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EUROPEAN HEAVY-DUTY VEHICLES: COST-EFFECTIVENESS OF FUEL-EFFICIENCY TECHNOLOGIES FOR LONG-HAUL TRACTOR-TRAILERS IN THE 2025–2030 TIMEFRAME

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EXECUTIVE SUMMARY

The European Union (EU), a global leader in environmental policy, is considering options for increasing fuel efficiency in freight transportation. Technology and policy developments point to the potential for more efficient new freight trucks. Other major markets such as the United States, Canada, China, Japan, and most recently India have adopted heavy-duty vehicle CO_2 standards, a substantial step to improving efficiency. There is potential for accelerated deployment into the freight market of existing and emerging efficiency technologies, which should enable similar technology deployment in the EU. This study assesses the future costs of advanced long-haul tractor-trailer technologies as an input into the EU policy dialogue on heavy-duty vehicle efficiency standards. Specifically, the study investigates the costs associated with the technologies evaluated in a companion study, *Fuel Efficiency Technology in European Heavy-Duty Vehicles: Baseline and Potential for the 2020-2030 Time Frame* by the International Council on Clean Transportation (ICCT). The companion study relies on simulation modeling to investigate the technology potential for reducing tractor-trailer fuel consumption.

The fundamental approach in this assessment involves deriving technology costs from the best available data on heavy-duty vehicle and engine technologies to assess the cost-effectiveness of increasingly efficient tractor-trailer technology packages. Economic impact metrics are investigated, including investment payback period, lifetime fuel savings, and the marginal cost associated with various technology packages under a range of economic assumptions. Such assumptions include three discount rates—4%, 7%, and 10%—and three diesel fuel prices per liter—€0.70, €1.10, and €1.40—reflecting 2016 euros and excluding value-added tax (VAT). The evaluated efficiency technology packages include per-kilometer fuel consumption reductions of as much as 43% relative to a 2015-era baseline tractor-trailer. The packages include individual technology options that address engine and powertrain efficiency, vehicle road load, waste energy recovery, and hybridization. All economic calculations include a ratio of 1.4 trailers for each tractor to account for the fact that the population of trailers that will need to be equipped with fuel consumption reduction technology exceeds the number of tractors. VAT is not included in this assessment. Freight transport is exempt from fuel VAT, and although the purchase of tractor-trailers and maintenance items is subject to VAT, that portion of such costs is treated as a pass-through cost. An alternative analysis including VAT would find longer payback periods and reduced lifetime savings than those reported in this study because technology and maintenance costs would increase while fuel savings, which carry an explicit VAT exemption, would not change.

The primary finding of this study is that substantial improvements are available to cost-effectively increase long-haul tractor-trailer efficiency. This reflects wide-ranging technology availability and extensive lifetime mileage. While upfront technology and net present value maintenance costs can be significant, the economic return more than justifies an investment in efficiency for the entire range of cases investigated. A representative baseline long-haul tractor with 1.4 trailers costs approximately €139,500 in 2016 euros, excluding VAT.[1] Available efficiency technology packages offering moderate fuel consumption reductions of as much as 27% are projected to cost €7,000-€7,750 in 2025-2030 based on best available cost data and conventional technology learning assumptions. The potential discounted[2] lifetime fuel savings for

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[1] All cost calculations in this report reflect 2016 euros and exclude VAT.

[2] Discounted fuel savings correct for the time value of money. For example, €1,000 saved 10 years from now is worth less than €1,000 today because a lesser amount could be invested today to return €1,000 in 10 years. This lesser value is referred to as the net present value of that future savings. In this study, all future cash flow, be it incremental maintenance costs or fuel savings, is discounted to equivalent net present value so that the time value of money is properly considered.

these moderate efficiency packages range from €41,900-€106,450 per tractor-trailer, depending on discount rate and fuel price assumptions. The most advanced technology package offers a 43% distance-specific fuel consumption reduction and is estimated to cost €30,550-€35,150 in 2025-2030. But this package would generate lifetime fuel savings of €65,850-€167,550 per tractor-trailer. For the most advanced technology package, the efficiency component costs are roughly equally distributed among the powertrain, the hybrid system, the tractor, and the trailer.

Figure ES-1 depicts the estimated fuel-consumption reductions and associated payback periods for evaluated technology packages in 2030. Moving down the figure, the data represent the sequential addition of more advanced efficiency technologies. The average payback periods estimated in this study generally increase with more advanced technology packages. The "whiskers" of each payback band reflect the range of payback periods across high and low technology cost estimates, and varying economic assumptions for diesel fuel prices ranging from €0.70-€1.40 per liter and discount rates ranging from 4-10%. Payback periods for the moderate technology packages, offering reductions of as much as 27% in fuel consumption, are generally one year or less. The most advanced technology packages, with 35% or greater reductions in fuel consumption, result in payback periods of 1.4-1.9 years under average economic assumptions.

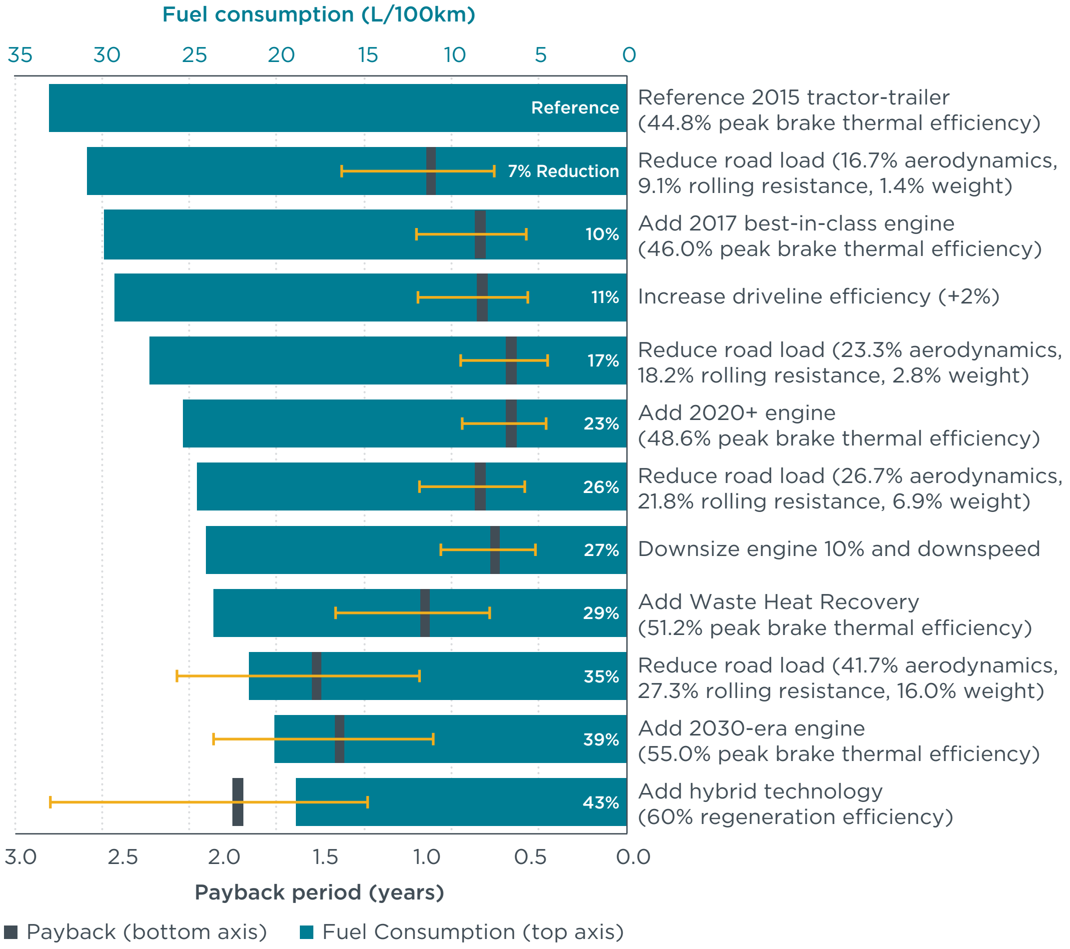

Figure ES-1. Cumulative fuel consumption impacts and associated 2030 payback periods for tractor-trailer efficiency technologies

The findings from this study point to several policy implications related to heavy-duty vehicle fuel-efficiency standards in Europe for 2020 and beyond.

1. ***Available efficiency technologies for long-haul tractor-trailers have fuel savings that greatly exceed the up-front costs of technology and maintenance.*** Findings indicate that available tractor-trailer efficiency technology can reduce distance-based fuel consumption by 27% from baseline 2015 technology and deliver payback periods to tractor-trailer owners that are generally less than one year. Fuel savings from these packages exceed increased technology costs by a factor of 4-17, depending on evaluated economic conditions. Based on technology availability, this level of efficiency technology can be widely deployed in the 2020-2025 timeframe.

2. ***Emerging advanced efficiency technologies offer more substantial fuel savings and attractive payback periods over the long term.*** Study findings indicate that technology packages with long-term road load and engine technologies in the post-2025 timeframe can achieve a 43% reduction in fuel consumption from baseline 2015 technology. For these advanced technology pathways, the payback periods from fuel savings are less than 1.9 years for average economic assumptions. Technology-forcing standards that cannot be met using currently marketed technology and sufficient lead time would be needed to promote the development and deployment of these advanced technologies post 2025.

3. ***Tractor-trailer efficiency technologies' attractive payback periods persist even in the event of higher technology costs and low fuel prices.*** Based on this study's investigation of varying technology costs and economic assumptions, including an average fuel price as low as €0.70 per liter through 2030, the attractive payback findings in this study are robust. The more advanced technology packages, delivering a 35-43% reduction in fuel consumption, have payback periods of 1.0-3.3 years, even assuming high technology costs, high discount rates, and low fuel prices. When adjusting vehicle kilometers of travel per year (VKT) specifically for long-haul tractor-trailers, payback periods drop to 0.7-2.2 years. The attractive and robust payback-period findings indicate that there are prevailing market barriers to technology introduction, warranting the introduction of stringent tractor-trailer efficiency standards.

4. ***Tractor-trailer efficiency technologies offer first-owner fuel savings that greatly exceed the increased upfront capital and maintenance impact costs.*** For typical first owners of a tractor, available efficiency technologies that reduce fuel consumption by 27% offer €28,400-€62,150 in discounted fuel savings over the first five years of ownership and result in benefits that are four to nine times greater than the upfront technology and maintenance impact costs, depending on economic assumptions. The most advanced emerging technology package, offering a 43% reduction in fuel consumption for new 2030 tractor-trailers, would result in €44,650-€97,750 in fuel savings, exceeding costs by 1.5-3.3 times. When taking into account the savings over a tractor's entire lifetime, beyond the typical five years of first-owner operation, the benefit-to-cost ratio is even greater. This points to a clear opportunity for efficiency standards to simultaneously mitigate climate-related emissions, provide overall economic benefits, and offer an attractive return on investment for fleets. Benefits increase further when long-haul tractor-trailer VKT is adjusted to equal 140 percent of average tractor-trailer VKT.

While this study focuses on the cost-effectiveness of tractor-trailer technology in the EU, the implications are not limited by geography. The manufacturers and suppliers that are developing efficiency technologies could leverage their investments by deploying the same technologies at greater volume globally. Establishing stringent heavy-duty vehicle standards in a market the size of the EU can play a key role in advancing market opportunities globally, especially given the primacy of EU regulations as benchmarks for vehicle regulation in many non-EU countries.

I. INTRODUCTION

The EU, a global leader in environmental policy, is considering options for increasing fuel efficiency in the freight transportation sector. This industry represents an increasingly important source of carbon dioxide (CO_2) emissions in the EU. In the 24 years from 1990 to 2014, road transportation was the only sector to record an increase in CO_2 emissions, which climbed 17% over that period (European Environment Agency [EEA], 2016a; EEA, 2016b). The sector accounted for 24% of CO_2 emissions in the EU in 2014, with commercial vehicle CO_2 growing 25%, more than double the 12% for passenger cars (EEA, 2016b; EEA, 2016c). Diesel-powered heavy-duty vehicles (HDVs) account for about one quarter of total on-road CO_2 emissions (EEA, 2016c), and this share is expected to increase to around 45% under a business-as-usual scenario (Façanha, Miller, & Shao, 2014). Such a trend is incompatible with an EU goal of achieving a 60% reduction from 1990 in greenhouse gas (GHG) emissions by 2050 (European Commission [EC], 2016), and more specifically with the transport-specific goal for 2030 of reducing emissions by 30% from a 2005 baseline (EC, 2014a). Fuel-efficiency standards for HDVs, setting mandated fuel consumption targets for new vehicles, are critical to counteract the negative impacts on climate change and energy security from continuing increases in freight demand.

HDV manufacturers in the EU are major players in the global market, accounting for 40% of the global production of HDVs above 3.5 tonnes (Hill et al., 2011). The United States, Canada, China, Japan, and India, markets in which EU manufacturers sell their products, have already introduced GHG standards for HDVs, mandating fuel-consumption reductions from a 2010 baseline of as much as 44% in the 2020-2030 timeframe (Sharpe, Lutsey, Delgado, & Muncrief, 2016). As a result, the lack of EU action to address the fuel consumption and CO_2 emissions of HDVs can negatively affect the competitiveness of European manufacturers in the global marketplace. Well-designed and implemented standards incentivize research and development of new fuel-efficiency technologies and increase the market penetration of commercially available technologies at a faster rate than would occur through market forces alone. EU policy makers have a demonstrated influence in the international arena, as exemplified by the adoption of EU-legislated pollutant emission standards throughout key global markets, including China, Brazil, India, Russia, and Indonesia. The development and implementation of CO_2 standards for HDVs is critical to maintaining the EU's global leadership.

In recognition of these issues, the EU has taken important preliminary steps. The development of the Vehicle Energy Consumption Calculation Tool (VECTO) model provides for the estimation of complete vehicle fuel consumption and CO_2 emissions (Zacharof & Fontaras, 2016). This is not a trivial matter for vehicles such as road tractors that can consist of an engine and chassis developed by different manufacturers, which can be mated to a wide variety of semi-trailers. The EU has also developed a proposed strategy for addressing the regulatory aspects of an HDV CO_2 control program (EC, 2014b). Following the adoption of the Paris Agreement by the 21st session of the Conference of the Parties, in which the EU committed to cutting emissions to at least 40% below 1990 levels by 2030, the EC provided a clear signal in July 2016 that it will start developing mandatory efficiency standards for HDVs (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 communicated that it envisages a proposal for HDV CO_2 standards in the EU for the first half of 2018 (EC, 2017a).

Evaluation of the fuel-saving potential of different HDV technologies is a fundamental step in the development of HDV CO_2 standards. The ICCT recently published a white paper titled *Fuel Efficiency Technology in European Heavy-Duty Vehicles: Baseline* *and Potential for the 2020-2030 Time Frame.* The paper reports on a detailed, state-of-the-science vehicle simulation modeling analysis undertaken to evaluate the level of fuel-consumption reduction that can be achieved in the freight transportation sector in the 2020-2030 timeframe (Delgado, Rodríguez, & Muncrief, 2017). The study documented in this report serves as a companion to that simulation modeling, adding an assessment of the cost-effectiveness of long-haul tractor-trailer technology. Specifically, this study takes the fuel-consumption results of the companion tractor-trailer simulation work (Delgado et al., 2017) as a given, develops estimates of future costs for the evaluated technologies, and derives associated economic estimates for consumer payback and lifetime fuel savings. Corresponding assessments for other HDV sectors may be developed in the future.

BACKGROUND

The potential of technology options for reducing CO_2 emissions by HDVs has been investigated in several studies over the past several years in the U.S. and EU markets. Of particular relevance for the European market are the companion ICCT simulation modeling report (Delgado et al., 2017) and reports by Ricardo-AEA (Norris & Escher, 2017; Hill et al., 2011), IFEU (Dünnebeil et al., 2015), Transport & Mobility Leuven (Breemersch & Akkermans, 2015), and TIAX (Law, Jackson, & Chan, 2011). Similar relevant studies for the U.S. market include those documented in HDV CO_2 rulemaking materials prepared by the U.S. Environmental Protection Agency (EPA, 2016a; EPA, 2011;) and those of the Southwest Research Institute (Reinhart, 2016; Reinhart, 2015), the ICCT (Delgado & Lutsey, 2015), the National Research Council (NRC, 2010), NESCCAF (Cooper, Kamakaté, Reinhart, Kromer, & Wilson, 2009), and TIAX (Kromer, Bockholt, & Jackson, 2009). These studies generally agree that long-haul tractor-trailers have the greatest potential for substantial and cost-effective efficiency improvement, reflecting their extensive mileage accumulation. Moreover, long-haul tractor-trailers are responsible for the majority of fuel use and GHG emissions in the on-road freight sector in the EU, as well as in most other markets (Sharpe & Muncrief, 2015). In the EU, tractor-trailers account for 57% of new HDV registrations and 75% of the HDV CO_2 emissions. Tractor-trailers with a 4×2 axle configuration are the single highest contributor (Delgado et al., 2017).

The underlying technology assessment that serves as the foundation for this study (Delgado et al., 2017) evaluates the fuel-efficiency potential of available and emerging technologies expected to be available in the long-haul tractor-trailer market in the 2020-2030 timeframe. Particular emphasis is placed on technologies that can potentially be promoted by EU regulatory standards. This includes engine and vehicle technology but generally excludes behavioral strategies that target drivers, operations, and logistics. All technology is evaluated via a physics-based full vehicle simulation model, using recent engine dynamometer test data, engine energy audit information, and tractor-trailer technology inputs. Given an inherent ability to evaluate complex interactions between technologies, physics-based simulation modeling is widely recognized as a robust means of assessing the impacts of future technologies (see, for example, NRC, 2010).

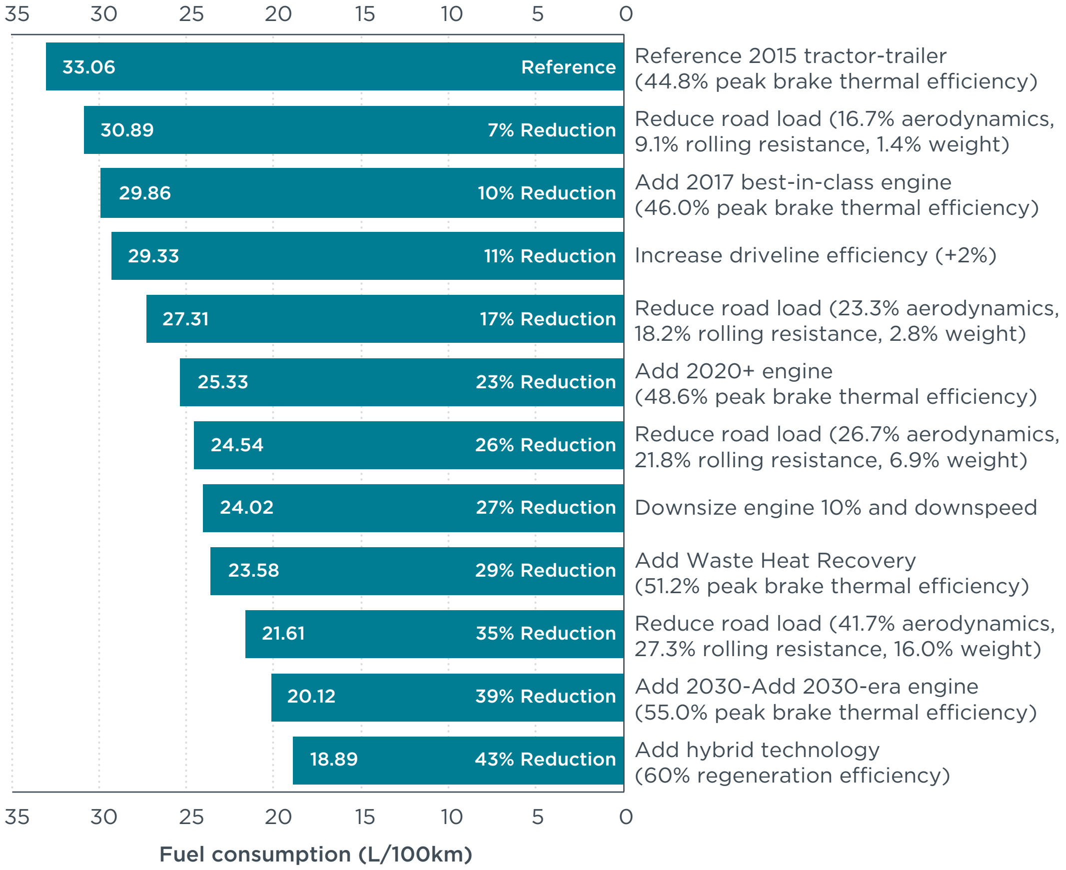

Figure 1. Potential cumulative fuel-consumption reduction from selected tractor-trailer efficiency technologies in the EU in the 2020-2030 timeframe (Delgado et al., 2017)

The tractor-trailer simulation modeling that underlies this study is documented in detail in the ICCT companion report (Delgado et al., 2017). Readers are referred to that report for detailed information, but Figure 1 below presents a summary of the modeling results that serve as the basis for this study. As depicted, evaluated technology packages provide for fuel-consumption reductions ranging from zero to 43% relative to a 2015 baseline tractor-trailer, as estimated for the EU long-haul driving cycle (Luz et al., 2014). Baseline tractor-trailer characteristics are as follows:

Tractor Curb Weight	7,400 kg
Trailer Curb Weight	7,000 kg
Tractor-Trailer Gross Combined Weight	40 tonnes
Maximum Payload	25.6 tonnes
Modeled Payload	19.3 tonnes
Axle Configuration	4×2
Engine Displacement	12.8 liters
Fueling System	2000-2500 bar common rail
Turbocharger	Single Stage VGT
Peak Cylinder Pressure	~205 bar
Maximum BMEP	23.6 bar @ 1000-1400 rpm
Maximum Torque	2400 Nm @ 1000-1400 rpm
Engine Output	350 kW (Rated)
Engine Brake Thermal Efficiency	44.8% (Peak)
Engine Brake Thermal Efficiency	41.9% (Average over the VECTO Long Haul Cycle)
Emissions Certification	Euro VI

EGR	Cooled High Pressure
Aftertreatment System	SCR+DPF
Transmission	12 Speed AMT
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 Tractor (×6) 385/65R22.5 Trailer (×6)
Aerodynamic Drag Coefficient	0.6
Tractor-Trailer Drag Area	10 m^2
Aerodynamic Drag Area	6 m^2
Tire Rolling Resistance	5.5 kg/tonne
Accessory Demand	5.6 kW

OVERVIEW

The primary objective of this follow-on study is to evaluate the cost and cost-effectiveness of the available and emerging long-haul tractor-trailer efficiency technologies evaluated in the underlying ICCT simulation modeling study (Delgado et al., 2017) for application in the EU in the 2020-2030 timeframe. The fundamental approach for the cost assessment is to derive best-estimate costs from existing research on heavy-duty vehicle and engine technologies, and use these derived cost estimates to calculate economic impact metrics that offer the opportunity to assess the viability of the fuel-efficiency technologies. Vehicle and engine technologies and their associated fuel-efficiency impacts are taken as given in the underlying simulation modeling study. This follow-on study relies on previous government, industry, academic, and independent consulting research to quantify costs in the tractor-trailer market, as well as a range of conventional economic assumptions to evaluate impacts on tractor-trailer operators.

This report is organized as follows. Following this introductory section, Section II provides foundational discussion related to the various HDV efficiency technologies evaluated in the underlying simulation modeling study. Section III presents the methodologies and data sources used to develop technology cost estimates, the derived cost estimates, and the assumptions employed in conducting economic analysis for the modeled technology packages. Section IV presents various economic analysis metrics, including calculated payback periods for technology investment, discounted lifetime fuel savings estimates net of technology cost, and the marginal cost of technology investment. Section V concludes with a summary of findings, potential associated implications, and policy recommendations.

II. VEHICLE EFFICIENCY TECHNOLOGY BACKGROUND

While the focus of this follow-on study is on the cost of technologies evaluated in the companion simulation modeling study (Delgado et al., 2017), a basic review of evaluated fuel-efficiency technology is important for a robust understanding of the associated cost estimates. There are three fundamental means of improving the fuel efficiency of a vehicle. Fuel demand can be reduced by: (1) reducing the amount of energy required to move a vehicle, (2) reducing the energy losses associated with the conversion and transmission of the chemical energy stored in fossil fuels to the tractive energy delivered to a vehicle's drive wheels, and (3) by capturing and reusing energy that is lost during non-tractive events such as braking.

The first of these general efficiency approaches focuses on reducing the road load of the vehicle, which is generally related to the vehicle's mass or weight and aerodynamic and rolling resistance profiles. This means producing lighter and more aerodynamic tractors and trailers and improving tire design and performance. Reducing energy losses associated with the conversion and transmission of energy generally entails developing more efficient powertrains, including engine, transmission and final drive components, and more efficient accessories to reduce non-tractive engine loads. Capturing and reusing otherwise lost energy generally involves the introduction of secondary energy capture, storage, and distribution systems such as electrical or hydraulic machines, and associated integration componentry. This study analyzes technologies in each of these three fuel-efficiency categories, as defined in the companion tractor-trailer simulation modeling study. A brief description of each of the evaluated technologies follows.

VEHICLE ROAD LOAD TECHNOLOGY

Vehicle design aspects independent of the powertrain play a significant role in determining the net load a vehicle must overcome to induce a given tractive motion. This load, generally referred to as road load, has a direct impact on fuel efficiency, as energy and thus fuel input requirements for a given powertrain will vary directly with road load. For a given acceleration and grade profile, the major determinants of road load are aerodynamic drag, tire rolling resistance, and vehicle weight. Technologies associated with reducing one or more of these determinants can significantly reduce overall energy consumption.

Aerodynamic improvements. Aerodynamic drag is particularly significant for long-haul HDV operation because of the large amount of time spent at sustained highway speeds. Under continuous high-speed operation, aerodynamic drag power dissipation, which is proportional to the cube of speed, greatly exceeds that of other road load determinants. The design of tractors and trailers and the interaction between the two contribute to the aggregate system aerodynamics of tractor-trailers. There are a number of technologies available to reduce aerodynamic drag, including improved tractor design, integrated tractor and trailer design, gap reduction at the tractor/trailer interface, tractor and trailer side skirts, trailer rear-end aerodynamic devices such as boat-tails, and trailer underbody devices.

Low rolling resistance tires. The rolling resistance of tires represents a significant contributor to overall road load power requirements and fuel use. The dissipation of energy from the flexing of tire sidewalls and heat generation during tire revolution varies with tire design and is proportional to tractor-trailer weight and speed. There are many heavy-duty vehicle tire suppliers and developers offering products with increasingly lower rolling resistance, and there is potential to achieve overall reductions of approximately 25-45% from 2015 baseline tires (Viegand Maagøe, 2016; European Policy Evaluation Consortium [EPEC], 2008).

Weight reduction. The energy required to induce a given motion, overcoming rolling resistance and road grade, is directly related to tractor-trailer weight. Using lightweight materials and improved design to reduce weight can affect efficiency either directly in terms of reduced fuel consumption for a given load or by increasing payload capacity, which increases load-specific fuel efficiency. The net effect of either is increased energy efficiency. The potential for lightweighting in tractor-trailers is significant. In the United States, an advanced-design tractor-trailer developed by Walmart has a demonstrated weight reduction for the trailer alone of 1,800 kg (Walmart, 2014). Estimates of potential combined tractor-trailer weight reduction for the EU have been consistent around 2,275 kg by 2030, with potential reductions by 2050 almost doubling to 4,350 kg (Hill et al., 2015). Optimized computer-aided engineering approaches can maximize reductions by evaluating tractor, trailer, and powertrain design as an integrated system. Such an approach will enable the optimized design not only of individual parts, but also of associated systems and subsystems to capture the synergies of component weight reductions as well as the compounding effect of secondary weight reductions. The concept of weight-reduction compounding is discussed in more detail in Section III, and additional background information can be found in many reports associated with vehicle weight reduction, including a recent Ricardo-AEA report prepared for the European Commission (Kollamthodi, Kay, Skinner, Dun, & Hausberger, 2015).

Road load technology packages. As with engine technology, the variety of approaches available for improving road load characteristics makes it difficult to set defined technology pathways. Instead, a series of increasingly efficient technology packages are evaluated in the technology simulation modeling undertaken to estimate fuel-consumption rates. The specific levels of road load technology evaluated are summarized in Table 1.

Table 1. Road load definition

Vehicle configuration	Curb weight change	Drag coefficient change	Rolling resistance change
Baseline	0%	0%	0%
Incremental	-1.4%	-16.7%	-9.1%
Moderate	-2.8%	-23.3%	-18.2%
Advanced	-6.9%	-26.7%	-21.8%
Long Term	-16.0%	-41.7%	-27.3%
Vehicle configuration	**Curb weight (kg)**	**Drag area (C_dA) (m^2)**	**Rolling resistance (kg/tonne)**
Baseline	14,400	6.0	5.5
Incremental	14,200	5.0	5.0
Moderate	14,000	4.6	4.5
Advanced	13,400	4.4	4.3
Long Term	12,100	3.5	4.0

ENGINE TECHNOLOGY

Five distinct levels of diesel heavy-duty engine improvement, generally classified in terms of peak brake thermal efficiency (BTE), are evaluated as shown in Table 2. The first two classifications reflect the study baseline 2015 average and 2017-era best-in-class engine technology. The remaining three classifications reflect increasingly more efficient engines. The underlying efficiency technologies that enable the evaluated level of performance are described below.

Table 2. Engine efficiency definitions

Engine configuration	Peak brake thermal efficiency[a] (BTE)	Waste heat recovery system
2015 Baseline	44.8%	None
2017 Best-In-Class	46.0%	None
2020	48.6%	Turbo compounding
2020+WHR	51.2%	Organic Rankine Cycle
Long Term	55.0%	Organic Rankine Cycle

[a] For configurations that include waste heat recovery (WHR) technology, peak brake thermal efficiency is the effective efficiency of an engine that produces equivalent output.

Engine friction reduction. Engine efficiency is affected by frictional losses and the churning of lubricating oil in bearings, valve trains, and piston-cylinder interfaces. Friction reduction provides direct brake work efficiency gains.[3] Available and emerging efficiency technologies to reduce losses include improved piston ring designs, better low-viscosity lubricants, and low-friction coatings and surface finishes.

Combustion system optimization. Optimization of diesel fuel combustion, with improved high-pressure injection systems, is in active and continuing development. Combustion optimization improves energy conversion, or work extraction, and reduces exhaust and heat-transfer losses. Optimization strategies include increased injection pressure, injection rate shaping, improved atomization and in-cylinder fuel distribution, increased compression ratio, optimized combustion chamber design, insulation of ports and manifolds, increased coolant operational temperature, and improved thermal management.

Advanced engine control. Improved engine controls are linked to various efficiency-related systems, including fuel injection, air intake, exhaust gas recirculation (EGR), auxiliaries, thermal management, and aftertreatment. The transition to model-based engine calibration continues to produce efficiency gains while reducing development times. While not analyzed in the simulation modeling underlying this study, future closed-loop engine calibration and control would allow further advances through real-time optimization of engine operating parameters and potentially those of transmission and vehicle auxiliaries.

On-demand engine accessories. Engine and vehicle accessories including the water pump, oil pump, fuel injection pump, air compressor, power steering pump, cooling fan, alternator, and air conditioning compressor are traditionally gear or belt driven. These auxiliary loads, or parasitic losses, tend to increase with engine speed. Decoupling accessories from the engine when their operation is not needed, operating them at optimal speeds, or utilizing vehicle inertia as a supplementary auxiliary energy source when excess inertial energy is available can reduce loads and increase brake efficiency. Potential technologies include clutches to engage/disengage the accessories, variable speed electric motors, and variable flow pumps.

Aftertreatment improvements. Several aftertreatment-related systems directly affect engine energy loss characteristics. A typical engine with a variable geometry turbocharger (VGT) will experience increased pumping losses when higher EGR rates are used for NO_x control, due to the higher backpressure required to force exhaust gases back through the intake system. Diesel particulate filtration also creates additional

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[3] Brake work is a measure of the amount of energy that an engine makes available at the crankshaft and which can subsequently be used to perform required functions such as moving a vehicle. For a given fuel input, engine efficiency increases as brake work increases.

backpressure that increases with particulate loading. Improvements in aftertreatment technology can act synergistically with advanced engine controls and combustion optimization technology to reduce pumping, exhaust, and coolant losses. For example, enhanced NO_x aftertreatment systems allow for higher engine-out NO_x levels, thus enabling efficiency-biased calibration of fuel injection timing and combustion parameters as well as reduced EGR.

Turbocharger system improvement. Turbocharging technology uses exhaust energy to increase intake pressure, thereby improving volumetric efficiency. Efficient turbocharging increases engine power density and facilitates efficient EGR. Advanced turbocharger design, based on technologies such as an asymmetric turbocharger system consisting of a twin-scroll turbine with one scroll designed for efficient EGR and the second designed for efficient intake boosting, have the potential to reduce pumping, exhaust, and coolant losses.

Turbo compounding. Turbo compounding technology taps exhaust energy captured via an exhaust stream turbine to boost engine output, reclaiming a fraction of waste heat as useful energy. Mechanical turbo compounding systems route energy reclaimed through the turbine to a mechanical transmission connected directly to the engine crankshaft, increasing torque and brake output and reducing exhaust losses. Electrical systems route turbine output to an electrical generator, allowing reclaimed energy to be stored and used to power electric accessories, or provide torque assist through an electric motor in appropriately equipped hybrid powertrains. Turbo compounding increases backpressure and lowers exhaust temperature, so effects on the thermal management of aftertreatment systems and on the engine's pumping losses are an important consideration.

Waste heat recovery (WHR). In the Organic Rankine Cycle (ORC), waste heat recovery systems convert heat that is typically wasted through the exhaust and engine cooling systems into useable mechanical energy. "Organic" signifies a low-temperature working fluid. ORC is a more efficient waste heat recovery system than turbo compounding. In an ORC system, waste heat is passed through a heat exchanger to evaporate a working fluid in a closed secondary power circuit. The extra mechanical power output of this circuit can be fed to the crankshaft through a gearbox, or can be used to generate electric power. As with turbo compounding, the reclaimed energy reduces primary engine energy demand for a given system work output. Potential considerations include addressing heat rejection requirements for the ORC condenser, safety issues related to the selected working fluid, and additional weight and packaging issues.

Although both turbo compounding and ORC systems—as well as conventional turbochargers for that matter—are designed to capture otherwise wasted heat energy, these technologies are treated separately in this analysis to distinguish associated cost and efficiency impacts. Unless otherwise specified, WHR is intended to signify an ORC system, and turbo compounding is referred to explicitly. It is noted that there are many WHR systems in development that are configured in different ways, as seen for example in U.S. Department of Energy (DOE) SuperTruck demonstration projects (Delgado & Lutsey, 2014). In this analysis, a WHR system without turbo compounding is assumed. Conventional and emerging intake pressurization turbochargers are treated as an integral component of all diesel engine packages.

Additionally, it is noted that neither turbo compounding nor WHR increases engine efficiency directly but rather augments available output by reclaiming a portion of energy otherwise lost as heat as well as inducing system-level improvements that allow engine operation to fall more frequently within optimal efficiency speed/load regions. While it is, therefore, not precisely correct to treat such technologies in terms of enhancing engine efficiency, such treatment does nonetheless accurately define the net brake efficiency of the combined system and facilitate both fuel efficiency and cost analysis. Thus, this analysis addresses WHR technology in terms of improved engine efficiency, but the reader should recognize that it is the net brake efficiency of the combined engine plus heat-recovery system for a given fuel energy input that is actually increasing. The specific control volume defined as “engine” in this study includes the engine per se, the WHR system if any, and the emissions aftertreatment system.

Engine downsizing. Vehicle improvements that reduce road load power requirements may shift the operational speed/load characteristics of an engine to lower efficiency regions. Downsizing, or reducing the displacement of an engine, can force operation at higher load, which generally corresponds with higher efficiency. Vehicle performance can be maintained at pre-downsizing levels through a combination of road load power requirement reductions in conjunction with various other engine and transmission efficiency technologies, as described separately. Downsized engines are also expected to increase exhaust temperatures faster, assisting in the improvement of aftertreatment and WHR performance. Potential considerations include lower peak efficiency due to less-favorable surface-to-volume ratios, which increase heat losses, and drivability issues if torque capabilities are not adequate for applications that include driving steep grades.

Engine technology packages. It is difficult to treat engine technologies individually without assuming explicit and inflexible technology pathways. That is because of the variety of approaches available for improving engine efficiency as well as associated interrelationships among not only the technologies but also their associated loss mechanisms. The efficiency technology pathways for this analysis are based on the five levels of net engine efficiency as described earlier in this section (see Table 2). The “2015 baseline” engine technology package in Table 2 is a representative, average-technology EU engine, with specific design parameters as delineated in Section I. The table’s “2017” engine represents a best-in-class, currently available engine that includes higher compression ratio and injection pressure technology, a reduction in EGR rates, and improved accessory management.

The projected “2020” engine incorporates more advanced technologies that are expected to be commercially available by 2020. Reductions in friction and pumping losses are projected to result from improved technology and optimized system integration enabled by the use of advanced model-based controls. These same controls are expected to enable the application of turbo compounding technology. The net effect is a projected increase in power density, which should provide an opportunity for engine downsizing. Incremental advances in aftertreatment systems with reduced thermal inertia and backpressure are also expected. The “2020+WHR” engine is a “2020” engine that incorporates the effects of a WHR system in place of turbo compounding technology.

The “Long Term” engine in Table 2 represents the DOE’s long-term engine objective of 55% peak BTE and is consistent with parallel development work in the EU (NRC, 2015; Lam et al., 2015; DOE, 2016). Potential strategies for achieving the target BTE include dual-fuel and low-temperature combustion as well as more conventional incremental improvements in reducing parasitic losses, optimizing combustion, improving injection characteristics, reducing heat transfer, and optimizing the WHR system (Wall, 2014; Ashley, 2015). Such improvements are expected to be achievable by 2025 and commercially available by 2030.

TRANSMISSION AND DRIVELINE TECHNOLOGY

Transmission and driveline technology have the potential to reduce tractor-trailer energy use in several ways. Increased internal efficiency of transmission and driveline componentry reduces frictional losses incurred during the transmission of energy from the engine to the wheels, resulting in direct increases in net tractive efficiency. Advanced technologies involving improved controls and integrated transmission-engine strategies can result in powertrain optimization, increasing the time that the engine is able to operate at high-efficiency speed/load conditions. Unlike the United States, where dual drive-axle and conventional manual transmission tractors are common, a single drive-axle tractor with an automated manual transmission (AMT) represents the baseline driveline technology in the EU. Thus, single drive-axle and AMT technologies do not represent available CO_2 reduction options for most of the EU fleet and are therefore not included in the simulation modeling or this cost study. As baseline technologies, both are included at zero incremental cost in all modeled technology packages.

Driveline efficiency. Internal friction in the transmission, driveline shaft, differentials, and axles can be incrementally reduced through improvements in in-gear efficiency, dry sump lubrication, improved lubricants, and improved bearings. Smart lubrication systems reduce lubrication pump parasitic losses as part of dry sump systems. Direct-drive transmissions offer lower gear mesh and oil churning losses than overdrive transmissions.

Dual clutch transmission. Dual clutch transmission (DCT) technology is similar to AMT technology excepting that it includes two separate clutches, one for odd and one for even gears. This design enables uninterrupted shifting, reducing engine power excursions and increasing the time an engine operates under high-efficiency conditions. DCT technology enables greater downspeeding than AMT technology, but this gives rise to engine design considerations. To maintain equivalent power at lower speed, the engine needs to operate at higher torque and in-cylinder pressure, and turbochargers need to be matched for lower compressor speed and higher mass flow requirements. Other considerations related to downspeeding include increased heat transfer, increased in-cylinder pressures, and torsional vibration. Although DCT is an available technology in the long-haul market, none of the technology packages analyzed in this study include a DCT.

Hybridization. Hybrid internal combustion and electric power system integration is ongoing among many manufacturers and suppliers in the heavy-duty long-haul market. Technology potential includes regenerative braking; stop-start and coasting, or shutting off the internal combustion engine in stopping and downhill conditions; and torque assist for propulsion, with an associated potential for engine downsizing if grade specifications are not dominant. Braking energy losses can be recovered through an electric generator and returned to the vehicle as electricity for powering accessories, or for torque-assist using an electric motor. There are other approaches to hybridizing internal combustion engines that offer similar benefits, such as hydraulic hybrids, but this study focuses on electric machine technology.

III. ANALYSIS OF EFFICIENCY TECHNOLOGY COST

While the long-haul tractor-trailer simulation modeling underlying this study (Delgado et al., 2017) provides insight into the fuel-efficiency impacts of potential technologies, this study's cost analysis provides the additional context required to assess the cost-effectiveness of those technologies. This analysis evaluates best-estimate technology costs, based on a review and synthesis of existing technology cost data reported in recent scientific, consulting, and government literature on tractor-trailer efficiency technology. The following discussion summarizes the technology cost estimation approach and data sources.

APPROACH TO COST DATA PROCESSING

Cost data reviewed for this study are expressed in terms of study-dependent currencies. To ensure consistency, all technology cost data are converted into 2016 euros. Cost estimates derived from studies expressed in euros are converted to equivalent 2016 euros using EU price indices from the EU Harmonized Index of Consumer Prices (EC, 2017b; ECB, 2017). The only exception is in cases where a study reporting euros explicitly included internal currency conversion factors, in which case those internal conversions were applied to restore cost estimates to the original underlying currency. Cost estimates derived from studies expressed in U.S. dollars for years between 2005 and 2012 are first converted to 2013 dollars using U.S. price indices given in the EPA's Phase 2 HDV CO_2 rulemaking document (EPA, 2016a), and then converted to 2016 dollars using consistent U.S. price indices from the U.S. Bureau of Economic Analysis (BEA, 2017). Cost estimates derived from studies expressed in 2014 or 2015 U.S. dollars are converted to 2016 dollars using the same BEA price index data (BEA, 2017). All U.S. dollar cost data are then converted to 2016 euros using the annual average exchange rate for 2016 (X-Rates, 2017).[4] This ensures that all analysis data are maintained and presented in consistent monetary terms. All cost data presented in this report are in 2016 euros unless otherwise indicated.

Available cost data often are based on differing assumptions about indirect costs such as research and development, overhead, marketing and distribution, and profit markups. To account for those differences, all derived cost data are first adjusted to a direct manufacturing cost (DMC) basis. DMCs reflect the costs of materials and labor required to produce and assemble technology componentry and essentially represent the cost of a component to the vehicle or engine manufacturer. Indirect cost multipliers (ICMs) are then applied to the DMCs to estimate indirect costs (ICs) and thus total costs (TCs) for each technology, so that TC equals DMC plus IC. TCs are generally equivalent to the expected impact on retail prices associated with a particular technology, excluding VAT. However, manufacturers' actual pricing strategies may include influences that extend beyond specific technology cost—for example, adjustments designed to promote the sales of a specific technology or model.

This DMC/IC/TC costing methodology is structurally identical to the methodology used by the EPA to support its Phase 1 and 2 HDV efficiency standards (EPA, 2016a) and similar to U.S. light-duty vehicle rulemakings. The methodology has been subjected to rigorous development and review and has been used by the ICCT to support previous EU light-duty vehicle analyses. Additionally, the ICCT has previously commissioned a study of the applicability of U.S. light-duty vehicle ICM data to the EU (Kolwich, 2013). That study found U.S. values to be generally consistent—within 10% plus or minus—with EU indirect costs during the early years of technology introduction. But the values were found to substantially overestimate EU and probably U.S. ICs beginning about five years

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[4] Monthly averages are converted to annual averages by weighting each monthly average by the number of days in the month. The annual average for 2017 is based on data through May.

after technology introduction. Projected 2025-era ICs were found to be overestimated by a factor of about five on average, so that the use of U.S. data could result in substantial IC overestimation.

Nevertheless, given the light-duty focus of the U.S./EU ICM comparison and the generally conservative nature of using the U.S. data directly, the indirect cost multipliers developed in support of the U.S. Phase 2 rulemaking, as presented in Table 3, are used without change for this study. As indicated in the table, indirect costs vary with the complexity of associated technology and are roughly estimated to range from 15-75% of direct manufacturing costs. Generally, technology that is either currently marketed or only moderately evolutionary relative to current technology is assumed to be low complexity. Longer-term technologies are assigned higher-complexity ICMs in accordance with their still-developing nature. As also depicted in Table 3, ICMs are established on a separate basis for warranty-related and non-warranty costs under the assumption that warranty-related costs decline with direct costs over time, while the non-warranty costs remain a function of baseline direct costs, with a single step change when production changes from near to long term. For a given technology, this study assumes the same level of complexity as that assumed by the EPA for technologies included in the engineering analysis conducted by the agency for the Phase 2 HDV CO_2 rulemaking (EPA, 2016a).

Table 3. Indirect cost multipliers used to convert from efficiency technology direct manufacturing cost to total (retail level) cost

ICM focus	Technology complexity level	Near-term warranty costs	Near-term non-warranty costs	Long-term warranty costs	Long-term non-warranty costs
Diesel engine technology (DE)	Low	0.006	0.149	0.003	0.122
	Medium	0.022	0.213	0.016	0.165
	High1	0.032	0.249	0.016	0.176
	High2	0.037	0.398	0.025	0.265
Gasoline engine technology (GE)	Low	0.012	0.230	0.005	0.187
	Medium	0.045	0.343	0.031	0.259
	High1	0.065	0.499	0.032	0.314
	High2	0.074	0.696	0.049	0.448
Truck technology (HDV)	Low	0.013	0.165	0.006	0.134
	Medium	0.051	0.252	0.035	0.190
	High1	0.073	0.352	0.037	0.233
	High2	0.084	0.486	0.056	0.312

See U.S. Phase 2 HDV CO_2 rulemaking document (EPA, 2016a) for more information.

Table 4 lists the specific ICM complexity level assignments assumed in this study. The listed U.S. Phase 2 technologies generally correspond on a one-to-one basis with the technologies investigated in this study. Readers interested in additional detail about the various assumptions that underlie listed technology levels should consult the U.S. Phase 2 HDV CO_2 rulemaking document (EPA, 2016a). Generally, successive technology levels represent progressively increasing stringency. The only complexity level not assigned to at least one technology is the "High 2" complexity level, as this level is generally reflective of revolutionary technology not included in this study, such as dedicated electric propulsion componentry. Note also that the assignments in Table 4 include three technologies that are assigned gasoline-engine ICMs. No diesel-engine ICMs are included in the EPA reference document for these technologies, but this is not problematic because the gasoline ICMs are generally higher than their diesel counterparts (see Table 3). Consequently, the effect is conservative in that indirect cost estimates will be higher than would be derived using an ICM for diesel-engine technology.

Table 4. Technology indirect cost and learning curve assignments

Technology Type	Component Technology Assignments from U.S. Phase 2 HDV CO_2 Rule	Assigned Learning Curve			Assigned ICM		
		Type	Curve No.	Base Year	Focus[a]	Level	Near-Term End
Engine technology	Aftertreatment Improvements - Level 1	Flat	2	2014	DE	Low	2022
	Aftertreatment Improvements - Level 2	Flat	2	2014	DE	Low	2024
	Cylinder Head Improvements - Level 1	Flat	2	2014	DE	Low	2022
	Cylinder Head Improvements - Level 2	Flat	13	2021	DE	Low	2027
	EGR Cooler - Level 1	Flat	2	2014	GE	Low	2022
	EGR Cooler - Level 2	Flat	13	2021	GE	Low	2027
	Fuel Injector Improvements - Level 1	Flat	2	2014	DE	Low	2022
	Fuel Injector Improvements - Level 2	Flat	13	2021	DE	Low	2027
	Fuel Pump Improvements - Level 1	Flat	2	2014	DE	Low	2022
	Fuel Pump Improvements - Level 2	Flat	13	2021	DE	Low	2027
	Fuel Rail Improvements - Level 1	Flat	2	2014	DE	Low	2022
	Fuel Rail Improvements - Level 2	Flat	13	2021	DE	Low	2027
	Oil Pump Improvements - Level 1	Flat	2	2014	DE	Low	2022
	Oil Pump Improvements - Level 2	Flat	13	2021	DE	Low	2027
	Piston Improvements - Level 1	Flat	2	2014	DE	Low	2022
	Piston Improvements - Level 2	Flat	13	2021	DE	Low	2027
	Turbocharger Efficiency - Level 1	Flat	2	2014	DE	Low	2022
	Turbocharger Efficiency - Level 2	Flat	13	2021	DE	Low	2027
	Turbo compounding - Level 1	Flat	2	2014	DE	Low	2022
	Turbo compounding - Level 2	Flat	13	2021	DE	Low	2027
	Valve train Friction Improvements - Level 1	Flat	2	2014	DE	Low	2022
	Valve train Friction Improvements - Level 2	Flat	13	2021	DE	Low	2027
	Variable Valve Timing	Flat	8	2015	GE	Medium	2018
	Waste Heat Recovery	Steep	14	2021	HDV	Medium	2027
	Water Pump Improvements - Level 1	Flat	2	2014	DE	Low	2022
	Water Pump Improvements - Level 2	Flat	13	2021	DE	Low	2027
Tractor Aerodynamic drag technology	Aerodynamic Drag Improvements - Level 3	Flat	2	2014	HDV	Low	2022
	Aerodynamic Drag Improvements - Level 4	Steep	4	2014	HDV	Low	2022
	Aerodynamic Drag Improvements - Level 5	Steep	4	2014	HDV	Medium	2025
	Aerodynamic Drag Improvements - Level 6	Steep	4	2014	HDV	Medium	2025
	Aerodynamic Drag Improvements - Level 7	Steep	4	2014	HDV	Medium	2025
Trailer Aerodynamic drag technology	Aerodynamic Drag Improvements - Level 3	Flat	2	2014	HDV	Low	2018
	Aerodynamic Drag Improvements - Level 4	Flat	2	2014	HDV	Low	2018
	Aerodynamic Drag Improvements - Level 5	Flat	2	2014	HDV	Low	2018
	Aerodynamic Drag Improvements - Level 6	Flat	2	2014	HDV	Low	2018
	Aerodynamic Drag Improvements - Level 7	Flat	2	2014	HDV	Low	2018
	Aerodynamic Drag Improvements - Level 8	Flat	2	2014	HDV	Low	2018
Tractor-Trailer Rolling resistance technology	Low Rolling Resistance Tires - Level 1	Flat	2	2014	HDV	Low	2022
	Low Rolling Resistance Tires - Level 2	Flat	2	2014	HDV	Low	2022
	Low Rolling Resistance Tires - Level 3	Flat	12	2018	HDV	Medium	2025
	Low Rolling Resistance Tires - Level 4	Flat	13	2021	HDV	Medium	2028
	Low Rolling Resistance Tires - Level 5	Flat	13	2021	HDV	Medium	2031
Tractor, weight reduction technology	Weight Reduction - Short Term	Flat	2	2014	HDV	Low	2022
	Weight Reduction - Medium Term	Flat	2	2014	HDV	Medium	2022
Trailer, weight reduction technology	Weight Reduction - Short Term	Flat	2	2014	HDV	Low	2022
	Weight Reduction - Medium Term	Flat	2	2014	HDV	Medium	2022
Hybrid technology	Parallel Hybrid	Steep	15	2014	HDV	High1	2024
Downsizing, downspeeding	Right Sized Engine	None	1	2014	HDV	Low	2010
	Axle Downspeed	Flat	12	2018	HDV	Low	2022
Driveline technology	High Efficiency Axle	Flat	12	2018	HDV	Low	2022
	High Efficiency Gearbox	Flat	13	2021	HDV	Low	2022

[a] The focus parameter indicates the type of ICM that is applicable (DE=diesel engine, GE=gasoline engine, HDV=heavy-duty vehicle). See Table 3. See also U.S. Phase 2 HDV CO_2 rulemaking document (EPA, 2016a) for more information.

This study also assumes that the direct manufacturing costs of technology are subject to reduction over time as manufacturers gain design and production experience. Consistent with the approach for ICMs, this study applies a series of technology-specific learning curves established by the EPA for its Phase 2 HDV CO_2 rulemaking (EPA, 2016a). Table 4 includes the applicable learning curve assignments for each technology. All of the learning curves are variations on an underlying general design that assumes newly introduced low production volume technology will undergo two or more cycles of "steep" learning in which costs decline by 20% after each two successive years of production. This is followed by a relatively flatter experience period that assumes typically five years of 3% annual cost reductions, followed by five years of 2% annual cost reductions. After five more years of 1% annual cost reductions, DMCs are assumed to stabilize.

The major difference in the various learning curves developed to support the U.S. rule is where in this learning process a particular technology is in its development cycle. More mature technologies will reflect a flatter curve as their periods of steep cost decline have occurred in the past. Less-mature technologies may reflect one or more periods of steep cost decline before moderating. Warranty-related indirect costs decline with direct costs and are thus inherently tied to the same learning curve. Non-warranty indirect costs are more fixed in nature and are tied to baseline direct costs, not subject to learning. Such indirect costs do undergo a step reduction as technology ages from near to long term (see Tables 3 and 4) in recognition of the full recovery of some fixed-cost components. However, it should be noted that the ICCT-commissioned EU indirect-cost study (Kolwich, 2013) found EPA-based long-term indirect costs to be greatly overestimated for application in the EU. Thus, use of the U.S. data is likely to result in higher estimates of indirect costs than would be estimated using EU-specific ICMs.

Figure 2 depicts the subset of EPA learning curves used in this study (see the learning curve assignments listed in Table 4). As indicated, these curves range from a perfectly flat learning of curve 1 with no cost reductions over time to the significant learning reflected in curve 4, where 2030-era direct manufacturing costs decline to about 47% of baseline DMC. Note that this does not translate to a 53% decline in total costs as the bulk of indirect costs are non-warranty in nature and do not decline with learning. In all cases, the baseline direct costs estimated for this study apply in the earliest year for which the DMC multiplier is unity.[5] Thus, the largest 2030-era cost adjustment is the 0.47 DMC multiplier of learning curve 4. Most technologies reflect 2030-era multipliers in the range of 0.73-0.81 (learning curves 2 and 13).

Two specific adjustments are made to the EPA learning curves for this study. First, the U.S. curves reflect learning only through 2027. The curves are extended through 2030 for this study by analyzing the year-over-year changes of each U.S. curve and extending the pattern through years 2028, 2029, and 2030. The maximum year-over-year adjustment applied for any of the curve extensions is 2%, with adjustments of 1% and zero for curves that have expended their allocated number of 2% and 1% adjustments.[6] Second, learning curve 15, used for hybrid technology, is created for this study from the U.S. hybrid technology learning curve. Curve 15 and the U.S. hybrid learning curve reflect identical

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[5] The baseline direct cost year for most currently available technologies is 2014, meaning that the baseline direct costs assumed for such technologies in this study are applicable to that year. For more advanced technologies, the baseline direct cost year is some future year. Waste heat recovery technology, for example, has a baseline cost year of 2021. For such technologies, direct costs in years prior to the baseline cost year will be greater than estimated baseline direct costs. Although this study presents summary costs only for years 2025 and later, there are a number of figures that show individual technology costs in both 2014 and 2030 to illustrate the degree and impact of assumed learning.

[6] As previously discussed, learning curves are based on a certain number of years in which 3%, 2%, and 1% cost reductions are assumed. The terminology "expended" means that the number of allocated cost-reduction years for one of the percentage changes has been reached and the curve is extended by shifting to the next lower percentage change assumption.

learning, but curve 15 is shifted in time to reflect a 2015 baseline DMC, whereas the U.S. hybrid learning curve assumes a 2021 baseline. The hybrid vehicle costs used in this study are developed specifically from 2015-era cost data and are treated accordingly. The adjusted curve results in projected cost reductions that closely match battery and motor cost reductions estimated independently by the ICCT (Wolfram & Lutsey, 2016).

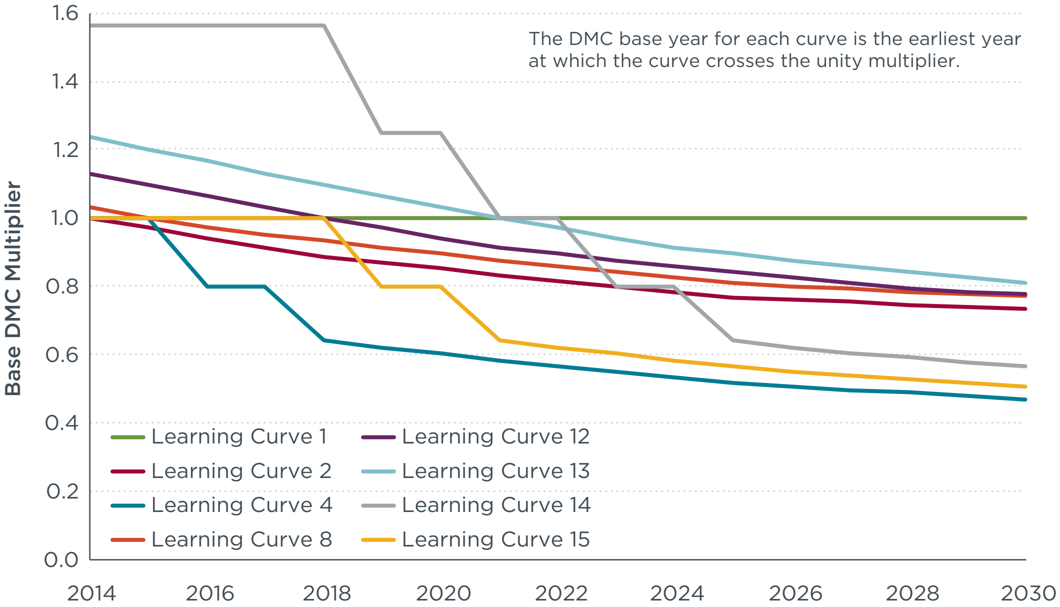

Figure 2. Direct manufacturing cost learning curves for technology cost reductions over time

Algorithmically, the direct costs of technology, which decline over time as shown in Figure 2, are summed with associated indirect warranty and indirect non-warranty costs, from Tables 3 and 4, to determine total retail cost excluding taxes as follows.

$$TC_{year} = (DMC_{base} \times LF_{year}) + (DMC_{base} \times ICM_{non\text{-}warranty}) + (DMC_{base} \times LF_{year} \times ICM_{warranty})$$

Where: TC_{year} = total technology cost in given evaluation year
DMC_{base} = base year direct manufacturing cost (as estimated in this study)
LF_{year} = learning factor in given evaluation year (see Table 4 and Figure 2)
$ICM_{non\text{-}warranty}$ = non-warranty indirect cost multiplier (see Tables 3 and 4)
$ICM_{warranty}$ = warranty indirect cost multiplier (see Tables 3 and 4)
base = base year
year = evaluation year

OVERVIEW OF DATA SOURCES

Cost data for this study are derived from a number of sources. For the most part, data are accepted as published except in cases where obvious deficiencies are present—or data is unjustifiably inconsistent with data from other sources. All instances where data are adjusted are described in detail in the discussion that follows. Unless otherwise stated, all cost data that are originally expressed in terms of retail price equivalent (RPE), are converted to their DMC-equivalent cost and processed using the DMC/IC/TC approach described above to ensure that all costs for this study are developed on a consistent basis.[7]

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[7] RPE is another method for converting parts cost into a retail equivalent. Unlike the ICM approach, RPE-based studies rely on a single markup factor to convert all technology costs to retail-level estimates. Generally, RPE markup factors are based on studies relating the retail costs of entire vehicles to the parts costs of those same vehicles. This method necessarily assumes that all parts contribute equally to the markup. The ICM markup approach is a more recent, more advanced methodology that bases markup costs on the complexity of associated technology and the timing of its introduction. A more detailed discussion of the two retail markup methods can be found in the U.S. Phase 2 HDV CO_2 rulemaking documentation (EPA, 2016a).

Although the total number of reports and research papers consulted to conduct this study is extensive, primary data sources are limited. Four sources are responsible for the majority of the cost data utilized. These are:

- A study on EU heavy-duty vehicle CO_2 reduction technology and cost conducted by Ricardo-AEA (Norris & Escher, 2017).
- A study on lightweighting technology for heavy-duty vehicles conducted by Ricardo-AEA for the European Commission (Hill et al., 2015).
- A study on greenhouse gas emissions from heavy-duty vehicles conducted by Ricardo-AEA for the European Commission (Hill et al., 2011).
- Analysis conducted by the EPA and the U.S. National Highway Traffic Safety Administration (NHTSA) in support of their Phase 2 fuel-efficiency rulemaking for medium- and heavy-duty vehicles and engines, as documented in the Regulatory Impact Analysis for the rulemaking (EPA, 2016a).

In addition, a number of secondary data sources are used either to validate estimates from the primary data sources or provide alternative estimates in cases where primary source data are either unavailable or inconsistent. Such secondary sources include:

- A study on fuel saving and greenhouse gas reduction measures for heavy-duty vehicles in the EU conducted by the Heidelberg Institute for Energy and Environmental Research and the Graz University of Technology (Dünnebeil et al., 2015).
- Analysis conducted by the EPA and NHTSA in support of their Phase 1 fuel-efficiency rulemaking for medium- and heavy-duty vehicles and engines, as documented in the Regulatory Impact Analysis for the rulemaking (EPA, 2011).
- A study on long-haul tractor-trailer fuel consumption and CO_2 emissions conducted by the U.S. Northeast States Center for a Clean Air Future, the International Council on Clean Transportation, the Southwest Research Institute, and TIAX LLC (Cooper et al., 2009).

A wide range of tertiary data sources, including myriad engineering papers and presentations, were consulted, and in many cases used to fill gaps or provide alternative estimates on a one-time technology-specific basis. These data sources are too numerous to list here but are referenced as appropriate in the detailed technology discussions that follow. Non-identification here is in no way indicative of any lesser value, but rather in recognition of the more focused scope of these sources, a focus that is more appropriately referenced as applicable. Each of these targeted sources is as critical to this report as the broader-scope sources identified here.

KEY ECONOMIC ASSUMPTIONS

To evaluate the cost-effectiveness of tractor-trailer technology, the costs of various technology packages are compared with the associated economic benefits. This essentially entails comparing the fuel savings associated with higher-efficiency technology with the associated capital costs of that same technology. A number of specific parameters are required to undertake such analysis.

Evaluation years. In the interest of simplifying both the presentation and clarity of findings, all economic metrics are presented for two evaluation years only—2025 and 2030. Evaluation year 2025 represents the midrange year and provides a representative indication of median-level economic metrics for the larger 11-year period. Given the lead time that would be required for any newly adopted HDV control program to achieve the stringent fuel-consumption reductions reflected in the more advanced technology packages evaluated in this study, it is unlikely that such reductions would be required earlier than 2025. This should not be interpreted as encouraging extended adoption delay as it is critical for standards to be adopted as soon as possible in order to establish a glide path toward the stringent standards required to deliver reductions of the levels associated with the advanced technology packages considered in this study. The 2030 evaluation year reflects the timing when the most advanced technology packages are expected to be commercially available and the year when standards of equivalent stringency could be implemented.

Diesel fuel price. Analysis is conducted for three diesel fuel price scenarios, representing low, best estimate, and high levels. All three estimates are derived from an analysis of historic EU diesel fuel prices, in conjunction with projected changes in crude oil prices. Historic fuel prices for 2005 through 2016 for the EU are taken from the Weekly Oil Bulletin published by the European Commission's Directorate-General for Energy (DG-ENER, 2017). These data are reported with and without taxes and are, therefore, readily analyzed in terms of commodity price and taxes independently. Because commercial haulers are exempt from fuel VAT throughout the EU, fuel prices are adjusted to remove the VAT component, assuming an average EU VAT of 20%.[8] Commercial haulers are also eligible for excise tax rebates in some EU countries (DKV, 2017a). Since the excise tax rebate is not available throughout the EU, associated fuel price impacts are calculated as an offset as described in the text that follows the basic forecasting analysis.

Real oil price forecasts (World Bank, 2017a; World Bank, 2017b) are used to derive commodity price-change factors for all years from 2017 through 2030. These factors are then applied to diesel commodity prices to derive price forecasts through 2030. Non-VAT taxes for each forecast year are based on the average tax change in real terms observed in the historic fuel price data, which show non-VAT taxes increasing by an average of €0.0028 per liter per year. Although not applicable to this analysis, diesel pump prices are forecast by adjusting the projected commodity and tax price estimates for the assumed VAT. Thus, the diesel fuel pump price forecast is equal to 1.2 × [commodity price + non-VAT taxes], where the 1.2 factor is based on the assumed VAT rate of 20%. Figure 3 depicts the data used and results of the fuel price forecast. As indicated, the projected VAT-excluded diesel price ranges from €1.11-€1.17 per liter, with an average price of €1.14 per liter over the 2020-2030 period. Accordingly, this study assumes a rounded best-estimate fuel price excluding VAT of €1.15 per liter. This equates to a pump price including VAT of €1.38 per liter.

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[8] Based on EU population (EC, 2017c) and country-specific VAT (TCU, 2017) data, the population-weighted average VAT for the EU in 2015 was 21%. However, the rate has generally increased over time. Since the fuel analysis covered a decade of fuel prices, the average VAT for the fuel price analysis only is revised downward by one percentage point.

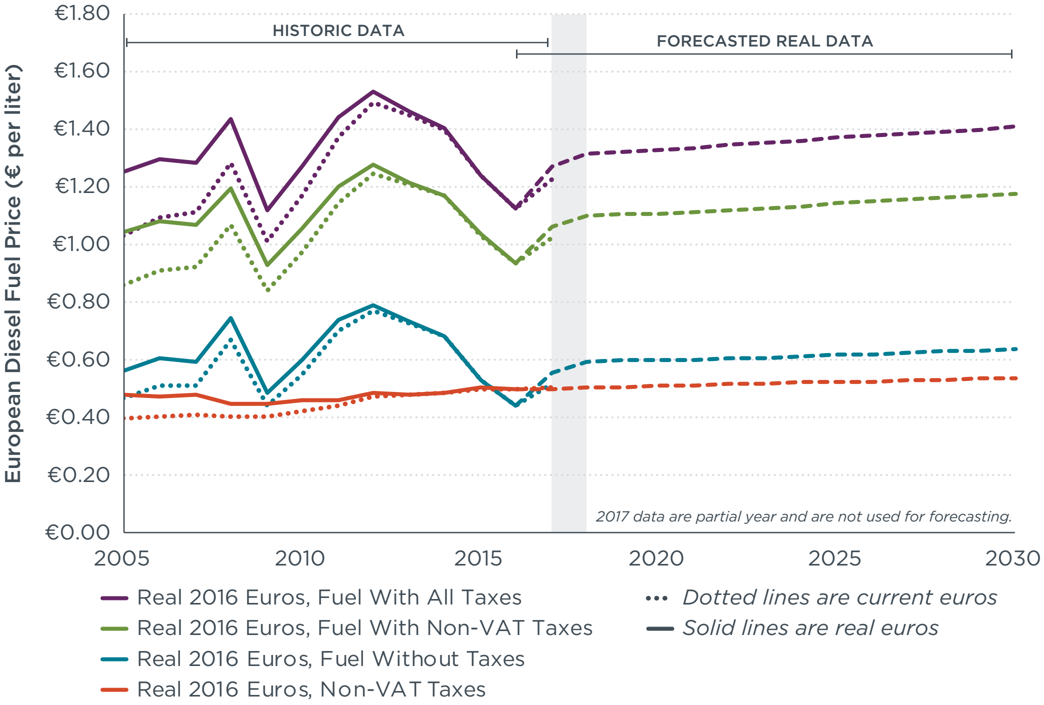

Figure 3. Diesel fuel price data

Fuel excise tax rebates are available in Belgium, France, Hungary, Italy, Slovenia, and Spain. Analysis of 2017 fuel price data (DKV, 2017b) indicates that the effect of these rebates equates to an EU-weighted net rebate of €0.042 per liter. Based on the fuel tax forecast described above, this is expected to increase to an average of €0.044 per liter over the 2020-2030 period, assuming the countries offering the rebate remain unchanged. To account for the effects of this rebate, the rounded best-estimate fuel price for long-haul tractor trailers excluding VAT is adjusted from €1.15 to €1.10 per liter.

Low fuel price estimates are set nominally at -35% and high fuel price estimates are set at +25%, as measured from the pre-excise tax rebate best-estimate fuel price of €1.15. This range is roughly equivalent to the range of fuel prices observed across the EU over the last several years. The resulting rounded low fuel price estimate excluding VAT is €0.75 per liter and the high, €1.45. Those equate to pump prices with VAT of €0.90 and €1.74. To account for the effects of available excise tax rebates, estimated to be €0.044 per liter over the 2020-2030 period, the rounded low and high fuel price estimates for long-haul tractor trailers excluding VAT are adjusted to €0.70 from €0.75 and €1.40 from €1.45 per liter, respectively. Note that on an EU-wide basis, non-VAT taxes alone are estimated to be about €0.54 per liter in 2030, so the likelihood of a non-VAT fuel price as low as €0.70 per liter on an EU-wide basis is remote. While it is possible that such prices could be observed in individual EU member states, the low fuel price estimate should serve as a reasonable lower bound on study-derived estimates of the economic returns associated with fuel-efficiency technology investment.

Economic discount rate. Since technology cost effects and fuel savings accrue over differing time scales, it is necessary to estimate the present value of future cash flows to derive a meaningful comparison of technology costs and benefits. For this study, all technology costs that affect the purchase price of a tractor-trailer are assumed to accrue immediately and are not discounted or financed in any way. Associated maintenance cost impacts and fuel savings are discounted beginning in the year immediately following technology adoption.

Because this study treats all costs, both initial and future, in real 2016 euros, the discount rates applied reflect real rate of return discounts, excluding inflationary effects. Unfortunately, discount rates are by nature subjective because what one individual, business, or group of individuals might define as an acceptable rate of return for a lost investment opportunity may be different from that of another entity. This is especially true for societal impacts such as those resulting from regulatory requirements, which tend to directly affect financially a restricted segment of society while producing benefits for society as a whole. Since regulatory costs are likely to be indirectly spread across society over time through increased consumer costs, it can be argued that social-level discounts are the most appropriate metric. However, directly affected businesses or individuals are likely to disagree as their valuation of potential return on an equivalent investment is likely to be considerably higher. For convenience, these can be referred to as social and financial discounts.

To surmount such subjectivity, economic analysis in this study is conducted for three real discount rates: 4%, 7%, and 10%. The 4% rate reflects the EU's recommended social discount rate for regulatory impact assessment (EC, 2017d). The 7% rate reflects the financial discount rate recommended for application in U.S. regulatory analyses (OMB, 1992). This is higher than the real financial discount rate of 5% recommended by the EU for infrastructure investment decisions (EC, 2008). That rate was not selected for this analysis because it is not substantially different from the recommended social discount rate of 4%. The 10% scenario is intended to reflect an upper-bound financial assumption.

Vehicle kilometers of travel (VKT). The rate at which fuel savings accrue is dependent on both the assumed discount rate and accumulated VKT by age. Age-dependent VKT data for tractor-trailers are taken from the EU TRACCS database, a collection of data assembled to support transport and climate change analysis (Papadimitriou et al., 2013). TRACCS relies on the EU Eurostat system (EC, 2017e) and supplemental data obtained from EU-member regulatory agencies to define a number of transport statistics, including VKT and population by vehicle type and age, for vehicles up to 30 years old. Six sizes of tractor-trailers are included in the TRACCS data, ranging from 14 tonnes to 60 tonnes gross combined weight (GCW). Two of these ranges, 34-40 tonnes and 40-50 tonnes, span the 40-tonne combination analyzed in this study. All VKT estimates used in this study reflect the combined estimates of these two TRACCS size ranges. TRACCS covers calendar years 2005-2010. This study averages these data to derive a single VKT age distribution.

TRACCS does not explicitly distinguish short and long-haul statistics, instead treating VKT and population statistics for tractor-trailers in the aggregate. This has the effect of underestimating long-haul tractor-trailer VKT. TRACCS does provide aggregate tractor-trailer tonne-kilometer statistics for four trip length ranges: <300 km, 300-500 km, 500-1000 km, and >1,000 km. Assuming that trips of <300 km are not long-haul trips and that all other trips are 100% long-haul, and assigning average trip lengths of 200 km, 400 km, 750 km, and 1,000 km to the four trip length ranges, it is possible to estimate the average length of a long-haul trip compared with the average length of all tractor-trailer trips. The resulting statistics indicate a ratio of long-haul to average trip length of 1.39-1.40 for data years 2005 through 2010 and for both of the evaluated vehicle size categories, 34-40 tonnes and 40-50 tonnes. It should be noted that setting the average length of <300 km trips to 300 km instead of 200 would reduce the ratio of long-haul to average trip length to 1.3, but such a ratio is based on maximum-length short-haul trips and constrained long-haul trips as all >1,000 km trips are assumed to be 1,000 km. Conversely, allowing the average length of >1,000 km trips to exceed 1,000 km produces long-haul to average trip length ratios of 1.5 or more. Given the underlying constraints on both short and long-haul trips, this study adopts a ratio of long-haul to average trip length of 1.40 as the most reliable estimate.

Based on the estimated trip length ratio, average TRACCS VKT data should be adjusted by a factor of 1.4 to derive long-haul specific VKT. Unadjusted TRACCS data indicate an average annual VKT for 34-50 tonne tractor-trailers of about 79,000 km for calendar years 2005-2010. This equates to an average tractor age of eight or nine years, as TRACCS VKT data by tractor age show that a tractor accumulates 79,000 km per year between ages 8 and 9. With the adjustment, the average annual VKT increases to about 110,000 km. The average age is unchanged as the VKT for all ages is adjusted by the same factor of 1.4. The TRACCS database also allows for the development of a scrappage curve for tractor-trailers that defines the fraction of original sales in operation in any given year. When applied to the VKT-by-age estimates, total lifetime VKT estimates are derived of 1.05 million km for an average tractor-trailer and 1.47 million km for a long-haul tractor-trailer.[9]

Substantial effort was undertaken to validate the VKT estimates. Most of the long-haul data in EU analyses appears to be speculative. In a 2012 study, the Graz University of Technology cites average annual activity of 135,000 km for long-haul tractor-trailers (TU Graz, 2013) but provides no estimate for the number of years involved. The study to which the 135,000 km figure is attributed (Hill et al., 2011), does include such an estimate as well as an alternative 130,000 km estimate, referencing both to the European Automobile Manufacturers' Association (ACEA). Interestingly, Hill et al. discuss issues similar to those discussed in this study, wherein activity estimates from Eurostat/TRACCS are substantially lower. They also conclude that the difference probably reflects an inability to properly isolate long-haul activity. Hill et al. indicate that the "often cited" average truck lifetime of 10 years is likely to be an underestimate, without providing a definitive alternative figure and defaulting to an estimate of 11 years. This equates to a total lifetime accumulation of between 1.3 million and 1.49 million km, both of which are quite consistent with the 1.47 million km estimate used in this study. It is notable, however, that this study assumes that level of travel only after a 30-year survival-weighted lifetime. Over 10 to 11 years, this study assumes travel ranging from 1.14 million to 1.19 million km.

A subsequent EU lightweighting study (Hill et al., 2015) estimates average annual long-haul travel at 100,000 km and vehicle lifetime at 10.8 years, implying average lifetime travel of only 1.08 million km.[10] The average annual VKT reduction may be because long-haul vehicles in the study include vehicles with gross weights as low as 7.5 tonnes, but it is not clear what affect this might have with respect to larger tractor-trailer combinations. An International Aluminum Institute study (Bertram et al., 2007) cited in the EU lightweighting study assumes average lifetime activity of 1.2 million km for long-haul tractor-trailers. In a 2017 study on EU HDVs (Norris & Escher, 2017), co-workers of Hill et al. reset the annual average activity for long-haul tractor-trailers to 130,000 km with a lifetime of 10 years, re-establishing a lifetime average travel estimate of 1.3 million km.

Other EU studies relying on annual average travel of 130,000 km include a 2011 ICCT study (Law, Jackson, & Chan, 2011), a 2015 study by the Heidelberg Institute for Energy and Environmental Research (Dünnebeil et al., 2015), and a 2012 study by the environmental consultant CE Delft (Schroten, Warringa, & Bles, 2012). All three also assume an average lifetime of eight years, resulting in average lifetime travel of 1.04 million km. This is consistent with the 1.01 million km assumed in this study over the first eight years of an average tractor-trailer life, but lower than the 1.47 million km assumed over the full average survival-weighted lifetime of such vehicles.

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[9] These estimates reflect the survival-weighted average VKT accumulated over the 30-year TRACCS VKT distribution. The median age of tractors based on the TRACCS survival data is about 12.4 years.

[10] Note that Table 4.14 in the 2015 study by Hill et al. transposes travel data for construction with travel by long-haul vehicles and does not, therefore, agree with the estimates cited here. Table 3.24 in the Hill et al. study lists the data correctly.

While the VKT estimates prepared for this study are generally consistent with EU estimates by earlier researchers, they also appear to be based on substantially more robust analysis and therefore subject to an increased level of confidence. To provide additional context, the derived estimates are contrasted with those associated with similar long-haul vehicles operating in the United States. U.S. estimates are embodied in an EPA computer model denoted as MOVES, specifically MOVES2014a. MOVES estimates were used directly to estimate all tractor-trailer activity in support of the U.S. Phase 2 rulemaking for HDV CO_2 emissions (EPA, 2015; EPA, 2016b). As shown in Figure 4, which provides a comparison of EU (TRACCS) and U.S. (MOVES) annual VKT for a 40-tonne class long-haul tractor-trailer, travel in the United States is about 50% higher than estimated for the EU.[11] Without the long-haul EU adjustment, U.S. travel is about double that of the EU. Thus, the derived EU estimates are well below corresponding estimates for the United States, both with and without the long-haul adjustment.

The curves presented in Figure 4 do not, however, consider the fraction of vehicles that survive to a given age. Not all vehicles will survive to age 30, and therefore it is not reasonable to base economic effects for an average tractor-trailer on VKT curves that do not consider the probability of survival. The same TRACCS data that allow for the development of the VKT curves presented in Figure 4 also allow for the development of the tractor-trailer survival curve presented in Figure 5. Figure 5 also includes the corresponding U.S. survival curve for context. Here again, considerable differences are noted, with the EU fleet indicating a considerably shorter average life: about 12 years in the EU as compared with almost 20 years in the United States. The rapid decline in tractor survival over the first few years of ownership in the EU is not easily rationalized, but the data is retained and used without change in this analysis as it is based on the same source (TRACCS) as the associated VKT. However, it is likely that this retention results in some underestimation in the study's estimates of the economic attractiveness of new technology to initial vehicle owners.

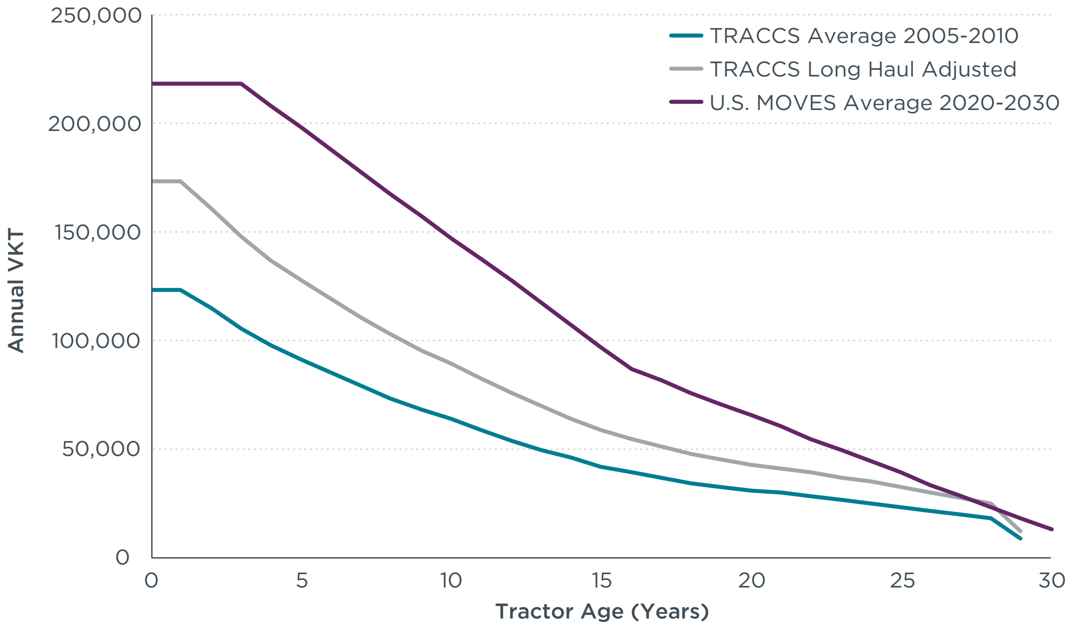

Figure 4. Annual VKT for a Surviving Tractor

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[11] In the United States, tractor-trailers are generally limited to a maximum gross combined weight of 80,000 pounds (36.3 tonnes), so the EU/U.S. comparison is between the EU VKT for a 40-tonne tractor-trailer and the U.S. VKT for a Class 8 (36.3 tonne) long-haul tractor-trailer. Notwithstanding the weight differential, the applications are comparable in terms of service characteristics.

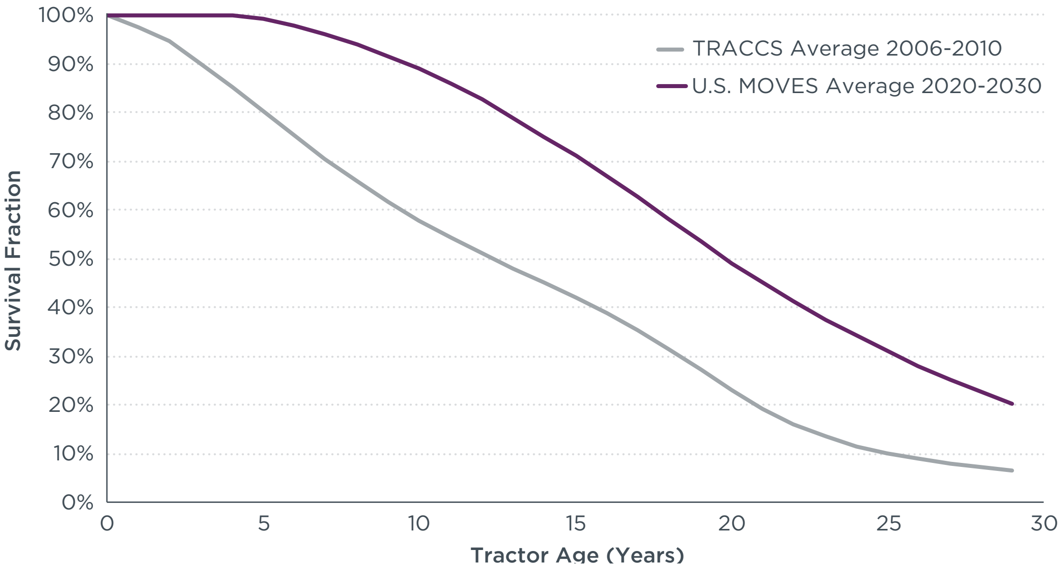

Figure 5. Tractor Survival Curves

The curves from Figures 4 and 5 are combined to create the survival-weighted curves shown in Figure 6. The curve denoted as the TRACCS Long Haul Adjusted curve is the VKT curve used for all economic analysis in this study. Differences relative to the United States are substantially greater due to the combined effects of greater U.S. per-vehicle VKT and extended U.S. survival rates. On a survival-weighted or average-tractor basis, U.S. VKT is about 2.7 times that of the unadjusted TRACCS data and about twice that of the long-haul adjusted data. Thus, even though the long-haul adjusted EU VKT estimates are higher than those used for some previous EU analyses, they remain considerably lower than corresponding estimates for the United States. Figure 6 also depicts the VKT curves in a cumulative format, showing that roughly 77% of survival-weighted VKT is accumulated during the first 10 years of vehicle operation, with a full 50% accruing during the first five years. This is important in understanding why the first-owner economic impacts presented later in this report are not inordinately different from lifetime impacts. Table 5 presents a summary of key VKT statistics derived from Figure 6 as well as comparative estimates used in other EU studies.

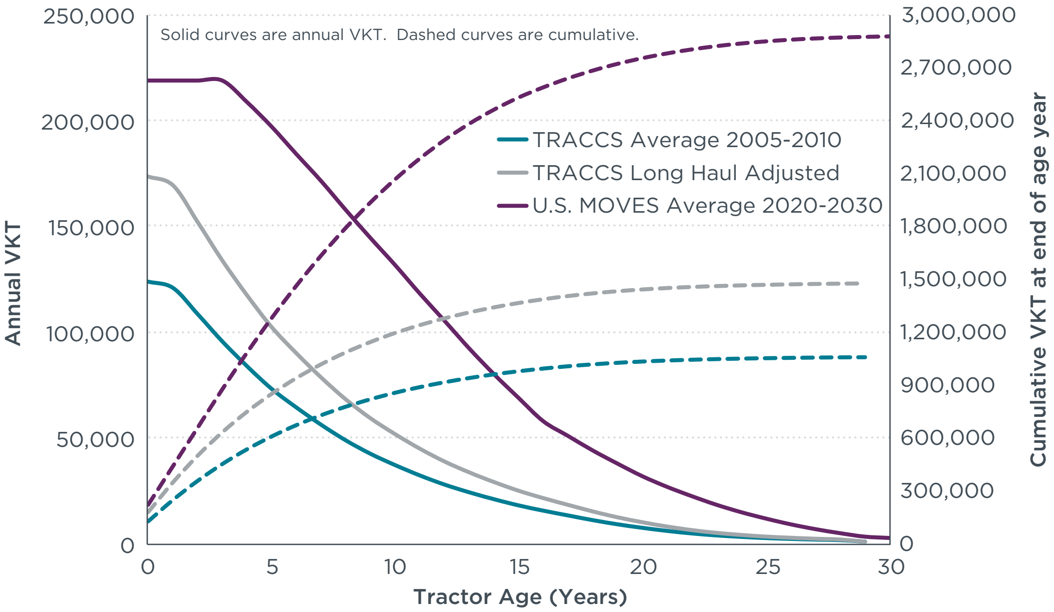

Figure 6. Survival-Weighted VKT for a Tractor (Average Tractor VKT)

Although it is believed that the long-haul VKT adjustment provides a better representation of long-haul VKT in the EU, it is also recognized that such data generally reflect lifetime VKT estimates that are higher than estimates used in previous EU analyses. Therefore, to ensure that the study does not overestimate the economic attractiveness of fuel-efficiency technology in the EU, primary economic metrics are calculated on the basis of unadjusted VKT estimates derived directly from the EU TRACCS database and listed in Table 5 as the EU TRACCS Average 2005-2010 data. These data generally reflect VKT for an average tractor-trailer, including both short and long-haul applications. Note also that the study assumes that these VKT accumulate over a 30-year, survival-weighted lifetime as opposed to the 8 to 12 year lifetimes assumed in previous EU studies. As a result, economic results for this study are substantially more conservative as VKT accumulation extends over a longer period subject to increased discounting effects. To quantify the effect of the long-haul VKT adjustment on the estimated cost-effectiveness of fuel-efficiency technology, this study does provide comparative estimates for some economic parameters both with and without the adjustment. Such comparative data will allow for study results to maintain currency should more robust EU VKT data be developed in the future.

Table 5. Key VKT Statistics

Parameter	EU TRACCS Average 2005-2010	EU TRACCS Long Haul Adjusted	U.S. MOVES Average 2020-2030
Survival-Weighted Lifetime VKT (millions)	1.05	1.47	2.88
Median Lifetime (years)	12.4	12.4	19.8
Survival-Weighted VKT After 5 Years (millions)	0.53	0.74	1.08
5-Year Fraction of Lifetime VKT	50.5%	50.5%	37.6%
Survival-Weighted VKT After 10 Years (millions)	0.81	1.14	1.94
10-Year Fraction of Lifetime VKT	77.4%	77.4%	67.2%
Lifetime VKT From Other EU Studies (millions)	1.04-1.49		n/a
Lifetime From Other EU Studies (years)	8-12		n/a

Finally, with the exception of operating-cost elasticity effects, per-vehicle VKT is assumed to be constant throughout the forecast period of this study. While per-vehicle VKT growth is possible, previous work in the United States has suggested that VKT growth is more closely linked to vehicle population growth and that per-vehicle activity is relatively unaffected. This is a conservative assumption from an economic perspective as payback periods decrease and aggregate fuel savings increase with rising VKT.

VKT elasticity. VKT elasticity is a measure of the relationship between vehicle activity and operating cost. Assuming all other operating costs remain unchanged, decreasing the amount of money spent on fuel, either through a direct reduction in fuel price or an indirect reduction in fuel expenses due to improved fuel consumption, results in a net reduction in operating costs. An elastic relationship between operating costs and VKT assumes that a fraction of any operating cost savings will be consumed through increased travel. This effect is sometimes called the rebound effect.

Various estimates of the magnitude of such elasticity have been developed. This study uses an estimate of -0.05% change in VKT per 1% change in operating costs. This represents a relatively inelastic response to changes in operating costs but one that is consistent with the most recent studies. The recent U.S. Phase 2 rulemaking for HDV CO_2 (EPA, 2016a) includes an extensive review of recent elasticity studies, indicating that the most recent peer-reviewed studies find long-haul elasticity to be not significantly different from zero. The most relevant of these with regard to the EU is a study conducted for the

U.K. freight sector (Wadud, 2016), which found that "articulated trucks did not respond to changes in fuel prices." The zero-elasticity findings do not appear unreasonable given that long-haul tractor-trailer operation is likely to include negligible discretionary driving, which would be expected to be sensitive to fuel cost, and non-discretionary driving in the sector is subject to influences that are either independent of operational costs or subject to considerably more influence than operational costs alone, such as the total demand for freight. However, because other recent research (see for example Leard et al., 2016) continues to indicate the possibility of substantially higher elasticities, this study uses a relatively inelastic but non-zero estimate. This approach is consistent with that employed in the U.S. Phase 2 HDV CO_2 rulemaking.

It is important to recognize the effect that VKT elasticity can have on different economic impact metrics. Aggregate fuel and associated monetary savings will decline with increasing VKT elasticity as some of the savings that would have accrued will be redeemed for additional driving, incurring increased costs. Although not estimated in this analysis, the same effect will occur with regard to greenhouse gas or other pollutant emissions. Conversely, increasing the rate at which VKT is accumulated reduces the time period over which technology costs are recouped, leading to shorter payback periods.

Technology costs can be equated to a specific number of operational kilometers by dividing cost by euros per kilometer fuel savings. As VKT elasticity increases, the time required to accumulate this payback mileage is compressed. Beyond the point where increased activity exceeds that which would have occurred if VKT were inelastic, all fuel savings become negative as one begins using fuel that would not otherwise have been used. This occurs late in the lifetime of a vehicle, as only then will accumulated VKT exceed inelastic accumulated VKT. In any case, the effect is minor for the level of VKT elasticity assumed in this study but could be significant under higher elasticity scenarios.

It is also important to recognize the economic constraints associated with this study, which is essentially an engineering analysis of economic issues. What this study accounts for are technology costs and offsetting fuel savings, which are converted into equivalent cost savings using assumed fuel prices. A tractor owner currently buys a tractor for a given price and consumes a given volume of fuel over the useful life of the tractor. With the application of more advanced fuel-efficiency technology, that owner will spend more for a tractor but will use less fuel per kilometer traveled. This study quantifies precisely these values and only these values: the cost of the technology and the volume and associated value of fuel saved. These are the only economic parameters being estimated. So, when travel is inelastic, the tractor owner will save fuel for each kilometer driven, since total lifetime distance traveled does not change. When travel is elastic, the tractor owner will save fuel for each kilometer that would have been driven before new technology induced increased travel and will then begin to consume fuel that would not have been consumed before the new technology encouraged increased travel. This additional consumption eats into the fuel savings that accrued up to the point of increased travel. This does not mean that the increased travel is of no value to the tractor owner. Presumably, an economic return is received for every kilometer of travel, both original as well as efficiency-induced. If a tractor owner has an operation with a positive net per-kilometer return before additional travel, he will have a similarly positive net return for each kilometer of induced travel.

However, quantifying the complex interrelationships within the universe of economic influences affecting the freight sector is beyond the scope of this analysis. The fact that the trucking industry can change prices to reflect the additional cost of technology or a reduction in fuel costs leads to a cascading set of effects that span not only the road freight industry but also alternative freight options. Only a detailed economic analysis capable of teasing out the many complex interrelationships can provide insight into each effect. What this study does is evaluate whether additional technology costs are offset by associated fuel savings, or not. If they are, then the road transport industry can be no worse off than under baseline conditions since the cost of technology can be paid for without raising transport prices and sending ripples across the economic spectrum. If the costs are not offset, then additional economic analysis may be required to fully evaluate industry and related impacts. In short, this study looks at two key parameters, tractor-trailer and fuel costs, to determine whether additional economic analysis is necessary, or not.

Operating cost breakdown. VKT elasticity is expressed in terms of operating costs. Potential fuel-efficiency standards affect the vehicle purchase price, maintenance costs, and fuel costs, at least on a first-order basis. To determine overall impact on operating cost, it is therefore necessary to estimate the share of those components relative to total operating costs. This study relies on a breakdown of operating costs published by the ICCT in a July 2017 briefing on barriers to the adoption of fuel-saving technologies in the EU trucking sector (Sharpe, 2017) and the data underlying that briefing (BGL, 2017). This operating-cost distribution, based on 2013 data, indicates that fuel accounts for 25.7% of total operating costs; truck-purchase price, 10.4%; and maintenance costs, 7.5%. Other components such as insurance, licensing and permits, tolls, driver pay, driver benefits, and driver bonuses account for the remaining 56.4%. This study adjusts that distribution to account for differences in the base distribution fuel price, assuming a 2013 nominal VAT-excluded fuel price of €1.21 per liter as per DG-ENER, 2017, and the three fuel price scenarios evaluated in this study. The resulting adjusted distributions, shown in Table 6, are used as the basis for determining all VKT elasticity effects in this study.

Note that the VKT elasticity calculation considers both the change in fueling cost resulting from technology-induced reductions in per-kilometer fuel consumption, and the change in truck purchase and maintenance costs due to the incremental capital and maintenance costs relative to the 2015 baseline. Total operating cost changes reflect the net of all three components. This net change is the basis for determining operating-cost impacts on VKT. The three 2020-2030 operating-cost distributions shown in Table 6 serve as the basis for determining the required technology package-specific operating-cost effects.

Table 6. Distribution of long-haul operating costs for varying fuel prices, in 2016 euros excluding VAT

Distribution component	At 2013 fuel price (€1.22/liter)	At best estimate 2020-2030 price (€1.10/liter)	At low estimate 2020-2030 price (€0.70/liter)	At high estimate 2020-2030 price (€1.40/liter)
Fuel cost	25.7%	23.8%	16.5%	28.4%
Truck purchase	10.4%	10.7%	11.7%	10.0%
Maintenance	7.5%	7.7%	8.4%	7.2%
Other	56.4%	57.9%	63.4%	54.4%
Aggregate	100.0%	100.0%	100.0%	100.0%

Baseline tractor and trailer prices. To estimate the VKT elasticity effect associated with changes in truck purchase price, it is necessary to assume baseline vehicle costs. For this study, baseline tractor price is taken as €101,000 and baseline trailer price as €27,500, based on publicly available market data. That baseline tractor price is for a new 350 kW Euro 6 Mercedes Actros 1848 LS Streamspace 4×2 tractor equipped with a sleeper cab, which is consistent with the baseline vehicle characteristics of this study, as priced in August 2016 (lastauto omnibus, 2016). The baseline trailer price is for a new 3-axle, 6-tire, 13.65 meter, 36-tonne curtainside trailer as priced in August 2016 (lastauto omnibus, 2016). Although an average 21% VAT, calculated as the population-weighted average VAT for the EU as of January 2017 (EC, 2017c; TCU, 2017), would be levied on the purchase price of both tractor and trailer, the tax is excluded from this study as a pass-through cost. Baseline tractor and trailer price assumptions are used solely to estimate VKT elasticity effects, determining the percentage change in vehicle capital costs, and have no other influence on study results.

Baseline maintenance costs. To estimate the VKT elasticity effect associated with changes in maintenance costs, baseline costs for this study are taken as €0.091/km. This estimate is derived from detailed U.S. data (ATRI, 2015) but validated for consistency with EU practices. The latest detailed data available specifically for the EU dated from a 2006 study (Maibach, 2006). That study indicated a wide range of maintenance-cost estimates, including €0.02/km-€0.06/km for the eastern EU, €0.04/km for Spain, €0.08/km for the U.K., €0.081/km for Germany, and €0.15/km for France. A simple population-weighted average of these EU data yields an aggregate estimate of €0.081/km in 2005 euros. This is equivalent to a CPI-adjusted estimate of €0.098/km in 2016 euros. Given that not all of the EU population is reflected in the EU-specific data, combined with the relative consistency of the limited EU estimate with that of the more detailed and current U.S. estimate, this study relies on the more recent U.S. estimate to define baseline maintenance costs. This estimate is used solely to estimate VKT elasticity effects, determining the percentage change in vehicle maintenance costs, and has no other influence on study results.

Trailers per tractor. Based on data developed by Ricardo-AEA (Hill et al., 2011), it is estimated that there are 1.4 long-haul trailers in operation for every long-haul tractor. Note that Ricardo-AEA reports a ratio of "around 1:1," or roughly 2.2 million trailers and 1.7 million road tractors,[12] but that ratio and its underlying data includes both long and short-haul operators. Using TRACCS tractor-trailer distribution data (Papadimitriou et al., 2013), this study estimates long-haul units as those tractor-trailers with a gross combined weight of at least 34 tonnes. This criterion yields a long-haul to total tractor ratio of 0.791. Adjusting the Ricardo-AEA tractor population by this fraction yields a long-haul equivalent population of 1.34 million: 1.7 × 0.791 = 1.34. This study similarly adjusts the Ricardo-AEA trailer population by removing those trailers rated at less than 20 tonnes, the largest weight cutoff reported in the Ricardo-AEA data.[13] This results in a long-haul to total trailer ratio of 0.864. Adjusting the Ricardo-AEA trailer population by this fraction yields a long-haul equivalent population of 1.90 million: 2.2 × 0.864 = 1.90. These adjusted population estimates yield a long-haul trailer-to-tractor ratio of 1.4, dividing 1.90 by 1.34. Therefore, this study increases all per-trailer costs by a factor of 1.4 to account for the fact that 1.4 trailers will need to be upgraded for every improved tractor. Unless otherwise stated, the terminology tractor-trailer as discussed in the context of economic return on investment means a theoretical combination unit consisting of one tractor and 1.4 trailers.

Value Added Tax. Retail tractor-trailer, fuel, and maintenance prices in the EU are all subject to an average 21% VAT, calculated as the population-weighted average VAT rate for the EU as of January 2017 (EC, 2017c; TCU, 2017). Freight transport is, however, exempt from fuel VAT, so fuel prices and associated savings for this study do not include VAT. Although VAT is levied on the purchase price of tractors, trailers, and maintenance items, the tax is excluded from this study as a pass-through cost. As a result, the study excludes VAT from both the technology cost, or debit, and fuel savings, or asset, sides of

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[12] These figures apply to the 2008 fleet population, the latest data reported by Ricardo-AEA, and are reported only graphically in the Ricardo-AEA report on pages 74 and 80. Applying these data as stated would yield a trailer-to-tractor ratio of 1.29. Because the populations are estimated from report graphics, they are not precise and may differ modestly from the actual populations used by Ricardo-AEA to arrive at their conclusion of an approximate 1:1 ratio. Moreover, Ricardo-AEA also reports fleet data for years prior to 2008, and their conclusion may consider those data as well.

[13] The Ricardo-AEA data reports semi-trailer data for five capacity ranges: <5, 5-10, 10-15, 15-20, and 20 and greater tonnes. This study treats only the 20-tonnes and greater category as representative of long-haul operations.

all economic analysis. An alternative analysis that included levied VAT would find longer payback periods and reduced lifetime savings than those reported in this study, as technology and maintenance costs would increase while fuel savings, carrying an explicit VAT exemption, would not change.

Technology package real-world fuel consumption. All fuel-consumption impact estimates in this study are taken directly from the underlying ICCT simulation modeling assessment (Delgado et al., 2017), as summarized in Figure 1. Fuel consumption during real-world driving can be somewhat different from that achieved over standardized regulatory driving cycles, but this is less of an issue for long-haul tractor-trailers because of their more standardized and quasi-steady state operating characteristics, predominantly reflecting high-speed highway driving. As a result, this study assumes that real-world fuel consumption is equal to that estimated in the underlying modeling assessment.

INDIVIDUAL TECHNOLOGY COSTS

Technology costs form the basis of all economic analysis in this study. As indicated in Section I, the technology cost assessment is based on a review of existing research on heavy-duty vehicles and engines. As is the case with any study that evaluates future conditions, there is a level of uncertainty associated with study estimates. In a similar economic study of long-haul tractor-trailer fuel economy in the United States (Meszler, Lutsey, & Delgado, 2015), effort was made to capture the potential impact of such uncertainty by analyzing both “best-estimate high” and “best-estimate low” costs. Since the performance of that study, a considerable body of additional research has been reported to support regulatory programs for HDVs that have evolved beyond their nascent stages. Primary among these are the extensive cost data included in support of the U.S. Phase 2 CO_2 control program for HDVs (EPA, 2016a), as well as data included in several recent EU-focused studies (Hill et al., 2015; Dünnebeil et al., 2015; Norris and Escher, 2017). In light of this evolution, this study is based on a single set of best-estimate costs. That does not mean that all cost-estimate uncertainty has been resolved, but rather that sufficient research has now been conducted to allow the range of best-estimate costs to be reliably narrowed. While future refinement of cost estimates will continue as technologies evolve and become mainstream, this section presents the current best-estimate costs used for this study.

Engine technology. The various engine technology packages defined in accordance with the ICCT simulation modeling are treated on a quasi-aggregate basis from a costing standpoint in this study. The only deviation from aggregate treatment is for the engine technology packages that include either turbo compounding or ORC WHR. These technologies are costed separately and added to the aggregate cost of the included conventional, or non-heat recovery, engine technology. Conventional technology, depending on the specific technology package considered, can include improved valve control and valve train friction reduction, improved cylinder head designs, flow optimization, improved thermal management, an increased compression ratio, improved accessories and accessory management, improved turbocharging, increased fuel injection pressure and improved fuel control, improved EGR, reduced piston friction, and improved aftertreatment systems. The cost of such conventional gains is treated as a continuous function by relating cost to peak brake thermal efficiency (BTE).

Support documentation for the U.S. CO_2 Phase 2 HDV rulemaking (EPA, 2016a; Zhang, 2016) includes a number of engine maps that reflect EPA assumptions on engine improvements for years 2018, 2021, 2024, and 2027, reflecting peak BTEs as high as 49.2%. The technology assumptions underlying these maps do not reflect discrete technology applications, but rather reflect penetration-weighted averages of 2010 baseline and 2027 “maximum technology” maps. As such, it is not possible to tie the maps to any specific underlying technology package. EPA-estimated costs for assumed engines reflect the same penetration weighting, and it is not possible to factor out the penetration effects due to limitations on the resolution of the included data. Additional support material (Zhang, Brakora, & Cullen, 2015) does, however, document the 2027 “maximum technology” engine map and associated assumptions. While this additional support material does not include the associated engine map in detail, it does provide sufficient information to identify the peak BTE. Moreover, the material provides explicit information on the included technology and associated individual fuel-consumption impacts. Using these data, it is possible to extract the fuel-consumption impacts and costs of included WHR technology to derive a conventional technology cost and peak BTE estimate for the associated 2027 “maximum technology” engine. This data point can then be combined with two other data points to derive a relation between conventional technology cost and peak BTE. The first data point is the 2010 U.S. Phase 1 baseline, while the second is the 2017 U.S. Phase 2 baseline adjusted to remove turbo compounding technology. Data related to technologies assumed to be introduced between the 2010 and 2017 U.S. baseline engines—as required to factor out the effects of turbo compounding technology—that is not explicitly discussed in the U.S. Phase 2 documentation is reported in earlier documentation for the U.S. Phase 1 HDV CO_2 rulemaking (EPA, 2011). The resulting relation is then evaluated to determine the cost required to produce engines with the peak conventional technology BTEs assumed in the ICCT simulation modeling, or the engine-specific BTEs calculated by eliminating the impacts of waste heat recovery from the net system BTEs as applicable.

Additional costs are incurred for the ICCT engine technology packages that include waste heat recovery technology. The ICCT 2020-era engine technology package includes turbo compounding technology, for which the cost estimate is derived directly from the U.S. Phase 2 HDV CO_2 rulemaking (EPA, 2016a). The ICCT 2020+WHR engine technology package includes ORC WHR, the cost of which is also derived directly from the same U.S. reference. The ICCT long-term engine technology package includes improved ORC WHR technology, which is costed as an evolutionary improvement to base WHR systems. To estimate the impacts of this evolution the relationship between base and improved turbo compounding technology costs, both of which are included in the U.S. Phase 2 HDV CO_2 rulemaking, are analyzed to develop an estimate for the percentage change in cost per percentage change in fuel consumption impact. This rate of change in cost is then applied to current ORC WHR cost estimates to derive a cost estimate for improved ORC WHR. Note that the degree of WHR improvement being costed is less than 10%, so although the cost of this improvement is not based on a detailed ORC WHR analysis, any resulting error should be minor. The net cost for all engine configurations that include WHR technology reflects the sum of both basic engine improvements and WHR or WHR improvements, as applicable.

Developed engine technology cost estimates are presented in summary Table 10 appearing at the end of this section.

Driveline technology. The ICCT simulation modeling technology packages include the effects of two driveline technologies, increased transmission and axle efficiency. The specific efficiency assumptions are entirely consistent with those made by the EPA in the Phase 2 HDV CO_2 rulemaking analysis (EPA, 2016a). This study uses the cost estimates developed by the EPA for its high-efficiency gearbox and high-efficiency axle technologies, as estimated for heavy-duty tractor application. The resulting net driveline improvement costs are included in summary Table 10 at the end of this section.

Hybrid technology. Most of the parallel hybrid cost estimates for long-haul tractor-trailers in the United States are traceable to work published by the Northeast States Center for a Clean Air Future (NESCCAF) in 2009 (Cooper et al., 2009).

Derivative estimates appear in several subsequent studies (Kromer et al., 2009; Browning et al., 2010; NRC, 2010), but all remain consistent with the original NESCCAF work. The U.S. Phase 2 HDV CO_2 rulemaking does not include estimates for long-haul hybrid technology as the technology is not considered to be necessary to meet the adopted long-haul standards. A Ricardo-AEA (Hill at al., 2011) estimate of costs for the EU of €24,000 in 2010 euros are also consistent with the NESCCAF estimates. As a result, this study adopts the NESCCAF methodology to develop hybrid cost estimates but adjusts certain component costs to reflect two important changes. First, the sizing of the NESCCAF hybrid system with a 50 kW motor and a 4 kWh battery is not consistent with long-haul tractor systems in development today. These components are replaced with a 120 kW motor and a 2 kWh battery, consistent with the hybrid technology package simulated by the ICCT. Second, battery and motor costs have declined significantly over the last few years, and these reductions are reflected in the hybrid system estimates used in this study.

Modification of the NESCCAF estimates to reflect differential system sizes is straightforward as NESCCAF provides a stepwise cost estimation that includes explicit per-kW and per-kWh costs for the motor and battery. Thus, it is simple to reconstruct NESCCAF-equivalent estimates for alternative component sizing. To estimate current battery and motor costs, this study relies on recent estimates developed by FEV for the ICCT (FEV, 2015). The FEV study is topically related to light-duty vehicles but includes hybrid cost estimates for a range of battery and motor sizes so that generalized costing functions can be developed. The derived functions are then evaluated to estimate FEV-equivalent costs for a 120 kW motor and a 2 kWh battery. The estimated costs compare well on a per-kW and per-kWh basis to 2015-era battery and motor costs recently published by the ICCT (Wolfram & Lutsey, 2016). NESCCAF includes a separate line item cost for power electronics, but the cost for such componentry is included in the revised motor costs, so this line item cost is zeroed for this study. NESCCAF costs for transmission and accessory upgrades are retained without change, as is the NESCCAF approach for estimating wiring and balance of plant[14] costs as a fraction of other componentry costs. Using this approach, the developed low production volume cost for hybrid technology is €16,031. This cost is expected to decline over time reflecting learning and increased production volume as shown in summary Table 10 at the end of the section.

Given the differential in hybrid system estimates, it is perhaps important to briefly contrast the estimates used for this study with those of another recent EU study by IFEU (Dünnebeil et al., 2015). IFEU estimates low-volume hybrid system costs to be €40,000 in 2010 euros, equivalent to about €44,000 in 2016 euros. That is nearly triple the estimate used in this study. IFEU's projected costs of €15,000-€26,000 in 2016 euros after 10 years of additional development range from only slightly below on the low end to substantially higher on the high end than the initial low-volume costs used in this study. IFEU provides little discussion of the derivation of the estimates. Nevertheless, two conjectures are possible. First, the IFEU low-volume costs are not grossly different from the low-volume costs originally developed by NESCCAF on the basis of a 50 kW motor and 4 kWh battery and outdated motor and battery system costs. Second, and perhaps most informatively, IFEU provides separate cost estimates for a single replacement of the hybrid battery pack. The estimated cost for this replacement is €22,000 in 2016 euros for low-volume production and €8,000-€13,000 after 10 years of additional development. Such estimates are wildly inconsistent with battery costs even today, which for a 2 kWh pack excluding VAT would be approximately €1,000. IFEU does not provide information on the sizing of its hybrid system, but the data implies the

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[14] Balance of plant refers to all system parts not individually listed. Generally, these are supporting components such as switches, relays, packaging materials, etc.

assumption of a much larger battery or use of outdated battery costs, or a combination of both. In some respects, this would not be surprising as battery costs have declined dramatically over the past decade, dropping by about 80% since 2010 (Wolfram & Lutsey, 2016; Knupfer et al., 2017).

Engine downsizing/downspeeding. Cost estimates related to engine downsizing in the HDV sector are not widely available but are included in the rulemaking documents for the U.S. Phase 2 HDV CO_2 program (EPA, 2016a). That rulemaking assigns a savings of €471 for "slight" downsizing, which is also characterized as "right sizing," but the actual level of assumed downsizing is not stated. The rulemaking document cites Detroit Diesel and Volvo as properly implementing downsizing and downspeeding technology. Based on the cited references, it appears that Detroit Diesel is downsizing a 15 liter engine by 29% to 10.7 liters (Sisken, 2013; NRC, 2015) and that Volvo is downsizing a 13 liter engine by 15% to 11 liters (Pascal, 2014; NRC, 2015). It is not clear whether either of these downsizing levels is considered to be "slight," though it is hard to characterize 29% as such. In any case, it should also be noted that the EPA includes an estimated credit for downsizing as a component of the aggregated engine cost assessment. For this study, we remove the downsizing component from the engine technology costs and treat it as a separate technology for consistency with the ICCT simulation modeling analysis.

An earlier ICCT cost-effectiveness study for long-haul technology in the United States (Meszler et al., 2015) estimated the capital cost savings for downsizing technology from first principles, based on weight savings for a given level of downsizing and unit-weight material costs. For an engine downsized by 10%, the level evaluated in this study, capital costs were estimated to be reduced by €392. Given the general consistency between this estimate and the presumably more rigorous EPA Phase 2 savings estimate of €471, the EPA estimate for a "slightly" downsized engine is believed to be accurate for the purposes of this study, and is used directly.

While downspeeding technology carries no capital cost, it was assigned a modest cost of €62 in the U.S. Phase 2 rulemaking to account for the cost of testing and development. Although such cost should decline to zero over the near term as manufacturers gain familiarity with the technology, it is carried through 2030 with reductions for learning in the EPA analysis. Given its modest nature, this study does the same.

Summary Table 10 at the end of this section presents the net costs used in this study for downsizing/downspeeding technology.

Aerodynamic drag reduction. The U.S. Phase 2 HDV CO_2 rulemaking (EPA, 2016a) includes detailed data on the cost of aerodynamic drag-reduction technology for tractors and for trailers. For this study, all analysis is based on U.S. data for high-roof sleeper cab tractors as the baseline aerodynamic drag area for this configuration, 5.95 m^2, is equivalent to the baseline drag area of 6.0 m^2 for this study. Including pre-baseline configurations, the U.S. data for tractors spans seven aerodynamic configurations covering a wide range of drag areas, from a high of 7.45 m^2 to a low of 4.2 m^2. When coupled with the eight trailer configurations reflected in the U.S. data, the range of covered drag area expands to a low of 2.4 m^2. The difficulty associated with achieving drag performance in the lower end of the range covered by the U.S. data is well recognized. Such levels are well below the long-term drag performance of 3.5 m^2 evaluated in this study, but the breadth of U.S. data range is important as it allows costs for all of the performance levels evaluated in this study to be estimated from a wider range of explicitly costed technology.

This study covers five levels of aerodynamic drag, with drag areas of the baseline 6.0 m^2 as well as 5.0 m^2, 4.6 m^2, 4.4 m^2, and 3.5 m^2. These levels can be achieved through a wide range of tractor and trailer combinations, with improvement paths ranging from tractor-centric to trailer-dominant improvement, and every potential path in between.[15] For this study, the improvement path is structured to match that assumed in the ICCT simulation modeling study: concurrent tractor and trailer improvements. Initial modifications for the “incremental” aerodynamic drag package focus on modest tractor improvements and first-step trailer improvements such as side skirts and gap reducers. The “moderate” drag package includes additional tractor and trailer improvements such as side skirts plus rear fairings. The “advanced” and “long term” drag packages focus on progressively more advanced tractor technology. The most advanced aerodynamic drag technology evaluated in this study is characterized by a tractor with technology slightly more advanced than the sixth of seven U.S. tractor technology levels, reflecting a drag area of 4.5 m^2 when coupled with a baseline trailer. The actual combined trailer is assumed to have drag characteristics equal to the sixth of eight U.S. trailer technology levels, resulting in a drag reduction relative to a baseline trailer of 1.0 m^2 and an effective combination drag area of 3.5 m^2. There are other combinations of tractor and trailer improvements that can produce similar net drag performance, and many at lower overall cost. For all but the most extreme reductions, a tractor-centric focus will result in lower costs in large part because multiple trailers need to be improved for each improved tractor. While least-cost accounting would produce more cost-effective economic metrics, this study assumes a more “real world” approach of integrating both tractor and trailer improvements.

Because some of the tractor drag characteristics for this study reflect performance that is between discrete U.S. tractor technology levels, the U.S. relations for cost versus drag area are generalized using regression analysis. The correlation coefficients for this generalization range from 0.97 to 0.99 for all evaluation years through 2030. This results in a continuous improvement function for tractors, allowing costs to be estimated for any given tractor aerodynamic performance level. Such a given tractor can then be mated with any of the available trailer configurations and net costs determined by summing the individual tractor and trailer costs. In all cases, the cost of trailers is adjusted to reflect the ratio of trailers to tractors in the EU as described above, as multiple trailers will need to be modified for every tractor to ensure that in-use performance is equivalent to modeled performance.

Since the EU ratio of trailers to tractors is relatively close to unity, the effect of selecting an aerodynamic drag improvement path that favors tractors over trailers, or vice versa, is muted relative to a location where a higher ratio of trailers is observed. The net cost of trailer-based improvements scales directly with this ratio, so there is considerable economic sensitivity with regard to potential regulatory costs. By using the ratio of 1.4, this study takes a conservative approach relative to selecting an alternative value of unity as has been estimated in previous EU studies such as the HDV greenhouse gas emissions study by Ricardo-AEA for the European Commission (Hill et al., 2011).

Finally, although the level of cost estimation for aerodynamic improvements in available EU research is substantially less detailed, discrete data is available in studies such as that performed recently for EU HDVs by Ricardo-AEA (Norris & Escher, 2017). That study presents data for a 25% reduction in tractor-trailer drag. Figure 7 shows the cost estimated by Ricardo-AEA for that reduction versus the costs used in this study, as derived from the U.S. Phase 2 HDV CO_2 rulemaking data. As indicated, the Ricardo-AEA data point is quite consistent with the 2030 costs estimated in this study, especially if the Ricardo-AEA baseline drag characteristics are normalized with those of this

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[15] Note that neither tractor nor trailer-dominant improvements can reach all of the performance levels evaluated in this study. These approaches simply signify an initial focus. At some point trailer improvements will be required under a tractor-centric approach and vice versa.

study. It is not possible to precisely adjust the Ricardo-AEA estimate to account for a trailer-to-tractor ratio of 1.4, but the potential impact of such an adjustment is shown by the vertical dashed lines with arrows in Figure 7. If the fraction of Ricardo-AEA costs associated with trailer improvements were known, the Ricardo-AEA data point would move up the dashed line, with the tip of the arrow indicating the adjustment that would apply if 100% of the aerodynamic drag improvement were trailer-based. Smaller trailer-based fractions would scale proportionally. As indicated, the resulting Ricardo-AEA data point would lie neatly between the 2014 and 2030 cost curves used in this study. Thus, the drag reduction estimates derived from the U.S. data are quite consistent with findings based on alternative EU-specific data.

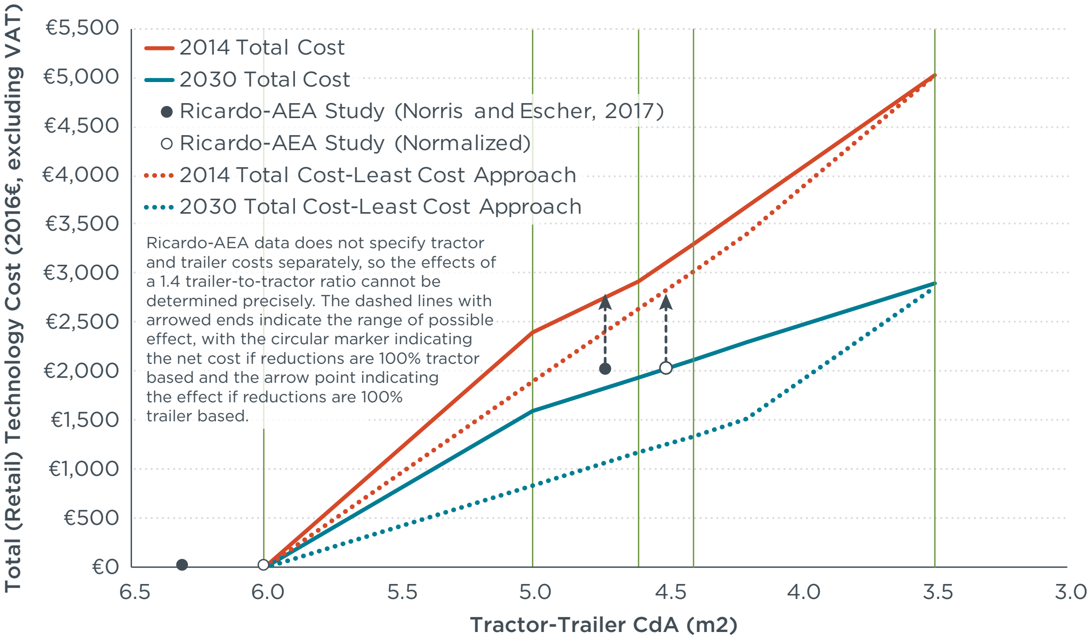

Figure 7. Aerodynamic drag technology cost curves (1.4 trailers per tractor)

Note that Figure 7 also depicts the costs that would have been estimated for a tractor-centric drag reduction approach. Costs incurred under such an approach would be lower for all but the most advanced technology packages in which trailer improvements are required to reach the demanded level of performance. These least-cost curves are provided for illustration only as this study relies on the integrated approach that assumes both tractor and trailer improvements across the range of evaluated aerodynamic performance.

Note also that Figure 7 depicts data developed for this study for two years, 2014 and 2030. The difference between these two years is that 2014 illustrates baseline cost data and 2030 illustrates equivalent data adjusted for learning throughout the intervening period. The intent is to illustrate the range of baseline and future costs of the associated technology. This same approach is employed throughout the study for various evaluated technologies.

Specific developed costs are included in summary Table 10 at the end of this section.

Rolling resistance reduction. As was the case for aerodynamic drag reduction technology, the most detailed cost data available is presented in the U.S. Phase 2 HDV CO_2 rulemaking documentation (EPA, 2016a). The EPA includes different cost estimates for drive, steer, and trailer tires, but the difference among the three for a given percentage change in rolling resistance is minor. The data covers reductions ranging from 15-45%, which more than covers the range of rolling resistance reductions evaluated in this study. On an absolute basis, the U.S. data does not reach the levels evaluated here, but this is not problematic as the nature of rolling resistance costs is such that an initial significant step change to more expensive designs and materials is followed by reasonably linear and comparatively modest additional costs for further evolutionary reductions. To avoid missing this step change in costs for moving from conventional to low rolling resistance tires, this study treats the U.S. technology cost data on a percentage reduction basis. In this manner, the step change is captured in the first step toward lower rolling resistance, regardless of the absolute level of performance. Incremental costs for subsequent improvements are estimated in accordance with the secondary linear function.

Even through the ICCT simulation modeling includes five levels of rolling resistance for the combined tractor-trailer unit, only three levels of rolling resistance tires are considered: energy efficiency class C tires with an assumed coefficient of rolling resistance (C_{rr}) of 5.5 kg/tonne, efficiency class B tires with an assumed C_{rr} of 5 kg/tonne, and efficiency class A tires with an assumed C_{rr} of 4 kg/tonne.[16] It is the combination of these three tires across the steer, drive, and trailer axles that results in the five levels of performance modeled by the ICCT. The ICCT baseline, with a C_{rr} of 5.5, lies at the midpoint of tire energy efficiency class C, which ranges from 5 to 6 kg/tonne. The “incremental” technology package includes class B tires on all axles. The “moderate” technology package includes class A trailer tires but retains class B tires on the tractor. The “advanced” package adds class A tires to the tractor steer axle, while the “long-term package” completes the transition to all class A tires by substituting class A tires for class B tires on the tractor drive axle. Thus, costs are developed for the three tire classes and weighted by tire count to determine the net cost for each of the five technology packages.

Two additional weighting factors are included in the net package cost calculation. First, trailer tires are weighting by a factor of 1.4 to reflect the ratio of trailers to tractors in the EU. This factor accounts for the fact that multiple trailers will need to be equipped for every equipped tractor to ensure that in-use performance is equivalent to that modeled. Second, an additional weighting factor for trailer tires is applied to reflect their typically differential width. For this study, it is assumed that trailer tires are 385 mm wide as compared with standard 315 mm tractor tires, and that such tires will carry incremental rolling resistance reduction costs relative to those of the standard tire. This study scales costs in accordance with the differential tire widths, so trailer tires are assumed to carry incremental costs that are 385/315, or 1.22, times the incremental costs of tractor tires. In effect, this study models costs for six-tire trailers as if they were equipped with 10.2 tractor tires (6 × 1.22 × 1.4).

Although the level of cost estimation for rolling resistance improvements in available EU research is substantially less detailed, discrete data is available in studies such as those performed recently by IFEU (Dünnebeil et al., 2015) and Ricardo-AEA (Norris & Escher, 2017). Figure 8 compares the data used in this study with corresponding data from the EU-specific studies. The IFEU study report is sufficiently detailed to allow estimated costs to be adjusted for the 1.4 trailer-to-tractor ratio used in this study, and the data depicted for IFEU includes such an adjustment. As a result, it is directly comparable to the data for this study. As indicated, this study assumes somewhat higher costs for all levels of evaluated rolling resistance.

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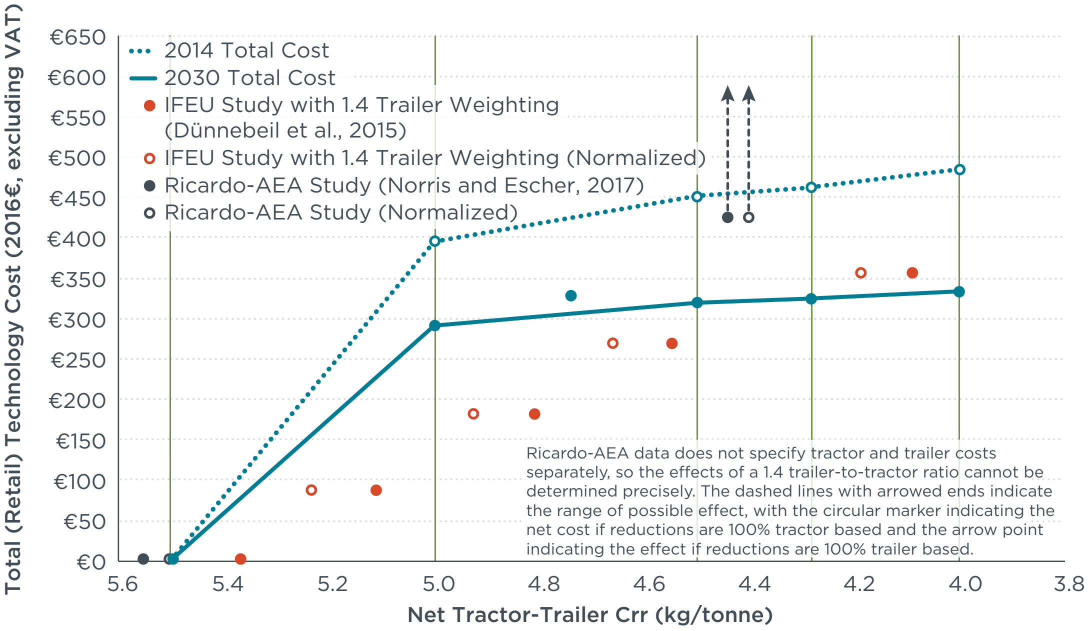
[16] The assumed C_{rr} for class C tires reflects the midpoint of tire energy efficiency class C, which ranges from 5 to 6 kg/tonne. For class B (4 to 5 kg/tonne) and class A (≤4 kg/tonne) tires, the assumed C_{rr} values reflect the upper end of each performance range. The use of the midpoint for class C tires is intended to reflect a mix of class B and class C tires on the baseline tractor-trailer.

Although Ricardo-AEA data are included in Figure 8, these data should be viewed with caution. According to the study report, Ricardo-AEA calculated rolling resistance costs as annual average costs that reflect both initial tire purchase and incremental maintenance costs incurred through the continuing need to procure low rolling resistance replacement tires. There is nothing fundamentally incorrect with such an approach; there is simply insufficient information in the Ricardo-AEA report to ensure that the resulting estimates are comparable to initial capital cost impacts.[17] As indicated, the Ricardo-AEA data point is quite consistent with the 2014 baseline costs estimated in this study. However, although it is not possible to precisely adjust the Ricardo-AEA estimate to account for a trailer-to-tractor ratio of 1.4, the maximum impact of such an adjustment, as shown by the dashed lines with arrowed ends, would indicate higher costs than assumed in this study. If the fraction of Ricardo-AEA costs associated with trailer improvements were known, the Ricardo-AEA data point would move up the dashed line, with the tip of the arrow indicating the adjustment that would apply if 100% of the rolling resistance improvement were trailer-based. Lesser trailer-based fractions would scale proportionally. Given the uncertainty associated with the Ricardo-AEA estimate and the general consistency of IFEU estimates, the rolling resistance reduction estimates derived from the U.S. data appear to be quite reasonable for application in the EU and are used accordingly in this study.

ICCT simulation modeling assumes that tires are properly inflated to appropriate pressure at all times. The use of technologies such as tire pressure monitoring or automatic tire inflation systems is not assumed and, therefore, the costs of such systems are not considered in this study. Summary Table 10 at the end of this section presents developed rolling resistance reduction costs.



Ricardo-AEA data does not specify tractor and trailer costs separately, so the effects of a 1.4 trailer-to-tractor ratio cannot be determined precisely. The dashed lines with arrowed ends indicate the range of possible effect, with the circular marker indicating the net cost if reductions are 100% tractor based and the arrow point indicating the effect if reductions are 100% trailer based.

Figure 8. Rolling resistance technology cost curves (1.4 trailers per tractor)

Weight reduction. Evaluating the costs of weight-reduction technology can be more complicated than cost evaluation for other efficiency-improving technology. This is because other technologies can include an inherent weight effect, either adding to or reducing vehicle weight. This must be properly considered to accurately quantify and cost a desired weight reduction. In this study, this complication is addressed by adjusting

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[17] Replacement tire costs are considered to be a maintenance impact in this study and are addressed along with other similar issues in the maintenance impact discussion included later in this section.

the simulation modeling fuel consumption estimates to include the incremental weight effects of any included technology, so that costs can be developed independent of such effects. As a result, each weight-reduction option is evaluated discretely from a costing standpoint. Table 7 presents the five weight-reduction options included in the analysis and illustrates the basic difference between the accounting approach employed in this study and the alternative approach that must be employed when technology weight effects are not explicitly accounted for in fuel-consumption estimates. To ensure that the differences between these approaches are transparent, additional discussion is included following presentation of the approach used in this study. The five levels of weight reduction range from 200-2,300 kg, representing reductions of up to 16% of baseline vehicle weight.

Detailed EU-specific capital cost data are available for weight-reduction technology, from two Ricardo-AEA studies in particular (Hill et al., 2015; Norris & Escher, 2017). The 2015 Ricardo-AEA study provides detailed information on the level of potential weight reduction achievable for a 40 tonne tractor-trailer, the timing over which specific weight reductions can be achieved, and the cost of the reductions. Moreover, these data are provided separately for tractors and trailers. The only downside to using the data from the 2015 study directly is that the included inventory of potential weight-reduction steps considers all potential measures, regardless of cost, so that a few very high-cost measures have an inordinate impact on aggregate option costs. For example, the study indicates that 876 kg of weight reduction at a cost of €5,957 could potentially be achieved by 2030 from a 40 tonne tractor with a base curb weight of 7,500 kg, but there is no way to know from data presented in the study report what fraction of the benefit and cost is due to very high-cost measures. However, the 2017 Ricardo-AEA study provides a mechanism to address this issue. The weight-reduction data included in the 2017 study is taken directly from the 2015 study with one distinction. The 2017 study includes a distribution of 2030 weight-reduction options by six explicit cost-effectiveness ranges and a seventh implicit range including all measures not included in the six explicit ranges. From this distribution, it is possible to determine the aggregate weight reduction and costs associated with any combination of the seven ranges of data. For this study, all weight-reduction options with cost-effectiveness ratios greater than 10 euros per kg are excluded, which results in achievement of 97.4% of the maximum potential weight reduction at 80.1% of the maximum potential costs.

Table 7. Weight reductions associated with ICCT simulation modeling

Weight reduction configuration	Curb weight (kg) This Study	Reduction (kg) This Study	Curb weight (kg) Alternative Method	Reduction (kg) Alternative Method
Baseline	14,400	0	14,400	0
Incremental	Varies by Package	200	14,200	Varies by Package
Moderate	Varies by Package	400	14,000	Varies by Package
Advanced	Varies by Package	1,000	13,400	Varies by Package
Long Term	Varies by Package	2,300	12,100	Varies by Package

The curb weight of each technology package in this study varies because the weight effects of included technologies are not offset but rather are accounted for in the fuel-consumption simulation modeling. The curb weight of each package is equal to the baseline curb weight of 14,400 kg plus the weight effects of included technologies minus the associated weight reduction. The costing analysis for this study includes only the nominal weight reductions with curb weight varying with technology. The curb weight for the alternative accounting method is fixed such that each package reflects a specified percentage weight reduction relative to the baseline technology package. To achieve these targets, the net weight reduction to be costed is equal to the sum of the nominal weight reduction and the weight effects of included technologies. Under the alternative accounting method, the fuel consumption impacts associated with the weight effects of added technology are zero since the effects are entirely offset through additional weight-reduction requirements.

The 2017 Ricardo-AEA study does not provide separate data for tractors and trailers or data explicit to other evaluation years as Ricardo-AEA evaluated three years: 2020, 2030, and 2050. As a result, identical high cost exclusion criteria[18] are applied in this study across all evaluation years and to both tractors and trailers separately. Because this study focuses on the 2020-2030 timeframe, only the 2020 and 2030 Ricardo-AEA data are considered. Thus, the 2015 Ricardo-AEA data are adjusted to reduce potential weight-reduction impacts by 2.6% and potential weight-reduction costs by 19.9% to eliminate the effects of high-cost weight-reduction options. Finally, this study also makes a marginal adjustment to normalize the Ricardo-AEA data to the curb weights assumed in the ICCT simulation modeling study. The tractor and trailer baseline curb weights assumed in the Ricardo-AEA study were 7,500 kg and 7,050 kg, respectively. The respective ICCT-assumed curb weights are 7,400 kg and 7,000 kg. To correct for the differential curb weight assumptions, this study reduces the Ricardo-AEA weight-reduction options for tractors and trailers by 1.3% and 0.7% respectively. Weight-reduction costs are unaffected by this normalization. Using these adjusted data, weight-reduction cost curves are developed for tractors and trailers individually.

Figure 9 depicts the derived cost curves as well as several comparative data points. The Ricardo tractor and trailer curves for 2014 and 2030 reflect the adjusted Ricardo-AEA data as used in this study. Figure 9 also shows data points from the weight-reduction cost curves developed to support the earlier ICCT economic study of long-haul tractor-trailer fuel economy in the United States (Meszler et al., 2015). The cost estimates developed for the U.S. study are quite consistent with those developed for this study using the Ricardo-AEA data. The primary cost difference is that the Ricardo-AEA data show lower trailer costs than were estimated for the U.S. study. Nevertheless, given that the data used for this study and that used for the U.S. study are entirely independent, the consistency is remarkable. At the time the U.S. study was performed, data on tractor-trailer weight reduction was quite limited, and a methodology was developed to adapt light-duty vehicle weight-reduction data. Based on the tractor-trailer data now available, it appears that the approach employed led to quite reasonable results.

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[18] As discussed in the preceding paragraph, options with cost-effectiveness ratios greater than 10 euros per kg are excluded. The Ricardo-AEA data show that 97.4% of maximum potential weight reduction can be achieved at 80.1% of maximum potential costs.

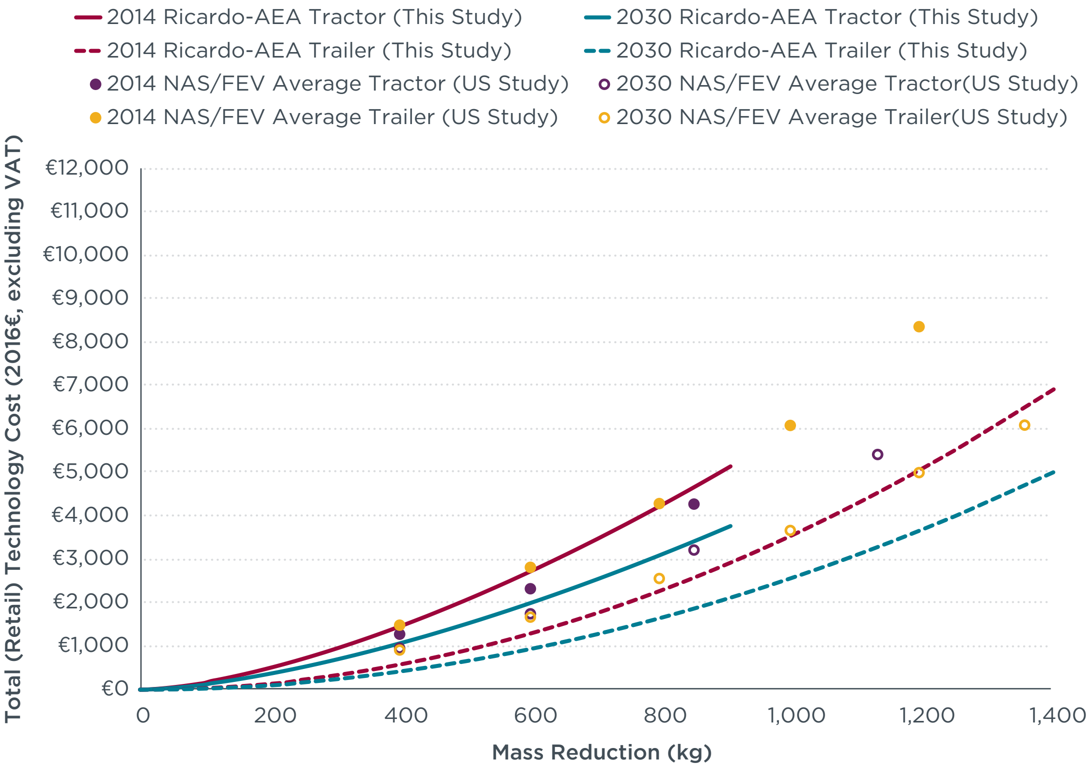

Figure 9. Weight reduction technology cost curves (1 trailer per tractor)

The biggest difference between the weight-reduction curves used for this and the U.S. study is the weight-reduction distribution potential for tractors versus trailers. For this study, the Ricardo-AEA data show a potential of about 853 kg for tractors and 1,364 kg for trailers in the 2030 timeframe. For the U.S. study, based on DOE data (DOE, 2013), the potential for 2030 is essentially reversed at 1,628 kg for tractors and 910 kg for trailers. No specific changes are implemented in this study as a result of this distinction, but it is notable that the weight-reduction potential may be larger than the cost curves in this study might otherwise imply. For this study, the maximum weight reduction evaluated is 2,300 kg, which is almost identical to the 2,196 kg—842 kg for the tractor and 1,354 kg for the trailer—data points used in the construction of the study cost curves. In actuality, the level of weight reduction achieved through material substitution could be somewhat lower depending on assumptions with regard to secondary weight reduction as described below, but this study assumes no secondary weight reduction beyond that explicitly considered by Ricardo. This is because opportunities for structural demand reduction are limited in the long-haul sector as the vehicle must always be capable of carrying a maximum payload. Since weight-limited payload capacity will increase in direct opposition to any vehicle weight decrease, the net structural load that a vehicle must be capable of handling will not change. Finally, it is perhaps also worth noting that the data in Figure 9 do not include the 1.4 trailer weighting factor as the intent of the figure is to show individual tractor and trailer impacts, although that factor is applied in all cost calculations in this study.

Finally, as discussed above, weight-reduction potential is not equally distributed between the tractor and the trailer. Because weight reduction can be targeted toward the tractor, the trailer, or both, some allocation strategy is required. For this study, it is assumed that all weight reduction is split between the tractor and the trailer in accordance with the share each contributes to the maximum potential weight reduction, or 842 kg for the tractor and 1,354 kg for the trailer. Thus, 38.3% of all weight-reduction requirements are allocated to the tractor and 61.7% to the trailer. All estimated trailer reduction costs are increased by 40% to account for the 1.4 trailer-to-tractor ratio assumed for the EU. Developed weight-reduction costs are presented in summary Table 10 at the end of this section.

The remainder of this section consists of additional background information on the two approaches to accounting for technology weight impacts and on secondary weight-reduction impacts. This discussion does not affect the results of the study and is provided solely for informational purposes.

As indicated above, weight-reduction accounting is somewhat more complicated than the accounting employed for other technologies. Because individual technologies can affect the weight of the host vehicle, achieving any level of nominal mass reduction can require weight reductions that are either greater or less than nominal in accordance with the applied technology package. In effect the actual weight reduction required to achieve a nominal weight reduction of say X kg will be technology-package dependent, and may be less than, equal to, or greater than X kg. To achieve a desired absolute change in vehicle curb weight, weight reductions must be allowed to vary in accordance with the weight effects of any given technology package. If a specific nominal weight reduction is applied to any given technology package, then vehicle curb weight will be technology-package dependent. The former approach results in weight-reduction costs that vary by technology package. The latter approach results in weight-reduction costs that are insensitive to technology package components but requires fuel- consumption estimates for each package to properly account for inherent package-specific weight effects. The earlier economic study of long-haul tractor-trailer fuel economy in the United States (Meszler et al., 2015) uses the former approach, whereas the ICCT simulation modeling that forms the basis of this study (Delgado et al., 2017) applies the latter. Table 7 depicts the differential implications of the two methods.

The major implication of fixed curb weight accounting from a costing standpoint is that weight-reduction costs must be developed on a continuous, as opposed to a discrete, basis so that the weight effects of any given package of technologies can be appropriately addressed. Even though this study addresses weight reduction in terms of five distinct invariant options, with reductions ranging from 200-2,300 kg and representing reductions of up to 16% of baseline vehicle weight, weight-reduction costs are still developed on a continuous basis as depicted in Figure 9. This ensures that the effects of the alternative approach of evaluating greater potential fuel-consumption reduction, but at greater cost, could be evaluated without additional cost estimation work.

In the non-freight sector, vehicle weight-reduction technology generally carries a secondary benefit. As the weight of a vehicle is reduced, the structural demand on materials also declines allowing for further design changes and weight reduction. A wide range of estimates of the magnitude of this feedback loop have been developed, but most of the differences can be explained through differences in the focus of the associated research. Studies that primarily focus on engine and body systems tend to show very large secondary weight-reduction potential, in some studies exceeding the potential of the primary weight reduction. For example, a detailed analysis of light-duty vehicle options adapted for the ICCT economic study of long-haul tractor-trailer fuel economy in the United States indicated a secondary weight-reduction potential of 79% of primary reduction potential when only engine and body systems were considered (Meszler et al., 2015). However, if the scope of primary reductions is extended to also include closures, bumpers, suspensions, brakes, and fuel system components, secondary weight-reduction potential declines substantially—in the case of the U.S. study analysis to 25% of primary reductions as systems with less secondary reduction potential are directly evaluated. Thus, the scope of a primary weight-reduction evaluation strongly influences secondary weight-reduction potential. This study assumes that the potential for secondary weight reduction in the freight sector is zero. Opportunities for structural demand reduction are limited as freight vehicles are capacity-rated by weight. These vehicles must always be capable of carrying their rated payload. Since weight-limited payload capacity will increase in direct opposition to any vehicle weight decreases, the net structural load that a freight vehicle must be capable of handling will not change, precluding opportunities for secondary weight reduction.

Other fixed costs. In the development of cost estimates for the U.S. Phase 2 HDV CO_2 rulemaking (EPA, 2016a), which form the basis for many of the cost estimates in this study, certain fixed costs are not accounted for in either direct or indirect costs. These are primarily related to compliance-demonstration and engine research and development. Those costs instead are allocated as a separate consideration and, to the extent they would apply to the EU, should be accounted for in this study as well since the same ICMs employed for the Phase 2 rule form the basis of indirect cost estimates for this study. Compliance-related costs are excluded from this study as they do not apply in the EU,[19] but engine research and development costs are applicable. To accommodate an accurate assessment of these costs, this study treats "fixed costs" as a distinct "technology," the cost of which is included in every evaluated, non-baseline technology package.

The absolute fixed costs of the U.S. Phase 2 rulemaking are translated for this study into per-vehicle total 2027 engine costs, direct plus indirect. This allows fixed costs to be expressed as a fraction of 2027 engine costs. The resulting factor of 15.1% can be directly applied to the estimated EU engine costs in 2027 to determine EU-equivalent fixed costs. This results in four levels of fixed costs, one for each of the non-baseline engine technology packages evaluated in this study. The U.S. Phase 2 rulemaking assumes that fixed costs are recovered over a four-year period, an assumption maintained in this study for consistency with the approach used to estimate per-vehicle costs. Table 8 shows the estimated fixed costs and the years they are assumed to be incurred.

Table 8. Per-vehicle fixed cost estimates (2016€, excluding VAT)

Engine configuration	Fixed cost	Recovery period
2015 Baseline	€0	not applicable
2017 Best-In-Class	€42	2018-2021
2020	€304	2020-2023
2020+WHR	€836	2022-2025
Long Term	€1,029	2025-2028

Maintenance impacts. A number of the technologies evaluated in this study carry impacts independent of initial cost differentials. This study treats such post-purchase costs as maintenance items and accounts for their impact by calculating their initial cost equivalent and adding that estimate to explicit initial vehicle purchase costs. The initial cost equivalent is the net present value (NPV) of all applicable maintenance impacts for a given evaluation year. Generally, this can be thought of as the sum of money that would have to be escrowed on the day of initial purchase to fund the incremental costs of all combined maintenance impacts without additional investment over the lifetime of an affected tractor-trailer. The magnitude of the escrow investment is equal to the lost opportunity cost, were the same funds put to alternative use. NPV estimation requires knowledge of the magnitude and timing of a stream of future payments and the assumption of an effective discount rate to convert future payments into initial cost equivalents. As discussed earlier, this study evaluates economic impacts under three discounting scenarios: 4%, 7%, and 10%.

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[19] Certainly some level of compliance cost would be applicable in the EU if fuel-efficiency standards for HDVs were adopted. Given the uncertainty associated with the form, stringency, reporting, and oversight requirements of an EU standard, this study does not attempt to quantify such costs. Nevertheless, it is expected that such costs would be modest on a per-vehicle basis.

The timing of maintenance impacts is determined in accordance with an assumed event frequency, expressed in terms of an activity interval, or the number of kilometers accumulated between each maintenance event, and the survival-weighted activity distribution described above and summarized in Figure 6. The NPV of lifetime maintenance is then calculated by summing the discounted cost of each event.

Five technologies are assumed to impose incremental maintenance costs in this study: low-viscosity engine oil, low rolling resistance tires, waste heat recovery systems, high efficiency axle lubricant, and hybrid system battery replacement. For all but low-viscosity engine oil, the associated maintenance intervals are taken from the U.S. Phase 2 HDV CO_2 rulemaking (EPA, 2016a). The maintenance interval for replacing low rolling resistance tires is 300,000 km, which equates to 3.0 events per survival-weighted lifetime. WHR system maintenance is every 160,000 km, resulting in 6.1 events per survival-weighted lifetime. The interval for axle lubricant is 800,000 km, or 0.8 maintenance events per survival-weighted lifetime. The hybrid battery replacement interval is 400,000 km, equating to 2.1 replacements per survival-weighted lifetime.

The maintenance interval for engine oil is set in accordance with Daimler Detroit Diesel specifications (DDC, 2017). The maintenance interval for conventional, CJ-4 grade oil is nominally set at the manufacturer's 80,000 km specification, but this study uses 40,000 km as the practical interval, equal to the manufacturer's severe-use maintenance interval. The maintenance interval for low-viscosity, FA-4 grade oil is nominally set at 113,000 km, the average of the manufacturer's 105,000-121,000 km specification. But this study uses 55,000 km as the practical interval, equal to the manufacturer's severe use maintenance interval. Thus, the number of maintenance events when using low-viscosity oil, 18.6, is reduced from the number using conventional oil, 25.8.

The cost per maintenance event for WHR and high-efficiency axle lubricant are taken from the U.S. Phase 2 HDV CO_2 rulemaking (EPA, 2016a) and are set at €283 for WHR and €94 for the axle lubricant. Although these costs are likely to decline in real terms with learning, they are held constant for this analysis. Replacement hybrid system battery costs are set at the battery costs estimated to be applicable for new vehicles sold in study evaluation years 2025 and 2030. These costs are estimated as described above for hybrid technology and are not assumed to decline beyond the effects of learning between now and the applicable evaluation year, even though replacement events will occur years after initial vehicle purchase. The costs for replacement of low rolling resistance tires are similarly estimated in that they are set at the low rolling resistance technology cost estimated for new vehicles sold in study evaluation years 2025 and 2030 as described above. As with the hybrid batteries, the costs are not assumed to exhibit any further learning after the study evaluation year even though replacement events will occur years after initial vehicle purchase. Unlike trailer initial incremental purchase costs, the costs for trailer tire replacement do not reflect a 1.4 trailer-to-tractor weighting factor. This is because, regardless of population ratios, operations are limited to a single combination. A population ratio greater than one simply means that trailers will accumulate mileage more slowly than tractors. While this study does not account for the small reduction in cost that would result from the greater discounting effects of an extended time interval between trailer maintenance events, it does properly treat maintenance as a unit-trailer event.

Data on the cost of low-viscosity oil is inordinately sparse given that such oils have entered the marketplace and are among the most frequent maintenance items. For this study, it is assumed that low-viscosity oil is an oil meeting new American Petroleum Institute (API) service category FA-4, and that it replaces alternative CJ-4 service category oil (API, 2016). Although oils meeting these specifications are available from all major oil producers, pricing information is limited. For this study, pricing data come from a Canadian distributor of BP-owned, U.K.-based Castrol products (Wakefield, 2017). Pricing for a baseline conventional CK-4 oil is compared to a semi-synthetic FA-4, both formulations of which meet major HDV manufacturer oil specifications. Although the ideal baseline oil would be of service category CJ-4, a comparative check of CJ-4 formulation prices indicates no significant price differential with the CK-4 formulation offered by the Castrol distributor. Moreover, the comparative prices used in this study are for small, 18.93 liter pails, and it is likely that the volume discounts associated with bulk purchases would result in smaller price differentials than those assumed in this study. It is worth noting, however, that identical oil products—same brand, formulation, and size—are subject to a very wide range of prices, and it is therefore difficult to isolate comparative data. That the pricing estimates for this study are taken from the pricing sheet of a single distributor should eliminate cross-distributor variability issues, but there is little doubt that prices obtained from different distributors will almost assuredly differ from the prices used for this study.

The study assumes the use of 37.8 liters of oil for every maintenance event and an increase in oil cost of €0.44 per liter, for a net increase in per-event costs of €16.58. However, because of the decrease in the number of required service events as a result of the extended life of the newest low-viscosity formulations, this results in a small net savings to tractor operators.

Table 9 summarizes the resulting NPV of incremental maintenance costs estimated for this study. As with incremental initial vehicle purchase costs, VAT is excluded from the cost of all maintenance events in determining the economic impacts of HDV fuel-consumption reduction technology in this study. Actual incurred costs for maintenance items will, on average, exceed the estimates presented in Table 9 by 21%, in accordance with the EU average VAT rate. It should also be recognized that since maintenance costs are a function of VKT, and since VKT is sensitive to vehicle operating costs as per the VKT elasticity discussion above, applied maintenance costs are adjusted from those presented in Table 9 in accordance with the elasticity impacts of each economic valuation scenario. The elasticity adjustment is generally minor, but applied costs will be marginally higher than those presented in a decreasing fuel- consumption environment as in this study.

Table 9. Nominal per-vehicle maintenance cost impacts (NPV 2016€, excluding VAT)

Technology/Configuration		2025 evaluation year			2030 evaluation year		
		Discount rate			Discount Rate		
		4%	7%	10%	4%	7%	10%
Low-Viscosity Engine Oil		-€276	-€246	-€223	-€276	-€246	-€223
Low Rolling Resistance Tires **Tractor**	**Baseline**	€0	€0	€0	€0	€0	€ 0
	Incremental	€259	€219	€189	€248	€210	€ 182
	Moderate	€259	€219	€189	€248	€210	€ 182
	Advanced	€281	€238	€205	€260	€220	€ 190
	Long Term	€324	€275	€237	€284	€240	€ 208
Low Rolling Resistance Tires **Trailer**	**Baseline**	€0	€0	€0	€0	€0	€ 0
	Incremental	€315	€267	€231	€302	€256	€ 221
	Moderate	€395	€334	€289	€345	€292	€ 253
	Advanced	€395	€334	€289	€345	€292	€ 253
	Long Term	€395	€334	€289	€345	€292	€ 253
Waste Heat Reduction		€1,367	€1,179	€1,035	€1,367	€1,179	€1,035
High Efficiency Axle Lubricant		€54	€43	€35	€54	€43	€35
Hybrid Battery		€978	€819	€699	€904	€757	€646

Individual technology cost summary. Based on the approaches described above, direct manufacturing and indirect costs are compiled for each of the technologies evaluated in this study. Table 10 summarizes the total cost of each individual technology, excluding independently accounted-for fixed costs that do not vary over time and maintenance costs as reported in Tables 8 and 9 above. The total costs are summarized for years 2015, 2020, 2025, and 2030, showing the effect of learning on technology costs over time. The total composite configuration estimates in the bottom rows of the table include a weighting factor of 1.4 trailers per tractor. All other trailer estimates are per-trailer.

Table 10. Individual technology costs (2016€ direct plus indirect, excluding VAT) for 2015, 2020, 2025, and 2030

Technology		2015	2020	2025	2030
Engine configuration	2015 Baseline	€0	€0	€0	€0
	2017 Best-In-Class	€362	€317	€284	€266
	2020	€2,638	€2,323	€2,065	€1,907
	2020+WHR	€11,199	€9,307	€5,763	€4,912
	Long Term	€13,302	€11,099	€7,081	€6,088
Weight configuration **Tractor**	Baseline	€0	€0	€0	€0
	Incremental	€103	€92	€81	€78
	Moderate	€330	€297	€255	€245
	Advanced	€1,347	€1,214	€1,044	€1,003
	Long Term	€4,845	€4,365	€3,755	€3,606
Weight configuration **Trailer**	Baseline	€0	€0	€0	€0
	Incremental	€50	€45	€39	€38
	Moderate	€217	€195	€168	€161
	Advanced	€1,320	€1,189	€1,023	€982
	Long Term	€6,819	€6,143	€5,285	€5,076
Aerodynamic configuration **Tractor**	Baseline	€0	€0	€0	€0
	Incremental	€573	€360	€335	€259
	Moderate	€764	€480	€446	€346
	Advanced	€1,146	€720	€669	€518
	Long Term	€2,865	€1,801	€1,673	€1,296
Aerodynamic configuration **Trailer**	Baseline	€0	€0	€0	€0
	Incremental	€1,271	€1,096	€1,005	€963
	Moderate	€1,510	€1,302	€1,194	€1,144
	Advanced	€1,510	€1,302	€1,194	€1,144
	Long Term	€1,510	€1,302	€1,194	€1,144
Rolling resistance configuration **Tractor**	Baseline	€0	€0	€0	€0
	Incremental	€143	€128	€113	€108
	Moderate	€143	€128	€113	€108
	Advanced	€153	€136	€122	€113
	Long Term	€175	€154	€141	€124
Rolling resistance configuration **Trailer**	Baseline	€0	€0	€0	€0
	Incremental	€174	€155	€137	€131
	Moderate	€212	€188	€172	€150
	Advanced	€212	€188	€172	€150
	Long Term	€212	€188	€172	€150

Technology		2015	2020	2025	2030
Composite weight, aerodynamic, and rolling resistance **Tractor + Trailer**[a]	Baseline	€0	€0	€0	€0
	Incremental	€2,911	€2,393	€2,183	€2,030
	Moderate	€3,951	€3,263	€2,961	€2,737
	Advanced	€6,905	€5,821	€5,180	€4,822
	Long Term	€19,841	€17,006	€14,880	€13,943
Engine downsize (+downspeed)	Baseline	€0	€0	€0	€0
	10% Reduction	-€345	-€352	-€359	-€362
Driveline configuration	Base Efficiency	€0	€0	€0	€0
	High Efficiency	€568	€498	€430	€397
Hybrid technology	No	€0	€0	€0	€0
	Yes	€16,031	€13,617	€9,231	€8,535

[a] *Includes a weighting factor of 1.4 trailers per tractor. Individual trailer technology costs are per-unit.*

TECHNOLOGY PACKAGE COSTS

Costs are evaluated for 12 technology packages, as analyzed in the ICCT long-haul tractor-trailer simulation modeling. These packages cover a wide range of fuel consumption, reflecting a baseline of 33.06 liters per hundred kilometers (L/100km) and extending to a minimum of 18.89 L/100km, as measured over the VECTO Long Haul cycle. The entirety of this range reflects as much as a 43% reduction in per-kilometer fuel consumption from the 2015 baseline tractor-trailer. Table 11 presents a summary of the technologies included in each package as well as an associated package description that is used for reference purposes in various data tables and results presented in this report. The order and composition of the presented technology packages matches the order and composition of the packages included in the ICCT simulation modeling as presented in Figure 1.

Table 12 shows the aggregate cost estimates associated with each technology package. Presented costs represent total, or direct manufacturing plus indirect, retail-level costs for base year 2015 and evaluation years 2020, 2025, and 2030. The costs are the aggregate of individual technology costs from Table 10, as applicable, and fixed costs from Table 8, as applicable, both excluding the EU-average 21% VAT, which is treated as a pass-through cost in this study. Included are the technology costs for one tractor and 1.4 trailers. These total retail-level cost estimates plus maintenance cost impacts are the basis for all economic analysis undertaken in this study. Maintenance NPV costs are not included in this table as they are sensitive to both the discount rate assumed and the VKT elasticity impacts associated with each economic analysis scenario. Scenario-specific costs, including maintenance NPV costs, are presented in Table 13 for economic analysis years 2025 and 2030. All costs presented in Tables 12 and 13 are incremental to a 2015-era baseline tractor-trailer.

Table 11. Technology package definitions

Component Technologies		Technology Package[a]											
		1	2	3	4	5	6	7	8	9	10	11	12
Engine configuration	2015 Baseline	X	X										
	2017 Best-In-Class			X	X	X							
	2020						X	X	X				
	2020+WHR									X	X		
	Long Term											X	X
Road load configuration	Baseline	X											
	Incremental		X	X	X								
	Moderate					X	X						
	Advanced							X	X	X			
	Long Term										X	X	X
Engine downsize (+downspeed)	Baseline	X	X	X	X	X	X	X					
	10% Reduction								X	X	X	X	X
Driveline configuration	Base Efficiency	X	X	X									
	High Efficiency				X	X	X	X	X	X	X	X	X
Hybrid technology	No	X	X	X	X	X	X	X	X	X	X	X	
	Yes												X
Fuel consumption		See technology package definitions in note a.											

[a] Technology packages defined as:
1. (33.06 L/100 km) Reference (baseline) 2015 tractor-trailer (44.8% peak brake thermal efficiency engine)
2. (30.89 L/100 km) Reduce road load (from baseline: 16.7% aerodynamic drag, 9.1% rolling resistance, 1.4% weight)
3. (29.86 L/100 km) Add 2017 best-in-class engine (46.0% peak brake thermal efficiency)
4. (29.33 L/100 km) Increase driveline efficiency (+2%)
5. (27.31 L/100 km) Reduce road load (from baseline: 23.3% aerodynamic drag, 18.2% rolling resistance, 2.8% weight)
6. (25.33 L/100 km) Add 2020+ engine (48.6% peak brake thermal efficiency)
7. (24.54 L/100 km) Reduce road load (from baseline: 26.7% aerodynamic drag, 21.8% rolling resistance, 6.9% weight)
8. (24.02 L/100 km) Downsize engine 10% and downspeed
9. (23.58 L/100 km) Add Waste Heat Recovery (51.2% peak brake thermal efficiency)
10. (21.61 L/100 km) Reduce road load (from baseline: 41.7% aerodynamic drag, 27.3% rolling resistance 16.0% weight)
11. (20.12 L/100 km) Add long term (2030-era) engine (55.0% peak brake thermal efficiency)
12. (18.89 L/100 km) Add hybrid technology (60% regeneration efficiency)

Table 12. Total (retail-level) technology package costs (2016€ direct plus indirect, excluding VAT) for 2015, 2020, 2025, and 2030

Technology Package		Evaluation year			
		2015	2020	2025	2030
1	**Reference 2015 tractor-trailer (44.8% peak BTE)**	€0	€0	€0	€0
2	**Reduce road load (16.7% Aero, 9.1% RR, 1.4% Weight)**	€2,911	€2,393	€2,183	€2,030
3	**Add 2017 best-in-class engine (46.0% peak BTE)**	€3,272	€2,752	€2,466	€2,295
4	**Increase driveline efficiency (+2%)**	€3,841	€3,250	€2,896	€2,692
5	**Reduce road load (23.3% Aero, 18.2% RR, 2.8% Weight)**	€4,881	€4,120	€3,675	€3,399
6	**Add 2020+ engine (48.6% peak BTE)**	€7,157	€6,388	€5,456	€5,040
7	**Reduce road load (26.7% Aero, 21.8% RR, 6.9% Weight)**	€10,111	€8,945	€7,674	€7,125
8	**Downsize engine 10% and downspeed**	€9,766	€8,593	€7,315	€6,763
9	**Add Waste Heat Recovery (51.2% peak BTE)**	€18,328	€15,273	€11,849	€9,768
10	**Reduce road load (41.7% Aero, 27.3% RR, 16.0% Weight)**	€31,263	€26,459	€21,549	€18,890
11	**Add 2030-era engine (55.0% peak BTE)**	€33,367	€28,251	€23,061	€20,067
12	**Add hybrid technology (60% regeneration efficiency)**	€49,398	€41,868	€32,292	€28,602

Technology costs include one tractor and 1.4 trailers; BTE=brake thermal efficiency; Aero=aerodynamic drag; RR=rolling resistance; Weight=tractor-trailer curb weight

Table 13. Total (retail level) technology package plus NPV of incremental maintenance costs (2016€ direct plus indirect, excluding VAT) for 2025 and 2030 evaluation years under varying discount rates and fuel prices

Evaluation Year	2025	2025	2025	2025	2025	2025	2025	2025	2025
Discount Rate	4%	4%	4%	7%	7%	7%	10%	10%	10%
Fuel Cost (€/liter)	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40
Reference 2015 tractor-trailer (44.8% peak BTE)	€0	€0	€0	€0	€0	€0	€0	€0	€0
Reduce RL (16.7% Aero, 9.1% RR, 1.4% Weight)	€2,757	€2,757	€2,757	€2,670	€2,669	€2,670	€2,603	€2,603	€2,603
Add 2017 best-in-class engine (46.0% peak BTE)	€3,040	€3,040	€3,041	€2,953	€2,953	€2,953	€2,886	€2,886	€2,887
Increase driveline efficiency (+2%)	€3,524	€3,524	€3,524	€3,426	€3,425	€3,426	€3,351	€3,351	€3,351
Reduce RL (23.3% Aero, 18.2% RR, 2.8% Weight)	€4,383	€4,383	€4,384	€4,273	€4,272	€4,273	€4,189	€4,189	€4,189
Add 2020+ engine (48.6% peak BTE)	€5,888	€5,888	€5,889	€5,808	€5,807	€5,808	€5,746	€5,746	€5,747
Reduce RL (26.7% Aero, 21.8% RR, 6.9% Weight)	€8,128	€8,128	€8,129	€8,044	€8,044	€8,044	€7,981	€7,980	€7,981
Downsize engine 10% and downspeed	€7,769	€7,769	€7,770	€7,685	€7,685	€7,685	€7,622	€7,621	€7,622
Add Waste Heat Recovery (51.2% peak BTE)	€13,674	€13,672	€13,675	€13,401	€13,400	€13,402	€13,194	€13,192	€13,195
Reduce RL (41.7% Aero, 27.3% RR, 16.0% Weight)	€23,419	€23,416	€23,420	€23,139	€23,137	€23,140	€22,926	€22,925	€22,928
Add 2030 era engine (55.0% peak BTE)	€24,931	€24,929	€24,933	€24,652	€24,649	€24,653	€24,439	€24,437	€24,440
Add hybrid technology (60% regen efficiency)	€35,144	€35,139	€35,147	€34,705	€34,701	€34,707	€34,372	€34,368	€34,374

Evaluation Year	2030	2030	2030	2030	2030	2030	2030	2030	2030
Discount Rate	4%	4%	4%	7%	7%	7%	10%	10%	10%
Fuel Cost (€/liter)	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40
Reference 2015 tractor-trailer (44.8% peak BTE)	€0	€0	€0	€0	€0	€0	€0	€0	€0
Reduce RL (16.7% Aero, 9.1% RR, 1.4% Weight)	€2,580	€2,580	€2,580	€2,496	€2,496	€2,496	€2,433	€2,433	€2,433
Add 2017 best-in-class engine (46.0% peak BTE)	€2,845	€2,845	€2,846	€2,761	€2,761	€2,761	€2,698	€2,698	€2,698
Increase driveline efficiency (+2%)	€3,296	€3,296	€3,296	€3,201	€3,201	€3,202	€3,130	€3,130	€3,130
Reduce RL (23.3% Aero, 18.2% RR, 2.8% Weight)	€4,047	€4,046	€4,047	€3,945	€3,945	€3,946	€3,869	€3,868	€3,869
Add 2020+ engine (48.6% peak BTE)	€5,412	€5,411	€5,412	€5,340	€5,340	€5,340	€5,286	€5,286	€5,286
Reduce RL (26.7% Aero, 21.8% RR, 6.9% Weight)	€7,509	€7,508	€7,509	€7,435	€7,435	€7,435	€7,380	€7,380	€7,380
Downsize engine 10% and downspeed	€7,147	€7,146	€7,147	€7,073	€7,073	€7,074	€7,018	€7,018	€7,018
Add Waste Heat Recovery (51.2% peak BTE)	€11,523	€11,521	€11,524	€11,260	€11,259	€11,261	€11,061	€11,060	€11,062
Reduce RL (41.7% Aero, 27.3% RR, 16.0% Weight)	€20,669	€20,667	€20,670	€20,403	€20,401	€20,404	€20,201	€20,199	€20,202
Add 2030 era engine (55.0% peak BTE)	€21,847	€21,844	€21,849	€21,581	€21,579	€21,582	€21,379	€21,377	€21,380
Add hybrid technology (60% regen efficiency)	€31,289	€31,285	€31,292	€30,876	€30,872	€30,878	€30,562	€30,559	€30,565

Technology costs include one tractor and 1.4 trailers; BTE=brake thermal efficiency; RL=road load; Aero=aerodynamic drag; RR=rolling resistance; Weight=tractor-trailer curb weight; regen=regeneration

Figure 10 summarizes the total technology costs, direct plus indirect, including the NPV of maintenance cost impacts associated with the evaluated efficiency technology packages. The figure shows basic cost curves for the 2025 and 2030 evaluation years under a 4% discount rate. Only maintenance costs are affected by the discount rate and, to avoid clutter, Figure 10 shows costs for only the lowest of the three discount rates evaluated. The lowest discount rate is selected for depiction because it results in the highest costs. Maintenance costs are also affected by VKT elasticity, the effect of which is not depicted in Figure 10, but the elasticity effects are so minor that additional elasticity-driven costs for the most expensive hybrid technology package are less than €15.

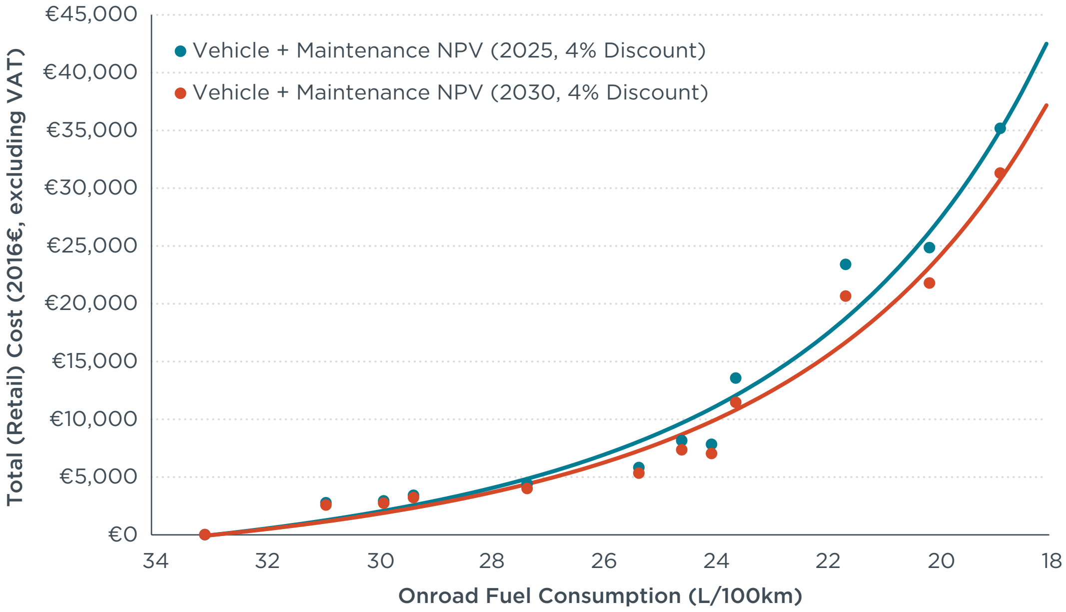

Figure 10. Summary of total technology package costs versus tractor-trailer fuel consumption for evaluation years 2025 and 2030

As shown in Figure 10, efficiency packages that approach 23 L/100km by 2025 cost about €13,700 per tractor-trailer, including the effects of an assumption of 1.4 trailers per tractor. Such packages reflect about a 30% reduction in per-kilometer fuel consumption relative to the baseline 2015-era tractor-trailer. Also shown in the figure are the costs of achieving more advanced efficiency technology levels. To achieve efficiency levels as low as 19 L/100km, a 43% per-kilometer fuel consumption reduction, 2025 costs range up to €35,000 per tractor-trailer, assuming 1.4 trailers per tractor.

IV. ECONOMIC FINDINGS

This section presents basic economic metrics associated with the total cost estimates for the evaluated technology packages as presented in Table 13 above. Specific investigated metrics consist of the payback period associated with each technology package, the lifetime savings associated with each package, and the marginal cost of long-haul tractor-trailer technology. The payback period is defined as the time required to recover the increased capital and NPV of future maintenance costs associated with each technology package. The lifetime cost of each technology package is defined as the lifetime cost savings that accrue reflecting decreased fuel use associated with each technology package, minus the sum of the fuel cost associated with any increase in VKT due to operating cost elasticity and the increased capital and NPV of future maintenance costs of the applicable technology package. Both the payback period and lifetime cost are measured relative to baseline tractor-trailer fuel consumption and cost. The marginal cost of long-haul tractor-trailer technology is measured as the effective cost in euros per liter of fuel saved for the next increment of fuel efficiency, and essentially measures the cost-effectiveness of the technology required to produce that next increment of fuel-consumption reduction. Marginal costs expressed in euros per liter saved can be readily compared with expected fuel prices to determine the cost-effective level of technology. As discussed in Section III above, all economic metrics are evaluated under three discount rate scenarios—4%, 7%, and 10%—and three fuel-price scenarios—€1.10, €0.70, and €1.40 per liter.

As indicated in the preceding section, technology cost estimates are developed for all calendar years between 2020 and 2030. Accordingly, economic metrics can be developed and presented for any of the years in this range. However, when each potential evaluation year is combined with three discount-rate and three fuel-price scenarios, a total of 99 separate measures of each economic metric for each technology package are generated. In the interest of simplifying both the presentation and clarity of findings, all economic metrics are presented for two evaluation years only, 2025 and 2030. Evaluation year 2025 represents the midrange year and provides a representative indication of median-level economic metrics for the larger 11-year period. Given the lead time that would be required for any newly adopted HDV control program to achieve the stringent fuel-consumption reductions reflected in the more advanced technology packages evaluated in this study, it is unlikely that such reductions would be required earlier than 2025. This should not be interpreted as encouraging extended adoption delay as it is critical for standards to be put into effect as soon as possible to establish a glide path toward the stringent standards required to deliver reductions of the levels associated with the advanced technology packages considered in this study. The 2030 evaluation year reflects the timing during which the most advanced technology packages are expected to be commercially available and therefore reflects the year in which standards of equivalent stringency could be implemented.

TECHNOLOGY PACKAGE PAYBACK PERIODS

Table 14 presents the economic payback periods for the 2025 and 2030 evaluation years. Because of the effect of learning on technology costs, payback periods are generally shorter in 2030 than in 2025. Both the NPV of maintenance impacts and fuel savings are inversely related to the assumed discount rate so that the effects of discount rate on costs and savings largely offset. The quick payback and the high VKT in the first several years of tractor-trailer use in the long-haul sector also serve to limit the impact of differential discount rates on estimated payback, since no discount is applied during the first year of operation. As is also shown, fuel price is inversely related to payback, with higher fuel prices resulting in shorter payback periods. It is perhaps worth noting that economic statistics for this study are generally consistent with those of the earlier economic study of U.S. long-haul tractor-trailers (Meszler et al., 2015), primarily because higher fuel prices in the EU result in greater savings that offset correspondingly lower VKT accumulation rates.

Table 14. Technology package payback periods (years)

Evaluation Year	2025	2025	2025	2025	2025	2025	2025	2025	2025
Discount Rate	4%	4%	4%	7%	7%	7%	10%	10%	10%
Fuel Cost (€/liter)	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40
Reference 2015 tractor-trailer (44.8% peak BTE)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Reduce RL (16.7% Aero, 9.1% RR, 1.4% Weight)	0.9	1.5	0.7	0.9	1.5	0.7	0.9	1.4	0.7
Add 2017 best-in-class engine (46.0% peak BTE)	0.7	1.1	0.5	0.7	1.1	0.5	0.7	1.0	0.5
Increase driveline efficiency (+2%)	0.7	1.1	0.5	0.7	1.1	0.5	0.7	1.0	0.5
Reduce RL (23.3% Aero, 18.2% RR, 2.8% Weight)	0.6	0.9	0.4	0.5	0.9	0.4	0.5	0.8	0.4
Add 2020+ engine (48.6% peak BTE)	0.6	0.9	0.4	0.6	0.9	0.4	0.5	0.9	0.4
Reduce RL (26.7% Aero, 21.8% RR, 6.9% Weight)	0.7	1.1	0.5	0.7	1.1	0.5	0.7	1.1	0.5
Downsize engine 10% and downspeed	0.6	1.0	0.5	0.6	1.0	0.5	0.6	1.0	0.5
Add Waste Heat Recovery (51.2% peak BTE)	1.1	1.7	0.8	1.0	1.7	0.8	1.0	1.7	0.8
Reduce RL (41.7% Aero, 27.3% RR, 16.0% Weight)	1.5	2.5	1.2	1.5	2.5	1.2	1.5	2.6	1.2
Add 2030 era engine (55.0% peak BTE)	1.4	2.3	1.1	1.4	2.4	1.1	1.4	2.4	1.1
Add hybrid technology (60% regen efficiency)	1.9	3.2	1.5	1.9	3.2	1.4	1.9	3.3	1.4
Evaluation Year	2030	2030	2030	2030	2030	2030	2030	2030	2030
Discount Rate	4%	4%	4%	7%	7%	7%	10%	10%	10%
Fuel Cost (€/liter)	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40
Reference 2015 tractor-trailer (44.8% peak BTE)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Reduce RL (16.7% Aero, 9.1% RR, 1.4% Weight)	0.9	1.4	0.7	0.8	1.4	0.7	0.8	1.3	0.6
Add 2017 best-in-class engine (46.0% peak BTE)	0.7	1.0	0.5	0.6	1.0	0.5	0.6	1.0	0.5
Increase driveline efficiency (+2%)	0.6	1.0	0.5	0.6	1.0	0.5	0.6	1.0	0.5
Reduce RL (23.3% Aero, 18.2% RR, 2.8% Weight)	0.5	0.8	0.4	0.5	0.8	0.4	0.5	0.8	0.4
Add 2020+ engine (48.6% peak BTE)	0.5	0.8	0.4	0.5	0.8	0.4	0.5	0.8	0.4
Reduce RL (26.7% Aero, 21.8% RR, 6.9% Weight)	0.6	1.0	0.5	0.6	1.0	0.5	0.6	1.0	0.5
Downsize engine 10% and downspeed	0.6	0.9	0.5	0.6	0.9	0.5	0.6	0.9	0.4
Add Waste Heat Recovery (51.2% peak BTE)	0.9	1.4	0.7	0.9	1.4	0.7	0.9	1.4	0.7
Reduce RL (41.7% Aero, 27.3% RR, 16.0% Weight)	1.3	2.2	1.0	1.3	2.2	1.0	1.3	2.2	1.0
Add 2030 era engine (55.0% peak BTE)	1.3	2.0	1.0	1.2	2.0	1.0	1.2	2.0	1.0
Add hybrid technology (60% regen efficiency)	1.7	2.7	1.3	1.7	2.8	1.3	1.7	2.8	1.3

Technology costs include one tractor and 1.4 trailers; BTE=brake thermal efficiency; RL=road load; Aero=aerodynamic drag; RR=rolling resistance; Weight=tractor-trailer curb weight; regen=regeneration

The payback periods for all evaluated technology packages, over all the varying economic assumptions and over the 2025 and 2030 evaluation years, are less than 3.3 years. Figure 11 depicts payback period as a continuous function. Note that the continuous regression-based function omits the three technology packages represented by the open markers in the figure. This omission is because the technology package simulation modeling did not include an underlying cost-effectiveness consideration, so the order of the evaluated packages was not rigorously established. This results in a less-than-optimum progression from one technology package to the next. The effects of non-optimization can be statistically ignored as in this study, but this is not a statistical anomaly. The same optimization will occur in practice as the most cost-effective technologies are adopted first.

Figure 11 focuses on best- and worst-case paybacks. The lower-cost evaluation year, 2030, reflects best-case conditions with low discounting and high fuel-price assumptions maximizing the value of fuel savings. The higher-cost evaluation year, 2025, reflects worst-case conditions with high discounting and low fuel-price assumptions that minimize the value of fuel savings. As shown, worst-case payback periods are estimated to be 3.3 years or less for fuel consumption rates as low as 19 L/100km due to fuel savings that significantly outweigh initial technology purchase and incremental maintenance costs. These same technology packages generally deliver 0.4- to 1.3-year payback periods for best-case cost and economic assumptions. The more moderate technology packages deliver payback periods of one year or less under any reasonable set of economic assumptions. Note that although practices vary widely, all of the estimated payback periods fall well within the four- to six-year typical initial ownership period for industry fleets, and nearly all satisfy the typical desire to achieve payback on technology investment within two years (Roeth et al., 2013). This first-owner issue is evaluated further below.

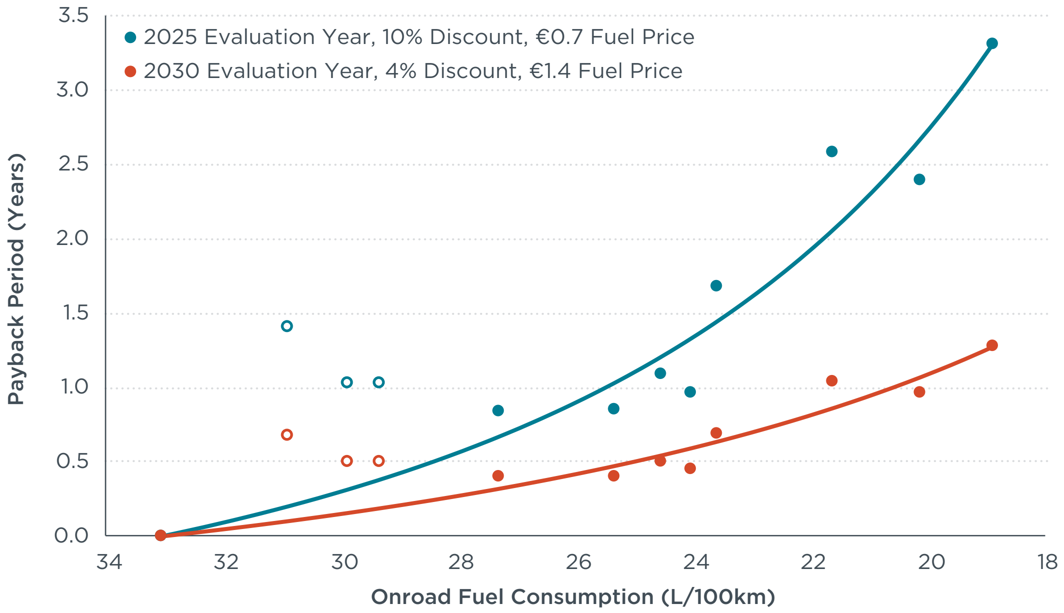

Figure 11. Tractor-trailer efficiency technology package payback periods under varying technology cost and economic assumptions

As discussed in Section III above, primary economic findings are based on the conservative assumption that long-haul tractor-trailer VKT is equal to that of an average tractor-trailer, or the average of the combined short and long-haul tractor population. However, Section III also describes an alternative approach in which average tractor-trailer VKT is adjusted to reflect long-haul tractor-trailer operations only. Table

15 presents the payback periods that would be required if the long-haul tractor-trailer VKT adjustment were implemented, meaning long-haul tractor-trailers accumulate VKT at 1.4 times the rate of an average tractor-trailer. In such a case, the expected decrease in payback time is nominally 29%. However, serving as confounding influences are factors such as changes in the NPV of maintenance costs, which are sensitive to VKT and discount rate, and the differential effect of discount rates on more expensive technologies, in which the payback period lengthens as VKT declines and discounting of future savings increases. Consequently, actual payback-period decreases range from 21-33%, with the greatest decreases applying to the most expensive technologies. As shown in Table 15, the payback period for most technology packages declines by less than 0.5 year, but decreases for the most expensive packages range as high as 1.1 years. All technology packages achieve a full return on investment in no more than 2.2 years.

LIFETIME SAVINGS ESTIMATES

Table 16 presents the net lifetime savings associated with each technology package in evaluation years 2025 and 2030. These estimates represent the net savings to vehicle owners, based on lifetime discounted fuel savings minus initial technology and discounted lifetime maintenance costs relative to an unimproved baseline tractor-trailer. These results also account for the fuel expenditure of additional driving due to VKT elasticity, without assuming any economic benefit for the additional driving. For a maximum-efficiency technology package in 2025, the net savings range from €31,500 to €132,400, rising to €35,300 to €136,200 by 2030. The fuel savings for the most advanced efficiency technology packages investigated are at least 1.9 times the initial technology cost under high technology costs, low future fuel prices, and a high discount rate, and up to 5.4 times the initial technology cost under low technology cost, high future fuel prices, and a low discount rate. Compared with the baseline tractor price of €101,000 assumed in this study, this means that the technology investment not only pays for itself, but also pays for no less than 30% and as much as 135% of the unimproved tractor as well. If the tractor and 1.4 trailers are considered, with each trailer assumed to be priced at €27,500, not only is the technology investment fully repaid, but no less than 23% and as much as 98% of the unimproved capital expenditure for the tractor and trailers is also covered.

Table 15. Technology package payback periods (years) if long-haul VKT equals 140% of average tractor-trailer VKT

Evaluation Year	2025	2025	2025	2025	2025	2025	2025	2025	2025
Discount Rate	4%	4%	4%	7%	7%	7%	10%	10%	10%
Fuel Cost (€/liter)	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40
Reference 2015 tractor-trailer (44.8% peak BTE)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Reduce RL (16.7% Aero, 9.1% RR, 1.4% Weight)	0.7	1.2	0.6	0.7	1.1	0.6	0.7	1.1	0.5
Add 2017 best-in-class engine (46.0% peak BTE)	0.5	0.9	0.4	0.5	0.8	0.4	0.5	0.8	0.4
Increase driveline efficiency (+2%)	0.5	0.9	0.4	0.5	0.8	0.4	0.5	0.8	0.4
Reduce RL (23.3% Aero, 18.2% RR, 2.8% Weight)	0.4	0.7	0.3	0.4	0.7	0.3	0.4	0.6	0.3
Add 2020+ engine (48.6% peak BTE)	0.4	0.7	0.3	0.4	0.6	0.3	0.4	0.6	0.3
Reduce RL (26.7% Aero, 21.8% RR, 6.9% Weight)	0.5	0.8	0.4	0.5	0.8	0.4	0.5	0.8	0.4
Downsize engine 10% and downspeed	0.5	0.7	0.4	0.5	0.7	0.4	0.5	0.7	0.4
Add Waste Heat Recovery (51.2% peak BTE)	0.8	1.3	0.6	0.8	1.3	0.6	0.8	1.2	0.6
Reduce RL (41.7% Aero, 27.3% RR, 16.0% Weight)	1.1	1.8	0.9	1.1	1.8	0.9	1.1	1.8	0.9
Add 2030 era engine (55.0% peak BTE)	1.0	1.7	0.8	1.0	1.7	0.8	1.0	1.7	0.8
Add hybrid technology (60% regen efficiency)	1.4	2.2	1.1	1.4	2.2	1.0	1.4	2.2	1.0

Evaluation Year	2030	2030	2030	2030	2030	2030	2030	2030	2030
Discount Rate	4%	4%	4%	7%	7%	7%	10%	10%	10%
Fuel Cost (€/liter)	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40
Reference 2015 tractor-trailer (44.8% peak BTE)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Reduce RL (16.7% Aero, 9.1% RR, 1.4% Weight)	0.7	1.1	0.5	0.7	1.1	0.5	0.6	1.0	0.5
Add 2017 best-in-class engine (46.0% peak BTE)	0.5	0.8	0.4	0.5	0.8	0.4	0.5	0.8	0.4
Increase driveline efficiency (+2%)	0.5	0.8	0.4	0.5	0.8	0.4	0.5	0.8	0.4
Reduce RL (23.3% Aero, 18.2% RR, 2.8% Weight)	0.4	0.6	0.3	0.4	0.6	0.3	0.4	0.6	0.3
Add 2020+ engine (48.6% peak BTE)	0.4	0.6	0.3	0.4	0.6	0.3	0.4	0.6	0.3
Reduce RL (26.7% Aero, 21.8% RR, 6.9% Weight)	0.5	0.8	0.4	0.5	0.7	0.4	0.5	0.7	0.4
Downsize engine 10% and downspeed	0.4	0.7	0.3	0.4	0.7	0.3	0.4	0.7	0.3
Add Waste Heat Recovery (51.2% peak BTE)	0.7	1.1	0.5	0.7	1.1	0.5	0.7	1.0	0.5
Reduce RL (41.7% Aero, 27.3% RR, 16.0% Weight)	1.0	1.6	0.8	1.0	1.6	0.8	1.0	1.6	0.8
Add 2030 era engine (55.0% peak BTE)	0.9	1.5	0.7	0.9	1.5	0.7	0.9	1.5	0.7
Add hybrid technology (60% regen efficiency)	1.2	2.0	0.9	1.2	1.9	0.9	1.2	1.9	0.9

Technology costs include one tractor and 1.4 trailers; BTE=brake thermal efficiency; RL=road load; Aero=aerodynamic drag; RR=rolling resistance; Weight=tractor-trailer curb weight; regen=regeneration

Table 16. Technology package net lifetime savings for varying evaluation year, discount rate, and fuel price (2016€)

Evaluation Year	2025	2025	2025	2025	2025	2025	2025	2025	2025
Discount Rate	4%	4%	4%	7%	7%	7%	10%	10%	10%
Fuel Cost (€/liter)	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40
Reference 2015 tractor-trailer (44.8% peak BTE)	€0	€0	€0	€0	€0	€0	€0	€0	€0
Reduce RL (16.7% Aero, 9.1% RR, 1.4% Weight)	€17,357	€10,088	€22,784	€14,966	€8,593	€19,725	€13,152	€7,459	€17,403
Add 2017 best-in-class engine (46.0% peak BTE)	€26,540	€15,847	€34,524	€22,982	€13,608	€29,983	€20,283	€11,908	€26,537
Increase driveline efficiency (+2%)	€30,981	€18,507	€40,297	€26,827	€15,891	€34,995	€23,676	€13,905	€30,973
Reduce RL (23.3% Aero, 18.2% RR, 2.8% Weight)	€48,906	€29,633	€63,305	€42,450	€25,552	€55,075	€37,552	€22,455	€48,830
Add 2020+ engine (48.6% peak BTE)	€65,789	€39,855	€85,169	€57,037	€34,299	€74,030	€50,397	€30,084	€65,577
Reduce RL (26.7% Aero, 21.8% RR, 6.9% Weight)	€70,894	€42,299	€92,264	€61,240	€36,169	€79,978	€53,916	€31,518	€70,655
Downsize engine 10% and downspeed	€76,029	€45,702	€98,697	€65,788	€39,198	€85,662	€58,016	€34,262	€75,771
Add Waste Heat Recovery (51.2% peak BTE)	€74,308	€42,469	€98,106	€63,740	€35,824	€84,606	€55,721	€30,782	€74,362
Reduce RL (41.7% Aero, 27.3% RR, 16.0% Weight)	€82,926	€44,429	€111,707	€70,102	€36,349	€95,336	€60,371	€30,217	€82,915
Add 2030 era engine (55.0% peak BTE)	€95,308	€51,767	€127,868	€80,772	€42,596	€109,319	€69,743	€35,638	€95,246
Add hybrid technology (60% regen efficiency)	€96,686	€48,941	€132,394	€80,881	€39,019	€112,189	€68,888	€31,490	€96,858

Evaluation Year	2030	2030	2030	2030	2030	2030	2030	2030	2030
Discount Rate	4%	4%	4%	7%	7%	7%	10%	10%	10%
Fuel Cost (€/liter)	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40
Reference 2015 tractor-trailer (44.8% peak BTE)	€0	€0	€0	€0	€0	€0	€0	€0	€0
Reduce RL (16.7% Aero, 9.1% RR, 1.4% Weight)	€17,532	€10,264	€22,959	€15,138	€8,765	€19,896	€13,321	€7,628	€17,572
Add 2017 best-in-class engine (46.0% peak BTE)	€26,732	€16,041	€34,717	€23,172	€13,798	€30,172	€20,470	€12,095	€26,724
Increase driveline efficiency (+2%)	€31,206	€18,733	€40,522	€27,049	€16,113	€35,217	€23,895	€14,125	€31,192
Reduce RL (23.3% Aero, 18.2% RR, 2.8% Weight)	€49,239	€29,967	€63,637	€42,775	€25,877	€55,398	€37,869	€22,774	€49,147
Add 2020+ engine (48.6% peak BTE)	€66,261	€40,329	€85,641	€57,501	€34,764	€74,493	€50,854	€30,541	€66,034
Reduce RL (26.7% Aero, 21.8% RR, 6.9% Weight)	€71,508	€42,914	€92,877	€61,844	€36,774	€80,581	€54,512	€32,116	€71,251
Downsize engine 10% and downspeed	€76,646	€46,321	€99,313	€66,395	€39,806	€86,268	€58,616	€34,862	€76,370
Add Waste Heat Recovery (51.2% peak BTE)	€76,442	€44,608	€100,236	€65,865	€37,953	€86,727	€57,839	€32,904	€76,477
Reduce RL (41.7% Aero, 27.3% RR, 16.0% Weight)	€85,654	€47,164	€114,431	€72,819	€39,071	€98,049	€63,080	€32,931	€85,620
Add 2030 era engine (55.0% peak BTE)	€98,371	€54,836	€130,926	€83,823	€45,653	€112,367	€72,785	€38,686	€98,285
Add hybrid technology (60% regen efficiency)	€100,514	€52,777	€136,217	€84,686	€42,831	€115,990	€72,677	€35,285	€100,643

Technology costs include one tractor and 1.4 trailers; BTE=brake thermal efficiency; RL=road load; Aero=aerodynamic drag; RR=rolling resistance; Weight=tractor-trailer curb weight; regen=regeneration

Assumptions related to future economic conditions, namely the fuel price and the fuel savings discount rate, play a significant role in determining absolute lifetime savings from the tractor-trailer efficiency technologies. Figure 12 depicts generalized relations for lifetime fuel-savings estimates in the best case, with low costs, a low discount rate, and a high fuel price, and the worst case, with high costs, a high discount rate, and a low fuel price. As shown, the economic factors of fuel price and discount rate play a large role in determining the overall benefits associated with the deployment of efficiency technology. The short payback period for even the most advanced technology package essentially ensures that technology cost is a relatively small factor in the overall cost-benefit evaluation, as compared with the effects of the economic assumptions.

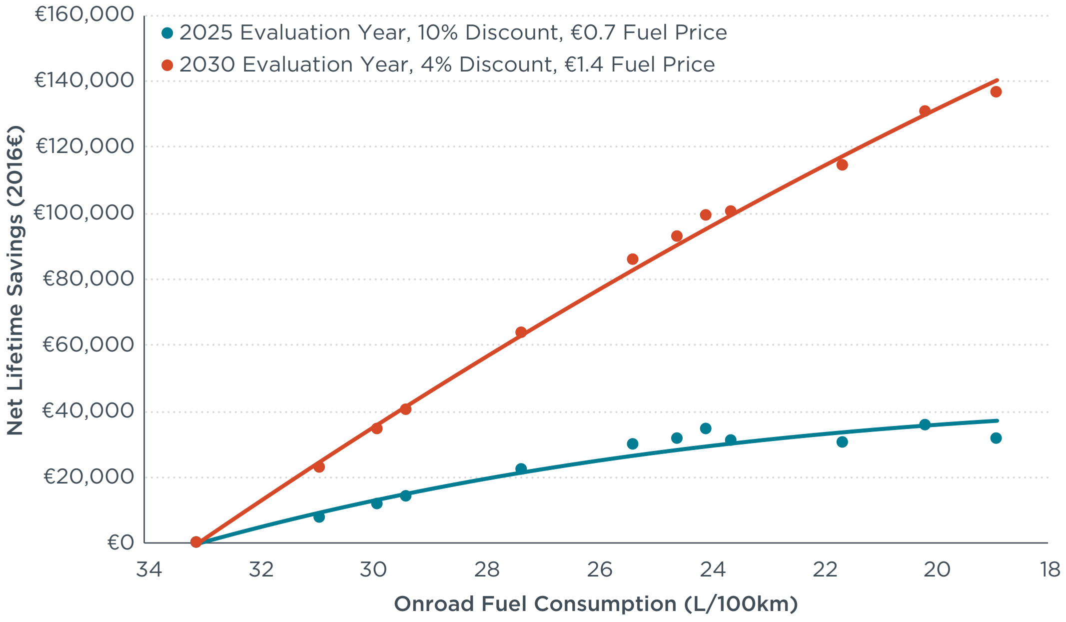

Figure 12. Net lifetime savings from tractor-trailer fuel-efficiency technologies for varying technology cost, discount rate, and fuel price (2016€)

Table 17 presents the net lifetime savings associated with each technology package if long-haul tractor-trailer VKT is adjusted to 1.4 times average tractor-trailer VKT. Given the increase in accumulated VKT, net savings increase by 40-80%, with the greatest increases associated with the most advanced technology packages. Fuel savings for even the most advanced efficiency technology packages increase to no less than 2.6 times the initial technology cost—under high technology costs, low future fuel prices, and a high discount rate—and to as much as 7.2 times the initial technology cost—under low technology cost, high future fuel prices, and a low discount rate.

Table 17. Technology package net lifetime savings for varying evaluation year, discount rate, and fuel price (2016€) if long-haul VKT equals 140% of average tractor-trailer VKT

Evaluation Year	2025	2025	2025	2025	2025	2025	2025	2025	2025
Discount Rate	4%	4%	4%	7%	7%	7%	10%	10%	10%
Fuel Cost (€/liter)	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40
Reference 2015 tractor-trailer (44.8% peak BTE)	€0	€0	€0	€0	€0	€0	€0	€0	€0
Reduce RL (16.7% Aero, 9.1% RR, 1.4% Weight)	€25,100	€14,924	€32,699	€21,750	€12,828	€28,412	€19,209	€11,237	€25,160
Add 2017 best-in-class engine (46.0% peak BTE)	€38,069	€23,099	€49,248	€33,086	€19,961	€42,887	€29,305	€17,580	€38,061
Increase driveline efficiency (+2%)	€44,444	€26,981	€57,487	€38,628	€23,317	€50,063	€34,215	€20,537	€44,431
Reduce RL (23.3% Aero, 18.2% RR, 2.8% Weight)	€69,841	€42,859	€89,999	€60,801	€37,144	€78,475	€53,942	€32,808	€69,732
Add 2020+ engine (48.6% peak BTE)	€94,159	€57,852	€121,292	€81,902	€50,068	€105,692	€72,602	€44,163	€93,855
Reduce RL (26.7% Aero, 21.8% RR, 6.9% Weight)	€102,190	€62,157	€132,110	€88,670	€53,570	€114,903	€78,412	€47,055	€101,848
Downsize engine 10% and downspeed	€109,237	€66,779	€140,971	€94,893	€57,667	€122,717	€84,010	€50,753	€108,867
Add Waste Heat Recovery (51.2% peak BTE)	€108,586	€64,010	€141,904	€93,773	€54,690	€122,985	€82,532	€47,617	€108,629
Reduce RL (41.7% Aero, 27.3% RR, 16.0% Weight)	€124,525	€70,629	€164,818	€106,553	€59,299	€141,881	€92,916	€50,700	€124,477
Add 2030 era engine (55.0% peak BTE)	€142,465	€81,507	€188,048	€122,097	€68,650	€162,063	€106,640	€58,894	€142,345
Add hybrid technology (60% regen efficiency)	€148,009	€81,165	€198,000	€125,863	€67,256	€169,695	€109,059	€56,701	€148,216

Evaluation Year	2030	2030	2030	2030	2030	2030	2030	2030	2030
Discount Rate	4%	4%	4%	7%	7%	7%	10%	10%	10%
Fuel Cost (€/liter)	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40
Reference 2015 tractor-trailer (44.8% peak BTE)	€0	€0	€0	€0	€0	€0	€0	€0	€0
Reduce RL (16.7% Aero, 9.1% RR, 1.4% Weight)	€25,287	€15,112	€32,885	€21,932	€13,011	€28,594	€19,387	€11,417	€25,338
Add 2017 best-in-class engine (46.0% peak BTE)	€38,273	€23,305	€49,452	€33,286	€20,162	€43,087	€29,502	€17,777	€38,257
Increase driveline efficiency (+2%)	€44,681	€27,219	€57,723	€38,861	€23,550	€50,296	€34,445	€20,767	€44,660
Reduce RL (23.3% Aero, 18.2% RR, 2.8% Weight)	€70,205	€43,224	€90,362	€61,153	€37,496	€78,826	€54,285	€33,151	€70,074
Add 2020+ engine (48.6% peak BTE)	€94,662	€58,356	€121,793	€82,393	€50,561	€106,181	€73,083	€44,646	€94,335
Reduce RL (26.7% Aero, 21.8% RR, 6.9% Weight)	€102,839	€62,809	€132,757	€89,306	€54,208	€115,537	€79,037	€47,682	€102,472
Downsize engine 10% and downspeed	€109,889	€67,433	€141,622	€95,531	€58,307	€123,354	€84,638	€51,383	€109,494
Add Waste Heat Recovery (51.2% peak BTE)	€110,749	€66,181	€144,062	€95,925	€56,848	€125,132	€84,675	€49,765	€110,768
Reduce RL (41.7% Aero, 27.3% RR, 16.0% Weight)	€127,292	€73,406	€167,580	€109,306	€62,059	€144,629	€95,657	€53,448	€127,213
Add 2030 era engine (55.0% peak BTE)	€145,566	€84,618	€191,143	€125,183	€71,745	€165,144	€109,715	€61,975	€145,415
Add hybrid technology (60% regen efficiency)	€151,909	€85,077	€201,894	€129,733	€71,135	€173,558	€112,904	€60,556	€152,057

Technology costs include one tractor and 1.4 trailers; BTE=brake thermal efficiency; RL=road load; Aero=aerodynamic drag; RR=rolling resistance; Weight=tractor-trailer curb weight; regen=regeneration

FIRST-OWNER SAVINGS ESTIMATES

As another indicator of the potential attractiveness of the initial technology purchase, first-owner net savings, or discounted fuel savings minus technology and incremental maintenance costs, with the various efficiency technology packages for tractor-trailers, are also estimated. Tractor ownership practices vary widely, but most companies tend to operate new long-haul tractors less than 10 years and conventional wisdom is that new long-haul tractors are held for four to six years (Roeth et al., 2013). This analysis assumes a five-year initial tractor ownership period for evaluating first-owner impacts.

Table 18 presents the estimated first-owner net savings. These savings are based only on the first five years of ownership, ignoring all fuel savings that accrue during the remaining useful life of the tractor. As indicated, the savings for the first owner are a substantial part of the overall lifetime savings. This is largely because the average tractor accrues half of its lifetime mileage in the first five years of operation. This should not be too surprising, even for the 30-year survival-weighted lifetime assumed in this study, as the median 30-year survival-weighted tractor age is 12.4 years (see Table 5). This statistic acts in tandem with an assumption of decreasing travel with age to create the situation in which half of average lifetime travel occurs in the first five years.

Efficiency technology package 8 reduces fuel consumption by 27%, based on a 10% downsizing of the engine, high-efficiency driveline, and advanced road load technology. The package costs €6,800-€7,400[20] and offers €28,400-€62,150 in discounted fuel savings during the first five years, depending on economic assumptions. This delivers benefits to the first owner that are 3.8-9.1 times greater than the upfront technology and incremental maintenance costs. As shown in Table 18, this package results in a net benefit of €21,000-€55,300 over the five years. The most advanced technology package, with a 43% reduction in fuel consumption and a cost of €29,650-€33,600, results in €44,650-€97,800 in fuel savings during the first five years. The first owner reaps benefits that are 1.3-3.3 times greater than the costs. The net delivered first-five-years benefit is €11,250-€67,900, as shown in Table 18.

Table 19 presents the estimated first-owner net savings associated with each technology package if the long-haul tractor-trailer VKT is adjusted to 140% of average tractor-trailer VKT. Net savings increase in tandem with the rise in accumulated VKT. Fuel savings for even the most advanced efficiency technology packages increase to at least 1.8 times the initial technology cost under high technology costs, low future fuel prices, and a high discount rate. They climb as high as 4.5 times the initial technology cost under low technology costs, high future fuel prices, and a low discount rate.

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[20] These costs are slightly lower than those presented in previous sections of this report as they include maintenance effects only through the first five years of operation.

Table 18. Technology package first-owner net lifetime savings for varying evaluation year, discount rate, and fuel price (2016€)

Evaluation Year	2025	2025	2025	2025	2025	2025	2025	2025	2025
Discount Rate	4%	4%	4%	7%	7%	7%	10%	10%	10%
Fuel Cost (€/liter)	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40
Reference 2015 tractor-trailer (44.8% peak BTE)	€0	€0	€0	€0	€0	€0	€0	€0	€0
Reduce RL (16.7% Aero, 9.1% RR, 1.4% Weight)	€9,336	€5,095	€12,504	€8,795	€4,753	€11,812	€8,308	€4,446	€11,191
Add 2017 best-in-class engine (46.0% peak BTE)	€14,577	€8,338	€19,237	€13,775	€7,830	€18,215	€13,054	€7,373	€17,296
Increase driveline efficiency (+2%)	€17,021	€9,742	€22,458	€16,083	€9,147	€21,264	€15,240	€8,613	€20,190
Reduce RL (23.3% Aero, 18.2% RR, 2.8% Weight)	€27,175	€15,927	€35,577	€25,721	€15,004	€33,727	€24,415	€14,175	€32,065
Add 2020+ engine (48.6% peak BTE)	€36,293	€21,159	€47,604	€34,327	€19,906	€45,104	€32,560	€18,781	€42,857
Reduce RL (26.7% Aero, 21.8% RR, 6.9% Weight)	€38,353	€21,665	€50,825	€36,185	€20,285	€48,069	€34,237	€19,044	€45,592
Downsize engine 10% and downspeed	€41,500	€23,801	€54,729	€39,201	€22,337	€51,805	€37,134	€21,021	€49,177
Add Waste Heat Recovery (51.2% peak BTE)	€38,687	€20,105	€52,575	€36,316	€18,611	€49,549	€34,184	€17,268	€46,828
Reduce RL (41.7% Aero, 27.3% RR, 16.0% Weight)	€39,686	€17,219	€56,482	€36,810	€15,403	€52,814	€34,225	€13,771	€49,517
Add 2030 era engine (55.0% peak BTE)	€46,283	€20,872	€65,285	€43,025	€18,813	€61,130	€40,096	€16,962	€57,395
Add hybrid technology (60% regen efficiency)	€43,334	€15,469	€64,173	€39,795	€13,246	€59,652	€36,615	€11,247	€55,587

Evaluation Year	2030	2030	2030	2030	2030	2030	2030	2030	2030
Discount Rate	4%	4%	4%	7%	7%	7%	10%	10%	10%
Fuel Cost (€/liter)	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40
Reference 2015 tractor-trailer (44.8% peak BTE)	€0	€0	€0	€0	€0	€0	€0	€0	€0
Reduce RL (16.7% Aero, 9.1% RR, 1.4% Weight)	€9,497	€5,256	€12,664	€8,955	€4,914	€11,973	€8,468	€4,607	€11,351
Add 2017 best-in-class engine (46.0% peak BTE)	€14,756	€8,517	€19,416	€13,954	€8,008	€18,393	€13,232	€7,552	€17,474
Increase driveline efficiency (+2%)	€17,233	€9,954	€22,669	€16,295	€9,359	€21,475	€15,451	€8,824	€20,401
Reduce RL (23.3% Aero, 18.2% RR, 2.8% Weight)	€27,472	€16,225	€35,874	€26,017	€15,301	€34,023	€24,709	€14,470	€32,359
Add 2020+ engine (48.6% peak BTE)	€36,730	€21,596	€48,040	€34,763	€20,343	€45,539	€32,994	€19,216	€43,291
Reduce RL (26.7% Aero, 21.8% RR, 6.9% Weight)	€38,926	€22,239	€51,398	€36,757	€20,857	€48,640	€34,807	€19,615	€46,161
Downsize engine 10% and downspeed	€42,076	€24,378	€55,304	€39,775	€22,912	€52,379	€37,707	€21,595	€49,750
Add Waste Heat Recovery (51.2% peak BTE)	€40,784	€22,206	€54,671	€38,412	€20,710	€51,643	€36,280	€19,366	€48,922
Reduce RL (41.7% Aero, 27.3% RR, 16.0% Weight)	€42,367	€19,904	€59,161	€39,490	€18,087	€55,491	€36,904	€16,453	€52,193
Add 2030 era engine (55.0% peak BTE)	€49,299	€23,892	€68,298	€46,039	€21,831	€64,142	€43,109	€19,978	€60,406
Add hybrid technology (60% regen efficiency)	€47,079	€19,219	€67,916	€43,537	€16,991	€63,390	€40,352	€14,989	€59,322

Technology costs include one tractor and 1.4 trailers; BTE=brake thermal efficiency; RL=road load; Aero=aerodynamic drag; RR=rolling resistance; Weight=tractor-trailer curb weight; regen=regeneration

Table 19. Technology package first-owner net lifetime savings for varying evaluation year, discount rate, and fuel price (2016€) if long-haul VKT equals 140% of average tractor-trailer VKT

Evaluation Year	2025	2025	2025	2025	2025	2025	2025	2025	2025
Discount Rate	4%	4%	4%	7%	7%	7%	10%	10%	10%
Fuel Cost (€/liter)	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40
Reference 2015 tractor-trailer (44.8% peak BTE)	€0	€0	€0	€0	€0	€0	€0	€0	€0
Reduce RL (16.7% Aero, 9.1% RR, 1.4% Weight)	€13,816	€7,877	€18,251	€13,064	€7,405	€17,289	€12,388	€6,981	€16,425
Add 2017 best-in-class engine (46.0% peak BTE)	€21,267	€12,531	€27,791	€20,150	€11,826	€26,366	€19,145	€11,192	€25,085
Increase driveline efficiency (+2%)	€24,860	€14,669	€32,472	€23,553	€13,843	€30,806	€22,378	€13,100	€29,308
Reduce RL (23.3% Aero, 18.2% RR, 2.8% Weight)	€39,369	€23,622	€51,133	€37,340	€22,336	€48,550	€35,517	€21,181	€46,228
Add 2020+ engine (48.6% peak BTE)	€52,798	€31,609	€68,633	€50,053	€29,863	€65,140	€47,585	€28,294	€62,001
Reduce RL (26.7% Aero, 21.8% RR, 6.9% Weight)	€56,564	€33,201	€74,025	€53,537	€31,276	€70,174	€50,815	€29,545	€66,712
Downsize engine 10% and downspeed	€60,826	€36,048	€79,347	€57,614	€34,005	€75,261	€54,727	€32,169	€71,588
Add Waste Heat Recovery (51.2% peak BTE)	€58,686	€32,672	€78,131	€55,353	€30,566	€73,880	€52,357	€28,674	€70,059
Reduce RL (41.7% Aero, 27.3% RR, 16.0% Weight)	€63,955	€32,502	€87,470	€59,916	€29,946	€82,321	€56,285	€27,650	€77,693
Add 2030 era engine (55.0% peak BTE)	€73,796	€38,221	€100,398	€69,221	€35,324	€94,568	€65,109	€32,721	€89,328
Add hybrid technology (60% regen efficiency)	€73,507	€34,496	€102,682	€68,514	€31,344	€96,313	€64,027	€28,512	€90,588

Evaluation Year	2030	2030	2030	2030	2030	2030	2030	2030	2030
Discount Rate	4%	4%	4%	7%	7%	7%	10%	10%	10%
Fuel Cost (€/liter)	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40	€1.10	€0.70	€1.40
Reference 2015 tractor-trailer (44.8% peak BTE)	€0	€0	€0	€0	€0	€0	€0	€0	€0
Reduce RL (16.7% Aero, 9.1% RR, 1.4% Weight)	€13,986	€8,047	€18,420	€13,233	€7,574	€17,457	€12,556	€7,149	€16,592
Add 2017 best-in-class engine (46.0% peak BTE)	€21,454	€12,719	€27,978	€20,336	€12,013	€26,552	€19,331	€11,378	€25,270
Increase driveline efficiency (+2%)	€25,081	€14,890	€32,692	€23,773	€14,062	€31,025	€22,597	€13,319	€29,526
Reduce RL (23.3% Aero, 18.2% RR, 2.8% Weight)	€39,688	€23,942	€51,451	€37,657	€22,654	€48,866	€35,832	€21,497	€46,542
Add 2020+ engine (48.6% peak BTE)	€53,256	€32,068	€69,091	€50,509	€30,321	€65,596	€48,039	€28,749	€62,454
Reduce RL (26.7% Aero, 21.8% RR, 6.9% Weight)	€57,162	€33,800	€74,623	€54,132	€31,872	€70,768	€51,408	€30,139	€67,304
Downsize engine 10% and downspeed	€61,427	€36,650	€79,947	€58,213	€34,605	€75,859	€55,323	€32,766	€72,184
Add Waste Heat Recovery (51.2% peak BTE)	€60,806	€34,796	€80,247	€57,470	€32,688	€75,994	€54,473	€30,793	€72,172
Reduce RL (41.7% Aero, 27.3% RR, 16.0% Weight)	€66,665	€35,217	€90,177	€62,623	€32,659	€85,026	€58,990	€30,359	€80,395
Add 2030 era engine (55.0% peak BTE)	€76,840	€41,271	€103,439	€72,262	€38,371	€97,606	€68,148	€35,765	€92,364
Add hybrid technology (60% regen efficiency)	€77,284	€38,280	€106,455	€72,286	€35,122	€100,081	€67,795	€32,285	€94,352

Technology costs include one tractor and 1.4 trailers; BTE=brake thermal efficiency; RL=road load; Aero=aerodynamic drag; RR=rolling resistance; Weight=tractor-trailer curb weight; regen=regeneration

MARGINAL COST OF TECHNOLOGY

Payback period and lifetime savings provide important insights into the economic viability of the evaluated technology packages. However, since both are measured relative to baseline unimproved technology, neither offers critical insight into whether a specific level of evaluated technology represents an optimum investment. Such insight can be gained through a marginal cost analysis that estimates the relative cost of each incremental technology investment. The previous economic calculations in this section have estimated cumulative costs without qualification as to whether one set of cumulative costs is more economically efficient than another. In other words, is each successively more advanced technology package economically efficient even after the adoption of the less advanced lower-cost technologies before it?

To answer this question, the benefits and costs of a given technology package must be compared not with baseline technology but with the technologies that are adopted before it. This study evaluates these marginal costs in terms of the investment required per liter of fuel saved. Marginal costs in terms of euros per liter can be readily compared with expected fuel prices. The optimum technology investment is associated with the point at which the marginal cost equals the expected fuel price. Any technology investment beyond that point is economically inefficient because it is cheaper to pay for fuel than to invest in additional technology.

To undertake the marginal cost analysis, technology costs for 2025 and 2030 are first expressed in terms of their estimated discounted lifetime liters of fuel saved.[21] The relationship between efficiency technology package cost and discounted lifetime fuel savings is depicted in Figure 13. The data presented in the figure are limited to bounding conditions producing the highest and lowest marginal cost estimates. Since high fuel prices have the greatest VKT elasticity effects, they decrease the quantity of fuel saved, as opposed to the value of saved fuel, to a greater extent than low fuel prices and so, in conjunction with the highest discount rates, define the lowest fuel quantity savings. Conversely, low discount rates and low fuel prices define the highest fuel quantity savings.[22] This study uses 2025 and 2030 evaluation years in the marginal cost analysis to capture technology cost differentials. Minimum fuel quantity savings are coupled with the higher, or 2025, technology costs and maximum fuel savings are coupled with the lower, or 2030, technology costs. Other combinations of fuel savings and costs will produce marginal cost estimates for the 2025-2030 period that lies between those presented. Note that the continuous regression-based function omits the three technology packages represented by the open markers in the figure. This omission is because the technology package simulation modeling did not include an underlying cost-effectiveness consideration, so the order of the evaluated packages was not rigorously established. This results in a less than optimum progression from one technology package to the next. The effects of non-optimization can be statistically ignored as in this study, but this is not a statistical anomaly as the same optimization will occur in practice as the most cost-effective technologies are adopted first.

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[21] Discounting future saved fuel volume is equivalent to discounting the value of the saved fuel volume under a fixed fuel price. The discounted value of future fuel savings is equal to the liters of fuel saved (V) times the price per liter (P) times the applicable discount rate (D). Given the capital cost of a technology package (C), the fuel price required to offset that cost is determinable by setting C equal to V×P×D and solving for P as C/(V×D), where V×D is the discounted volume of fuel saved. In short, the fuel price required to recoup a technology investment is a function of the discounted volume of fuel saved. It is also easily seen that the value of saved fuel is identical whether one discounts savings (S) directly, or applies a specified fuel price to already-discounted saved fuel volume (V×D). S equals P×V×D directly, which is exactly the same as P×(V×D). Discounting fuel volume is functionally identical to discounting fuel savings.

[22] The assumed discount rate is, by far, the primary determinant of the volume of discounted fuel saved. Fuel price effects are minor but nonetheless act as described.

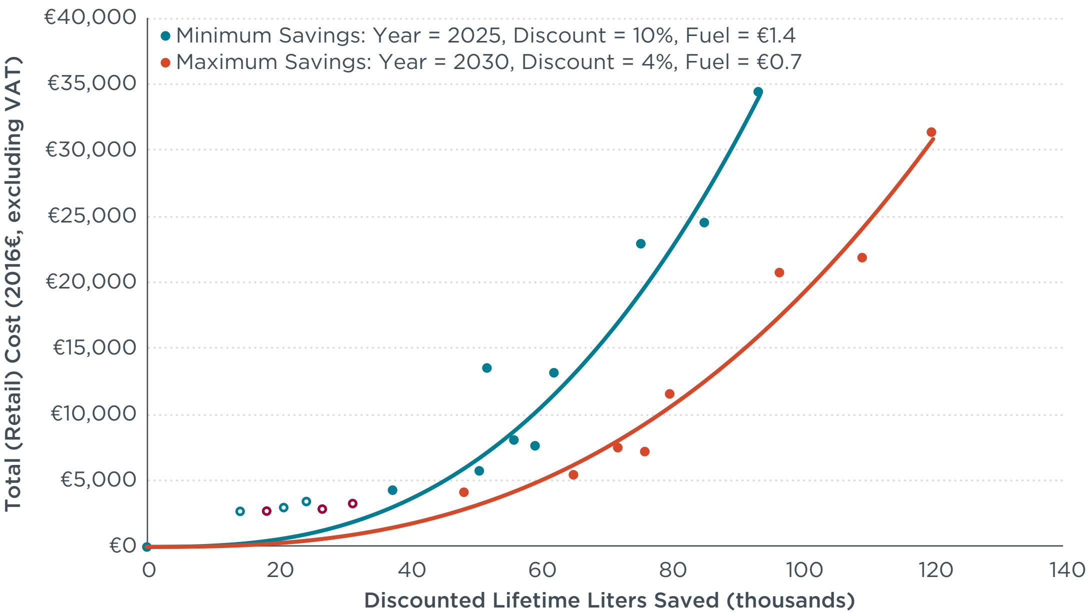

Figure 13. Technology package cost and discounted lifetime fuel savings for best- and worst-case economic assumptions

Marginal cost curves, as presented in Figure 14, are developed from the lifetime discounted fuel savings functions presented in Figure 13. For the most advanced technology package included in this study, which has an associated fuel consumption of 18.9 L/100km, the marginal cost of technology ranges from €0.67 per liter of fuel saved under high savings, low cost conditions to €0.97 per liter of fuel saved under low-savings, high-cost conditions. Thus, the full slate of technology packages evaluated in this study are marginally cost-effective given the nominal and high fuel prices expected between 2020 and 2030 of €1.10 and €1.40 per liter. Under the lowest evaluated fuel price of €0.70 per liter, the full slate of technology packages is cost-effective under the high-savings, low-cost economic conditions of 2030 costs and a low discount rate, but falls outside the cost-effective limit under the low-savings, high cost, and high discount rate conditions of 2025. Under low-savings, high-cost conditions, the minimum fuel consumption that is marginally cost-effective at a fuel price of €0.70 per liter is 21.4 L/100km, representing a per-kilometer reduction of 35% from 2015 baseline. However, as discussed above, the likelihood of future fuel prices being as low as €0.70 per liter is very small given that non-VAT taxes alone contribute about €0.54 per liter to the expected fuel price in 2030.

Figure 15 presents marginal cost curves associated with an assumption that long-haul tractor-trailer VKT accumulates at a rate equal to 140% of average tractor-trailer VKT. Under such conditions, the full slate of technology packages evaluated in this study remain marginally cost-effective under any evaluated economic conditions for expected nominal and high 2020-2030 fuel prices of €1.10 and €1.40 per liter. However, due to an increase in the volume of fuel saved through an increase in lifetime VKT, the full slate of technology packages evaluated in this study also become marginally cost-effective under any evaluated economic conditions at the lowest evaluated fuel price of €0.70 per liter.[23]

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[23] On a precise basis, the minimum marginally cost-effective fuel consumption for a fuel price of €0.70 per liter under the worst-case economic conditions evaluated is 18.95 L/100km. The fuel consumption associated with the most advanced technology package is 18.89 L/100km, which is cost effective at a precise fuel price of €0.7049. This exceedingly minor excursion is overlooked. On a precise basis, a 42.7% fuel-consumption reduction is marginally cost effective under all evaluated economic conditions at a fuel price of €0.70 per liter, as opposed to the 42.9% fuel-consumption reduction associated with the most advanced technology package evaluated.

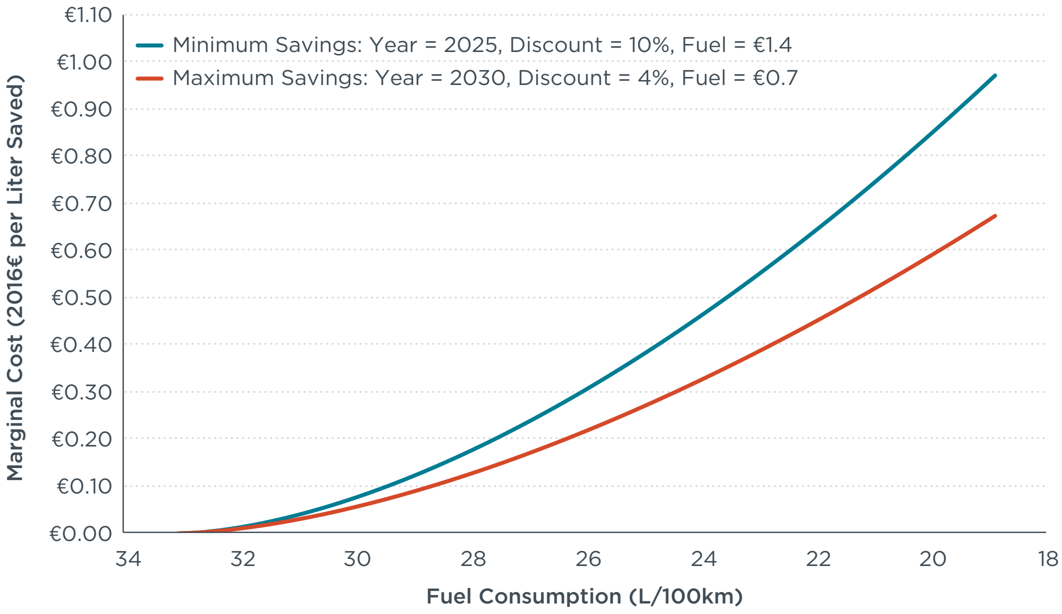

Figure 14. Best- and worst-case marginal cost per liter of fuel saved in the 2025-2030 timeframe

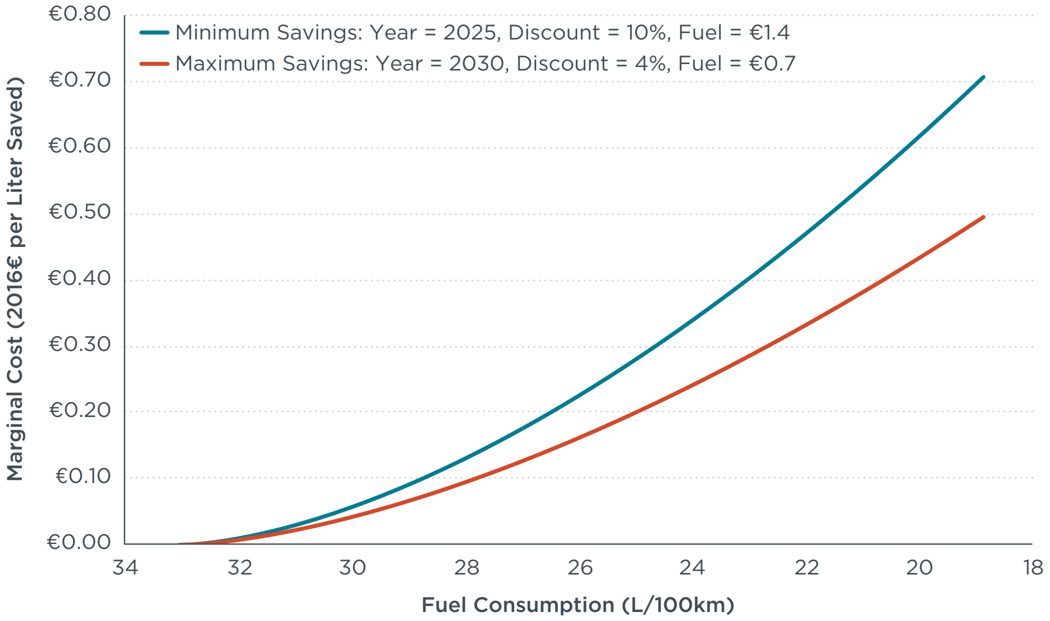

Figure 15. Best- and worst-case marginal cost per liter of fuel saved in the 2025-2030 timeframe if long-haul VKT equals 140% of average tractor-trailer VKT

V. CONCLUSIONS

This study evaluates the cost impacts of long-haul tractor-trailer efficiency technology packages that are emerging and could become widely deployed in the 2020 to 2030 timeframe. The specific technology packages evaluated in the study, based on ICCT tractor-trailer simulation modeling (Delgado et al., 2017), are presented in Figure 1 of this report. In total, the packages generate per-kilometer fuel-consumption reductions of as much as 43%. On a non-discounted but survival-weighted basis, the most advanced of the packages offers potential lifetime savings of more than 149,000 liters of diesel fuel per equipped tractor-trailer.

This study finds that consistent and comprehensive cost estimates are available for the various components of the technology packages. Based on developed technology costs, a series of metrics are investigated to determine the economic impact of the efficiency technology packages. A summary of specific findings is presented below, but, in general, the analysis shows that there are available and emerging technology options to dramatically and cost-effectively increase new long-haul tractor-trailer efficiency.

ECONOMIC FINDINGS

Upfront costs for individual technologies and technology packages can be significant. Moderate efficiency technology packages, based on technologies largely available in the market, offer per-kilometer fuel consumption reductions of as much as 27% and are estimated to cost €7,000-€7,750 in the 2025-2030 timeframe based on best available cost data and conventional technology learning assumptions. The most advanced technology package, based on emerging technologies, offers a 43% per-kilometer reduction in fuel consumption and is estimated to cost €30,550-€31,300 per new combination tractor-trailer in 2030. All cost estimates assume 1.4 trailers are equipped for every tractor. A representative baseline long-haul tractor with 1.4 trailers, as implied by EU population statistics, costs about €139,500. On average, total vehicle costs increase by about 5% for the moderate package and by about 22% for the most advanced efficiency package.

Figure 16 depicts the breakdown of costs for the most advanced technology package in 2030. The presented technology costs are the average of minimum and maximum estimated costs, as developed for one tractor and 1.4 trailers. The advanced technology package shown in the figure delivers a tractor-trailer fuel consumption of 18.9 L/100km, providing a 43% per-kilometer reduction in fuel consumption relative to the 2015 baseline technology package. For this most advanced technology package, the efficiency component costs are roughly equally distributed among the powertrain, the hybrid system, the tractor, and the trailer.

Figure 17 shows the estimated fuel-consumption reductions and the associated payback periods for evaluated technology packages in 2030. Moving down the figure, the data represent the generally sequential addition of more advanced efficiency technologies. The figure depicts how the average estimate of the payback periods evaluated in this analysis generally increase with more advanced technology packages. The “whiskers” of each payback band reflect the range of payback periods across high and low technology cost estimates under varying economic assumptions for fuel prices ranging from €0.70 to €1.40 per liter and discount rates ranging from 4-10%. Payback periods for the moderate technology packages, offering as much as a 27% per-kilometer fuel-consumption reduction, are generally one year or less. The most advanced technology packages, with 35% or greater reductions in fuel consumption, result in payback periods of 1.4-1.9 years for average economic assumptions. Under a scenario in which long-haul tractor-trailer VKT is adjusted to 140% of average tractor-trailer VKT, payback for moderate technology packages under average economic conditions is achieved in about 0.5 year, while the payback period for the most advanced technology packages decreases to 1.1-1.4 years.

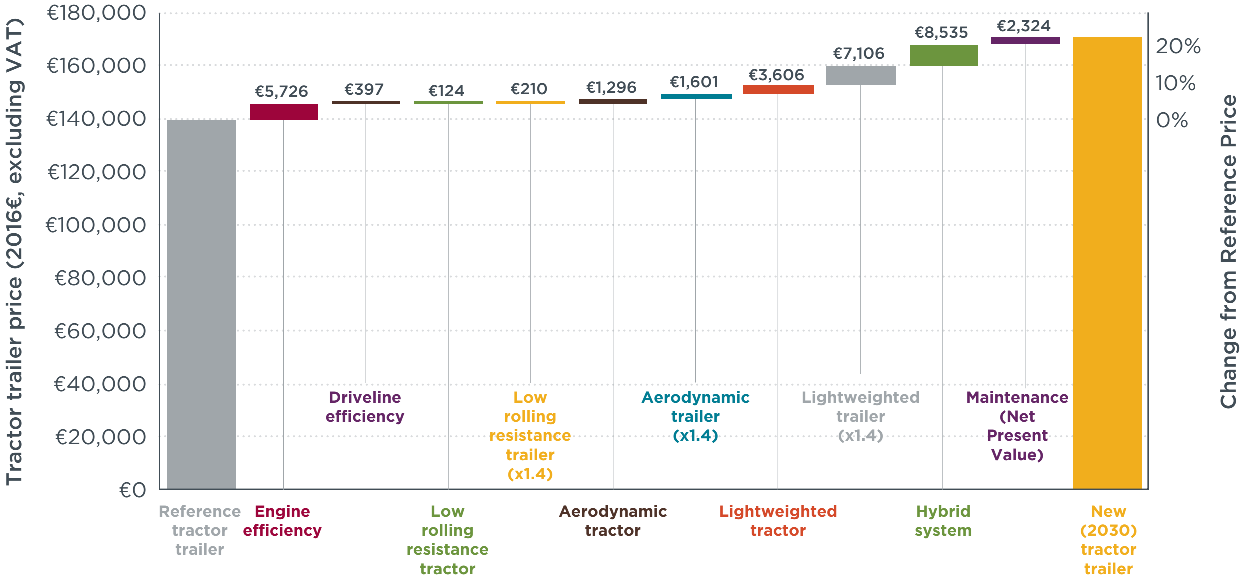

Figure 16. Tractor-trailer technology cost increase for the most advanced efficiency technology package in 2030, based on one tractor and 1.4 trailers

The discounted fuel savings over the average tractor-trailer lifetime greatly exceed the associated up-front technology and net present value maintenance costs of the efficiency packages. The potential discounted lifetime fuel savings for the moderate 27% per-kilometer fuel-consumption reduction technology package range from €41,900-€106,450 per tractor-trailer, depending on discount rate and fuel price assumptions. This compares with technology costs of €7,100-€7,750. The most advanced technology package offers a 43% per-kilometer fuel-consumption reduction and is estimated to cost €30,550-€35,150, resulting in €65,850-€167,550 of lifetime fuel savings per tractor-trailer.

Substantial net lifetime savings accrue for all evaluated technology packages, with savings increasing more rapidly than technology costs for the full range of evaluated technology. For the moderate, 27% per-kilometer fuel-consumption reduction packages, discounted savings range from €34,250-€99,300 per tractor-trailer depending on evaluation year, discount rate, and fuel price. For the most advanced, 43% reduction in per-kilometer fuel-consumption packages, discounted savings range from €30,200-€136,200 per tractor-trailer. These fuel savings largely accrue to the first owner of the tractor, due to high mileage typically averaging more than 110,000 kilometers per year in the first several years of ownership. The study analysis of a typical five-year ownership cycle indicates that approximately half of the lifetime fuel savings would fall to the first owner.[24] Under a scenario in which long-haul tractor-trailer VKT is adjusted to 140% of average tractor-trailer VKT, net lifetime savings increase substantially, to €50,750-€141,600 for moderate packages and to €47,600-€201,900 for the most advanced technology packages.

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[24] Vehicle lifetime for this study is defined on a 30-year survival-weighted basis. The associated median age of tractors is 12.4 years.

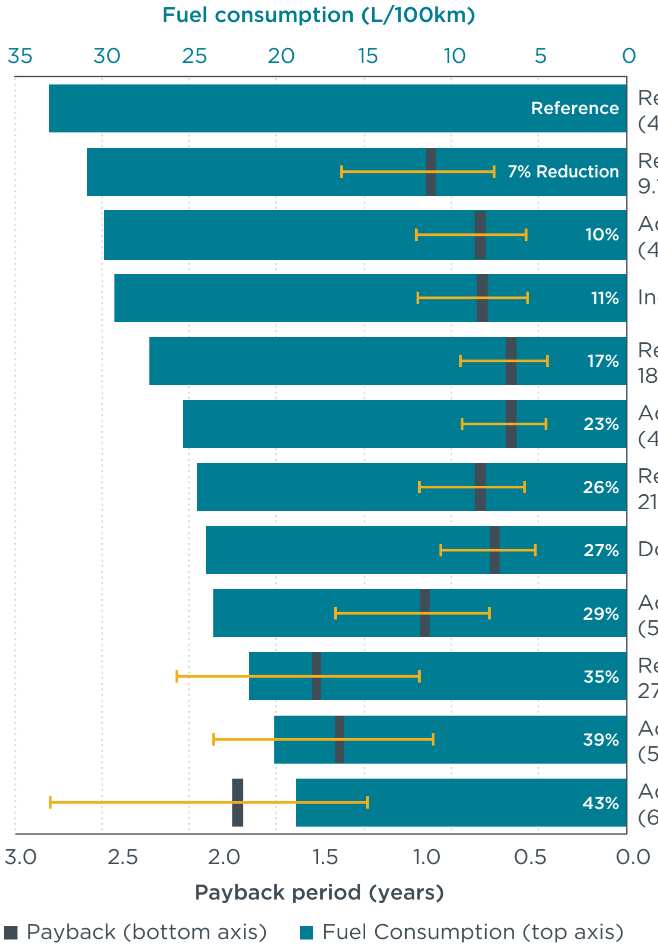

Figure 17. Fuel consumption impacts and associated 2030 payback periods for tractor-trailer efficiency technologies

All technology packages are marginally cost-effective under all evaluated technology cost and discount rate scenarios for fuel prices expected in the 2020 to 2030 timeframe, with the exception of the most advanced technology packages under worst-case evaluation conditions of high discount rate, 2025 technology costs, and a fuel price of €0.70 per liter. Under such conditions, the marginal cost of the most advanced technology package is about €0.97 per liter, below the nominal fuel-price estimate of €1.10 per liter and the high estimate of €1.40 but above the low-estimate of €0.70. Under best-case conditions, the marginal cost of the most advanced technology package is about €0.67 per liter, well below all fuel price estimates. Given that non-VAT taxes alone would contribute about €0.54 per liter to fuel price in 2030, the likelihood of future fuel prices as low as €0.70 per liter is very small. Moreover, although the marginal cost of the most advanced technology package exceeds the lowest expected fuel price under worst-case evaluation conditions, significant fuel-consumption reductions of at least 35% on a per-kilometer basis continue to be marginally cost-effective under such conditions. Under a scenario in which long-haul tractor-trailer VKT is equal to 140% of average tractor-trailer VKT, all technology packages are marginally cost-effective under all evaluation scenarios.

POLICY DISCUSSION AND RECOMMENDATIONS

The results of this cost analysis reinforce the policy implications of the underlying ICCT simulation modeling study (Delgado et al., 2017). In particular, consideration of lead time is a critical element of any regulatory program and can significantly affect the potential stringency of regulatory standards. Further, the more advanced efficiency technologies investigated in this study would require technology-forcing regulations to drive them into the marketplace.[25] Commercializing such advanced technologies requires a long-term regulatory signal as a basis for the necessarily large supplier and manufacturer investments. Regulatory stringency levels are ideally predicated upon available technology, state-of-the-art understanding of technology effectiveness through modeling, and rigorous cost evaluation as conducted in this study.

With the EU investigating HDV standards for 2020 and beyond, this research improves the understanding of the cost implications of emerging advanced tractor-trailer efficiency technologies. The findings from this technology cost and payback investigation generally show that there is substantial potential to cost-effectively increase long-haul tractor-trailer efficiency in the EU. Key findings include:

1. ***Available efficiency technologies for long-haul tractor-trailers offer fuel savings that greatly exceed up-front technology and maintenance impact costs.*** Findings indicate that available tractor-trailer efficiency technology can reduce per-kilometer fuel consumption by 27% from baseline 2015 technology and deliver payback periods to tractor-trailer owners that are generally within one year. Fuel savings from these packages exceed increased technology costs by a factor of 4-17, depending on evaluated economic conditions. Based on technology availability and attractive cost-effectiveness to end users, this level of efficiency technology can be widely deployed in the 2020-2025 timeframe.

2. ***Emerging advanced efficiency technologies offer more substantial fuel savings and attractive payback periods over the long term.*** Study findings indicate that technology packages with long-term road load and engine technologies can achieve, in the post-2025 timeframe, a 43% per-kilometer reduction in fuel consumption from baseline 2015 technology. For these advanced technology pathways, the payback periods from fuel savings are less than 1.9 years under average economic assumptions. Technology-forcing standards and sufficient lead time would be needed to promote the development and deployment of these advanced efficiency technologies post 2025.

3. ***Tractor-trailer efficiency technologies' attractive payback periods persist even in the event of higher technology costs and low fuel prices***. Based on this study's investigation of varying technology costs and economic assumptions—including an average fuel price as low as €0.70 per liter through 2030—the attractive payback findings in this study are robust. The more advanced technology packages, delivering a 35-43% per-kilometer fuel-consumption reduction, have payback periods of 1.0-3.3 years even when high technology costs, high discount rates, and low fuel prices are assumed. When long-haul tractor-trailer VKT is adjusted to 140% of average tractor-trailer VKT, payback periods drop to 0.7-2.2 years. The attractive and robust payback-period findings indicate that there are prevailing market barriers to technology introduction, warranting increasingly stringent tractor-trailer efficiency standards.

4. ***Tractor-trailer efficiency technologies offer first-owner fuel savings that greatly exceed the increased upfront capital and maintenance impact costs.*** Examining typical first tractor owners' discounted future fuel savings, available efficiency technologies that reduce fuel consumption by 27% offer €28,400-€62,150 in discounted fuel savings and result in benefits that are 4-9 times greater than

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[25] A technology-forcing standard generally requires the development and commercialization of technologies that would otherwise be unlikely to be introduced into the market. In contrast, a technology-tracking standard accelerates the market adoption of current off-the-shelf technologies with low adoption rates.

the upfront technology and maintenance impact costs, depending on economic assumptions. The most advanced emerging technology package, offering a 43% fuel-consumption reduction for new 2030 tractor-trailers, results in €44,650-€97,750 in fuel savings, benefits that exceed costs by 1.5-3.3 times. When full tractor lifetime benefits are considered, the benefit-to-cost ratio is even greater, pointing to a clear opportunity for efficiency standards to simultaneously mitigate climate-related emissions, provide overall economic benefits, and offer an attractive investment for fleets. Positive benefits increase further when long-haul tractor-trailer VKT is adjusted to equal 140% of average tractor-trailer VKT.

A number of issues remain beyond the scope of this research. For example, the study does not investigate the mechanisms by which tractor and trailer efficiency technologies might be effectively regulated under a combined standard. Although used in tandem, tractors and trailers are not marketed as a unit and are generally not under the control of one regulated entity. As a result, road load technologies that span tractors and trailers pose significant administrative and design issues with regard to establishing a program structure to ensure that required improvements are achieved in use. Additionally, the study focuses on efficiency and cost-effectiveness for the long-haul tractor-trailer segment, but the same methodology could be employed to evaluate technology improvements and costs for other vehicle sectors, whole fleets of vehicles, and other duty cycles. Interactions between efficiency technologies, technologies to control conventional air pollution, and their costs are not investigated.

While this study is focused on tractor-trailer technology cost-effectiveness in the EU, the implications extend well beyond any restricted geography. The manufacturers and suppliers that are developing the efficiency technologies evaluated in this study could leverage investment by deploying the same technologies at greater volume globally. Establishing stringent HDV standards in a market the size of the EU, especially given the primacy of EU regulations as benchmarks for vehicular regulation in many non-EU countries, can play a key role in advancing market opportunities globally.

ABBREVIATIONS AND ACRONYMS

ACEA	Association des Constructeurs Européens d'Automobiles (European Automobile Manufacturers' Association, Brussels)
AMT	Automated Manual Transmission
ANL	Argonne National Laboratory (United States)
API	American Petroleum Institute (United States)
ASME	American Society of Mechanical Engineers (United States)
BEA	Bureau of Economic Analysis (United States)
BGL	Bundesverband Güterkraftverkehr Logistik und Entsorgung (Federal Association of Road Transport Logistics and Disposal, Frankfurt am Main, Germany)
BMEP	Brake Mean Effective Pressure
BTE	Brake Thermal Efficiency
C_d	Coefficient of Drag
C_dA	Aerodynamic Drag Area (Vehicle frontal area times C_d)
CO_2	Carbon Dioxide
C_{rr}	Coefficient of Rolling Resistance
DCT	Dual Clutch (automated manual) Transmission
DE	Diesel Engine
DG-ENER	European Commission Directorate-General for Energy
DMC	Direct Manufacturing Cost
DOE	Department of Energy (United States)
DPF	Diesel Particulate Filter
EAA	European Aluminium Association
ECB	European Central Bank
EEA	European Environment Agency
EC	European Commission
EGR	Exhaust Gas Recirculation
EPA	Environmental Protection Agency (United States)
EPEC	European Policy Evaluation Consortium (Brussels)
EU	European Union
GCW	Gross Combined Weight (tractor plus trailer plus payload)
GE	Gasoline Engine
GHG	Greenhouse Gas(es)
HDV	Heavy-Duty Vehicle
IAI	International Aluminium Institute
ICCT	International Council on Clean Transportation
IC	Indirect Cost
ICM	Indirect Cost Multiplier
IFEU	Institut für Energie- und Umweltforschung (Institute for Energy and Environmental Research, Heidelberg, Germany)
kg	kilogram(s)
km	kilometer(s)
kW	kilowatt(s)
kWh	kilowatt-hour(s)
L	liter(s)
L/100km	liters per hundred kilometers
m	meter(s)
mm	millimeter(s)
MOVES	Motor Vehicle Emission Simulator (U.S. Vehicle Emissions Model)
m^2	square meters
NAS	National Academy of Sciences (United States)

NESCCAF	Northeast States Center for a Clean Air Future (United States)
NHTSA	National Highway Traffic Safety Administration (United States)
NO_x	Oxides of Nitrogen
NPV	Net Present Value
NRC	National Research Council (United States)
OMB	Office of Management and Budget (United States)
ORC	Organic Rankine Cycle WHR technology
RPE	Retail Price Equivalent
rpm	revolutions per minute
SAE	Society of Automotive Engineers
SCR	Selective Catalytic Reduction
SwRI	Southwest Research Institute (United States)
TC	Total (retail level) Cost (excluding VAT). TC = DMC + IC.
TCU	European Commission Taxation and Customs Union
TRACCS	TRansport data collection supporting the quantitative Analysis of measures relating to transport and Climate Change (an EU database)
TU Graz	University of Technology Graz (Austria)
U.K.	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
U.S.	United States
VAT	Value Added Tax
VECTO	Vehicle Energy Consumption Calculation Tool
VGT	Variable Geometry Turbocharger
VKT	Vehicle Kilometers of Travel
WHR	Waste Heat Recovery (specifically Organic Rankine Cycle technology)

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