.6, 4.4, 3.4, 2.6, 2.0, 1.6, 1.3, 1.0 |
| **Rear axle ratio** | 2.64 |
| **Tire size** | 315/80R22.5 (steer and drive), 315/70 R22.5 (trailer) |

The configuration selected for this study results in an engine speed of 1,215 revolutions per minute (RPM) when the tractor-trailer cruises at 85 km/h. We note that, even though the configuration selected is representative of the market, the transmission gear ratios, rear axle ratios, and tire sizes are typically specified by the truck's end user based on engine size, expected duty cycle, road topography, and expected payloads.

### Road Load Parameters

The fundamental relationship between vehicle power required and the various forces that must be overcome to move a vehicle is described in the road load equation as follows:

$$P = C_{RR} mgV\cos\theta + \frac{1}{2}\rho A C_D V^3 + mV\frac{dV}{dt} + mgV\sin\theta$$

P represents the tractive power demanded by the vehicle at the drive wheels, m is the mass of the vehicle, $C_{RR}$ represents the coefficient of rolling resistance, g is the acceleration due to gravity, V is the instantaneous velocity, $\rho$ is the ambient air density, A is the frontal cross sectional area of vehicle, $C_D$ is the aerodynamic drag coefficient, and $\theta$ is the road inclination. Some of the parameters in this equation, such as vehicle speed, acceleration, and road grade, are set by the vehicle duty cycle. The remaining parameters are vehicle properties and are discussed below.

*Tire rolling resistance*

The coefficient of rolling resistance ($C_{RR}$) is a parameter that relates the force opposing the rotating motion of the tires to the normal force between the tire and the surface. Even though $C_{RR}$ is a dimensionless coefficient, it is typically expressed in units of kg/tonne or N/kN.

**Table 4.** Tire efficiency classification

| Tire Energy Efficiency Class | Coefficient of Rolling Resistance (N/kN) |
|---|---|
| **A** | Lower than 4.0 |
| **B** | 4.1 to 5.0 |
| **C** | 5.1 to 6.0 |
| **D** | 6.1 to 7.0 |
| **E** | 7.1 to 8.0 |
| **F** | Larger than 8.1 |

Europe introduced a tire labeling system in 2009 (EC, 2009) requiring all the tires sold in the European Union after 1 November 2012 to display information concerning tire rolling resistance, external tire noise, and wet braking performance. The regulation allows end users to make more informed choices when purchasing tires. Table 4 shows the tire label efficiency classes ranging from efficiency class A, the most fuel efficient (i.e., with lowest rolling resistance), to class F, the least fuel-efficient. Furthermore, regulation No 117 of the United Nations Economic Commission for Europe (UNECE) establishes maximum thresholds of tire rolling resistance in order to phase out inefficient tires (UNECE, 2011). For heavy-duty vehicle tires, the limits of rolling resistance are 8.0 N/kN by November 2016 (phasing out Class F tires) and 6.5 N/kN by November 2020 (phasing out Class E tires and tires with $C_{RR}$ higher than the midpoint of Class D). A verification tolerance of 0.3 N/kN between the declared and measured value is allowed. Retreaded tires are not included in the regulations, although the European Commission intends to review whether retreads will be brought into scope. An independent analysis of rolling resistance data from 2007 to 2015 found no relevant improvement of average $C_{RR}$ values despite implementation of the mandatory labeling system (Dünnebeil & Keller, 2015). A recent analysis by Viegand Maagøe A/S shows a slight shift toward better fuel efficiency classes than the lowest permissible; nevertheless, the penetration of tire classes A and B is less than 1%, indicating a large potential for improvement (Viegand Maagøe A/S, 2016). On the other hand, a position paper from the European Tyre & Rubber Manufacturers' Association (ETRMA, 2016) states an improvement of approximately 1 N/kN between 2007 and 2014. ETRMA foresees a reduction of the rolling resistance coefficient of HDVs of 1% per year until 2030.

An exact, sales-weighted rolling resistance is currently not available for Europe. There are no regularly updated and differentiated tire sales databases with $C_{RR}$ data. In the absence of better statistical sources, Dünnebeil and Keller (2015) used tire offer information available from selected tire shops as an approximation of the present $C_{RR}$ distribution of truck tires, and estimated a 2015 weighted average rolling resistance coefficient of 6.3 N/kN. From the report, it is evident that Class A tires are not yet widely available in the market. Table 5 presents a summary of the literature review conducted on the rolling resistance coefficient ($C_{RR}$) values of recent tractor-trailers.

**Table 5.** Literature review: Rolling resistance for tractor-trailers

| $C_{RR}$ (N/kN) | Notes | Source |
|---|---|---|
| 5.01 | Coastdown test of a 40-tonne tractor-trailer on a closed track | Roche & Mammetti, 2015 |
| 5.14 | Average of coastdown tests from five Euro V trucks on a closed track | Stenvall, 2010 |
| 5.23 | Average of coastdown tests from three Euro V trucks | Raja & Baxter, 2010 |
| 5.37 | BC-BBB tire class distribution. $C_{RR}$ calculated using the class' upper limit | Dünnebeil et al., 2015 |
| 5.48 | Average of constant speed tests of two trucks with different trailer loads | Hausberger, Rexeis, Blassnegger, & Silberholz, 2011 |
| 5.5 | Typical vehicle specification from data collected for LOT2 and LOT3 reports | Luz et al., 2014 |
| 5.8 | Baseline assumption in the EU $CO_2$RE project | Engström, 2015 |
| 6.02 | Generic $C_{RR}$ for 40 t tractor: 5.55 steer, 6.28 drive, 35/65 weight distribution | VECTO generic tractor-trailer vehicle configuration file |
| 6.13 | 2015 average of two large datasets with over 30,000 tires and 2,500 tire models | Viegand Maagøe A/S, 2016 |
| 6.2 | Average of 7 coastdown tests on a MAN 18.440 Euro V truck | Süßmann & Lienkamp, 2015 |
| 6.3 | Weighted average based on market offer of online tire shops | Dünnebeil & Keller, 2015 |
| 6.31 | Coastdown test available to the ICCT | Knibb, Gormezano and Partners (KGP), 2015 |
| 6.8 | Reference value | Hill et al., 2011 |
| **5.5** | **Median of $C_{RR}$ found in the literature, Equivalent to the midpoint of the tire efficiency class C** | **This study** |

The $C_{RR}$ values found in the literature range between 5 and 6.4 N/kN. The value chosen for this study, 5.5 N/kN, corresponds to the median of the $C_{RR}$ values presented in Table 5. Conversations with experts, including a European tire manufacturer, provide further confirmation for this selection. A baseline rolling resistance coefficient of 5.5 N/kN represents the midpoint of the tire efficiency class C.

*Aerodynamic drag*

Publicly available data on aerodynamic drag coefficients of European HDVs is scarce. ICCT conducted a thorough literature review and, in addition, was able to access some coastdown and constant speed test results.

Table 6 shows a summary of the aerodynamic drag values that were obtained through this process. The coefficient of aerodynamic drag ($C_D$) values are determined by either experimental measurement or computational fluid dynamics (CFD) analysis. The $C_D$ values found in the literature range from 0.47 to 0.75. These numbers represent individual tractor-trailer configurations and the variability observed can be attributed to differences in their aerodynamic features. For example, the highest values would represent tractor-trailers with few aerodynamic features (perhaps just a simple roof deflector on the tractor), while the lowest values may represent tractor-trailers with state-of-the-art aerodynamic features. Other sources of variability include testing or estimation methodology (e.g., constant speed, coastdown, CFD) and other wind parameters measured or assumed. The median $C_D$ value in Table 6 is 0.61. A $C_D$ value of 0.6 was selected in this study to represent the aerodynamics of an average tractor-trailer combination.

Trailers in Europe generally do not have aerodynamic treatments. According to market data provided by KGP, the market penetration for side panels is lower than 10% (Rodriguez et al., 2017). Boat tails are another option to enhance trailer aerodynamics, but their market penetration in the European Union is negligible. In 1996, Directive 96/53/EC (Council of the European Union, 1996) imposed a length limit of 16.5 m for tractor trailers. Because of this limit, there has been an increase in the cab-over-engine design, which minimizes the cab length and maximizes the trailer length. This directive imposes a barrier for the addition of aerodynamic features on the front of the tractor and rear of the trailer. Currently, the maximum length of a tractor-trailer combination in the European Union is 16.5 m. Trailer lengths are typically 13.6 m to 13.7 m, about 2.5 m shorter than typical 53-foot (16.15 m) trailers in the United States. In April 2015, the European Union released the Directive 2015/719 (Parliament and Council of the European Union, 2015) amending Directive 96/53/EC, and establishing a dimensional allowance for the aerodynamic redesign of tractors and the use of aerodynamic add-on devices on trailers. The new regulation allows retractable or foldable aerodynamic devices attached to the rear of vehicles with a maximum length of 50 cm. The directive must be brought into force in EU member states by May 7, 2017. By May 27, 2017, the EC must assess the need to adopt or amend any technical requirements for type-approval of aerodynamic devices.

**Table 6.** Literature review: Aerodynamic drag coefficient ($C_D$) for tractor-trailers

| $C_D$ | Method | Notes | Source |
|---|---|---|---|
| 0.47 | CFD-RANS | Reference case: Standard box trailer with side bumpers and underneath spare wheel. Yaw = 0 degrees | Håkansson & Lenngren, 2010 |
| 0.53 | Constant speed test | Euro VI tractor-trailer measured following the procedure described in LOT3 (Luz et al., 2014). Yaw = 0 degrees | Dünnebeil et al., 2015 |
| 0.55 | Constant speed test | Mean of 39 runs at 90 km/h of a Euro V truck (called vehicle 2) with a yaw angle of less than 2 degrees | Peiró Frasquet & Indinger, 2013 |
| 0.57 | Not available | Representative tractor-trailer used in the EU $CO_2$RE project. $C_D \times A$ = 5.82 $m^2$, A = 10.2 $m^2$ is assumed | Engström, 2015 |
| 0.581 | CFD-RANS | Tractor-trailer with roof and side fairings. Cooling system and mirror mountings are neglected. Yaw = 0 degrees | Salati, Cheli, & Schito, 2015 |
| 0.586 | Coast-down test | Average of 7 measurements of a MAN Euro V tractor-trailer, with tractor side panels and standard curtain side trailer | Süßmann & Lienkamp, 2015 |
| 0.6 | Not available | $C_D$ of a 40-tonne tractor-trailer identified in HDV-LOT 1 | Hill et al., 2011 |
| 0.61 | Constant speed test | Mean of 33 runs at 90 km/h of a Euro V truck (called vehicle 1) with a yaw angle of less than 1 degree | Peiró Frasquet & Indinger, 2013 |
| 0.61 | Coastdown test | Coastdown test measurement for a selected tractor-trailer | KGP, 2015 |
| 0.618 | Not available | Base vehicle with typical specifications based on collected data in LOT 2 and 3. $C_D \times A$ = 6.3 $m^2$, A = 10.2 $m^2$ is assumed | Luz et al., 2014 |
| 0.623 | CFD-DES | Tractor-trailer with roof and side fairings. Cooling system and mirror mountings are neglected. Yaw = 0 degrees | Salati et al., 2015 |
| 0.65 | Coastdown test | $C_D$ measurement of a 40-tonne tractor-trailer on a closed track | Roche & Mammetti, 2015 |
| 0.65 | CFD-RANS | Reference case: Standard box trailer with side bumpers and underneath spare wheel. Yaw = 5 degrees | Håkansson & Lenngren, 2010 |
| 0.661 | CFD-RANS | Tractor-trailer with roof and side fairings. Cooling system and mirror mountings are neglected. Yaw = 5 degrees | Salati et al., 2015 |
| 0.679 | CFD-DES | Tractor-trailer with roof and side fairings. Cooling system and mirror mountings are neglected. Yaw = 5 degrees | Salati et al., 2015 |
| 0.691 | Constant speed test | Measurement of a representative Euro V tractor (M.B. Actros) with a standard trailer (Krone) | Hausberger et al., 2011 |
| 0.72 | CFD-RANS | Experimentally validated computational analysis on a simplified but representative geometry | Ekman, Gårdhagen, Virdung, & Karlsson, 2015 |
| 0.75 | Coastdown test | Mean of results for 3 trucks of 3 manufacturers (SCANIA, DAF, M.B.). Assumptions: Air density = 1.2 kg/$m^3$, A = 10.2 $m^2$ | Raja & Baxter, 2010 |
| 0.75 | Coastdown test | Mean of results for 5 Euro V trucks of 5 manufacturers (SCANIA, DAF, M.B., Volvo, Renault). | Stenvall, 2010 |
| **0.6** | | **Median of $C_D$ found in the literature (excluding the cases with high yaw angle)** | **This study** |

*Notes: CFD stands for Computational Fluid Dynamics. RANS stands for Reynolds Averaged Navier Stokes. DES stands for Detached Eddy Simulation.*

As shown in the road load equation above, aerodynamic forces are proportional not only to the aerodynamic drag coefficient but also to vehicle's frontal area. Size regulations are given in EC Directive 96/53/EC and its amendments (Council of the European Union, 1996). For dimensions, this specifies the maximum width at 2.55 m and the maximum height at 4.0 m (4.4 m in the United Kingdom). This provides a maximum allowed frontal area of 10.2 $m^2$. Furthermore, the European Commission also stipulates to use a 2.55 m wide and 4 m high configuration as the standard semi-trailer body configurations for the aerodynamic drag test procedure (EC, 2017c). Some tractors can be lower in height but the trailers that they pull also influence the frontal area. Trailers are designed to maximize volume capacity, so most of them are built to the maximum allowable heights. Based on this, we assumed that the average tractor frontal area is 10 $m^2$. For modeling purposes, the frontal area is treated as a given and we therefore only analyzed changes in $C_D$.

*Tractor-trailer curb weight*

The road load equation above shows that a heavier truck would require more energy to accelerate, climb hills, and overcome rolling resistance. Only the aerodynamic term of the road load equation is independent of vehicle mass. Total vehicle mass includes the tractor-trailer curb weight plus the carried payload.

Table 7 presents tractor and trailer curb (i.e., empty) weights found in the literature. Typical Euro VI tractors weigh around 7.0 to 8.2 tonnes, while standard curtain-side trailers – with around 45% market penetration (Hill et al., 2011) – weigh around 6.2 to 7.5 tonnes. In many European countries, the maximum weight of a tractor-trailer combination is 40 tonnes; thus, the maximum payload capabilities of these vehicles range between 24 and 26 tonnes. This study assumes tractor curb weight of 7,400 kg and trailer curb weight of 7,000 kg.

**Table 7.** Literature review: Tractor-trailer curb weight

| Tractor curb weight (kg) | Trailer curb weight (kg) | Total weight (kg) | Source |
|---|---|---|---|
| 7,800 | 6,200 | 14,000 | Süßmann & Lienkamp, 2015 |
| 7,000 | 7,400 | 14,400 | Dünnebeil et al., 2015 |
| 7,450 | 7,550 | 15,000 | Žnidarič, 2015 |
| 8,200 | 7,500 | 15,700 | ACEA, 2016 |
| 7,500 | 7,050 | 14,550 | Hill et al., 2015 |
| – | 7,500 | – | VECTO reference value |
| – | 7,500 | – | EC, 2017c |
| **7,400** | **7,000** | **14,400** | **This study** |

### Power Demand of Accessories

Accessories are vehicle systems such as the air conditioning system or the pressurized air system whose functions are not related to propulsion. Average power demand values from the literature for tractor-trailer accessories are listed in Table 8. The table shows specific values that are characteristic of U.S. long-haul operations (Badain, Reinhart, Cooper, MacIsaac, & Whitefoot, 2015) as well as typical accessory demands for European trucks (Dünnebeil et al., 2015; Luz et al., 2014). This study uses the midpoint of the range of values found in the literature for total accessory power demand. Accessories such as the oil, coolant, and fuel pumps that are needed for proper operation of the engine also consume power and affect fuel consumption. However, the power consumption of the main engine accessories is captured in the steady state fuel map discussed above.

**Table 8.** Literature review: Accessories power demand

| Vehicle Accessory | Power demand (kW) | Source |
|---|---|---|
| **Generator** | 1.36 | Dünnebeil et al., 2015 |
| | 1.25 | Badain et al., 2015 |
| | 1.24 | Luz et al., 2014 |
| **Air compressor** | 1.59 | Dünnebeil et al., 2015 |
| | 0.65 | Badain et al., 2015 |
| | 1.34 | Luz et al., 2014 |
| **Power steering** | 0.72 | Dünnebeil et al., 2015 |
| | 1.25 | Badain et al., 2015 |
| | 0.72 | Luz et al., 2014 |
| **Cooling fan** | 0.52 | Dünnebeil et al., 2015 |
| | 2.00 | Badain et al., 2015 |
| | 1.09 | Luz et al., 2014 |
| **Air conditioning** | 0.36 | Dünnebeil et al., 2015 |
| | 1.50 | Badain et al., 2015 |
| | 0.35 | Luz et al., 2014 |
| **Total accessories power demand** | 4.55 | Dünnebeil et al., 2015 |
| | 6.65 | Badain et al., 2015 |
| | 4.74 | Luz et al., 2014 |
| | **5.6** | **This study** |

### Summary

Table 9 shows a summary of the major input parameters and key efficiency characteristics for ICCT's model year 2015 long-haul EU tractor-trailer baseline. As mentioned above, many sources have been considered, and the baseline parameters are chosen to represent, to the best extent possible, average tractor-trailer characteristics. The default values in Autonomie for the mass and rotational inertia of tires, axles, differential, transmission, and engine have been selected. Also, Autonomie defaults were used for the driver control system and the transmission shifting logic.

**Table 9.** Baseline tractor-trailer input parameters

| Vehicle parameter | Value |
|---|---|
| Gross vehicle weight (t) | 40 |
| Vehicle curb weight (t) | 14.4 |
| Maximum payload (t) | 25.6 |
| Typical payload (t) | 19.3 |
| Axle configuration | 4×2 |
| Engine Displacement (L) | 12.8 |
| Engine power (kW) | 350 |
| Engine Emissions | Euro VI |
| Engine peak BTE (%) | 44.8 |
| Transmission type | AMT |
| Transmission gear number | 12 |
| Transmission gear ratios | 14.93–1.0 |
| Rear axle ratio | 2.64 |
| Tire size | 315/80R22.5 |
| Tire radius (m) | 0.52 |
| Aerodynamic drag area ($m^2$) | 6 |
| Tire rolling resistance (N/kN) | 5.5 |
| Accessory power demand (kW) | 5.6 |

## RIGID TRUCK BASELINE DEVELOPMENT

The rigid truck market is the second largest sales category of HDVs in the European Union behind tractor-trailers (Muncrief & Sharpe, 2015). The 4×2 rigid truck segment represents 19% of new HDV registrations and 10% of $CO_2$ emissions (see Figure 1). Rigid trucks have a much wider range of applications than tractor-trailers and there is much more heterogeneity in terms of vehicle configurations, payloads, and duty cycles. This study focuses on freight delivery applications and does not consider construction, dump trucks, and refuse hauling, all of which usually require a larger number of driven axles (e.g., 6×4), larger engines, and larger payload capabilities. For that end, the object of study selected is a 12-tonne GVW, 4×2 rigid truck.

Although the most commonly sold rigid trucks are 16 tonnes and above,[5] a 12-tonne truck was selected for this analysis because it represents the other end of the spectrum from long-haul tractor-trailers. Rigid trucks below 16 tonnes, such as the one selected for this analysis, are typical in urban operation and have a different set of applicable technologies compared with larger rigid trucks on regional and long-haul operation. The adopted regulation[6] for the certification of $CO_2$ emissions and fuel consumption of heavy-duty vehicles (EC, 2017c) does not consider the Urban Delivery cycle for vehicles heavier than 16 tonnes. Because this study adheres to the prescribed duty

5 2015 sales data supplied by IHS Global SA show that rigid trucks over 16 tonnes, in all axle configurations are 70% of the sales.

6 The regulation outlining the $CO_2$ certification methodology was adopted on May 11, 2017 by the Technical Committee – Motor Vehicles. At the time of writing of this paper, the regulation had not been published in the *Official Journal of the European Union*.

cycles and payloads in the regulatory text, the examination of urban delivery operation was addressed with the aforementioned vehicle selection. However, it must be pointed out that the set of technologies studied in this report is applicable to heavier rigid truck classes operating in similar duty cycles.

As was done with the tractor-trailer analysis, different data sources were used to select the input parameters to create the baseline vehicle model for the rigid truck. The number of available sources for rigid truck technical information is smaller than for tractor-trailers. Table 10 shows a summary of the major input parameters and key efficiency characteristics for ICCT's 2015 rigid truck baseline. AVL List GmbH was commissioned by the ICCT to develop a fuel map for a 5 L displacement[7] engine compliant with Euro VI emissions limits. The engine has a similar layout as the one presented in Figure 2, with a common rail of 2,000 bar, VGT, and cooled EGR plus SCR for $NO_x$ control. The engine has a rated power of 170kW and provides a maximum torque of 900 Nm. The rigid truck has a 4×2 axle setup, a six-speed manual transmission, and 19.5-inch tires.

**Table 10.** Baseline rigid truck input parameters

| Vehicle parameter | Value |
|---|---|
| **Gross vehicle weight (t)** | 12 |
| **Vehicle curb weight (t)** | 6.5 |
| **Maximum payload (t)** | 5.5 |
| **Typical payload (t)** | 3.0 |
| **Axle configuration** | 4×2 |
| **Engine Displacement (L)** | 5 |
| **Engine power (kW)** | 170 |
| **Engine Emissions** | Euro VI |
| **Engine peak BTE (%)** | 42.2 |
| **Transmission type** | MT |
| **Transmission gear number** | 6 |
| **Transmission gear ratios** | 6.75–0.78 |
| **Rear axle ratio** | 4.00 |
| **Tire size** | 265/70R19.5 |
| **Tire radius (m)** | 0.43 |
| **Aerodynamic drag area ($m^2$)** | 5.28 |
| **Tire rolling resistance (N/kN)** | 6.6 |
| **Accessory power demand (kW)** | 3.63 |

7 2015 sales data supplied by IHS Global SA show that 4.5–5.5 L engines have a 28% market share in the 4×2 rigid truck segment, while 6.5–7.5 L displacement engines have a 25% market share.

## TEST CYCLES

As part of the process to establish a $CO_2$ certification procedure for HDVs using the VECTO tool, the European Commission has developed a suite of test cycles to represent various HDV mission profiles, including the Long Haul, Regional Delivery, and Urban Delivery cycles (Luz et al., 2014).

Tractor-trailer performance was analyzed over the Long Haul cycle (Figure 3), which is meant to represent typical long-haul, highway-dominated driving, and over the Regional Delivery cycle (Figure 4), which involves both suburban and highway driving. For the rigid truck, performance was analyzed over three different cycles that include the two aforementioned cycles and the Urban Delivery (Figure 5) cycle, which represents typical stop-and-go driving within European cities. All the test cycles are distance-based and include road grade (Luz et al., 2014).

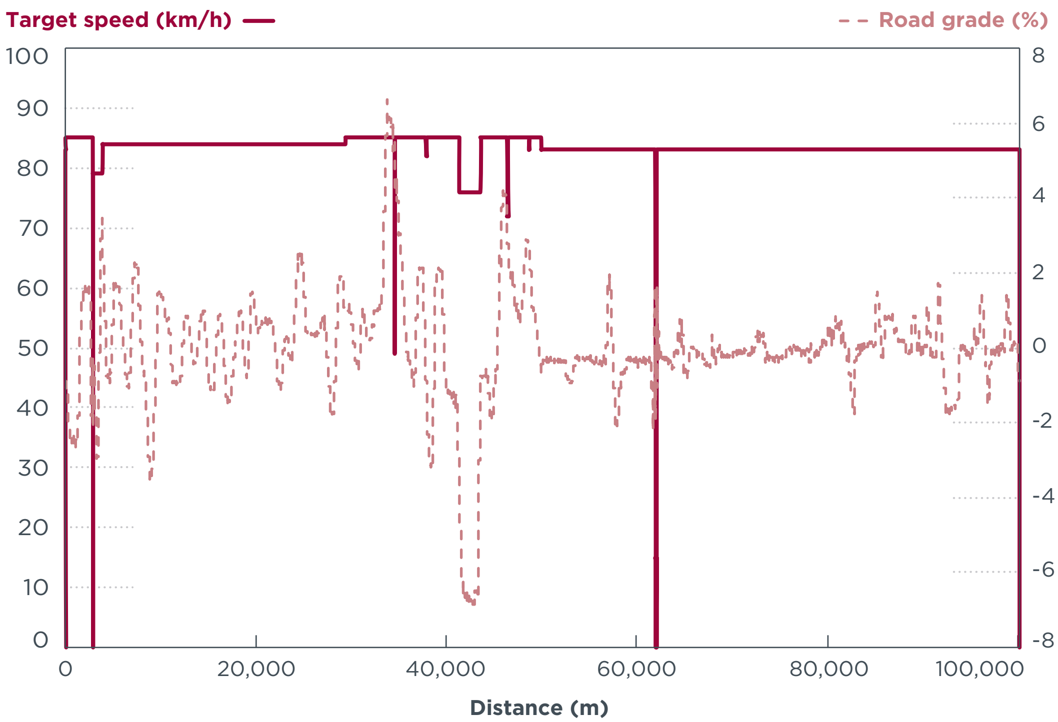



**Figure 3.** VECTO Long Haul cycle

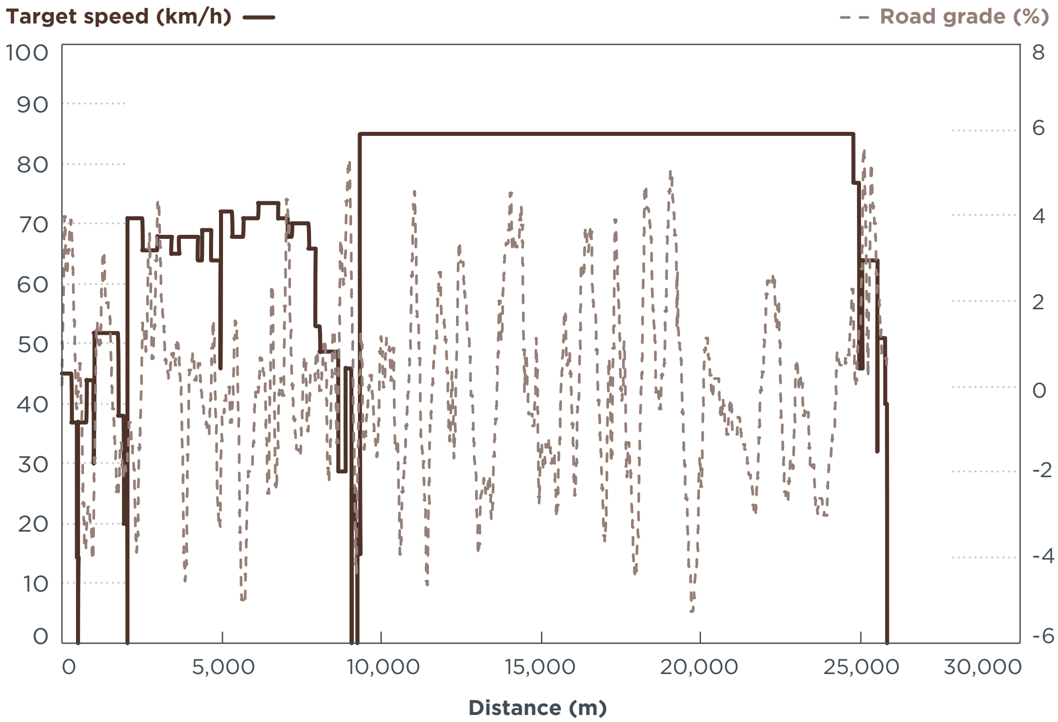



**Figure 4.** VECTO Regional Delivery cycle

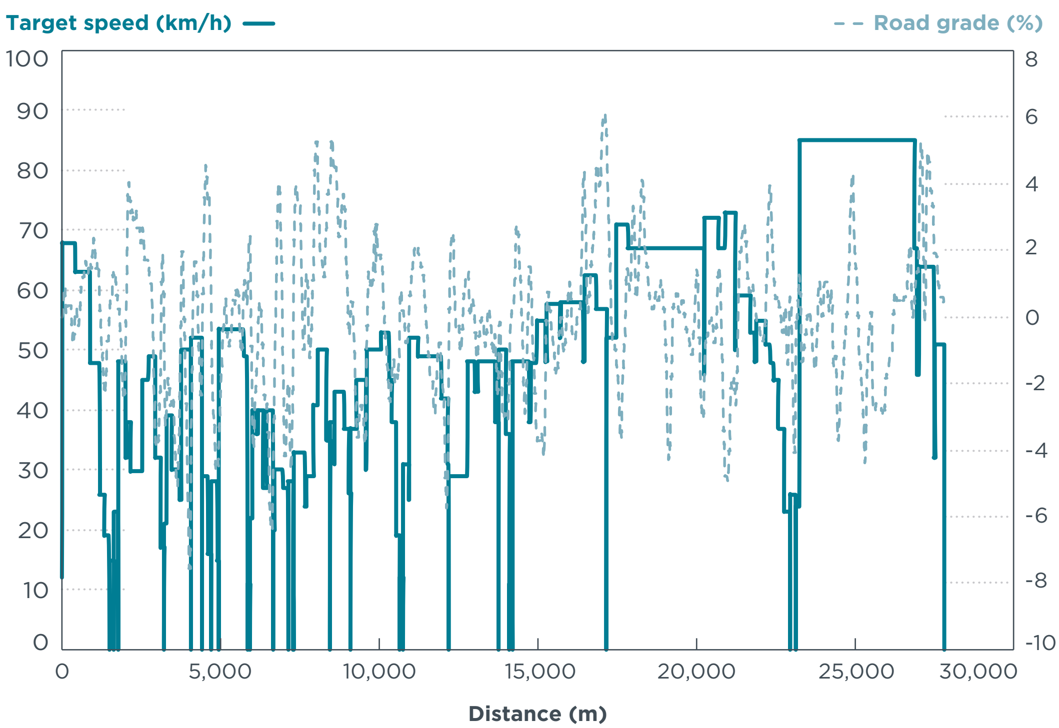



**Figure 5.** VECTO Urban Delivery cycle

## BASELINE RESULTS

### Tractor-Trailer Baseline Fuel Consumption

Figure 6 shows the range of fuel consumption values for the baseline tractor-trailer analyzed over VECTO Urban Delivery, Regional Delivery, and Long Haul cycles. The results are shown for empty, a representative payload (12.9 tonnes for the Urban Delivery and Regional Delivery cycles and 19.3 tonnes for the Long Haul cycle), and full payload (25.6 tonnes).

The test cycle has a large impact on fuel consumption. The fuel consumption over the Long Haul cycle at the aforementioned proposed regulatory payload (19.3 tonnes) is 33.1 L/100km. Fuel consumption is 10% higher over the Regional Delivery cycle and 30% higher over the Urban Delivery cycle despite having a lower representative payload (12.9 tonnes). Test cycle effects are more pronounced at higher payloads. At maximum payload, fuel consumption is 30% higher for the Regional Delivery cycle and 58% higher over the Urban Delivery cycle than for the Long Haul cycle.

Payload also has a large impact on fuel consumption. For the Long Haul cycle, fuel consumption at empty conditions is 28% lower and fuel consumption at full payload is 9% higher than at representative payload. The effect of payload is more relevant at transient driving conditions. For the Urban Delivery cycle, fuel consumption at empty is 35% lower and fuel consumption at full payload is 33% higher than at representative payload.

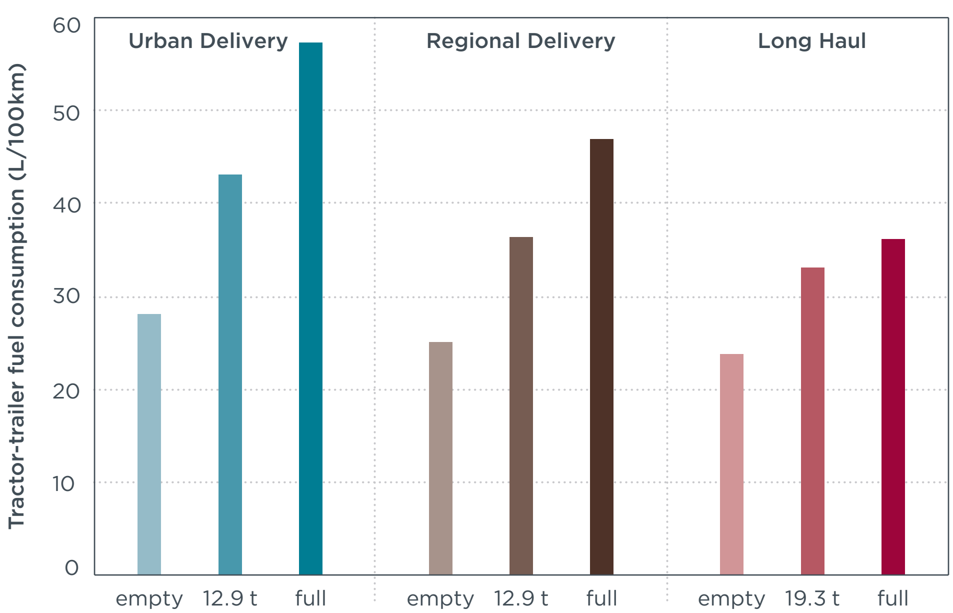



**Figure 6.** Tractor-trailer baseline fuel consumption

## Comparison of Autonomie and VECTO Baseline Results

The simulation tool selected in this study, Autonomie, offers a high level of flexibility, analysis capabilities, and results transparency to evaluate fuel consumption and potential fuel consumption reductions from a wide set of technologies. The simulation tool developed by the European Commission, VECTO, has been conceived as a certification instrument for the fuel consumption and $CO_2$ emissions from HDVs; as such it provides a lower level of flexibility. VECTO has two distinct user modes. In declaration mode, all applicable parameters and test cycles are automatically assigned as soon as the vehicle group is defined. In engineering mode, the user has greater flexibility and can select and change the input parameters independent of the vehicle group. Given the relevance of VECTO in upcoming regulations and that at least one previous study (Dünnebeil et al., 2015) has used VECTO for its technology potential analysis, a direct comparison of these two simulation tools is warranted.

Using the baseline tractor-trailer and test cycles described in the previous sections, both tools were used to simulate the fuel consumption using a set of identical inputs. Three different payload levels were simulated, resulting in a total of nine comparison points. Because Autonomie and VECTO use the same set of underlying physics-based models (Franco, Delgado, & Muncrief, 2015), the main differences will stem from the shifting strategy used by each tool. The shifting strategy used in Autonomie is the software's default "look-ahead driver." The parameterization of the VECTO[8] shifting strategy (traction interruption interval, minimum hold gear period, and torque reserve) was adjusted to resemble the Autonomie strategy as closely as possible. Nevertheless, the differences in the shifting strategies could not be completely eliminated.

Table 11 shows the results of the comparison exercise; the root-mean-square deviation (RMSD) of the nine conditions compared is 0.23 L/100km. In comparison with Autonomie, VECTO slightly under predicts the fuel consumption in the Regional Delivery cycle and slightly over predicts the fuel consumption during the Urban Delivery cycle. The observed small differences are due to the shifting patterns built into both tools, and the built-in crosswind and rolling resistance corrections. Nevertheless, the results between the two tools are in good agreement with a maximum difference of 2.6%.

**Table 11.** Comparison of fuel consumption results from Autonomie and VECTO for the baseline tractor-trailer

| Cycle | Payload (tonnes) | Payload level | Autonomie FC (L/100km) | VECTO FC (L/100km) | Difference |
|---|---|---|---|---|---|
| **Long Haul** | 25.6 | Full | 36.16 | 36.96 | 2.2% |
| **Regional** | 25.6 | Full | 46.9 | 46.38 | -1.1% |
| **Urban Haul** | 25.6 | Full | 57.31 | 58.81 | 2.6% |
| **Long Haul** | 19.3 | Typical | 33.06 | 33.56 | 1.5% |
| **Regional** | 12.9 | Typical | 36.37 | 35.78 | -1.6% |
| **Urban** | 12.9 | Typical | 43.09 | 43.81 | 1.7% |
| **Long Haul** | 0 | Empty | 23.74 | 23.56 | -0.8% |
| **Regional** | 0 | Empty | 25.03 | 25.00 | -0.1% |
| **Urban** | 0 | Empty | 28.05 | 28.20 | 0.5% |

8 VECTO Version 3.1.2.748 was used in this analysis.

## Tractor-Trailer Energy Audit

Another way to represent the baseline vehicles is via their energy audits, or the breakdown of the overall energy distribution according to the various losses for the vehicles. Figure 7 shows the baseline tractor-trailer energy consumption as a percent of total fuel input energy according to six energy loss categories over three VECTO cycles as well as over two different U.S. cycles: the U.S. real-world highway cycle (Delgado & Lutsey, 2015) and the ARB Transient cycle (U.S. EPA & U.S. DOT, 2016a). The U.S. cycles were included in the analysis to illustrate both ends of the operational profile spectrum: a relatively low speed, transient cycle (ARB) and a higher-speed, highway-dominated cycle (U.S. real-world highway). A representative payload of 19.3 tonnes was used for this analysis.

Engine losses range from 57% to 61% (i.e., cycle-averaged BTE of 39% to 43%) of the fuel energy consumed. Aerodynamic drag losses, which are proportional to the square of vehicle speed, range from 3% for the ARB Transient cycle to up to 20% for the U.S. highway cycle. Tire rolling resistance losses, which are proportional to vehicle mass (which is held constant in the analysis) and to the rolling resistance coefficient, range from 9% to 15%. Braking losses indicate the level of stop-and-go type of driving and range from 5% for the close to steady speed U.S. highway cycle, to 20% for the very transient ARB Transient cycle. Higher braking losses also indicate increased potential for technologies such as hybrid powertrains, which recover a portion of braking losses, or predictive cruise control. It is important to highlight that the fraction of fuel energy loss obtained from the energy audit number does not directly impose an upper boundary on the fuel consumption reduction potential of a technology[9]. As the road load power requirements are reduced through improvements in the non-engine loss categories in Figure 7, the required energy output from the engine is also reduced together with the engine related losses.

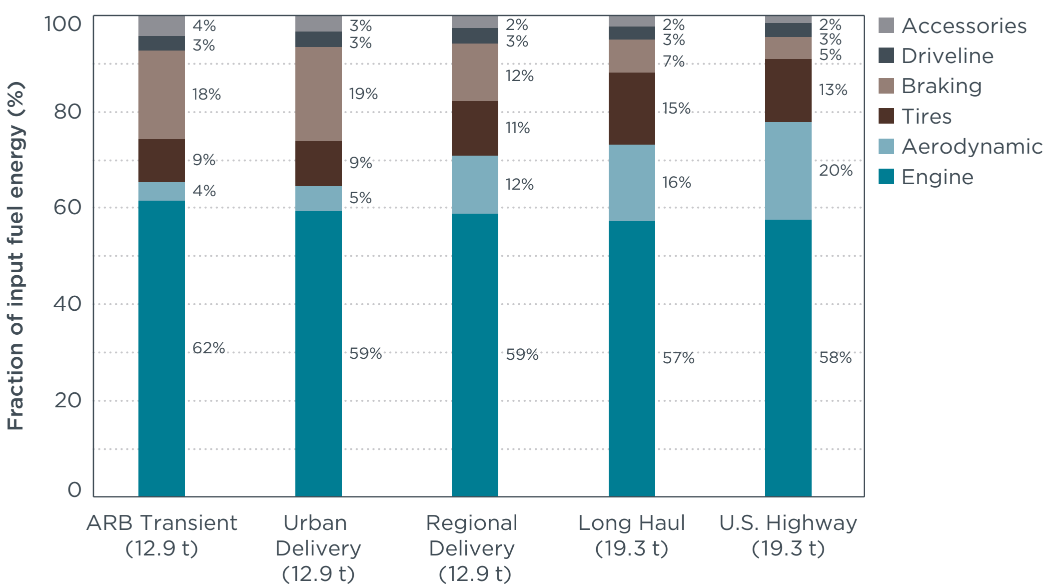



**Figure 7.** Tractor-trailer energy audit over different cycles

9 As an example, if the fuel energy fraction lost through braking is X%, the maximum theoretical potential of regenerative braking is not X% but the fraction of the braking losses with respect to the usable work, or X% divided by the cycle-averaged engine efficiency.

A comparison of this study's baseline (Long Haul in Figure 7) to a number of tractor-trailer energy audits over long-haul driving from previous studies is shown in Figure 8 (Dünnebeil et al., 2015; Holloh, 2008; Kopp, 2012). The relative shares of energy consumption for engine, aerodynamics, tire rolling resistance, braking, driveline losses, and accessories are consistently similar among the studies, with the three most prevalent loss categories of engine, aerodynamic, and rolling resistance ranging from 56% to 58%, 14% to 16%, and 15% to 16%, respectively.

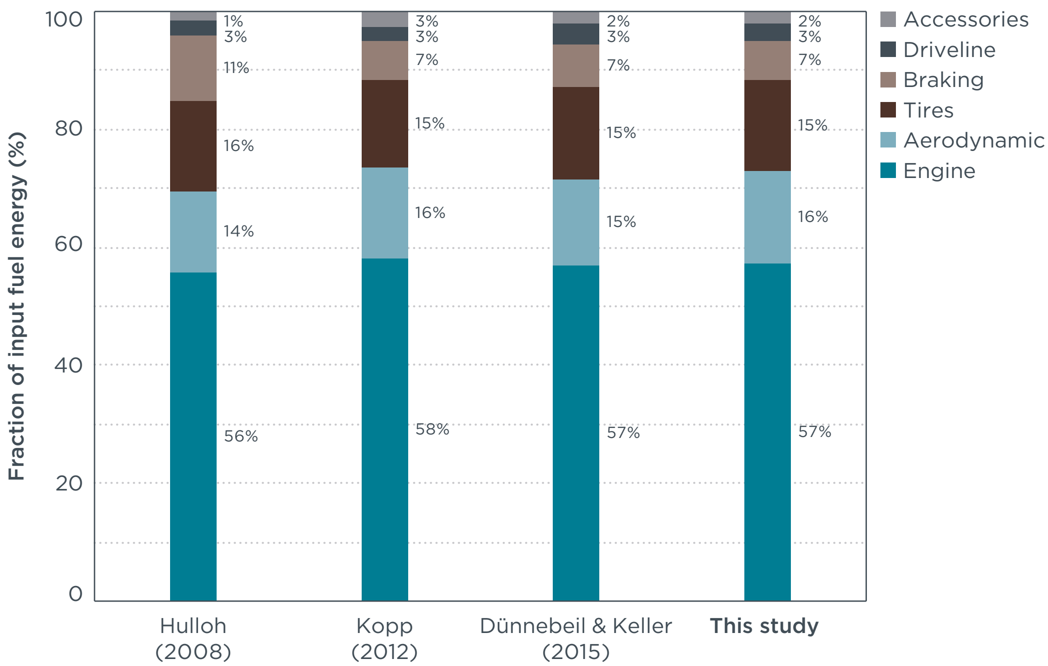



**Figure 8.** Long-haul tractor-trailer energy audit comparison

## Tractor-Trailer Measured Fuel Consumption

Publicly available, real-world fuel consumption data for tractor-trailers is relatively scarce in Europe. This data is usually available for transport operators and vehicle manufacturers, but it is typically kept confidential from the public. Certified values of $CO_2$ and fuel consumption, which would result from the future monitoring and reporting scheme for HDVs, are expected to be available by 2020 (EC, 2017b). A literature review was performed to find records of fuel consumption for recent model year tractor-trailers over long-haul operation. Table 12 shows that reported fuel consumption values range from 30 to 35.2 L/100km. This study's baseline tractor-trailer fuel consumption was found to be 33.1 L/100km, which is around the midpoint of this range.

**Table 12.** Literature review: Tractor-trailer fuel consumption values

| Fuel Consumption (L/100km) | Notes | Source |
|---|---|---|
| **30.0** | Best in class Euro VI, 18.2 t payload over the ACEA LH cycle | European Automobile Manufacturers Association (ACEA), 2016 |
| **31.7** | Measured at 80 km/h steady speeds in high-speed test track | Roche & Mammetti, 2015 |
| **32.5** | 2014 long-haul reference vehicle | Breemersch & Akkermans, 2015 |
| **32.7** | Euro VI, in-use conformity PEMS testing | KBA, 2015 |
| **33.1** | Euro V truck over the VR test* at a 25.5 t payloads | Süßmann & Lienkamp, 2015 |
| **34.2** | Measured at 90 km/h steady speeds in high-speed test track | Roche & Mammetti, 2015 |
| **34.5** | Euro VI truck over the VECTO Long Haul cycle at a 19.3 t payload | Dünnebeil et al., 2015 |
| **35.2** | Average overall fuel consumption of 21 Euro VI tractor-trailers | Lastauto Omnibus, 2016 |
| **33.1** | Baseline tractor-trailer identified in this study over the VECTO Long Haul cycle | **This study** |

**VerkehrsRundschau test (for details see Süßmann & Leinkamp, 2015)*

### Rigid Truck Baseline Fuel Consumption

Figure 9 shows the range of fuel consumption values for the baseline rigid truck analyzed over VECTO Urban Delivery, Regional Delivery, and Long Haul cycles. The results are shown for empty, representative payloads (9.8 tonnes for Long Haul cycle and 3 tonnes for Regional and Urban Delivery cycles), and full payloads (12.6 tonnes for Long Haul cycle and 5.5 tonnes for Regional and Urban Delivery cycles). Note that we followed the adopted EU HDV $CO_2$ certification regulation, which assumes that rigid trucks over the Long Haul cycle are hauling a trailer (EC, 2017c).

The rigid truck fuel consumption over the Urban Delivery cycle at the representative payload of 3 tonnes is 21.6 L/100km. Fuel consumption at empty over the same cycle is 18% lower and at full payload is 15% higher. The fuel consumption over the Regional Delivery cycle at the representative payload of 3 tonnes is 19.9 L/100km. Fuel consumption at empty over the same cycle is 13% lower and at full payload is 10% higher. These results show a similar trend as was observed for tractor-trailers, where the effect of payload is more pronounced at more transient conditions. For the Long Haul cycle, the fuel consumption at the representative payload of 9.8 tonnes is 24.9 L/100km. Fuel consumption at empty over the same cycle is 22% lower and at full payload is 5% higher. Note that this case is not directly comparable with the Urban Delivery and Regional Delivery cases because of the additional payload capacity (and additional curb weight) from the trailer. The test cycle impact on fuel consumption is lower for rigid trucks than for tractor-trailers. As mentioned in the tractor-trailer analysis, test cycle effects are more pronounced at higher payloads.

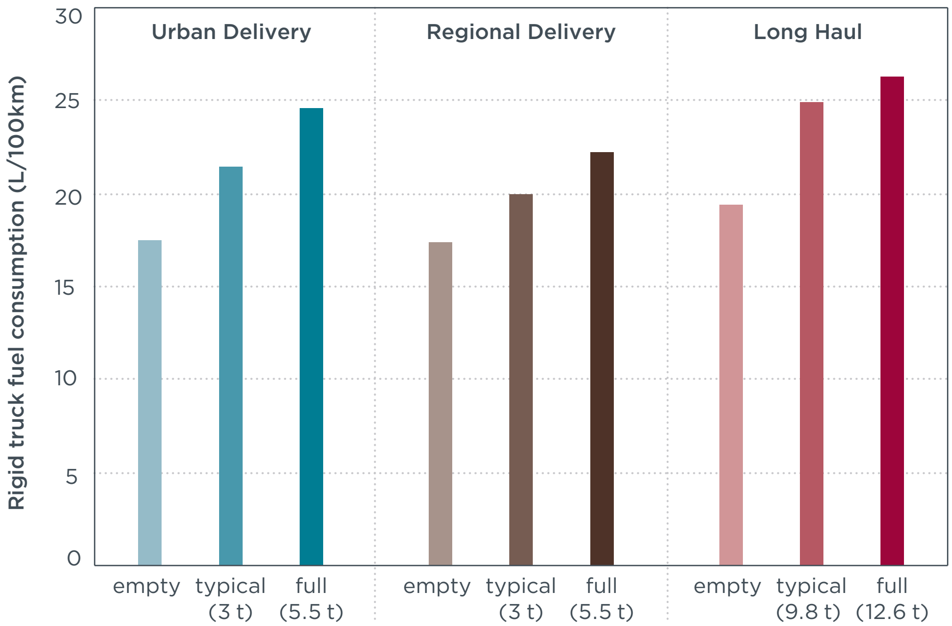



**Figure 9.** Rigid truck baseline fuel consumption

## Rigid Truck Energy Audit

Figure 10 shows the baseline rigid truck energy consumption as a percentage of total fuel input energy according to six energy loss categories over VECTO Urban Delivery, Regional Delivery, and Long Haul cycles. A payload of 3 tonnes is assumed for this analysis. The Long Haul cycle was also simulated at 9.8 tonnes, in accordance with the VECTO protocol.

Engine losses range from 59% to 63% (i.e., cycle averaged BTE of 37% to 41%) of the fuel energy consumed. Aerodynamic drag losses, second in magnitude for all cycles, range from 9% to 24%. Tire rolling resistance losses range between 8% and 14% of the energy consumed. The rolling resistance losses are proportional to both rolling resistance coefficient and vehicle mass. Because the vehicle mass of the rigid truck is low relative to the tractor-trailer, the rolling resistance has lower relative importance than for the tractor-trailer results shown in Figure 7. Braking losses indicate the level of stop-and-go type of driving and range from 2% to 12%. Generally, braking losses and aerodynamic losses follow opposite trends. The duty cycles with higher braking losses are those with stop-and-go driving behavior and low average speeds. Lower speeds reduce the aerodynamic losses because those losses are proportional to the square of average speed. Higher braking losses indicate increased potential for hybrid powertrain technologies, while higher aerodynamic losses indicate increased potential for aerodynamic drag reduction technologies.

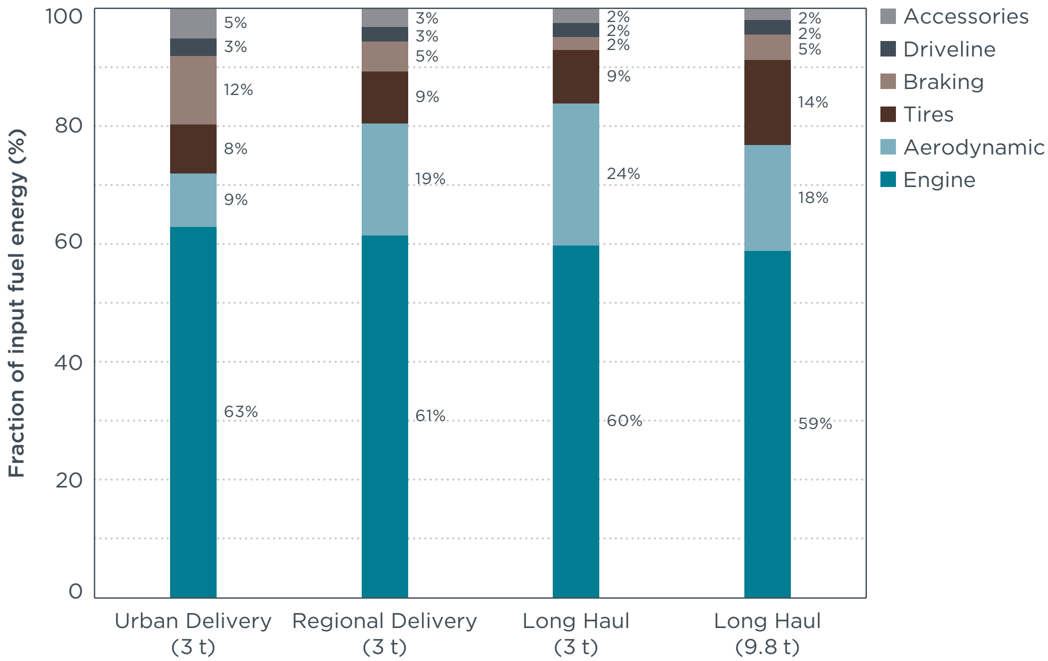



**Figure 10.** Rigid truck energy audit over different cycles

## BASELINE SUMMARY

This section discussed the systematic efforts undertaken to determine a representative set of vehicle specifications for the two HDV segments with the highest contribution to $CO_2$ emissions: 4×2 rigid trucks and 4×2 tractor-trailers[10]. The baseline vehicle specifications used in this study are summarized in Table 13.

10 In this report, the selection of the two 4×2 trucks studied was done to cover the two ends of the operation spectrum; long-haul and urban freight transportation selection. The resulting GVW selected, 12-tonne, is not the most representative GVW for 4×2 rigid trucks (see Figure 1). For the studied tractor-trailer, the selected GVW and axle configuration is, however, the most representative among tractor-trailers.

**Table 13.** Summary of baseline vehicle specifications

| Baseline specifications | Rigid truck | Tractor-trailer |
|---|---|---|
| **Gross vehicle weight (t)** | 12 | 40 |
| **Vehicle curb weight (t)** | 6.5 | 14.4 |
| **Maximum payload (t)** | 5.5 | 25.6 |
| **Typical payload* (t)** | 3.0 | 19.3 |
| **Axle configuration** | 4×2 | 4×2 |
| **Engine displacement (L)** | 5 | 12.8 |
| **Engine power (kW)** | 170 | 350 |
| **Engine emissions** | Euro VI | Euro VI |
| **Engine peak BTE (%)** | 42.2 | 44.8 |
| **Transmission type** | AMT | AMT |
| **Transmission gear number** | 6 | 12 |
| **Transmission gear ratios** | 6.75–0.78 | 14.93–1.0 |
| **Rear axle ratio** | 4.00 | 2.64 |
| **Tire size** | 265/70R19.5 | 315/80R22.5 |
| **Tire radius (m)** | 0.43 | 0.52 |
| **Aerodynamic drag area ($m^2$)** | 5.28 | 6.0 |
| **Tire rolling resistance (N/kN)** | 6.6 | 5.5 |
| **Accessory power demand (kW)** | 3.63 | 5.6 |

**The typical payloads used are those proposed in the draft technical annex for the certification of the $CO_2$ emissions and fuel consumption of heavy-duty vehicles (EC, 2014b). The payloads shown in this table correspond to those used in the Urban Delivery cycle for the rigid truck, and in the Long Haul cycle for the tractor-trailer*

The fuel consumption of the selected baseline vehicles was determined for three different payload levels and over three different duty cycles. The baseline fuel consumption results are summarized in Table 14.

**Table 14.** Summary of baseline fuel consumption

| HDV type | Cycle | Fuel consumption (L/100km) | | |
|---|---|---|---|---|
| | | Empty | Typical payload* | Full payload** |
| **Rigid truck** | Urban Delivery | 17.5 | 21.4 | 24.6 |
| | Regional Delivery | 17.4 | 20.0 | 22.2 |
| | Long Haul | 19.4 | 24.9 | 26.3 |
| **Tractor-trailer** | Urban Delivery | 28.1 | 43.1 | 57.3 |
| | Regional Delivery | 25.0 | 36.4 | 46.9 |
| | Long Haul | 23.7 | 33.1 | 36.2 |

**Rigid truck: 3 tonnes over the Urban Delivery and Regional Delivery cycles, 9.8 tonnes over Long Haul cycle. Tractor-trailer: 12.9 tonnes over the Urban Delivery and Regional Delivery cycles, 19.3 tonnes for the Long Haul cycle.*

***Rigid truck: 5.5 tonnes over the Urban Delivery and Regional Delivery cycles and 12.6 tonnes over the Long Haul cycle. Tractor-trailer: 25.6 tonnes*

# 4. ANALYSIS OF TECHNOLOGY POTENTIAL

The main objective of this section is to provide an analysis of the potential for fuel efficiency improvements of tractor-trailers and rigid trucks, starting from the baseline values determined in Section III. A literature review was performed to identify individual fuel-saving technologies that may already be available or are expected to be ready for market introduction in the 2020–2030 time frame. These technologies include engine, driveline, and road load reduction technologies. Their individual potential was estimated by a combination of literature review and use of vehicle simulation software over representative duty cycles and payloads. After the individual technology analysis, the combined technology potential of technology packages with increasing levels of engine, driveline, and road load reduction technologies was assessed. The combined potential of technologies was determined by simulating the combined packages in Autonomie and/or by multiplicative aggregation[11] of individual technologies' reduction potentials.

## TRACTOR-TRAILER TECHNOLOGIES

This research utilizes the Autonomie vehicle simulation platform to incorporate advanced technologies into the baseline vehicle models. No structural changes to the architecture of the model or the driver parameters were made. In some cases, the individual technology effectiveness of certain technologies was estimated by engineering analysis and modeled with post-processing, as some technologies cannot be directly simulated in Autonomie. The following sections about engine, driveline, road load, and accessories describe the individual technologies that were applied to the baseline vehicle as well as their impact on fuel consumption.

### Engine Technologies

Internal combustion engines with compression ignition date back to 1890. Since then, the diesel engine has gradually evolved into its current form. Given the engine's technological maturity, the many technologies available and under development to reduce engine fuel consumption have a limited improvement potential when applied individually. However, when applied in the form of engine technology packages, the efficiency improvements are significant. The approach followed in this study for modeling the fuel efficiency potential of future diesel engines is based on a detailed understanding of the individual technologies and on their interactions at the system level. The baseline engine maps were adjusted and scaled in the simulation tool to represent the efficiency improvement estimates of different engine packages according to the findings of the literature review. The following paragraphs present the main areas of research and development as well as the corresponding technologies for the reduction of fuel consumption in HDV diesel engines. Several of the concepts presented below have been developed and put into practice during a 4-year collaborative consortium for the $CO_2$ Reduction for long distance transport ($CO_2$RE) focusing on powertrain efficiency. The $CO_2$RE work group consists of 16 partners from truck manufacturers, Tier 1 suppliers, engineering service providers, universities and the European Commission (European Council for Automotive R&D [EUCAR], 2015).

11 The combined fuel consumption reduction is calculated as $\%FC_{combined} = 1-\prod_i(1-\%FC_i)$, where $\%FC_i$ is the fuel efficiency improvement associated with technology *i*.

*Combustion optimization*

The combustion process in diesel engines is a complex phenomenon that is strongly dependent on the mixing of the injected fuel with a limited amount of air in a confined space. As such, the injection strategy has a heavy influence on the combustion behavior. Higher pressure results in smaller and faster fuel droplets at the exit of the injection nozzle, which in turn improves the fuel mixing and evaporation. The use of increasingly higher fuel pressures has been mainly driven by the higher exhaust gas recirculation (EGR) rates needed for nitrogen oxides ($NO_x$) control. EGR reduces the peak combustion temperature and reduces the formation of $NO_x$; however, the higher EGR rate also slows down the combustion chemistry and reduces the soot oxidation, resulting in higher fuel consumption and particulate matter (PM) emissions. Higher fuel injection pressures are then necessary to offset these disadvantages of high EGR rates (Ehleskog, Gjirja, & Denbratt, 2009). For Euro VI engines, the fuel injection pressure has risen to a maximum of around 2,700 bar and injection systems able to deliver 3,000 bar are commercially available. For engines with low-EGR rates, the required pressure is below 2,000 bar (Kendall, 2014). Another important strategy for combustion control consists of adjusting the fuel injection rate throughout the injection event. This can be achieved through multiple injections or injection rate shaping. In the future, flexible injection systems in heavy-duty applications, such as continuous injection rate shaping or closed-loop combustion control, will provide the additional freedom that engine calibrators require for optimizing the fuel consumption while keeping the engine-out pollutant emissions within the required margins (Weatherley, 2015).

The use of higher compression ratios offers theoretical benefits on the brake thermal efficiency; however, the increased friction and higher heat losses brought along by the higher temperature and pressure can offset the efficiency gains by more than half (Funayama, Nakajima, & Shimokawa, 2016). The current average compression ratio of European HDV engines is 18 and is expected to increase to 20 in the future (Schreier, Walter, Decker, & Theissl, 2014). Lastly, the combustion chamber geometry and the fuel spray plume characteristics resulting from the injector configuration significantly influence the combustion process and, thereby, the emission formation and fuel consumption. The optimization of the combustion chamber and injector configuration is an active area of research. However, the applicability of a given geometry is limited to a specific engine and a one-size-fits-all approach does not exist.

The timing, duration, and lift profile of the intake and exhaust valve trains impact the fuel consumption and emissions performance of internal combustion engines. Variable valve actuation (VVA) is a mature technology that has been applied extensively in LDV engines. In large diesel engines, VVA offers limited benefits due to the narrower speed range, higher air flow requirements, complex EGR and turbocharging technologies, and the smaller clearance volume at top-dead center (Deng & Stobart, 2009). Nevertheless, VVA cannot be ruled out as a future technology for HDV diesel engines, as it provides flexibility for charge motion control, cylinder deactivation, internal EGR, extended expansion ratio, ignition delay control, and thermal management of the exhaust after-treatment system (De Ojeda, 2010; Schneider & Naujoks, 2016; Sjöblom, 2014).
In the $CO_2$RE project, a VVA system was experimentally demonstrated in combination with a high-efficiency turbocharging system. The VVA system allows for late inlet valve closure (Miller cycle), which reduces the effective compression ratio of the engine. The lost volumetric efficiency is compensated for by the turbocharging system in order to maintain the required air flow. Because part of the compression work is done by the intercooled turbocharging system, the engine efficiency increases while at the same

time reducing the peak cylinder temperature and, thus, the $NO_x$ formation (Engström, 2016). The EPA/NHTSA GHG HDV Phase 2 regulatory impact analysis (RIA) estimates the fuel consumption reduction – from a 2017 baseline – of combustion optimization at 1.1% for tractor-trailers (U.S. EPA & U.S. DOT, 2016b).

*Heat transfer losses and waste heat recovery systems*

Heat transfer to the environment is a significant fuel energy loss mechanism in internal combustion engines. In modern HDV diesel engines, approximately 20% of the fuel energy is lost through the coolant radiator, charge air cooler (CAC), EGR cooler and directly to the surrounding ambient air (Thiruvengadam et al., 2014). The concept of a Low Heat Rejection Engine (LHRE) was the subject of a body of research during the 1980s and 1990s; however, the theoretical potential of LHREs did not materialize in the magnitude that the research community expected (Serrano, Arnau, Martin, Hernandez, & Lombard, 2015). Furthermore, the resulting higher temperatures of LHREs caused additional challenges due to the thermal fatigue of the engine components and the deterioration of the properties of the lubricating oil. A review of nine experimental LHRE studies shows mixed results; five studies reported efficiency improvements while the remaining four measured efficiency degradation (Jaichandar & Tamilporai, 2003). A more recent study on LHREs (Das & Roberts, 2013) suggests that increased rates of EGR and higher coolant temperatures result in a reduction in heat transfer rates without the need of ceramic coatings in the combustion chamber. However, the study acknowledges that a greater potential exists in waste heat recovery (WHR) than in low heat rejection concepts. WHR systems can convert the rejected thermal energy from the combustion process back into usable mechanical or electric energy. WHR systems tap into the hot exhaust gases and cooling flows as heat sources and use either thermo-electric generators (TEGs) or a closed Rankine cycle for power generation. TEGs make use of the Seebeck effect to generate electricity from temperature differentials. The Rankine cycle, on the other hand, uses the wasted thermal energy to evaporate a high-pressure liquid; the vapor is then expanded in a mechanical device to generate work. A computational study carried out by Volvo trucks, the University of Liege, and the University of Lyon estimates that an optimized WHR system can provide 4.1% and 7.2% of the engines work under steady and transient conditions, respectively (Grelet, Reiche, Lemort, Nadri, & Dufour, 2016). The experimental results of the *European NoWaste Project*, which aimed at developing Rankine cycle systems for integration into long-haul trucks, show that a WHR system based on an ethanol Rankine cycle can provide between 1.5% and 3% of the total engine power at steady-state conditions (Bettoja et al., 2016). A recent study on WHR systems used simulation, test bench, and public road testing to assess the potential of an Organic Rankine Cycle (ORC) applied to a Euro VI, 353 kW, 11-liter engine. The results indicate a potential fuel consumption reduction of up to 3.5% over real-life European operating cycles (Glensvig et al., 2016).

*Engine accessories power demand reduction*

The correct functioning of the engine is dependent on several supporting systems, also known as engine accessories. These include the low and high-pressure fuel pumps, and the coolant fluid and engine oil pumps. The power necessary to drive these accessory loads is traditionally taken directly from the engine, which impacts fuel performance. Decoupling the accessories from the engine has the potential to reduce fuel consumption by engaging the loads based on the engine operating conditions (on-demand control) and by optimizing the moment when the accessories are engaged (e.g., the vehicle's inertia can be used to drive the loads). Table 15 presents a summary of the technologies aimed at reducing the engine accessories' power consumption.

**Table 15.** Engine accessories fuel efficiency technologies

| System | Fuel-saving technology description | Further information |
|---|---|---|
| **Fuel system** | Electric lift pumps allow fuel metering to the high-pressure fuel pump and enable on-demand control of the low-pressure fuel system. | Sommerer, Schmid, Lengenfelder, & Thomas, 2015 |
| **Coolant and oil pumps** | Active control of the cooling and oil pumps can be achieved through viscous-couplings or through complete pump electrification. The first approach is available due to the progress in visco-clutch fans, while the latter requires a higher voltage architecture. | Boëté, 2015; Schultheiss, Edwards, Banzhaf, & Mersch, 2012 |

*Engine friction reduction*

Depending on the speed/torque operating point, engine friction can be responsible for losses of up to 4.5% of the fuel's energy (Thiruvengadam et al., 2014). The piston assembly accounts for approximately 45% of the friction losses; around 30% are caused by the hydrodynamic lubrication of bearing and seals; and the remaining 25% is caused by the valve train and other engine components (Holmberg, Andersson, & Erdemir, 2012). Given the importance of the piston assembly on engine friction, significant research efforts have sought to understand the friction mechanisms of the piston ring pack (Baelden & Tian, 2014; Fang & Tian, 2016), the piston skirt (Totaro, Westerfield, & Tian, 2016; Westerfield, Totaro, Kim, & Tian, 2016), and the lubricant properties (Molewyk, Wong, & James, 2014; Plumley, Wong, Molewyk, & Park, 2014). The combined effect of optimizing the piston rings' shape, tension, and material; improving the piston skirt surface geometry and finish; and the reformulation for reduction of lubricant viscosity can result in significant gains. This potential was demonstrated experimentally in the $CO_2$RE project. Using a 7.7-liter engine as platform (Daimler's OM 936) and focusing on the piston assembly and oil viscosity, the $CO_2$RE consortium was able to reduce the piston-related friction up to 36%, translating to a fuel consumption reduction of over 1% (Engström, 2016). Similarly, the U.S. Department of Energy (U.S. DOE, 2016a) is currently funding research efforts to reduce the frictional losses of modern engines by 50%.

*Aftertreatment system improvement*

The continuous tightening of the HDV emission limits in Europe has resulted in the development and implementation of several technical measures. A typical Euro VI compliant emissions control system consists of an EGR loop, a diesel oxidation catalyst (DOC), a selective catalytic reduction (SCR) system, and a diesel particulate filter (DPF). The physicochemical principles dictating the formation of $NO_x$ and PM in the combustion process give rise to a well know $NO_x$/PM trade-off. As a result, the specification of the emissions control system is tightly connected to the engine calibration strategy and, consequently, to the engine efficiency. The following two approaches illustrate this interdependence.

» 1. *High engine-out PM emissions:* Delayed injection timing and higher rates of EGR reduce the combustion temperature and result in low $NO_x$ formation. At the same time, the soot oxidation rates are reduced, resulting in higher engine-out PM emissions. The DPF system and its regeneration strategy are tailored to accommodate the higher PM flow, while at the same time relaxing the $NO_x$ conversion efficiency requirements of the SCR system. The delayed combustion phasing and the backpressure from the EGR and DPF systems negatively impact the fuel efficiency.

» 2. *High engine-out $NO_x$ emissions:* Lower EGR rates and injection timings optimized for higher fuel efficiency increase the combustion temperature and result in higher engine-out $NO_x$ emissions and lower engine-out PM emissions. The SCR system and the urea injection strategy need to be optimized to deal with the higher $NO_x$ flow, while relaxing the requirements on the DPF and its regeneration. The earlier injection and combustion timing, together with the lower backpressure from the reduced EGR rates and DPF loading, result in better fuel efficiency.

Improvements in the conversion efficiency of SCR systems have the potential to allow the emissions control strategies to migrate from the first approach presented above (more commonly found in Euro VI HDV) to the second approach (Jiao, 2015). A key and active area of research on SCR systems is the improvement of low temperature $NO_x$ conversion, for exhaust temperatures below 300°C. Higher conversion efficiencies can be achieved through modifications on the catalyst substrates, the urea solution, or the control strategies. The most straightforward approach is to increase the number of active catalytic sites in the SCR coating. A further option consists in enabling the so-called *fast SCR reaction* using an upstream oxidation catalyst with a high platinum loading to achieve the optimum $NO_2/NO_x$ ratio. Another approach uses the addition of a low concentration of ammonium nitrate to the urea solution in order to increase the SCR conversion at low temperatures (Marchitti, Hemings, Nova, Forzatti, & Tronconi, 2016). The approach used in the project $CO_2$RE achieved a 30% reduction in tailpipe $NO_x$ emissions through the use of a third generation copper exchanged zeolite, urea vaporization, addition of ammonium nitrate, and advance control algorithms to estimate the catalyst ammonia storage and SCR reaction kinetics (Engström, 2016).

Developments are also occurring in DPF substrates aimed at reducing the back pressure from the soot and ash loading in the filter. During the $CO_2$RE project, Johnson Matthey developed a DPF with a 30% higher soot burn rate and an approximately 4% lower backpressure due to the substrate's higher porosity (Engström, 2016). A final technology pathway is the integration of SCR and DPF systems into a single substrate in other to improve the catalyst warm-up, improve packaging, and reduce the aftertreatment system backpressure. Combined, aftertreatment improvements have the potential to reduce fuel consumption by 2% to 4% in line-haul applications (Delgado & Lutsey, 2015).

*Turbo systems*

The use of turbines for the extraction of unused exhaust energy is a concept as old as the combustion engine itself. Turbocharging technologies have matured significantly, expanding their operation ranges and thermodynamic efficiency, and have become a standard technology in diesel engines, ensuring high levels of efficiency and power density. Nevertheless, turbocharging technology, and its integration with the engine and aftertreatment system, is still relevant for improving the fuel consumption. Several turbocharging configurations are available to satisfy the needs of different powertrain concepts. These include single-stage waste-gate turbocharger (WGT), single-stage variable geometry turbocharger (VGT), single stage asymmetric twin-scroll turbine (ATS), two-stage fixed geometry turbocharger (WGT+FGT) and two-stage variable geometry turbocharger (VGT+FGT) (Liu, Wang, Zheng, Zou, & Yao, 2016). The selection of the turbocharging architecture and the matching of the turbine and compressor wheels is a complex process that is of significant relevance for the powertrain efficiency. Several factors are considered in this matching process, such as cost, low speed torque, high speed power, transient response, desired boosting level, and required EGR rate. Innovative concepts aiming to strike a balance between the aforementioned requirements include the asymmetric twin scroll turbine from Daimler (Chebli, Müller, Leweux, & Gorbach, 2013) and a high-efficiency, dual-stage turbocharger from Honeywell featuring ball bearings, airfoil diffusers, an axial-radial configuration, and a nozzled axial turbine (Engström, 2016). Improvements in the turbine and compression efficiency, as well as the reduction of the backpressure generated by the turbocharger, can result in fuel efficiency improvements of up to 5% in long-haul applications (Delgado & Lutsey, 2015).

Another alternative to extract work from the exhaust energy is turbocompounding. Contrary to turbocharging, the work extracted by the exhaust turbine is not used to compress intake air, but to perform tractive work. In mechanical turbocompounding systems, the recovered energy is transmitted directly to the crankshaft. The mechanical coupling results in a fixed ratio between the turbine and the engine speeds. This reduces the flexibility of the system and can result in additional power losses at low exhaust flows typical of low engine speed operation (He & Xie, 2015). Electric turbocompounding uses the extracted energy to power an electric generator and stores the produced electric energy in a battery. As such, electrical turbocompounding provides greater flexibility regarding energy management as the recovered electric energy can be used to power electrical accessories, provide direct assist to the powertrain, or improve the boosting transient response through an electric compressor. In the case of long-haul HDVs, turbocompounding can result in fuel consumption reduction between 3% and 4.5% (Cooper et al., 2009) The EPA/NHTSA GHG HDV Phase 2 rule estimates the benefit of turbocompounding at 1.8% (U.S. EPA & U.S. DOT, 2016a).

*Engine technology packages*

The effectiveness of individual technologies is difficult to isolate because of the deep interaction among the different engine systems. As an example, engine calibration of exhaust gas recirculation rates affects combustion efficiency, cooling requirements, and backpressure requirements of the engine, thus affecting more than one energy loss mechanism at the same time.

Due to the difficulty to isolate the specific contribution of individual technologies, engine technology packages were developed for a previous ICCT study that focused on the North American market (Delgado & Lutsey, 2015; Thiruvengadam et al., 2014). These packages are applicable to this study because they start from a baseline U.S. EPA 2010 compliant engine, which is very similar in terms of hardware, efficiency levels, and emissions controls to a Euro VI engine (Jiao, 2015). Table 16 summarizes the engine technology packages analyzed in this study. Starting from the baseline Euro VI engine described in Section III, the next step represents an incremental technology deployment to achieve current best-in-class engine efficiency (2017 BIC). The 2020+ package utilizes well understood, commercially available technologies that allow the engine to obtain 49% peak brake thermal efficiency. This technology level is expected to be achieved by 2020 and commercialized by 2025 at the latest. The advanced 2020+ with WHR package adds a WHR system that increases the peak BTE to 51%. WHR systems are expected to be commercialized by 2027 at the latest. Finally, the long-term engine package represents technologies that are being analyzed in manufacturer research and development laboratories, government agencies, and universities. These technologies would enable peak engine BTEs of 55%, which is an objective of the U.S. Department of Energy (NAS, 2015). Although current prototypes with these efficiency levels do not yet exist, Cummins demonstrated during the U.S. SuperTruck program a diesel engine with a peak BTE of 50%, and laid out the pathway to achieve 55% peak BTE through the use of advanced combustion, turbocharger efficiency improvements, and waste heat recovery (Ashley, 2015). Similarly, Volvo and researchers at Lund University are setting a pathway for 56% peak BTE through the use of split cycle engines, where the compression and expansion processes are split into a low-pressure and a high-pressure cycle (Lam et al., 2015). An alternative pathway that could achieve 55% BTE without the use of waste heat recovery has been proposed by Achates Power and consists of a two-stroke opposed piston engine (Abani, Nagar, Zermeno, Chiang, & Thomas, 2017). The key advantages over conventional engines are the absence of a cylinder head, which reduces the heat transfer losses, and the leaner operation allowed by the 2-stroke cycle, which improves the thermodynamic properties of the combusting gases (higher isentropic coefficient). In the United States, the SuperTruck II initiative will fund four teams to develop and demonstrate cost-effective technologies for doubling freight efficiency and produce an engine with 55% peak BTE. Among the participating teams are Daimler Trucks and Volvo Trucks (U.S. DOE, 2016b). The technological improvements from the SuperTruck II program are expected to be achieved by 2025 and commercialized by 2030.

Table 16 contains the engine technology packages considered in this study. The selected baseline engine has a peak BTE of 44.8% (see Table 2 for further detail). The baseline engine features a common rail system with fuel injection pressure up to 2,500 bar, a single-stage VGT, cooled EGR, and SCR plus DPF for emissions control. The **2017 best in class level** has a higher compression ratio, which results in higher brake mean effective pressure, and is able to withstand the associated maximum peak cylinder pressures. Furthermore, an increase in the fuel injection pressure enables advanced injection strategies for in-cylinder $NO_x$ control, reducing the EGR rates required and the associated backpressure. The 2017 BIC engine also features improvements in the engine accessories' power demand management. The **2020+ level** includes higher boosting, mean effective, and peak cylinder pressures. Improvements in the injection hardware and control strategy will enable advanced combustion concepts and further in-cylinder $NO_x$ control improvements. As a result, lower EGR rates are necessary and the turbocharger focus shifts from reducing the backpressure necessary for driving the EGR toward improvements in the actual turbocharger efficiency. Furthermore, friction is reduced with low viscosity lubricants, piston skirt, and ring pack redesign. Enhanced SCR conversion efficiency ensures the reduction of the higher engine-out $NO_x$ emissions, and DPF systems with higher porosity reduce the associated backpressure. Lastly, a turbocompounding system recovers some of the unused energy in the exhaust stream that would be otherwise wasted. The **2020+ with WHR level** improves the energy recovery system in comparison with turbocompounding through the use of an organic Rankine bottoming cycle. In the **long-term level**, electrified accessories reduce the parasitic losses; advanced combustion systems with heat release rate shaping reduce the engine-out pollutant emissions, reducing the fuel economy impact of the aftertreatment system; and improvements in the WHR system result in an estimated 55% peak brake thermal efficiency. It is worth pointing out that many of the technologies described in this specific pathway from 45% to 55% BTE are not discrete, but are the result of small, but continuous, improvements.

**Table 16.** Engine technology packages

| Package | Technologies considered | Peak BTE |
|---|---|---|
| **Baseline** | Representative Euro VI engine | 45% |
| **2017 best in class** | Increase in compression ratio and injection pressure; reduction in EGR rates and accessories' management | 46% |
| **2020+** | 2017 best in class + reductions in friction and pumping losses; enhanced aftertreatment and turbo efficiency; turbocompounding | 49% |
| **2020+ with WHR** | 2020+ with a waste heat recovery system using an organic Rankine bottoming cycle instead of turbocompounding | 51% |
| **Long-term** | Reduced parasitic losses, advanced injection and combustion strategies, improvements in the WHR system (Wall, 2014)<br><br>Alternative pathways: opposed piston engine, low temperature combustion, dual fuel combustion and split cycle engines | 55% |

Technology potential fuel consumption reduction from engine technology is significant. T&M Leuven estimates that a 5% improvement is feasible by 2020 and up to 9% is technologically feasible (Breemersch & Akkermans, 2015). IFEU estimates that the maximum technology potential by 2020 is 11% (Dünnebeil et al., 2015). The impact assessment of the European Commission estimates technology potential at 13.1% (EC, 2014a). The latter value was recently scrutinized by the Impact Assessment Institute (2016) and no adjustments were suggested. Table 17 shows four engine technology steps and their corresponding fuel consumption reductions over the Regional Delivery and Long Haul cycles. Fuel consumption reductions of up to 9.5% can be obtained with currently available technologies. The addition of a waste heat recovery system, which is at an advanced stage of development, can achieve up to 11.7% fuel consumption reduction. The long-term engines are not yet available, but pathways to achieve such levels of efficiency (up to 18.1% fuel consumption reduction) have been identified.

**Table 17.** Engine packages effectiveness

| Engine package | Regional | | Long Haul | |
|---|---|---|---|---|
| | FC (L/100km) | FC reduction | FC (L/100km) | FC reduction |
| **Baseline** | 36.37 | – | 33.06 | – |
| **2017 best in class** | 35.17 | 3.3% | 31.97 | 3.3% |
| **2020+** | 33.28 | 8.5% | 29.91 | 9.5% |
| **2020+ with WHR** | 32.32 | 11.1% | 29.18 | 11.7% |
| **Long-term** | 30.64 | 15.8% | 27.07 | 18.1% |

## Driveline Technologies

The transmission and driveline have the potential to reduce tractor-trailer energy use in several ways. Increased efficiency reduces the frictional losses through the driveline components that connect the engine torque to propulsion at the wheels, while other technologies create synergies that optimize engine operation.

*Transmission efficiency*

There is the potential to improve transmission gear efficiency and to reduce losses related to the transmission lubrication systems (e.g., lubrication pump parasitic losses). Default input values for VECTO indicate average transmission efficiency of about 93% at indirect gears and about 96% at direct gear. Maximum values are about 96% for indirect gear and about 99% for direct gear. Consultation with transmission manufacturers indicate values of 99.1% for indirect gears and 99.7% for direct gears for current best in class transmissions. U.S. EPA and U.S. DOT (2016a) project that transmission efficiency could improve by 1% in the U.S. Phase 2 timeline (2018–2027). In this study, effectiveness was modeled by increasing transmission efficiency by 1 percentage point, which resulted in fuel consumption reduction of 0.9% in both the Regional Delivery and the Long Haul cycles.

*Axle efficiency*

Axle efficiency is improved by reducing mechanical losses from the friction between mating gears and spin losses from axle rotation. Generally speaking, frictional losses are proportional to the torque on the axle and spin losses are a function of rotational speed of the axle (U.S. EPA & U.S. DOT, 2016b). Axle efficiency is sensitive to axle reduction ratio. In general, rear axles with lower axle ratios are more efficient than rear axles with higher axle ratios. Default input values for VECTO indicate average axle efficiency of about 95% and maximum values of about 98%. The U.S. Phase 2 assessment of axle improvements found that axles built in the Phase 2 timeline (2018–2027) could be 2 percentage points more efficient than a 2017 baseline axle, whose mechanical efficiency was estimated at 96% (U.S. EPA & U.S. DOT, 2016a). In this study, it is assumed that improved axle gear designs and low friction axle lubricants contribute to 1 percentage point higher axle efficiency, for a resulting axle efficiency of 97%. Based on this assumption, the fuel consumption reduction from axle efficiency technology is 0.9% in the Regional Delivery cycle, and 1.3% in the Long Haul cycle.

*Engine Downspeeding*

Downspeeding consists of using faster (i.e., numerically lower) rear axle ratios to reduce engine speed at cruising speed. Lower speeds reduce friction and pumping losses in the engine and enhance fuel efficiency, especially in the low range of engine speeds. However, to keep the power output constant at lower engine speed, the engine torque needs to be increased, resulting in higher peak cylinder pressures (PCPs). Downspeeding an engine for which the air handling (i.e., turbocharging and EGR) has not been optimized can have a detrimental effect as the air/fuel ratio becomes less favorable for efficient operation. Downspeeding, together with a potential increase in the compression ratio, pushes the limits of current allowable PCPs (around 170 bar). In the context of the $CO_2$RE project, Daimler demonstrated a downsped engine concept with an increased PCP of 230 bar (Engström, 2016). Downspeeding also requires more frequent transmission shifting, which increases the number of engine transient events and might reduce the engine's operational efficiency (Delgado & Lutsey, 2015).

Dual-clutch transmissions (DCTs), which have already been introduced in Europe (Volvo Trucks, 2014), could facilitate downspeeding by reducing the traction interruption period during transmission shifting. A DCT operates similarly to an AMT, but with two clutches. Gear changes occur by swapping engine torque between clutches, which eliminates the torque interruption during shifts observed in manual and AMT transmissions. Faster gearing is thus possible. DCTs enable greater levels of downspeeding (around 900–1,000 rpm) when compared with AMTs. Table 18 shows fuel consumption results for four different levels of downspeeding. By pushing the limits of what AMTs are capable of, a fuel consumption reduction of around 1% can be obtained with downspeeding. DCT-enabled downspeeding would reduce fuel consumption by up to 3%. There is no fuel penalty for the increased shifting with a DCT. Note that besides using direct drive and a very low axle ratio (2.11), this level of downspeeding can also be achieved with an overdrive AMT and a conventional axle ratio (2.6). However, with current overdrive gear efficiencies, the fuel benefits will be lower than using direct drive and low axle ratios.

Volvo has indicated that fuel consumption with the I-Shift Dual Clutch is the same as the I-Shift AMT (Volvo Trucks, 2014). However, besides the potential for higher downspeeding levels, there are many synergistic benefits from DCTs. The power shifting allows for faster shifting and avoids power loss or torque interruption by having the engine loaded during shifts. As a result, the turbocharger efficiency is maintained and the engine avoids transient operation (which consumes energy and temporarily reduces boosting pressure, thus the air/fuel ratio, resulting in higher soot formation) and operation in low BTE areas. The absence of torque loss during DCT shifting also reduces the need for torque backup for smooth engine operation, which facilitates potential engine downsizing efforts. An intermediate solution to reduce the gearshift time of AMTs, reducing the torque interruption periods, is to use a shaft brake. The brake is able to reduce the speed of the shaft quicker than traditional synchronous rings; that accelerates the synchronization process of the gears when upshifting. Layshaft brake AMTs have already been introduced in Europe (Scania, 2016b). Downspeeding and downsizing have synergistic benefits by shifting engine operational points to areas of higher engine efficiency (Delgado & Lutsey, 2015). When using a downsized (i.e., lower displacement) engine, the power and torque capabilities are expected to be lower. That matches with the reduced power and torque demands of vehicles with advanced road load reduction technologies. A smaller engine would operate at higher loads, which usually correspond to higher brake thermal efficiency operational areas, reducing fuel consumption. If acceptable power and torque levels are achieved, the smaller displacement engine also has the advantage of lower internal friction, lower mass, and lower volume.

**Table 18.** Driveline-enabled engine downspeeding effectiveness

| Rear Axle Ratio | Engine Speed at 85 km/h | Transmission type | Regional Delivery | | Long Haul | |
|---|---|---|---|---|---|---|
| | RPM | | FC (L/100km) | FC reduction | FC (L/100km) | FC reduction |
| **2.64** | 1,215 | AMT | 36.37 | – | 33.06 | – |
| **2.51** | 1,130 | AMT | 36.38 | 0.0% | 32.79 | 0.8% |
| **2.38** | 1,070 | AMT | 36.37 | 0.0% | 32.77 | 0.9% |
| **2.24** | 1,008 | DCT | 35.84 | 1.5% | 32.49 | 1.7% |
| **2.11** | 950 | DCT | 35.6 | 2.1% | 32.08 | 3.0% |

*Engine-transmission integration*

Engines and transmissions are managed by individual electronic controls: the engine control unit (ECU) and the transmission control module (TCM). Engine-transmission deep integration consists of the combination of enhanced engine-transmission communication and advanced shifting strategies that optimize engine and transmission operation to achieve fuel consumption savings. Constant ratio steps and simplistic shifting controls can be enhanced, especially when co-optimized with the engine. The purpose of the transmission is to keep the engine operation locus as close as possible to its peak brake thermal efficiency. An estimation of the potential benefits of engine-transmission deep integration thus can result from the ratio of cycle-averaged thermal efficiency values against peak brake thermal efficiency values. For an idealized engine-transmission integration, the engine would operate 100% of the time at peak efficiency, resulting in a deep-integration ratio equal to 1. For the engines under consideration in this study, this ratio varies between 0.95 and 0.97, so the maximum potential for improvement ranges from 3% to 5%. The effectiveness of a deep-integrated engine-transmission combination is estimated at 1.5% for both the Regional Delivery and Long Haul cycles. In real-world driving, the potential might be higher because the simulation software already uses an optimized shifting strategy and the actual operational points may further deviate from the optimal case. As previously mentioned, the default vehicle driver model and shifting strategy of the vehicle simulation tool, Autonomie, were not modified.

*Hybrid powertrains*

The fuel economy advantages of hybrid powertrains mainly stem from the ability to recover mechanical energy. The energy that might otherwise have been dissipated as heat through the wheel brakes, the engine brake, or the retarder is converted to electricity by a generator and subsequently stored in a battery to provide traction power at a later stage. The amount of energy available for regenerative braking is highly dependent on the frequency of deceleration events and the fraction of downhill operation during the duty cycle.

Long-haul heavy-duty hybrid systems are under development by truck manufacturers, an EU-funded consortium, and Tier 1 suppliers. MAN Truck and Bus presented a hybrid tractor concept featuring a 328-kW diesel engine, a 130-kW electric motor and a Li-ion battery with a capacity of 3.8 kWh (MAN Truck & Bus, 2014). Scania (2016a) is investigating the potential of electrified highways with a hybridized tractor-trailer equipping a 268-kW diesel engine, a 130-kW motor, and a Li-ion battery with a capacity of 5 kWh. The research consortium ECOCHAMPS has built a long-haul hybrid truck demonstrator based on a product of the project coordinator DAF; however, no specific details are available regarding the parallel hybrid electric powertrain (Hummel, Häußler, & Eckstein, 2016). Eaton's vision for long-haul application involves the use of electric turbocompounding, a relatively small motor at 90 kW, and a relatively large battery system at 23 kWh that can capture energy during braking and coasting and provides a 13% fuel consumption benefit (Busdiecker, 2013). Bosch (2014a) designed a 120-kW parallel hybrid system for heavy-duty long-haul operations with a 2-kWh battery and fuel consumption reductions of up to 6% with the potential of further efficiency benefits by electrification of accessories and/or downsizing of the diesel engine. The fuel consumption benefit of long-haul combination hybrid vehicles is highly dependent on the grade profile of the cycle. A simulation-based analysis of different hybrid long-haul configurations in a 40-tonne tractor-trailer over different types of operation routes in southern Finland shows a fuel consumption benefit between 2% and 5%, even when the driving speed is almost constant (Lajunen, 2014).

An estimation of the potential benefits of a hybrid powertrain is performed by analyzing the second-by-second braking power dissipation rate. The post-processing approach assumes a parallel hybrid configuration with the electric machine (motor/generator) being located between the clutch and the gearbox. The algorithm calculates the share of the braking losses that can be recovered through regenerative braking based on the motor/generator maximum power, the characteristic motor/generator efficiency curve, the battery capacity, battery round-trip efficiency (charging to discharging), and state of charge boundaries. The hybrid powertrain parameters used are shown in Table 19.

**Table 19.** Tractor-trailer hybrid powertrain characteristics

| Hybrid powertrain parameter | Value | Source |
|---|---|---|
| **Motor/generator power (kW)** | 120 | Bosch, 2014a |
| **Battery capacity (kWh)** | 2 | Bosch, 2014a |
| **Max./min. state of charge** | 90%/30% | Sharer, Rousseau, Nelson, & Pagerit, 2006 |
| **Battery round-trip efficiency** | 95% | Genikomsakis & Mitrentsis, 2017 |
| **Motor/generator efficiency** | Load dependent (max. 95%) | Genikomsakis & Mitrentsis, 2017 |

The regenerative braking potential of the hybrid powertrain is sensitive to the road load characteristics of the base vehicle. Table 20 shows the fuel consumption reduction over the Regional Delivery and Long Haul cycles of the hybrid powertrain in comparison with the baseline tractor-trailer, and the non-hybrid tractor-trailer with the long-term engine and road load technology packages. The vehicle and hybrid powertrain simulations indicate that as the road load losses are reduced in the long-term, the effectiveness of hybrid powertrains (in terms of relative fuel consumption improvement) increase significantly.

**Table 20.** Hybrid powertrain effectiveness in tractor-trailers

| Vehicle and powertrain package | Regional Delivery | Long Haul |
|---|---|---|
| **FC reduction of hybridization applied to <u>baseline</u> technology package** | 14.8% | 3.8% |
| **FC reduction of hybridization applied to <u>long-term</u> technology package** | 20.9% | 6.5% |

## Road Load Technologies

Similar to the treatment of engines, technology packages with increasing levels of road load reduction technology were evaluated. The following sections describe the packages in terms of aerodynamics, tire rolling resistance, and mass reduction.

*Aerodynamics*

As shown in Figure 7, the energy dissipated by aerodynamic drag represents up to 16% of tractor-trailer overall fuel use. Aerodynamic drag energy dissipation is proportional to speed squared and is particularly significant in long-haul operation because it involves higher highway speeds (typical EU tractor-trailers cruise at around 85 km/h).

The design of tractors and trailers, and the interaction between the two, contribute to the combined vehicle aerodynamic drag. There are various technologies available to reduce the aerodynamic resistance; they include streamlining of the tractor cab's nose, top, and sides, as well as adding side panels and rear fairings to the trailer. Complete tractor-trailer redesigns are also possible. As previously discussed, the amendment[12] to the maximum weight and dimensions regulation[13] establishes a dimensional allowance that enables the redesign of the cabin for aerodynamic improvements and the installation of rear fairings.

This study simulates a range of tractor-trailer aerodynamic drag coefficients ($C_D$) from the baseline of 0.6 to the 0.35 targets achieved by the SuperTruck program in the United States (Delgado & Lutsey, 2014). Some concept trucks in the European Union have surpassed such targets and have achieved a $C_D$ value of 0.3 (Kopp, 2012; Kopp, Schönherr, & Koos, 2009), mainly through measures such as cabin elongation and redesign, tapered elongated trailers, boat tails, and side panels. Table 21 summarizes aerodynamic packages, which are mainly based on the work of Dünnebeil et al. (2015). From a reference vehicle, the incremental package consists of the addition of trailer side panels and short (50 cm) rear fairings. The moderate package adds rearview cameras and trailer underbody devices, and the advanced package includes a redesign of the tractor. The long-term package would consist of an integrated tractor-trailer design similar to SuperTruck designs or other advanced concept tractor-trailer combinations.

**Table 21.** Aerodynamic packages

| Aerodynamic package | $C_D$ reduction | $C_D$ | Description |
|---|---|---|---|
| **Baseline** | 0.0% | 0.60 | Reference vehicle |
| **Incremental** | 16% | 0.50 | Reference + trailer side-skirt and rear fairing |
| **Moderate** | 23% | 0.46 | Incremental + active grille shutter, rearview cameras, wheel covers, and trailer underbody device and/or full skirting |
| **Advanced** | 27% | 0.44 | Moderate + advanced tractor and trailer aerodynamic devices and design features |
| **Long-term** | 42% | 0.35 | Advanced + integrated tractor-trailer design including tear drop trailers |

Table 22 shows the technology effectiveness of the aerodynamic technology packages described above. Fuel consumption reductions of up to 13.2% are possible. Trailer aerodynamic technologies are estimated to contribute about two-thirds of the potential savings. Because aerodynamic drag is proportional to vehicle speed squared, aerodynamic devices are more effective in the long-haul cycle with an average return factor (i.e., percent fuel consumption reduction per percent drag coefficient reduction) of 0.32, while the average return factor for the Regional Delivery cycle is 0.16.

12 Directive (EU) 2015/719 (Parliament and Council of the European Union, 2015)

13 Directive 96/53/EC (Council of the European Union, 1996)

**Table 22.** Aerodynamic packages effectiveness

| Aerodynamic package | Regional Delivery | | Long Haul | |
|---|---|---|---|---|
| | FC (L/100km) | FC reduction | FC (L/100km) | FC reduction |
| **Baseline** | 36.37 | – | 33.06 | – |
| **Incremental** | 35.19 | 3.2% | 31.3 | 5.3% |
| **Moderate** | 34.75 | 4.5% | 30.61 | 7.4% |
| **Advanced** | 34.52 | 5.1% | 30.26 | 8.5% |
| **Long-term** | 33.51 | 7.9% | 28.71 | 13.2% |

*Tires*

As shown in Figure 7, the energy dissipated by the tires represents up to 15% of tractor-trailer overall fuel use. The dissipation of energy is proportional to tire rolling resistance coefficient, and tractor-trailer weight and speed. Advancements in low rolling resistance tire designs and materials are applicable to reduce rolling resistance losses. For example, a possible solution is wide-base single tires for the drive axle of tractor trucks. They feature a lower sidewall count (two sidewalls instead of four), which results in reduced energy dissipation in the deformation process and thus in lower rolling resistance.

Starting from the baseline assumption, Table 23 shows four packages with increasingly improved rolling resistance. Incremental technology utilizes best available tires (i.e., Class B) in steer, drive, and trailer axles. The remaining technology steps incrementally adopt Class A tires in the trailer, steer, and drive tires, respectively. Note that Class A tires are already commercially available (e.g., Michelin 315/70R22.5 X Line Energy D2).

Consultants commissioned by the ICCT reported that tire development is ongoing and a rate of rolling resistance reduction of about 2% per year is feasible (Norris & Escher, 2017). This would imply reductions of about 27% by 2030. This annual reduction rate is consistent with the scenario modeling results from Viegand Maagøe A/S, which estimated an annual reduction rate of 2.04% between 2015 and 2030 (Viegand Maagøe A/S, 2016), and is lower than the reduction rates estimated in the impact assessment of the tire labeling regulation in the slow and fast pace market scenarios at 2.8% and 4.1% respectively (European Policy Evaluation Consortium, 2008).

**Table 23.** Tires packages

| Tires packages | Steer | Drive | Trailer | $C_{RR}$ (N/kN) | $C_{RR}$ reduction |
|---|---|---|---|---|---|
| **Baseline*** | C | C | C | 5.5 | – |
| **Incremental** | B | B | B | 5.0 | 9% |
| **Moderate** | B | B | A | 4.5 | 19% |
| **Advanced** | A | B | A | 4.3 | 23% |
| **Long-term** | A | A | A | 4.0 | 27% |

**5.5 N/kN is the midpoint of the tire energy efficiency class C for N3 vehicles*

Table 24 shows technology effectiveness of the tire technology packages described above. Fuel consumption reductions of up to 8.4% are possible. Low rolling resistance trailer tires are estimated to contribute about 54% of the potential savings. The dissipation of energy is proportional to tractor-trailer weight and speed. Consequently, tire rolling resistance reduction is more effective in the Long Haul cycle (which, besides having a higher average speed, is simulated at a higher payload than the Regional Delivery cycle) with an average return factor (i.e., percent fuel consumption reduction per percent rolling resistance reduction) of 0.31, while the average return factor for the Regional Delivery cycle is 0.19.

**Table 24.** Tire packages effectiveness

| Tires package | Regional Delivery | | Long Haul | |
|---|---|---|---|---|
| | FC (L/100km) | FC reduction | FC (L/100km) | FC reduction |
| **Baseline** | 36.37 | – | 33.06 | – |
| **Incremental** | 35.76 | 1.7% | 32.14 | 2.8% |
| **Moderate** | 35.14 | 3.4% | 31.13 | 5.8% |
| **Advanced** | 34.92 | 4.0% | 30.76 | 7.0% |
| **Long-term** | 34.55 | 5.0% | 30.27 | 8.4% |

Proper tire inflation is necessary to achieve the fuel efficiency benefits of low rolling resistance tires. Tires with low inflation pressure exhibit a larger footprint on the road, more sidewall flexing, and tread shearing. Therefore, they have greater rolling resistance than tires operating at their optimal inflation pressure. Tire inflation pressure can be maintained by an automatic tire inflation system (ATIS), which monitors tire pressure and automatically keeps tires inflated to a specific pressure, depending on the payload. A tire pressure monitoring system (TPMS) notifies the operator of tire pressure but requires the operator to manually inflate the tires to the optimum pressure (U.S. EPA & U.S. DOT, 2016a). Van Zyl et al. (2013) estimated fuel savings between 0.2% and 0.4% for European tractor-trailers equipped with TPMS. The U.S. Phase 2 regulatory impact analysis (U.S. EPA & U.S. DOT, 2016b) estimated benefits from TPMS at 1.0% and from ATIS at 1.2% for tractor-trailers. However, we do not consider these technologies in our packages and it is assumed that tires are inflated to appropriate pressure at all times.

*Mass reduction*

The mass of the tractor-trailer is proportional to the energy required to accelerate, overcome rolling resistance, and overcome road grades. Utilizing lightweight materials and design to reduce vehicle curb weight can impact efficiency in different ways. For tractor-trailers that operate at their maximum allowable weight (i.e., generally 40 tonnes) lightweighting allows for an increase in the payload without changing the fuel consumption (units of L/100km) but increasing load-specific fuel consumption (units of L/100tkm). For tractor-trailers that are volume-constrained, weight reduction will not affect the payload but will lead to reduced fuel consumption as well as load-specific fuel consumption. Volume-limited operation is more prominent in the European Union. Hill et al. (2015) quantified the share of the road transport market that is constrained by weight limitations to be between 10% and 19.5% for long-haul operation.

In the United States, the SuperTruck program achieved weight reductions of up to 1.5 tonnes. The teams acknowledged that there are significant synergies between powertrain component sizing and lightweighting. Breemersch and Akkermans (2015) note that the total weight reduction potential is around 2 tonnes; their survey suggests however that a more realistic reduction would be 600 to 700 kg spread evenly between the tractor and the trailer.

Hill et al. (2015) evaluated the potential of lightweighting as a means of improving HDV fuel efficiency. The results show that a 2.5% curb weight reduction (363 kg) is possible by 2020 with available state-of-the-art options, which mainly include small design changes to components, as well as an increased use of higher grade steels on the chassis, body, and suspensions. The study also shows that a 16% curb weight reduction (2,330 kg) is possible by 2030 mainly through material substitution of iron and steel by advanced high-strength steel and aluminum/magnesium for various components, as well as additional use of some composite materials.

Table 25 shows mass reduction levels and their effectiveness. Fuel consumption reductions of up to 5.6% could be realized with long-term lightweighting. Trailer lightweighting is estimated to contribute to about half of the potential savings. In general, mass reduction benefits are greater when the duty cycle is more transient, which is evident from the higher return factor (percent fuel consumption reduction per percent curb mass reduction) for the Regional Delivery cycle at 0.31, compared with 0.23 for the Long Haul cycle. These numbers assume no weight-limited operations (i.e., the benefits come from a lighter vehicle carrying a constant payload of 19.3 tonnes for the Long Haul cycle, or 12.9 tonnes for the Regional Delivery cycle).

**Table 25.** Mass reduction packages and their effectiveness (19.3 t payload constant)

| Lightweight package | Mass reduction | Regional Delivery | | Long Haul | |
|---|---|---|---|---|---|
| | kg | FC (L/100km) | FC reduction | FC (L/100km) | FC reduction |
| **Baseline** | 0 | 36.37 | – | 33.06 | – |
| **Incremental** | 200 | 36.19 | 0.5% | 32.95 | 0.3% |
| **Moderate** | 400 | 35.99 | 1.0% | 32.85 | 0.6% |
| **Advanced** | 1,000 | 35.48 | 2.4% | 32.54 | 1.6% |
| **Long-term** | 2,300 | 34.32 | 5.6% | 31.93 | 3.4% |

## Advanced Driver Assistance Systems

The technologies grouped under advanced driver-assistance systems (ADAS) have been developed to automate and enhance vehicle systems for improved driving. Currently, there are several ADAS commercially available for the improvement of fuel consumption, including adaptive cruise control (ACC), predictive cruise control (PCC), Eco-Roll, and speed limiters.

ACC systems are an extension of traditional cruise control systems, where instead of maintaining a constant vehicle speed, the speed is adjusted to preserve the distance to the vehicle driving ahead. When following a skilled driver, the fuel economy benefits of reducing unnecessary acceleration and deceleration events have been estimated at 1.9% as part of the euroFOT project (Faber et al., 2012).

Intelligent vehicle controls such as PCC and neutral coasting, also known as Eco-Roll, can also reduce the braking losses over a given cycle. Based on GPS elevation information, PCC systems optimize the shifting strategy, the vehicle velocity, and its acceleration to minimize the fuel consumption. By allowing the vehicle speed to vary within a narrow interval, the large mass of the long-haul HDV can be used as an effective kinetic energy storage system. In essence, the PCC reduces the speed during uphill operation and then switches to neutral (Eco-Roll) during downslope driving (Johannesson, Murgovski, Jonasson, Hellgren, & Egardt, 2015). Eco-Roll systems are also available independently from PCC systems (Eaton, 2015). In these transmission-specific solutions, the downhill operation can be detected without the aid of GPS, and the benefits of neutral coasting can be partially exploited. U.S. Phase 2 assessment assumes PCC fuel consumption reduction at 2% and neutral coasting at 1.5% (U.S. EPA & U.S. DOT, 2016b).

Speed-limiters can also result in significant fuel economy benefits due to the aerodynamic drag dependence on vehicle speed. Furthermore, the driveline and transmission frictional losses, as well as the rolling resistance, also have a speed dependent component. The benefits of speed-limiters over the Regional Delivery (Figure 4) and Long Haul (Figure 3) cycles was estimated by reducing the targeted vehicle speed on the duty cycles from 85 km/h to 80 km/h. The simulation results show a fuel consumption benefit of 3.0% over the Long Haul cycle, and of 2.0% over the Regional Delivery cycle.

### Accessories

Proper vehicle operation is dependent on a number of supporting systems, collectively known as vehicle accessories. This collection includes, among others, the power steering system, the cooling fan, the electric generator, the air compressor, and the air conditioning system. The power necessary to drive these vehicle accessories has a direct toll on the fuel consumption performance of the vehicle. Similar to the already described engine accessories, the decoupling of the associated loads can reduce fuel consumption by engaging the loads based on the power demand and on the engine's operating conditions. Table 26 presents a summary of the technologies aimed at reducing the vehicle accessories' power.

The potential for fuel consumption reduction from improvements in the accessories is dependent on the duty cycle. Ricardo AEA's analysis estimates this potential as up to 8% (Hill et al., 2011), IFEU's as 1% (Dünnebeil et al., 2015) and T&M Leuven as 1.5% to 1.7% (Breemersch & Akkermans, 2015). A maximum reduction of accessory energy demand of 50% (van Zyl, 2016) is assumed in this study, resulting in 2.0% reduction over the Regional Delivery cycle and 2.1% reduction over the Long Haul cycle.

**Table 26.** Vehicle accessories fuel efficiency technologies

| Accessory | Fuel saving technology description | Further information |
|---|---|---|
| **Power steering** | Electrically Powered Hydraulic Steering (EPHS) reduces the power steering losses, particularly during idling and highway cycles. On-demand control of the hydraulic power steering system can also be done using on/off electromagnetic clutches. | Gupta, Williams, & Sherwin, 2010; Sonchal, Gajankush, Kulkarni, & Pawar, 2012; Yu et al., 2015 |
| **Cooling fan** | The demand-based control of the cooling fan can be achieved using several technologies such as on/off electromagnetic clutches, passive bimetallic viscous-couplings, electronically controlled viscous-couplings, and hydraulically powered systems. | Phapale, Kommareddy, Sindgikar, & Jadhav, 2015; Wright, 2015; Zhang et al., 2016 |
| **Generator** | Traditional DC current rectifiers of generators are based on a diode bridge. Diodes have an intrinsic voltage drop (~1 volt) that affects the generator efficiency. The use of semiconductor active rectifiers improves the generator efficiency from around 65% up to 80%. | Bosch, 2014b, 2015 |
| **Air compressor** | Clutched air compressors reduce the losses associated with the off-period of the duty cycle (i.e., no pressure generation). | North American Council for Freight Efficiency, 2017 |
| **Air conditioning** | Battery and all-electric air conditioning systems | U.S. EPA & U.S. DOT, 2016b |

## Summary

Figure 11 summarizes the individual technologies' fuel consumption reduction results for EU tractor-trailers. The bars represent the best available data from this study, while the error bars represent the range of values found in the literature. Note that, generally, these technology effectiveness values are not additive, and use of vehicle simulation software allows for appropriate accounting of potential interactions among technologies.

Improvements in the engine peak brake thermal efficiency, going from 45% to 55%, result in an 18.1% reduction in fuel consumption over the Long Haul cycle. A significant share of the efficiency gains is driven by the continuous reduction in the accessory loads through on-demand management, reduction in engine friction, improvements in turbocharger efficiency, and combustion optimization. Furthermore, the use of technologies such as turbocompounding and waste heat recovery systems enable significant efficiency gains in the long term.

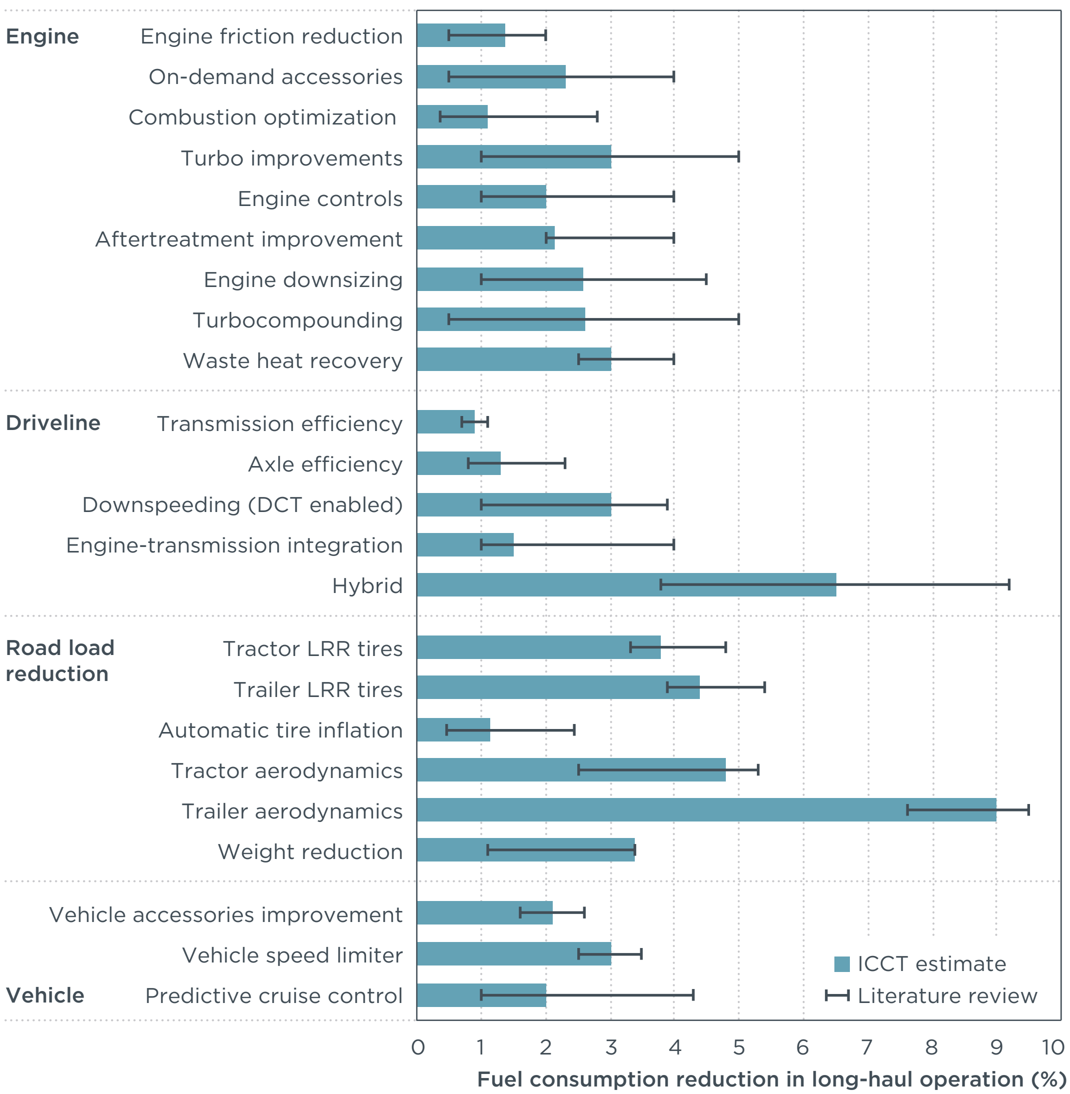



**Figure 11.** Fuel consumption reduction potential of individual technologies for tractor-trailers in long-haul highway operation. Error bars represent the ranges found in the literature.

On the transmission side, the continuous tribological improvements and the use of low viscosity lubricants enable the direct improvement of the mechanical efficiency of the powertrain, directly reducing the fuel consumption. Furthermore, the reduction of the shifting duration enables the use of downsped powertrains, minimizing the frictional losses of the driveline, which are proportional to their turning speed. Lastly, stop-start systems and hybrid powertrains reduce the idling and braking losses respectively.

Reduction on the road loads, that is, aerodynamic drag, rolling resistance and inertial forces, contribute significantly to the overall fuel consumption. Improvements in the aerodynamic drag coefficient, going from 0.6 to 0.35, result in approximately 13% reduction in fuel consumption. Similarly, a reduction in the average rolling resistance coefficient from 5.5 N/kN to 4 N/kN, results in an estimated 8% lower fuel consumption. Lastly, lightweighting the complete vehicle by 2 tonnes reduces the inertial and rolling resistance forces and, consequently, the fuel consumption by approximately 3%.

### Technology Packages for Tractor-Trailers

Figure 12 summarizes the efficiency potential of tractor-trailer technology packages that were developed for our study and could be implemented in the 2020–2030 time frame. The results shown in the figure are for the fuel consumption (in L/100km) for a 40-tonne tractor-trailer with 19.3 tonnes of payload over the Long Haul cycle. As shown, the reference 2015 tractor-trailer with 33.1 L/100km could see substantially reduced fuel consumption over the next 13 years. In descending order in the figure is a progression of efficiency technology packages with increasingly advanced technology and reduced fuel consumption.

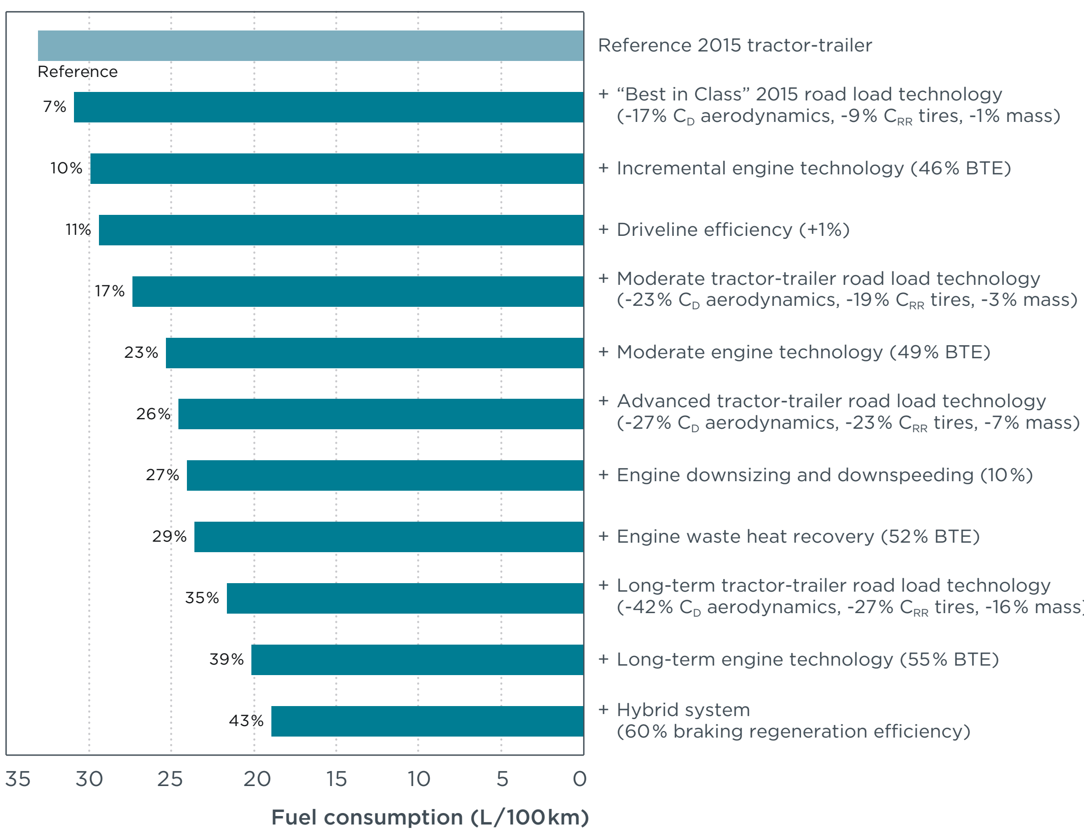



**Figure 12.** Potential fuel consumption reduction from selected tractor-trailer efficiency technologies in the 2020–2030 time frame over the VECTO Long Haul cycle

The sequencing of the technology packages presented in Figure 12 reflects our estimates for the general timing of technology availability, as was elaborated on throughout the preceding sections. Furthermore, the layout of the proposed technological pathway considered the existing synergies between technologies. The **incremental** or "best in class" technologies correspond to those already in use by some best performers in the market. The **moderate** level are those technologies that are commercially available in the marketplace, while the **advanced** level are technologies that are well understood by OEMs and Tier 1 suppliers, and are likely to be further developed and introduced in the near term (around 5 to 8 years). Lastly, the **long-term** package corresponds to technologies that exist at the prototype or concept level and are being studied by the research departments of companies, government agencies, and universities. Such technologies are expected to be introduced in the long term (around 10 to 13 years).

Starting from the baseline tractor-trailer, the **incremental** level of road load technologies makes use of readily available solutions and results in a 7% reduction in fuel consumption. In a second step, the **incremental** engine technology level results in further efficiency improvements totaling a 10% reduction with respect to the baseline (i.e., current best available tractor-trailers are 10% more efficient than the average tractor-trailers). The **moderate** level for road load and engine technologies brings along further reductions totaling a 23% reduction from the baseline. The **advanced** road load technology package, enabled by the implementation of the regulatory amendments to the tractor-trailer dimensions limit, results in a 26% fuel consumption reduction from the baseline. Further technological advancements in high-strength materials allow the engine to withstand higher cylinder peak and mean effective pressures, thus allowing the further downsizing and downspeeding of the powertrain. In combination with the introduction of waste heat recovery systems, the complete **advanced** technology packages result in 29% lower fuel consumption than the reference case. **Long-term** improvements in engine, hybridization, and road load optimization could increase tractor-trailer efficiency to achieve fuel consumption values under 19 L/100km, a 43% reduction from the baseline. It is important to point out that this individual vehicle analysis does not consider technology applicability at a national fleet level. We acknowledge that due to various technological, regulatory, or market barriers, it might not be possible for all technologies to achieve 100% market penetration.

## RIGID TRUCK TECHNOLOGIES

The portfolio of individual technologies available for the improvement of fuel consumption of rigid trucks is similar to that of tractor-trailers and has been discussed extensively in the previous section. The following sections highlight details specific to rigid trucks. Two technological steps are considered in this analysis, a **mid-term** package that includes currently available technologies expected to be deployed in the fleet in the 2020–2025 period and a **long-term** package that includes in-development technologies and available technologies requiring a large capital investment (e.g., hybrid powertrain), which are expected to be deployed in the 2025–2030 period.

### Engine Technologies

Engine efficiency of Euro VI engines is very similar to the engine efficiency of current U.S. EPA 2010 compliant engines. Both engines have similar components and typically use SCR and EGR for $NO_x$ control (Jiao, 2015). The U.S. EPA did an extensive study of engine potential in the development of Phase 2 fuel efficiency standards (U.S. EPA & U.S. DOT, 2016b). In this study, taking in consideration that some engine and vehicle manufacturers sell their products in both Europe and the United States, we assume that, in the mid-term, European rigid truck engines would be able to adopt a similar set of technologies as those required to comply with the Phase 2 engine fuel efficiency standards in the United States. The efficiency improvements estimated for the mid-term engines was 2.3% (43.1% peak BTE), which correspond to 2021 U.S. Phase 2 compliant engines. In the long term, an efficiency improvement of 5.1% (44.4% peak BTE) was estimated based on an analysis performed by Ricardo Energy and Environment (Norris & Escher, 2017). There is potential for even higher fuel consumption reductions. For example, Cummins (Eckerle, 2015) indicates that medium-duty engines can achieve a 5% to 11% fuel use reduction from 2017 within the 2020–2030 time frame. Achates Power plans to achieve 55% BTE engines using opposed piston 2-stroke cycle which relies on better stroke-to-bore ratio that reduces thermal losses to the engine block, better combustion due to port injection rather than overhead valves, and reduction of parasitic losses through removal of the valve-train (Abani et al., 2017). Testing results of a 4.9 L 3-cylinder opposed-piston diesel engine show a peak BTE of 48%, and cycle-average BSFC advantage of 18% during transient cycle compared with a U.S. 2010 EPA compliant engine (Sharma & Redon, 2016).

### Driveline Technologies

As was already presented for tractor-trailers, significant fuel efficiency benefits are possible through improvements in the driveline of rigid trucks. The areas of improvement considered for rigid trucks are engine-transmission integration, mechanical efficiency, start-stop systems, and powertrain hybridization. This section will be limited in scope to highlight the differences between what was already discussed for tractor-trailers, and the specifics of the technology application to rigid trucks.

*Engine-transmission integration*

The integration between the engine and the transmission, referred to as deep powertrain integration or advanced shifting strategy, is an effective way to reduce fuel consumption without sacrificing driving performance. An idealized engine-transmission integration would allow the engine to operate 100% of the time at peak efficiency, resulting in an integration ratio equal to 1. The integration ratio of the rigid truck considered in this study is between 0.91 (for the Urban Delivery cycle) and 0.97 (Long Haul cycle). The corresponding maximum benefit for deep integration in rigid trucks then ranges between 3% and 9%. Because this potential cannot be fully tapped by transmissions with a finite number of gears, this study estimates the potential of engine-transmission integration in one-third of the aforementioned maximum theoretical benefit. DCTs are a natural solution for powertrain deep integration, because the absence of torque interruption during gear shifting eliminates the disadvantages of the higher shifting frequency of deeply integrated powertrains. In comparison to the baseline manual transmission, the gearbox and shifting automation results in a fuel consumption improvement of up to 1.9% (for the Urban Delivery cycle).

For the mid-term driveline package, the combined effectiveness of the deep integration of a DCT is estimated as 5.0% over the Urban Delivery cycle, 2.4% over the Regional Delivery cycle, and 0.8% over the Long Haul cycle. As a reference point, the U.S. Phase 2 assessment found that potential benefits of deep integrated powertrains are between 3% and 6% for vocational[14] rigid trucks (U.S. EPA & U.S. DOT, 2016b).

14 Vocational vehicles are specialized vehicles, consisting of a very wide variety of truck and bus types (e.g., delivery, refuse, utility, dump, cement, transit bus, shuttle bus, school bus, emergency vehicles, and recreational vehicles) (U.S. EPA & U.S. DOT, 2016a)

*Transmission and axle efficiency*

The improvements in mechanical efficiency of the transmission and axle already described for tractor-trailers are directly applicable to rigid trucks as well. A 25% reduction potential in the gear frictional losses of the transmission and the axle are estimated based on the work conducted by IFEU and the Institute for Combustion Engines and Thermodynamics at Graz University of Technology (Dünnebeil et al., 2015). The reduction in frictional losses translates to approximately 1 percentage point higher mechanical efficiencies. The mid-term driveline package assumes an additional 25% improvement in the axle friction, bringing it up to 97% mechanical efficiency.

*Start-stop*

Start-stop systems reduce fuel consumption by reducing the amount of engine idling during short vehicle stops, such as those occurring in urban traffic. The EPA and NHTSA considered start-stop systems within the Phase 2 HDV GHG regulation. The estimated fuel efficiency improvements ranged from 1% to 14%, depending on the vocational vehicle subcategory and the characteristic duty cycle (U.S. EPA & U.S. DOT, 2016b). In this study, the effectiveness of start-stop systems was estimated from the time fraction that the vehicle was at standstill over the cycle and the curb-idle fuel consumption from the engine fuel map. Given that this estimation corresponds to an upper boundary of the fuel consumption reduction, the effectiveness value is adjusted by a correction factor of 90% to account for the real-world behavior of start-stop systems and the additional auxiliary work during the driving phases. This approach mirrors what was implemented in the certification simulation tool (GEM) of the U.S. HDV GHG Phase 2 regulation (U.S. EPA & U.S. DOT, 2016b). Based on the simulation results of the baseline rigid truck selected for this study, start-stop systems result in a fuel consumption reduction of 4% over the Urban Delivery cycle, 0.9% over the Regional Delivery cycle, and 0.1% over the Long Haul cycle.

*Hybrids*

Compared with long-haul trucks, rigid-trucks operating in regional and urban delivery have a greater potential for efficiency improvement through hybridization. The higher share of braking and deceleration events in urban and regional traffic make them more suitable for regenerative braking. In the recent past, truck manufacturers in the European market sporadically launched hybrid powertrains with small batteries (<2 kWh) to exploit this potential (Rodriguez et al., 2017). The chosen hybrid architecture in all cases locates the electric motor between the clutch and the gearbox to be able to decouple the electric powertrain from the combustion engine on demand. A limited amount of experimental fuel consumption values of hybrid vehicles is found in the literature; however, these values are difficult to compare due to their differences in vehicle types, payloads, and duty cycles. Transmission manufacturer Aisin reported results over several city test cycles that quantify the potential of hybridization at approximately 7% (Rahim, 2016). A simulation-based analysis at Oak Ridge National Laboratory in the United States estimates the potential of a 16-tonne hybrid truck in comparison to its conventional counterpart at 36% during an urban driving cycle. In highway operation the fuel consumption benefits of hybridization are reduced to approximately 3.5% (Daw et al., 2013). On-road investigations by FPInnovations on three 12-tonne hybrid vehicles showed a reduction in fuel consumption between 14.7% and 34.4% during specific pickup and delivery cycles (Proust & Surcel, 2012). The EPA and NHTSA considered hybridization within the Phase 2 HDV GHG regulation. A technology effectiveness between 23% and 26% was estimated with a technology penetration rate of 12% in vocational trucks by 2027 (U.S. EPA & U.S. DOT, 2016b).

Given the wide ranges of fuel consumption reduction found in the literature, and the strong dependence of these on the duty cycle, this study uses energy auditing to determine the regenerative braking potential. The estimation of the effectiveness of hybrid powertrains on rigid trucks follows the same approach already described for tractor-trailers. Using the braking power dissipation as an input, the post-processing algorithm calculates the energy recuperation through regenerative braking based on the hybrid powertrain specification. The parameters used for the hybrid rigid truck are shown in Table 27.

**Table 27.** Rigid truck hybrid powertrain characteristics

| Hybrid powertrain parameter | Value | Source |
|---|---|---|
| **Motor/Generator power (kW)** | 44 | Treusch, 2013 |
| **Battery capacity (kWh)** | 1.9 | Treusch, 2013 |
| **Max./min. state of charge** | 90%/30% | Sharer et al., 2006 |
| **Battery round-trip efficiency** | 95% | Genikomsakis & Mitrentsis, 2017 |
| **Motor/generator efficiency** | Load dependent (max. 95%) | Genikomsakis & Mitrentsis, 2017 |

Table 28 shows the fuel consumption reduction over the Urban Delivery, Regional Delivery, and Long Haul cycles of the hybrid powertrain (with start-stop) in comparison with the baseline rigid truck, and the non-hybrid rigid truck with the long-term vehicle, engine, and road-load technology packages.

**Table 28.** Hybrid powertrain fuel consumption reduction in rigid trucks

| Vehicle and powertrain package | Urban Delivery | Regional Delivery | Long Haul |
|---|---|---|---|
| **FC reduction of hybridization applied to baseline technology package** | 17.3% | 6.1% | 2.3% |
| **FC reduction of hybridization applied to long-term technology package** | 23.2% | 9.4% | 4.0% |

## Road Load Technologies

*Aerodynamics*

A drag coefficient reduction of 10% from a baseline $C_D$ value of 0.55 is possible in the mid-term when using lateral panels on the cabin structure, rounded leading edge structure, side panels, and a 50-cm rear device (Dünnebeil et al., 2015). Based on that, a $C_D$ value of 0.5 was assumed in our mid-term package. Landman et al. evaluated performance of drag reduction configurations on a cab-over-engine rigid truck in a full-scale wind tunnel. The best configuration includes a valence, cargo box front treatment, boat tail, and side panels to achieve 23% aerodynamic drag reduction from a baseline of 0.58 (Landman, Cragun, McCormick, & Wood, 2011). Based on that, a $C_D$ value of 0.45 was assumed in our long-term package. The fuel consumption reductions of such individual measures are listed at the end of this section.

*Tires*

Current best available tires are Class B steer tires and Class C drive tires (Dünnebeil et al., 2015). Based on that, a $C_{RR}$ value of 5.6 was assumed for our mid-term package. Class A tires are expected to be available for both steer and drive tires by 2030. Based on this, a $C_{RR}$ value of 4.0 was assumed for our long-term package. The fuel consumption reductions of such individual measures are listed at the end of this section.

*Mass reduction*

Hill et al. (2015) evaluated the potential of lightweighting as a means of improving heavy-duty vehicles' fuel efficiency. The results show that a 5% curb weight reduction is possible by 2020 and a 17% curb weight reduction is possible by 2030. The fuel consumption reductions of such individual measures are listed at the end of this section.

## Summary

Table 29 presents the summary of the individual technological improvements presented in the paragraphs above and their respective impact on fuel consumption over the Urban Delivery, Regional Delivery, and Long Haul cycles. As expected, the effectiveness of the individual technologies for reducing fuel consumption is highly dependent on the duty cycle. For the highly transient Urban Delivery cycle, a reduction of the vehicle mass, the addition of start-stop, and, most notably, the integration with a hybrid powertrain result in the highest benefits. For the Long Haul and Regional Delivery cycles, improvement in the road load losses, that is rolling resistance and aerodynamic drag, bring the largest reductions.

**Table 29.** Fuel consumption reduction potential of individual technologies for rigid trucks over the Urban Delivery, Regional Delivery, and Long Haul cycles

| Technology | Urban Delivery | Regional Delivery | Long Haul |
|---|---|---|---|
| **Baseline fuel consumption** | **21.40 L/100km** | **20.02 L/100km** | **24.90 L/100km** |
| **Mid-term engine (BTE = 43.1%)** | 2.3% | 2.3% | 2.3% |
| **Long-term engine (BTE = 44.4%)** | 5.1% | 5.1% | 5.1% |
| **Mid-term aerodynamics ($C_D$ = 0.494)** | 3.0% | 6.5% | 6.4% |
| **Long-term aerodynamics ($C_D$ = 0.45)** | 4.5% | 9.6% | 9.8% |
| **Mid-term tires ($C_{RR}$ = 5.6 N/kN; classes B-C)** | 2.6% | 2.9% | 5.2% |
| **Long-term tires ($C_{RR}$ = 4.0 N/kN; classes A-A)** | 6.2% | 7.0% | 12.5% |
| **Mid- and long-term transmission efficiency** | 0.8% | 0.8% | 0.8% |
| **Mid- and long-term axle efficiency** | 0.8% | 0.8% | 0.8% |
| **Mid-term lightweighting (–325 kg)** | 2.1% | 1.4% | 0.7% |
| **Long-term lightweighting (–1,105 kg)** | 6.8% | 4.9% | 2.4% |
| **Mid- and long-term accessory power consumption (reduction of 50%)** | 4.6% | 2.8% | 1.9% |
| **Start-stop (applied to baseline)** | 4.0% | 0.9% | 0.1% |
| **Hybrid powertrain (applied to baseline)** | 13.8% | 5.3% | 2.2% |

### Technology Packages for Rigid Trucks

The main characteristics of the mid-term and long-term technology packages are shown in Table 30. The mid-term package includes technologies that are readily available and currently being sold by certain manufacturers. The package includes an engine with 43.1% peak brake thermal efficiency and deep integration between engine and transmission with a DCT transmission. The transmission and axle frictional losses are cut by one-quarter, resulting in an approximate increase in mechanical efficiency of 1 percentage point. Regarding road load technologies, the aerodynamic package features cabin side panels and rounded leading edges on the cab. The rolling resistance coefficient corresponds to class C tires on the steering axle and class B tires in the drive axle. The curb vehicle mass is reduced by 325 kg, corresponding to approximately 5% of the curb weight. The use of on-demand accessories results in an estimated 50% reduction of the parasitic loads. Lastly, the package features start-stop technology. The resulting fuel consumption reductions from baseline for the mid-term package are 23%, 20%, and 18% for the Urban Delivery, Regional Delivery, and Long Haul cycles, respectively.

**Table 30.** Technology packages (Rigid Truck)

| Technology | Mid-Term Package | Long-Term Package |
|---|---|---|
| **Engine** | Equivalent to EPA 2021 | Equivalent to EPA 2027 |
| **Transmission** | DCT with deep integration | Hybrid |
| **Transmission** | 1% more efficient | Same as mid-term |
| **Axle** | 1% more efficient | Same as mid-term |
| **$C_{RR}$** | 5.6 (BC) | 4.0 (AA) |
| **$C_D$** | 0.5 | 0.45 |
| **Mass** | (–325 kg) | (–1,105 kg) |
| **Accessories** | 50% power demand | 50% power demand |
| **Others** | Start-stop | Included in hybrid system |
| **Package fuel consumption reduction Urban Delivery cycle** | 23% | 43% |
| **Package fuel consumption reduction Regional Delivery cycle** | 20% | 36% |
| **Package fuel consumption reduction Long Haul cycle** | 18% | 34% |

The long-term package corresponds to an additional effort in the R&D activities of the truck and component manufacturers as some of these technologies are only available in the demonstration stage, but are likely to be further developed and introduced to the market between 2025 and 2030. The long-term vehicle equips an engine with 43.9% peak brake thermal efficiency, mainly due to improvements in friction reduction, advanced turbocharging, and combustion control. The aerodynamic package includes, in addition to the technologies in the mid-term package, cargo box front treatment, boat tail, and side panels to achieve a drag coefficient of 0.45. The rolling resistance coefficient corresponds to class A tires in both the steering and drive axles. The curb vehicle mass is reduced by 1.1 tonnes, corresponding to approximately 17% of the curb weight. Lastly, the long-term package features a parallel hybrid powertrain with the motor/generator placed between the clutch and the engine, with a 44-kW electric power and a 1.9-kWh battery. The resulting fuel consumption reduction from the long-term package is higher for the Urban Delivery cycle than the Regional Delivery cycle due to the higher effectiveness of the hybrid powertrain in urban conditions. The long-term package reduces fuel consumption by 43%, 36%, and 34% for the Urban Delivery, Regional Delivery, and Long Haul cycles respectively.

Figure 13 shows the fuel consumption reduction potential, and the individual contributions of the different technologies, for the technology packages presented in Table 30. The improvements attributed to different technology areas have been estimated. Because the technologies interact with one another, it is not possible to give a precise breakdown of the fuel consumption reduction caused by any one technology in a given technology package.

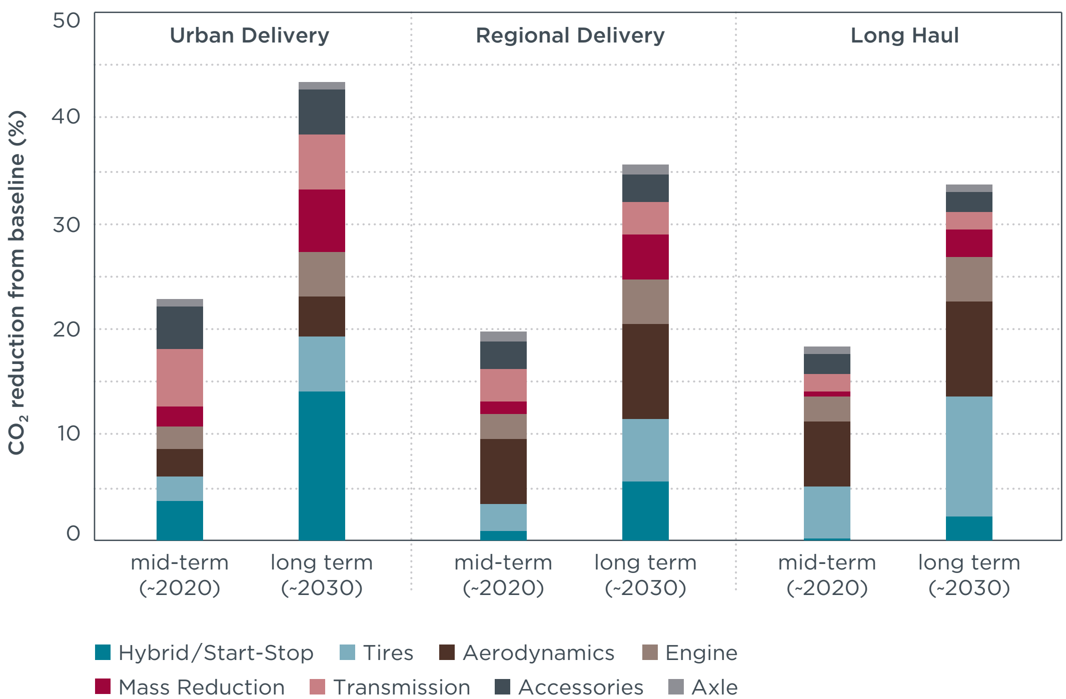



**Figure 13.** Potential fuel consumption reduction from selected rigid truck efficiency technologies in the 2020–2030 time frame over the VECTO Urban Delivery, Regional Delivery, and Long Haul cycles. Per VECTO's defined protocols, the payload modeled for the Urban and Regional Delivery cycles was 3 tonnes, while the payload modeled for the Long Haul cycle was 9.8 tonnes.

# 5. CONCLUSIONS

## TECHNOLOGY AND OPERATIONAL PROFILE

This study establishes a baseline and evaluates technology packages for trucks optimized to operate on either end of the freight hauling spectrum. On one end of the spectrum is a 40-tonne tractor-trailer designed for long-haul operation and on the other end is a 12-tonne delivery truck optimized for urban operation. Long-haul (motorway) operation is characterized by driving at high and relatively constant speeds whereas urban operation is characterized by lower speed transient driving. Regional operation, which sits between these two extremes, contains a combination of highway and urban driving. Figure 14 shows the technology potential for the mid- and long-term urban delivery truck and long-haul tractor-trailer driven over multiple cycles. The improvements attributed to different technology areas have been estimated. Because the technologies interact with one another, it is not possible to give a precise breakdown of the fuel consumption reduction caused by any one technology in a given technology package. It is important that the technology packages are strategically selected. If, for example, we were to consider a rigid truck that is more likely to be driven on a long-haul cycle, the optimal technology package would be more similar to the tractor-trailer technology package, rather than that of the rigid truck presented in this study. Because regional driving contains a combination of highway and urban driving, a truck driven over this cycle would see benefits from both long-haul and urban truck technology packages.

The best technology packages that we analyzed for both the long-haul tractor-trailer and urban delivery truck contain a hybrid system. It is important to note that these hybrid systems are different and have been selected based on the duty cycles over which the vehicles are being driven. The urban delivery truck 2030 technology package contains a hybrid system that is capable of recovering significant amounts of braking energy during stop-and-go driving. The system is a parallel hybrid powertrain with the motor/generator placed between the clutch and the engine, with a 44-kW electric motor and a 1.9-kWh battery. The long-haul tractor-trailer 2030 technology package contains a hybrid system that is designed for recovering braking energy used during downhill driving. The system is a parallel hybrid powertrain with a 120-kW motor/generator placed between the clutch and the engine, and a 2-kWh battery. The hybrid system that was chosen for the urban delivery vehicle will still produce some benefit over the long-haul driving cycle, but not as much benefit as the system that has been integrated with the advanced long-haul tractor-trailer package. One reason for this is that the long-haul tractor-trailer package has advanced aerodynamic improvements that would significantly reduce the vehicle's drag and create the need for larger amounts of recoupable braking when traveling downhill at high speeds. Conversely, the hybrid system that was selected for the Long Haul cycle will produce some benefit over the Urban Delivery cycle, but not to the same level as the system that was selected for the urban delivery truck due to the relatively smaller energy storage capacity.

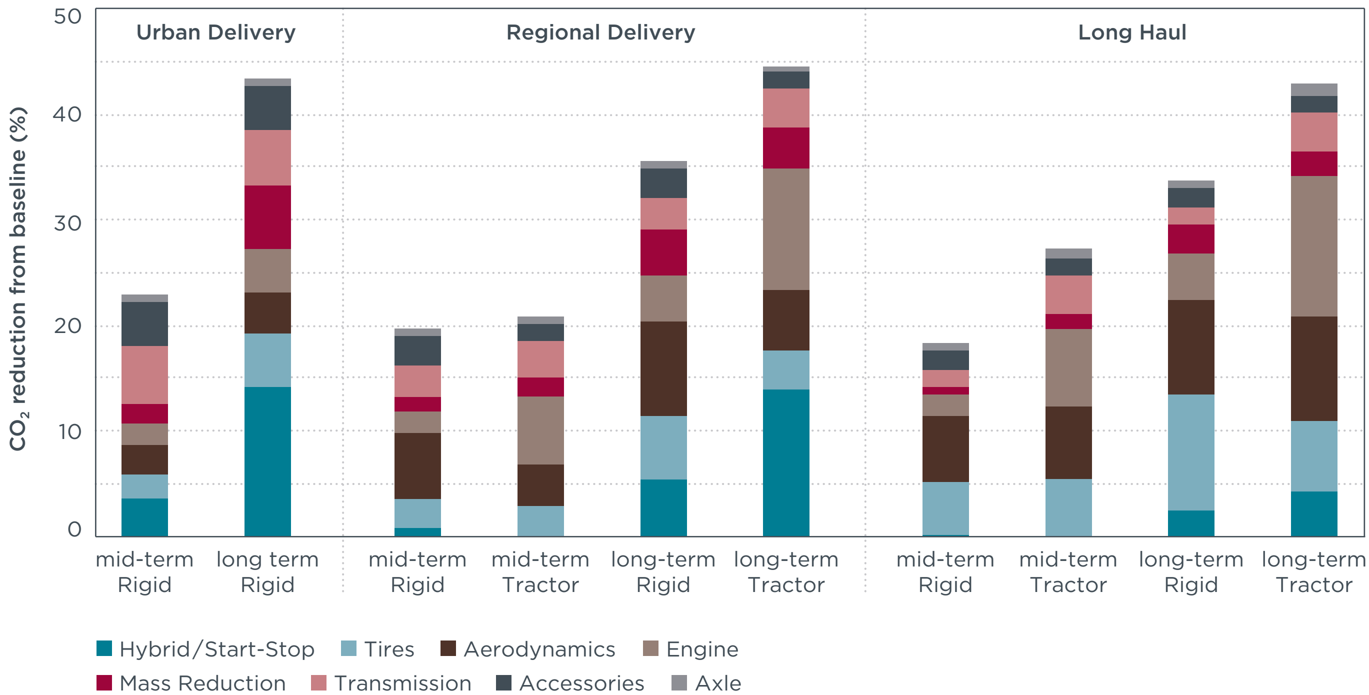



**Figure 14.** Potential fuel consumption reduction from selected rigid truck and tractor-trailer efficiency technologies in the 2020–2030 time frame over the VECTO Urban Delivery, Regional Delivery, and Long Haul cycles. Per VECTO's defined protocols, the payload modeled for both the Urban Delivery and Regional Delivery cycles was 3.0 tonnes for the rigid truck and 12.9 tonnes for the tractor-trailer, while the payload modeled for the Long Haul cycle was 9.8 tonnes for the rigid truck and 19.3 tonnes for the tractor-trailer.

## EU-U.S. TRACTOR-TRAILER COMPARISON

Historically, tractor-trailers sold in the European Union have had better efficiency than those sold in the United States. This is due in large part to the higher cost of fuel in the European Union that has helped accelerate the adoption of some efficiency technologies and measures. For example, for the past 4 years, the majority of EU trucks have been sold with AMTs that give, on average, 1% fuel consumption reduction compared with manual transmissions. In addition, the most common tractor-trailer engine sold in the United States has a displacement of approximately 15 L and a rated power of 350 kW, while the most common tractor-trailer engine sold in the European Union has a displacement of approximately 13 L and a rated power of around 340 kW. The EU engines are smaller than the U.S. engines, which could give a fuel consumption reduction of around 2% to 3% (Delgado & Lutsey, 2015). As shown in Figure 15, our modeling predicts that the average U.S. tractor-trailer in 2015 had 7% higher fuel consumption than the average EU tractor-trailer when simulated using the same payload and duty cycle. However, as has been presented in this study, there exist a number of technologies that could improve the efficiency of the average EU tractor-trailer. HDV efficiency standards in the United States have already begun driving the adoption of more technologies on U.S. tractor-trailers, effectively closing the efficiency gap between EU and U.S. tractor-trailers.

The best available data shows that the average fuel consumption of EU tractor-trailers has not changed significantly in over a decade. The same trend appeared to be true in the United States prior to the introduction of HDV fuel efficiency standards there. The United States finalized the Phase 1 HDV standard in 2011 and it was phased in between 2014 and 2017; the Phase 2 standard was finalized in 2016 and will be phased in between 2021 and 2027. The standards will ensure that the average new U.S. tractor-trailer will improve its fuel efficiency at a rate of around 3% per year over the next decade. Our modeling indicates that in the absence of an efficiency standard to compel similar fleet-averaged improvement in the European Union, U.S. tractor-trailers will be approximately 17% more efficient than EU tractor-trailers in 2027. In order for EU tractor-trailers to maintain equivalent efficiency to U.S. tractor-trailers by 2027, they would need to improve at an average rate of 2.3% per year starting in 2019, or 4.5% per year starting in 2023.

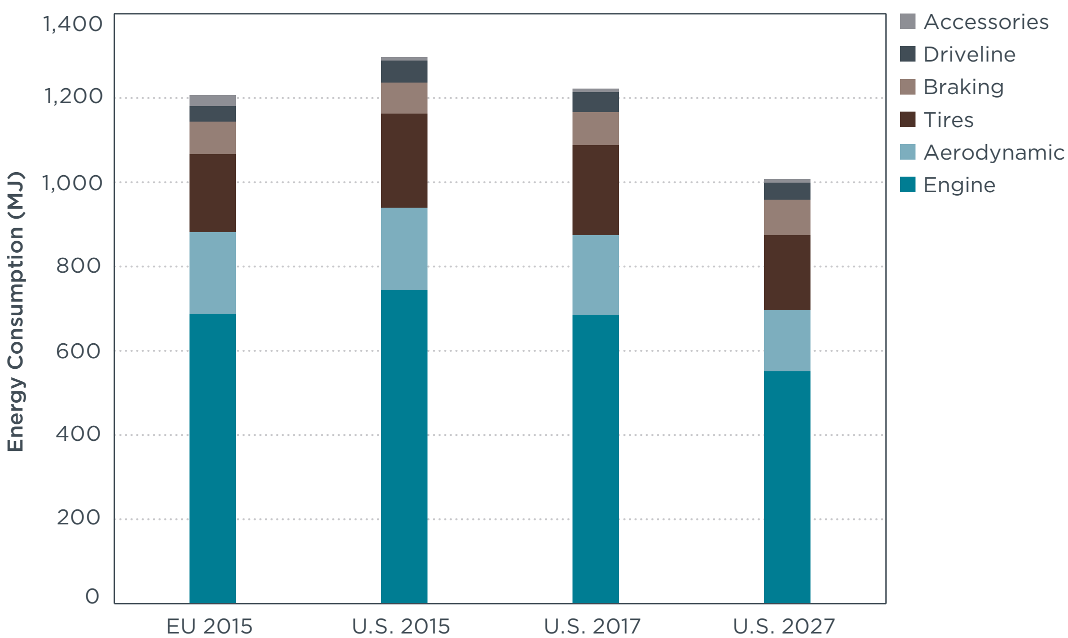



**Figure 15.** Energy consumption of EU baseline tractor-trailer compared against current and future U.S. tractor-trailers. (19.3 tonnes payload, Long Haul cycle)

## POLICY DISCUSSION

The findings from this analysis point to several policy implications for the development of EU heavy-duty vehicle greenhouse gas emissions and efficiency standards for 2020 and beyond.

### Setting a regulatory baseline

Determining a fuel consumption baseline is an important step for the development of a $CO_2$ emissions standard. The EU has recently finalized a $CO_2$ and fuel consumption certification procedure based on a vehicle simulation tool (VECTO) that determines an official $CO_2$ value for new HDVs. The tool classifies HDVs according to their body type, GVW, and axle configuration. Each vehicle is simulated in the tool according to the payload, duty cycle, and other requirements of the given vehicle group. Vehicle specific information, including mass, engine fueling map, tire rolling resistance, and aerodynamic drag area are all required inputs to the tool. The EC has indicated its intention to utilize VECTO as the main compliance tool for any HDV $CO_2$ standard. Therefore, it would make sense to establish the regulatory baseline using the same tool. In the ideal scenario, the EC would have a database of the official VECTO $CO_2$ values for all new HDVs on the market in order to determine the sales-weighted average baseline for each vehicle group. However, this data will not likely be available until 2020 at the earliest, through the EC regulatory proposal for the monitoring and reporting of $CO_2$ emissions for HDVs, which is likely to be adopted in 2018. Waiting for fleetwide official $CO_2$ values to establish a baseline on which to impose a $CO_2$ regulation is unnecessary and would not be in line with the EC's stated desire to propose standards in 2018. Therefore, a second strategy for regulatory baseline determination would be to estimate, using the best available data, the most representative VECTO inputs for each vehicle group and use the data to determine a representative VECTO baseline. This is similar to the strategy that U.S. policymakers used to determine their regulatory baseline based on the U.S. Greenhouse Gas Emissions Model (GEM).

The findings of this study could be used to inform the regulatory baseline. Section 2 of this report details the analysis that was conducted to determine the baseline vehicle fuel consumption values of the 40-tonne tractor-trailer and 12-tonne rigid truck that were selected for this study. The methodology used is very similar to the proposed strategy for determining a regulatory baseline discussed above. Vehicle simulation modeling using fixed payloads and duty cycles was used to determine the $CO_2$ baseline values. The aim was to create a baseline tractor-trailer and rigid truck that would represent the sales-weighted average of that entire vehicle segment. The legitimacy of this methodology relies completely on the accuracy of the simulation model's inputs. To ensure accurate fuel consumption information, we focused on acquiring representative values for the aerodynamic drag, rolling resistance, and engine fuel consumption maps to determine which tractor-trailer and rigid truck specifications would best represent fleetwide average composites for their respective segment. The aerodynamic drag baseline numbers are based on 14 sources, covering 21 different vehicles. The baseline rolling resistance value is the result of analyzing 13 sources, covering 16 different vehicles and more than 2,500 tire models. Lastly, the engine fuel maps used for our baseline analysis were provided by a recognized engineering service provider (AVL List GmbH), and are the result of their expertise in engine benchmarking. The baseline tractor-trailer used in our study gave a fuel consumption value of 33.1 L/100km when tested over the VECTO Long Haul cycle. The baseline urban delivery truck used in our study gave a fuel consumption value of 21.4 L/100km when tested over the VECTO Urban Delivery cycle.

### Technology potential

Setting a stringency for a regulation involves determining the amount of improvement from the regulatory baseline that the standard will compel. Key information that policymakers typically require to set a well-informed stringency include potential for improvement using known technology, timing of the commercial availability of a given technology, technology applicability across a given vehicle group, and technology cost and payback. The analysis performed in this report covers the first two topics: potential for improvement using known technology and timing of the commercial availability of a given technology. For this study, we analyzed technologies that were based on conventional diesel powertrains and therefore did not include an analysis of all-electric or alternatively fueled vehicles.

The technologies we considered were generally grouped into two main categories: (1) technologies that are already commercially available, but have low market penetration and are not considered as part of our baseline vehicle; and (2) technologies that are not yet commercialized but are either near commercialization, have been demonstrated as a prototype, or have a proven pathway to development. In general terms, we have considered that the first category of technologies could be phased in in the 2020–2025 time frame (referred to as mid-term technologies) and the second category of technologies could be phased in in the 2025–2030 time frame (referred to as long-term technologies). An efficiency standard that sets stringency so as to incentivize only the first category of technologies could be referred to as "technology tracking" as it mainly works to increase the fleetwide adoption of "off the shelf" or existing technologies. An efficiency standard that sets stringency so as to incentivize the second category of technologies could be referred to as "technology forcing" as it would work to force technologies to the market, in many cases faster than would occur with market forces on their own. It is even possible that in some cases a "technology forcing" standard could bring technologies to the market that may never have come in the absence of standards. In the United States, the Phase 1 regulation for HDV efficiency was a technology tracking standard as it only considered commercialized technologies. However, the Phase 2 standard is technology forcing and will help bring to market technologies that are not currently available.

The technology potential analysis for our mid-term tractor-trailer focused on technologies such as engine turbocompounding, low friction accessories, downsped drivelines, low rolling resistance tires, and trailer aerodynamic devices. Applying these technologies to our baseline vehicle, which represents the fleet average vehicle in 2015, would achieve 27% fuel consumption and $CO_2$ reduction over the VECTO Long Haul cycle. This represents an average reduction of 3.1% per year from 2015 to 2025. Considering long-term tractor-trailer technologies that are not yet commercially available but have been demonstrated and are predicted to be available on the market before 2030 could achieve a 43% reduction from the 2015 baseline by 2030. This would require an average annual reduction from 2015 to 2030 of 3.6%. For comparison, under the U.S. HDV standards, the average tractor-trailer fuel consumption reduction was 3.1% per year for Phase 1 (2010–2017) and 2.8% per year for Phase 2 (2017–2027).

The technologies incorporated in the analysis of the urban rigid delivery truck include some overlap with the long-haul tractor-trailer technologies as well as some technologies not considered for the tractor-trailer. In general, the technologies that are the most relevant for both vehicle segments are the low rolling resistance tires, mass reduction, and engine efficiency technologies. For tractor-trailers, the aerodynamic and waste heat recovery technologies are significant, but they are less so for trucks that follow an urban driving cycle. For urban delivery trucks, improved accessories, improved transmissions, and hybrid technologies are very pertinent. Applying commercially available technologies to our baseline 12-tonne delivery truck results in a 20% reduction in fuel consumption over the VECTO Urban Delivery cycle. An analysis of technologies that are not yet commercialized but are predicted to be available in the 2025–2030 time frame gives a reduction of 43%, representing an average reduction of 3.6% per year from 2015 to 2030. Note that although full hybrid delivery trucks are currently available on the market today, we opted to analyze this technology as part of our longer-term package. This is because as more advanced road load reduction technologies (i.e., low rolling resistance tires, aerodynamics, mass reduction) are applied, the braking losses increase, providing higher fuel consumption reduction potential for hybrid systems.

### Technology accounting

As previously mentioned, the main tool that the EC plans to use to determine official $CO_2$ values for HDVs is a vehicle simulation model called VECTO. This model is currently not configured to account for all technologies that were considered in this study. For example, this study found that the long-term technology package for tractor-trailers could result in a total of 43% fuel consumption reduction from the baseline. Approximately 15% of the fuel consumption reduction is due to improvements predicted to be made to the trailer. These improvements include aerodynamic improvements, lower rolling resistance trailer tires, and mass reduction technologies. The current version of VECTO does not include a defined methodology for accounting for improvements made to the trailer as the trailer defined by the EC in the proposed $CO_2$ certification methodology is a "standard" default trailer only. Another example is the fuel consumption reduction that comes from deep integration of the engine and transmission that was considered in our study. The current VECTO tool is not designed to account for this category of technological improvement.

Ultimately, the technology accounting methodology will need to align with the technology packages that are selected to inform any regulatory stringency. For comparison, in the U.S. Phase 1 regulation, the $CO_2$ certification protocol did not include a methodology to account for trailers or deeply integrated engines and transmissions. It did, however, include what was called an optional "innovative technology crediting" system that could be utilized for manufacturers wishing to get credits for technologies not directly covered in the main certification protocol. In the U.S. Phase 2 regulation, the certification methodology was expanded to account for improvements to the trailer technology as well as integrated engines and transmissions.

### Timing and benefits

The phase-in timing for any efficiency regulation will play a large part in determining the benefits in a given year. The European Union has set binding $CO_2$ reduction targets for 2030, so ideally any standard would start impacting new vehicles prior to this date in order to achieve measurable benefits by 2030. For example, Figure 16 shows the results of an analysis that looks at the benefits in 2030 compared with a business-as-usual case of an HDV standard started in either 2020 or 2025 with either 1%, 2%, 3%, or 4% annual improvement. If an HDV standard was put in place that started mandating annual sales-weighted average reductions of 2% per year from the new vehicle fleet starting in 2020, the overall fleetwide benefits in the year 2030 would be close to 10% below the business as usual case. However, if the same standard was put in place but did not begin until 2025, the overall benefits in 2030 would be 3% below the business-as-usual case. Therefore, timing as well as stringency would ideally be considered to maximize the benefits by 2030.

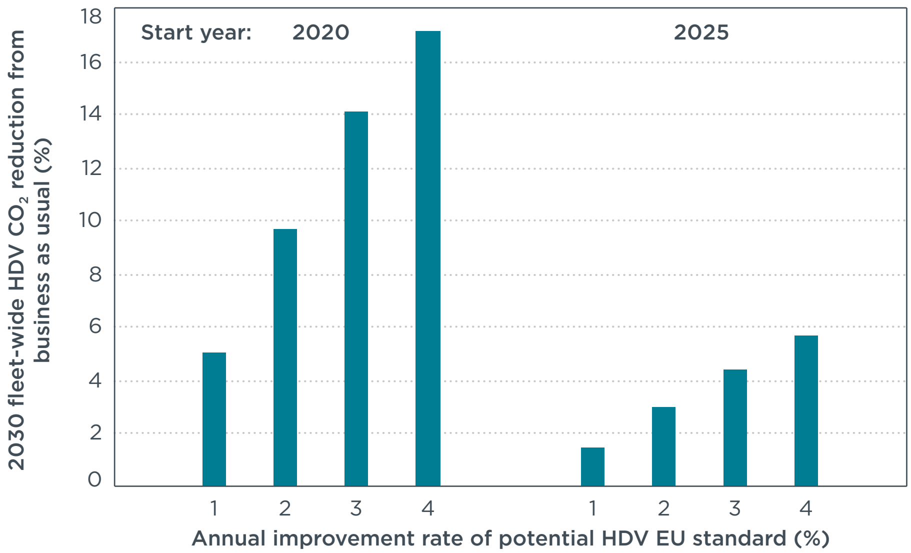



**Figure 16.** $CO_2$ reduction benefits to the EU HDV fleet compared with the business-as-usual case for different start dates and annual improvement rates of a potential new vehicle efficiency standard

There are additional research questions that were not covered within the scope of the research conducted for this report. Firstly, the research focused on technologies that would be applied to freight hauling HDVs in the European Union by specifically looking at a tractor-trailer and urban delivery truck. Therefore, other types of HDVs, such as construction equipment, service vehicles, and buses were not covered in this research. However, we note that the remaining types represent less than 10% of HDV $CO_2$ emissions. Secondly, this report did not assess the cost, payback, and cost-effectiveness of the individual technologies and technology packages that were analyzed for this project. Such topics will be assessed in a follow-up ICCT study.

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