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COST EFFECTIVENESS OF ADVANCED EFFICIENCY TECHNOLOGIES FOR LONG-HAUL TRACTOR-TRAILERS IN THE 2020-2030 TIME FRAME

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EXECUTIVE SUMMARY

The average fuel economy of combination tractor-trailers in the US has remained relatively unchanged for more than two decades. However, technology and policy developments point to the potential for increased efficiency in new trucks going forward. With the US government set to develop the second phase ("Phase 2") of heavy-duty vehicle standards in 2015-2016 for 2020 and later tractor-trailers, there is the potential for accelerated deployment of existing and emerging efficiency technologies into the market. This report assesses the future costs of advanced technologies as an input to the policy dialogue on tractor-trailer efficiency standards in the US in the 2020-2030 time frame. This report investigates the costs associated with tractor-trailer fuel efficiency technologies evaluated in a companion tractor-trailer simulation study, *Advanced tractor-trailer efficiency technology potential in the 2020-2030 timeframe*, by the International Council on Clean Transportation.

The fundamental approach employed in this assessment involves deriving technology costs from best-available data on heavy-duty vehicle and engine technologies to assess the cost effectiveness of increasingly efficient tractor-trailer technology packages. We investigate economic impact metrics including the payback period, lifetime savings, and marginal cost associated with various technology packages under a range of economic conditions for high and low technology cost estimates, three discount rates (3%, 7%, and 10%) and three fuel prices ($3.10, $4.10, and $5.40 per gallon). The evaluated efficiency technology packages include per-ton-mile fuel consumption reductions of up to 54% relative to a 2010-era baseline vehicle, and include individual technology options that address engine and powertrain efficiency, vehicle road load, and waste energy recovery.

The primary finding of the study is that, due to high technology availability and extensive lifetime mileage, substantial improvements are available to cost effectively increase long-haul tractor-trailers' efficiency. While upfront technology 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 three trailers per common industry practice, costs approximately $210,000, and additional efficiency technology costs were assessed incrementally from this baseline.

Available efficiency technologies, in a package that offers a per-mile tractor-trailer fuel consumption reduction of 38%, are estimated to have incremental technology costs in 2025 that include $1,100-$4,000 for the engine, $4,500-$5,700 for the transmission, $1,600-$1,800 in tractor aerodynamics, $3,600-$6,700 in tractor lightweighting, $1,100-$2,700 in trailer aerodynamics, and $1,700-$3,000 in trailer lightweighting. These costs are estimated from a 2010 reference tractor-trailer for the year 2025, based on best available cost data and conventional technology learning assumptions. The range of potential lifetime fuel savings for these moderate efficiency packages are up to $156,000-$382,000 per tractor-trailer, depending on discount rate and fuel price assumptions.

The most advanced technology package offers a 54% per-mile fuel consumption reduction and is estimated to have incremental technology costs in 2025 that include $5,300-$10,400 for the engine, $4,500-$5,700 for the transmission, $2,900-$4,700 in tractor aerodynamics, $7,000-$12,700 in tractor lightweighting, $15,000-$17,000 for a hybrid system, $1,900-$4,800 in trailer aerodynamics, and $3,000-$5,100 in trailer lightweighting. This most advanced technology package generates $226,000-$552,000

in lifetime fuel savings per tractor-trailer, depending on economic assumptions for the future fuel price and the discount rate.

Figure ES-1 depicts the estimated fuel consumption reductions and the associated payback periods for evaluated technology packages in 2025. Moving down the figure, the data represent the sequential addition of more advanced efficiency technologies. The figure depicts how the average estimate of the payback periods from the cases evaluated in this analysis increase with more advanced technology packages. The depicted "whiskers" of each payback band reflect the range of payback periods across high and low technology cost estimates and varying economic conditions for fuel prices ranging from $3.10-$5.40 per gallon and discount rates ranging from 3%-10%. Payback periods for the near-term technology packages, offering up to a 38% per-mile fuel consumption reduction, are less than a year for the base-case economic assumptions; the most advanced technology packages, with 40% or greater fuel consumption reduction, result in 0.9-1.3 year payback periods.

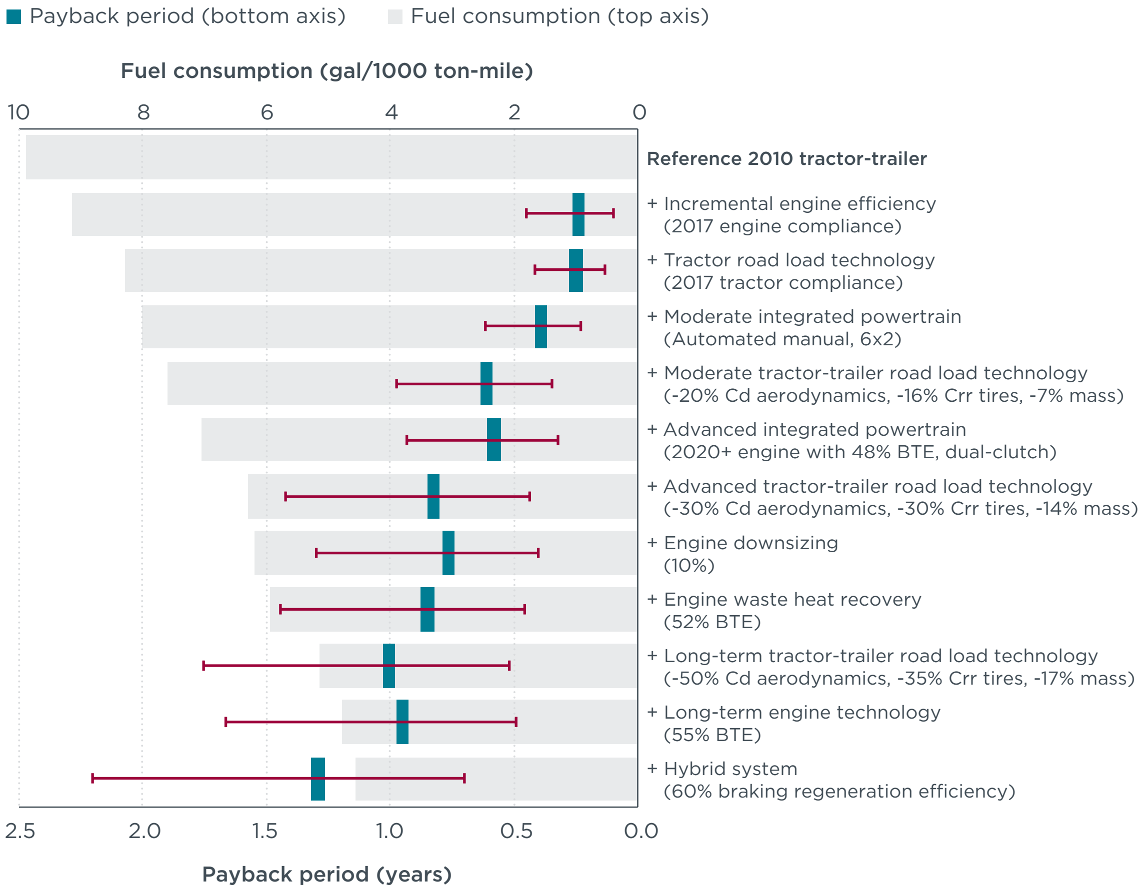

Figure ES-1. Fuel consumption impacts and associated 2025 payback periods for tractor-trailer efficiency technologies

The findings from this study point to several policy implications related to US greenhouse gas emission and efficiency standards for 2020 and beyond.

(1) *Available efficiency technologies for tractor-trailers have fuel savings that greatly exceed up-front technology costs.* The findings indicate that available tractor-trailer efficiency technologies can reduce per-mile fuel consumption by 38% from baseline 2010 technology, or by about 25% from 2017, the final year of the adopted standards, and deliver payback periods to tractor-trailer users that are generally within one year for base-case economic assumptions. Based on technology availability and the attractive cost-effectiveness to end users, this level of efficiency technology can be widely deployed in the 2020-2025 time frame.

(2) *Emerging advanced efficiency technologies over the long-term offer more substantial fuel savings and attractive payback periods.* This study's findings indicate that technology packages with long-term road load and engine technologies can achieve, in the 2025-2030 time frame, at least 50% per-mile fuel consumption reduction from baseline 2010 technology, or at least 40% from 2017. For these advanced technology pathways, the payback periods from the fuel savings are less than 1.5 years for base-case economic assumptions. Technology-forcing standards and sufficient lead time would be needed to promote the development and deployment of these advanced efficiency technologies in the 2025 time frame.

(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 of $3.10 per gallon through 2030, the attractive payback findings in this study are robust. The more advanced technology packages, with 48%-54% fuel consumption reduction, have payback periods of 1.4-2.2 years when high technology costs, high discount rates, and low fuel prices are assumed. The attractive and robust payback period findings indicate there are prevailing market barriers, and increasingly stringent tractor-trailer efficiency standards are warranted.

(4) *Tractor-trailer efficiency technologies offer first-user fuel savings that greatly exceed the increased upfront capital costs.* Examining typical first tractor users' discounted future fuel savings, available efficiency technologies that reduce fuel consumption by 38% offer $100,000-$194,000 in discounted fuel savings and result in benefits that are three to nine times greater than the upfront technology cost, depending on the economic assumptions. The most advanced emerging technology package, offering a 54% fuel consumption reduction for new 2025 tractor-trailers, results in $145,000-$281,000 in fuel savings, or two to five times greater benefits than costs. When including full tractor lifetime benefits, beyond the typical five years of operation by the first user, the benefit-to-cost ratio is even greater. The high benefit-to-cost ratio points to a clear opportunity for efficiency standards to simultaneously mitigate climate-related emissions, provide overall economic benefits, and offer an attractive investment for fleets.

While this study is focused on tractor-trailer technology cost-effectiveness in the US context, the implications extend well beyond the immediate US regulatory dialogue for 2020 and beyond. The manufacturers and suppliers developing the efficiency technologies evaluated in this study could further leverage their investments by deploying the same technologies at greater volume globally. And companies might be prompted to do just that. China, Canada, and Japan already have adopted some form of efficiency or greenhouse gas standards for heavy-duty vehicles and are working toward their next phase of regulations. India, Mexico, South Korea, and the European Union are also investigating new heavy-duty vehicle efficiency policies. As a result, heavy-duty vehicle efficiency technology and policy advancements could be greatly leveraged in the years ahead.

I. INTRODUCTION

The average fuel economy of combination tractor-trailers in the US has remained relatively unchanged for more than two decades (Davis et al, 2013). However, technology and policy developments point to the potential for increased efficiency in new trucks going forward. With the US government set to develop the second phase ("Phase 2") of heavy-duty vehicle standards in 2015 to 2016 for 2020 and later tractor-trailers, there is the potential for accelerated deployment of existing and emerging efficiency technologies into the market.

The 2011 adoption of heavy-duty vehicle efficiency standards by the US Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) placed new requirements on engine and truck manufacturers to increase the efficiency of their products through 2018 (US EPA and NHTSA, 2011a). These initial (or "Phase 1") standards provide for modest efficiency improvements as well as establish a foundation and regulatory framework for subsequent requirements. Proceedings for a proposed second phase of heavy-duty vehicle efficiency standards for 2019 and beyond are under way, with a rulemaking timetable that anticipates proposed standards in 2015 and finalized regulations in 2016 (White House, 2014). Among the more critical questions for the Phase 2 regulations are what the emerging efficiency technologies are, and what the associated technology costs, fuel savings, and payback periods for long-haul tractor-trailers are. The study by Delgado and Lutsey (2015), *Advanced tractor-trailer efficiency technology potential in the 2020-2030 timeframe*, addresses the fundamental technology question, using state-of-the-art vehicle simulation modeling to assess road load, engine, and transmission technologies.

This report adds a cost evaluation component to the estimated tractor-trailer technology impacts to provide a robust basis for evaluating the cost effectiveness of potential Phase 2 fuel efficiency and carbon reduction requirements. Specifically, this report builds on previous work to assess the future costs and lifetime fuel saving potential of advanced long-haul tractor-trailer technologies in the 2020-2030 time frame. This study takes the fuel efficiency results of the companion tractor-trailer simulation work (i.e., Delgado and Lutsey, 2015) as a given. While a brief overview of that technology work is presented here, the reader is referred to the referenced study report for additional details. More broadly, this cost analysis should be viewed as a continuation of the simulation work and four associated reports that document industry expectations from a stakeholder workshop (Lutsey et al., 2014), engine-specific technologies (Thiruvengadam et al., 2014), trailer technology (Sharpe et al., 2014), and the US Department of Energy SuperTruck project (Delgado and Lutsey, 2014). Together, these reports constitute a single extended assessment of tractor-trailers.

BACKGROUND

Technical analyses performed in the years leading up to the Phase 1 rulemaking evaluated both the potential and cost of heavy-duty vehicle and engine fuel efficiency technology. Prominent among this work are studies by Northeast States Center for a Clean Air Future et al (2009), TIAX (Kromer et al., 2009), and the National Research Council (NRC, 2010). These studies conclude that Class 8 tractor-trailers, as used in long-haul applications in particular, have the largest potential for significant and cost effective efficiency improvement among vehicles in the heavy-duty sector. The Phase 1 rulemaking process built upon this work through extensive communication with vehicle manufacturers and technology suppliers. Subsequent to the adoption of the Phase 1 rule, a number of studies and ongoing projects have continued to evaluate vehicle and engine fuel efficiency technologies and their potential availability in the 2015-2030 time frame. See Delgado and Lutsey, 2015, for a more detailed description of such work.

The underlying technology assessment that serves as the foundation for this study (i.e., Delgado and Lutsey, 2015) evaluates the fuel efficiency potential of emerging technologies expected to be available in the long-haul tractor-trailer sector in the 2020-2030 time frame. Particular emphasis is placed on technologies that could potentially be promoted by US regulatory standards. This includes engine and vehicle technology, but generally excludes behavioral strategies that target drivers, operations, and logistics improvements. All technology is evaluated via a full vehicle simulation model (ANL, 2014), using recent engine dynamometer test data, engine audit information, and tractor-trailer technology inputs. Due to an 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. For an example see NRC, 2010.

The tractor-trailer simulation modeling evaluates more than 40 advanced efficiency technology packages combining engine, transmission, and road load technologies expected to be commercially available in the 2020-2030 time frame. Readers are referred to the original report (Delgado and Lutsey, 2015) for detailed information, but Figure 1 presents a summary of the study results for a selection of advanced efficiency technology packages that span a wide range (i.e., from 0%-54%) of fuel consumption reductions.[1] The depicted ton-mile units are based on a 19-ton payload in a 70,500 pound gross combined weight tractor-trailer. For policy context with the adopted Phase 1 standards, the third technology package from the top in the figure represents nominal compliance with the model year 2017 long-haul tractor efficiency standards. Technology packages further down from the nominal 2017 technology therefore represent relevant technologies for the potential Phase 2 regulatory time frame from 2020 and beyond. Generally, the technology simulation study finds there are available near-term technologies that can deliver up to a 38% fuel consumption from the baseline 2010 technology, and also emerging technologies offering an approximate 50% fuel consumption reduction in the 2025 to 2030 time frame.

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[1] The Delgado and Lutsey (2015) efficiency study evaluated impacts over two driving cycles: (1) the heavy heavy-duty diesel truck 65 mile per hour cycle (HHDDT65) and (2) a “real-world” highway cycle that includes variable grade effects (based on approximately 120 miles of long-haul interstate travel from Wheeling, West Virginia to Columbus, Ohio). Only the latter is considered in this cost study as associated efficiency effects are considered to be more representative of the impacts that would be attained in actual tractor-trailer operation. Although the relationship varies across technology packages, fuel economy over the HHDDT65 cycle, as modeled, is generally about 5%-10% higher than that over the real world cycle.

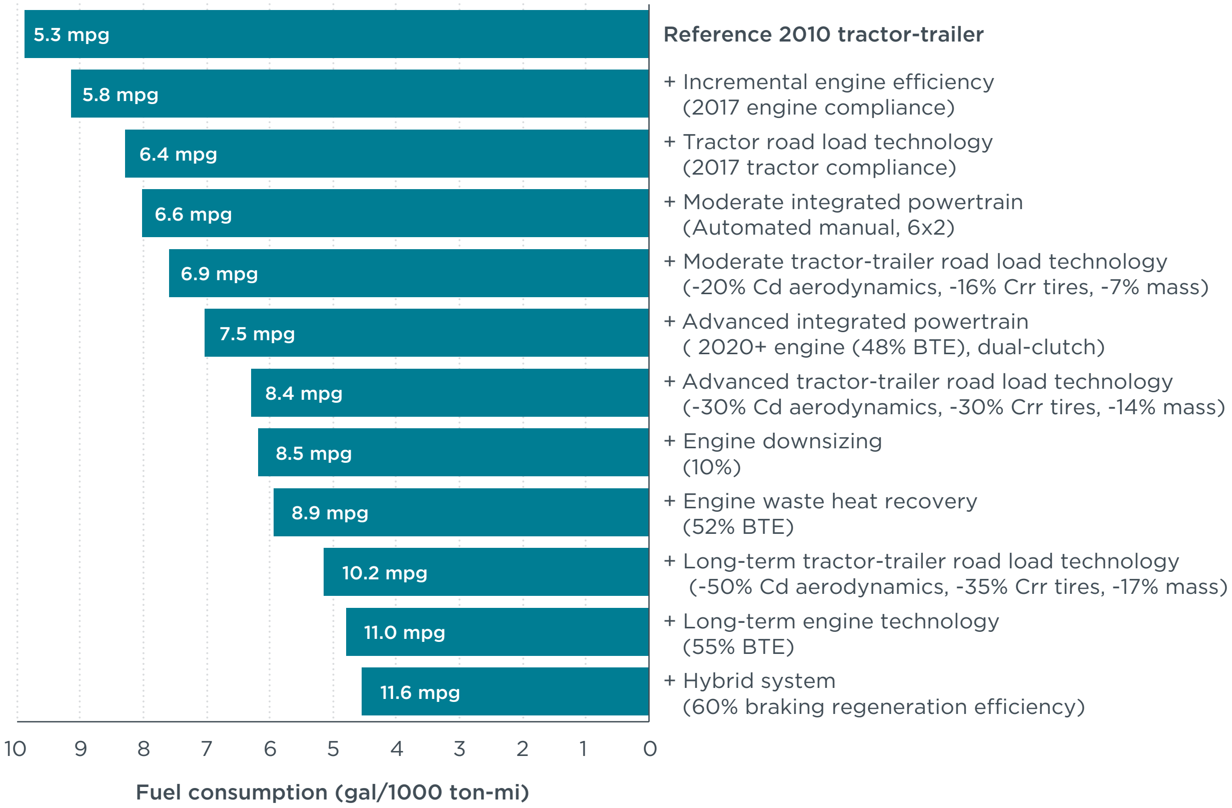

Figure 1. Potential fuel consumption reduction from selected tractor-trailer efficiency technologies in the 2020-2030 time frame on the real-world highway cycle

OVERVIEW

The primary objective of this follow-on study is to evaluate the cost and cost effectiveness of the available and emerging tractor-trailer efficiency technologies in the 2020-2030 time frame. 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 more fully assess the viability of the fuel efficiency technologies. Vehicle and engine technologies and their associated fuel efficiency impacts are taken as given in the companion technology modeling report. This study uses a variety of government, industry, academic, and independent consulting sources to quantify tractor-trailer costs, as well as a range of conventional economic assumptions to evaluate the impacts on tractor-trailer users.

This report is organized as follows. Following this introductory section, Section II provides foundational discussion related to heavy-duty vehicle efficiency technology. Section III presents the methodologies and data sources used to develop technology cost estimates, as well as the assumptions employed in conducting economic analysis of technology packages. Technology cost estimates are also presented in this section. 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 technology study (Delgado and Lutsey, 2015), a basic review of the evaluated fuel efficiency technology is important to a robust understanding of associated cost estimates. There are three fundamental means of improving the fuel efficiency of a vehicle. They consist of reducing fuel demand 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 fuel (in the case of 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 and aerodynamic and rolling resistance profiles. For tractor-trailers, this means targeting 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) 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 areas as defined in the companion tractor-trailer simulation study. A brief description of each of the evaluated technologies follows.

ENGINE TECHNOLOGY

Five distinct levels of diesel engine improvement, generally classified in terms of peak brake thermal efficiency, are evaluated and shown in Table 1. The first two classifications reflect 2010 (study baseline) and 2017-era engine technology as expected to achieve compliance with the Phase 1 heavy-duty vehicle efficiency standards. The remaining three classifications reflect increasingly more efficient engines. The underlying efficiency technology approaches are described below.

Table 1. Engine efficiency definitions

Engine configuration	Peak brake thermal efficiency[a] (BTE)	Waste heat recovery system
2010	42.8%	None
2017	45.8%	None
2020	49.0%	Turbocompounding
2020+WHR	52.0%	Organic Rankine Cycle
Long Term	55.0%	Organic Rankine Cycle

[a] For classifications that include waste heat recovery 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 lubricant oil churning in bearings, valve trains, and piston-cylinder interfaces. Friction reduction provides direct brake work gains. Available and emerging efficiency technologies for reducing losses include improved piston ring designs, improved 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 development. Combustion optimization improves work extraction and reduces exhaust and heat transfer losses. Optimization strategies include increased injection pressure, injection rate shaping, improved atomization and in-cylinder 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. Closed loop engine calibration and control allows real-time optimization of engine (and potentially transmission and vehicle auxiliary) operating parameters.

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 "parasitic" losses or auxiliary loads tend to increase with engine speed. Decoupling accessories from the engine when their operation is not needed, operating them at optimal speeds, or using 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 backpressure that increases with particulate loading. Improvements in aftertreatment technology can act synergistically with advanced engine controls and combustion optimization 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 timing and combustion parameters as well as reduced EGR.

Turbocharger system improvement. Turbocharging technology uses exhaust energy to increase intake pressure, 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, has the potential to reduce pumping, exhaust, and coolant losses.

Turbocompounding. Turbocompounding technology uses exhaust energy captured via an exhaust stream turbine to boost engine output, reclaiming a fraction of waste heat as useful energy. Mechanical turbocompounding 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. Turbocompounding increases backpressure and lowers exhaust temperature, so its effects on aftertreatment systems are an important consideration.

Waste heat recovery. Organic Rankine cycle (ORC) waste heat recovery (WHR) systems convert heat that is typically wasted through the exhaust and engine cooling systems to useable mechanical energy. Organic denotes a low temperature working fluid, such that ORC is also sometimes termed a bottoming cycle. ORC is a more efficient WHR system than turbocompounding, wherein 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 turbocompounding, 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 turbocompounding 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 turbocompounding 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 the US Department of Energy (DOE) SuperTruck demonstration projects (see Delgado and Lutsey, 2014). Conventional and emerging intake pressurization turbochargers are treated as an integral component of all diesel engine packages.

Additionally, it is noted that neither turbocompounding nor WHR increase engine efficiency directly, but rather augment available output by reclaiming a portion of energy otherwise lost as heat. They also can have system level improvements that cause engine operation to fall within optimal efficiency torque-speed regions more frequently. 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, and the reader should recognize that it is the net brake efficiency of the combined system for a given fuel energy input that is actually increasing.

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 (i.e., reducing the displacement of) an engine can force operation at higher load, which generally corresponds with higher efficiency operating regions. 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, which are described separately. Downsized engines also are 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 that increase heat losses and drivability issues if torque capabilities are not adequate for applications that include driving over steep grades.

Engine technology packages. The variety of approaches available for improving engine efficiency, and associated interrelationships among not only the technologies but also their associated loss mechanisms, make it difficult to treat engine technologies individually without assuming explicit and inflexible technology pathways. The efficiency technology pathways for this analysis are based on five levels of *net* engine efficiency as described earlier in this section. In addition to a 2010 baseline engine technology package, the 2017 engine assumes the deployment of technology as required to meet the Phase 1 heavy-duty vehicle standards. Such technology is expected to include selective catalytic reduction (SCR) system improvements such as closed-loop urea injection and thermal management, which should enable combustion optimization through advanced injection timing and higher in-cylinder pressures. Additional enhancements to turbocharging system architecture, such as asymmetric and dual-stage turbochargers, reduced EGR systems, and on-demand accessories are also expected. However, it is impossible to define a universal technology pathway; different engine manufacturers will follow potentially different technology development pathways to achieve Phase 1 compliance.

The 2020 engine uses more advanced technologies that are expected to be available in the approximate 2020 time frame. Further energy loss reduction is expected to result from optimized engine system integration, enabled through the use of advanced model-based controls. These same controls are expected to enable the application of turbocompounding technology. The net effect is an expected increase in power density, which should provide opportunity for engine downsizing. Incremental advances in aftertreatment systems such as integrated diesel particulate filtration (DPF)/SCR systems with reduced thermal inertia and backpressures may also be expected. The 2020+WHR engine is a 2020 engine that incorporates the effects of a WHR system in place of turbocompounding technology.

The Long-Term engine represents the DOE's long-term engine objective of 55% BTE (NRC, 2012). Potential strategies to achieve 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).

TRANSMISSION 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.

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.

Single drive axle (6x2). Increased deployment of single-drive axle 6x2 drivelines is driven by their ability to cost-effectively increase efficiency and reduce weight. The 6x2 configuration increases driveline efficiency by greatly reducing gearing-related energy losses through the use of only one drive axle. The second axle in the conventional tandem axle configuration is converted to a non-powered “dead” axle. The system results in a weight reduction of approximately 400 pounds and allows the use of non-traction tires on the dead axle. Potential considerations include increased drive tire wear and reduced traction capability. Automatic weight-transfer systems may help overcome traction issues by increasing drive axle load during low traction events.

Automated manual transmission. Automated manual transmission (AMT) technology is essentially a standard manual transmission augmented with additional sensors and actuators that allow the transmission control module to undertake the shifting activity that would otherwise be undertaken by the vehicle driver. Fuel savings come from the enabling of engine downspeeding,resulting in lower friction and pumping losses; shift strategy optimization, keeping engine operation at or near high efficiency conditions; and a reduction in driver-to-driver shift variability. Although competitive AMT products are already available in the market, potential improvements include optimized gearing (e.g., smaller gear ratios in higher gears) and optimized integration of engine and transmission controls. Potential considerations include addressing torque losses and engine transients associated with downspeeding.

Dual-clutch transmission. Dual-clutch transmission (DCT) technology is similar to AMT technology except that it includes two separate clutches, one for odd gears and one for even. 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 torques and in-cylinder pressures, and turbochargers need to be matched for lower compressor speeds and higher mass flow requirements. Other considerations related to downspeeding include increased heat transfer, increased in-cylinder pressures, and torsional vibration.

Hybridization. Heavy-duty long-haul hybrid internal combustion and electric, or hydraulic, power system integration is ongoing among many manufacturers and suppliers. Technology potential includes regenerative braking, stop-start and coasting (i.e., shutting off 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 or hydraulic system and returned to the vehicle as electricity for powering accessories or for torque assist using electric or hydraulic motors.

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. Energy requirements, 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 mass. Technologies associated with reducing one or more of these determinants can significantly reduce overall energy consumption.

Aerodynamic improvements. Aerodynamic drag is particularly significant in long-haul heavy-duty vehicle operations due to the large amount of time spent at sustained highway speeds of 55-70 miles per hour (mph). At these relatively steady high speeds, aerodynamic drag power dissipation (which is proportional to the cube of speed) greatly exceeds the 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 skirts, trailer tails, and trailer underbody devices.

Low rolling resistance tires. The rolling resistance of tires is 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 each revolution varies with tire design and is proportional to tractor-trailer weight and speed. There are many suppliers and developers of heavy-duty vehicle tires offering products with increasingly lower rolling resistance, and there is potential to achieve overall reductions of approximately 30%-35% from 2010 baseline tires (NRC, 2012).

Weight reduction. The energy required to induce a given motion, overcome rolling resistance, and overcome road grade, is directly related to tractor-trailer mass. Using lightweight materials and improved design to reduce mass can impact efficiency either directly, in terms of increased fuel efficiency, or by increasing payload capacity and thus increasing load-specific fuel efficiency. The net effect of either is one of increased energy efficiency. The potential for lightweighting in tractor-trailers is significant. For example, a research concept tractor-trailer developed by Walmart demonstrated the potential to reduce weight by approximately 4,000 pounds (Walmart, 2014). Maximum reductions will be enabled by optimized computer aided engineering approaches that investigate tractor, trailer, and powertrain design as an integrated system. Such an approach will enable not only the optimized design of individual parts, but also the optimized design of associated systems and subsystems to capture the synergies and compounding (i.e., secondary mass reduction) effects of component mass reductions.

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 modeling. The specific levels of road load technology evaluated are summarized in Table 2.

Table 2. Tractor-trailer configuration road load reduction definitions

Vehicle configuration	Curb weight change	Drag coefficient change	Rolling resistance change
2010	0%	0%	0%
Phase 1	-2%	-16%	-9%
Moderate	-7%	-20%	-16%
Advanced	-14%	-30%	-30%
Long Term	-17%	-50%	-35%

III. ANALYSIS OF EFFICIENCY TECHNOLOGY COST

While the tractor-trailer simulation results (i.e., Delgado and Lutsey, 2015) provide insight into the fuel efficiency impacts of potential tractor-trailer technologies, the cost analysis undertaken in this study provides the additional context required to assess the cost effectiveness of those technologies. This analysis evaluates the best-estimate technology costs, based on a review and synthesis of existing technology cost data in recent scientific, consulting, and government literature on tractor-trailer efficiency technologies. 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 dollars. To ensure consistency, all technology cost data derived from other studies or sources are first converted into 2014 dollars using Producer Price Index data for motor vehicle parts manufacturing (BLS, 2014). In the case of fuel prices used for economic analysis as described later in this report, dollar year adjustments are based on Consumer Price Index data used by the US Energy Information Administration to evaluate diesel fuel prices in its *Short-Term Energy Outlook* (US EIA, 2014b).

As available cost data often are based on differing assumptions with regard to indirect costs (e.g., research and development costs, overhead costs, marketing and distribution costs, profit markup costs), all derived cost data are first adjusted (if necessary) to a Direct Manufacturing Cost (DMC) basis. DMCs reflect the cost of materials and labor required to produce and assemble technology componentry. Indirect Cost Multipliers (ICMs) are then applied to developed DMC to estimate indirect costs and thus Total Costs (TCs) for each technology (where TC equals DMC plus indirect costs). TCs are generally equivalent to the expected impact on retail prices associated with a particular technology, although actual pricing strategies implemented by manufacturers may include influences that extend beyond specific technology cost. Adjustments designed to promote the sales of a specific model are one example of this.

This DMC/ICM/TC costing methodology is structurally identical to the methodology used by the EPA and NHTSA to support both the Phase 1 heavy-duty vehicle efficiency standards rulemaking (US EPA and NHTSA, 2011b) and similar light-duty vehicle rulemakings. Moreover, the actual ICMs developed in support of the Phase 1 rulemaking, as presented in Table 3, are used for this study. As indicated in the table, indirect costs are assumed to vary with the complexity of the associated technology. The table generally indicates how technologies' indirect costs are roughly estimated to be 20%-50% higher than the direct manufacturing costs. Generally, technologies that are either currently marketed or moderately evolutionary in nature relative to current technologies are assumed to be low complexity. This study assumes the same level of complexity as that assumed by the EPA and NHTSA for technologies included in the engineering analysis conducted by those agencies for the Phase 1 heavy-duty rulemaking (US EPA and NHTSA, 2011b). Longer term technologies are assigned higher complexity ICMs in accordance with their still-developing nature.

Table 3. Indirect cost factors used to convert from efficiency technologies' direct manufacturing cost to total cost

ICM focus	Technology complexity level	2014-2021 warranty costs	2014-2021 nonwarranty costs	2022+ warranty costs	2022+ nonwarranty costs
Engine technology	Low	0.006	0.149	0.003	0.122
	Medium	0.022	0.213	0.016	0.165
	High 1	0.032	0.249	0.016	0.176
	High 2	0.037	0.398	0.025	0.265
Truck technology	Low	0.013	0.165	0.006	0.134
	Medium	0.051	0.252	0.035	0.190
	High 1	0.073	0.352	0.037	0.233
	High 2	0.084	0.486	0.056	0.312

Table 4 lists the specific ICM complexity level assignments assumed in this study. 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 — such as dedicated electric propulsion componentry — not included in this study. As indicated in Table 3, indirect cost factors are established on a separate basis for warranty and non-warranty costs under the assumption that the former decline with direct costs over time while the latter remain unchanged as a fraction of baseline direct costs.

This study also assumes that the direct manufacturing costs of technology are subject to reduction over time due to learning as manufacturers gain design and production experience. Consistent with the approach for ICMs, this study uses a single technology-independent learning curve established by the EPA and NHTSA for the Phase 1 heavy-duty rulemaking (as well as for similar light-duty vehicle rulemakings). This curve assumes that newly introduced low production volume technologies will undergo two cycles of steep learning wherein costs decline by 20% after two years of production and another 20% after four years of production. These two steep cycles are followed by a relatively flatter experience period that assumes five years of 3% per year cost reductions, followed by five years of 2% per year cost reductions, followed by five years of 1% per year cost reductions, after which DMCs are assumed to stabilize (US EPA and NHTSA, 2011b).

Table 4. Indirect cost multiplier complexity and learning curves assigned to technologies

Technology type	Technology classification	ICM complexity level	Learning curve
Engine configuration	2010	Engine Low	Flat 1
	2017	Engine Low	Flat 1
	2020	Engine Medium	Flat 1
	2020+WHR	Engine High 1	Flat 1
	Long Term	Engine High 1	Flat 1
Drive configuration	6 × 4	Engine Low	Flat 1
	6 × 2	Engine Low	Flat 1
Transmission configuration	Manual	Engine Low	Flat 1
	AMT	Engine Low	Flat 1
	DCT	Engine Medium	Flat 1
Hybrid technology	No	Engine Low	Flat 1
	Yes	Engine High 1	Flat 1
Engine downsizing	No Change	Engine Low	Flat 1
	10% Reduction	Engine Medium	Flat 1
	15% Reduction	Engine Medium	Flat 1
Aerodynamic configuration	2010	Truck Low	Flat 1
	Phase 1	Truck Low	Flat 1
	Moderate	Truck Low	Flat 1
	Advanced	Truck Medium	Flat 1
	Long Term	Truck High 1	Steep 2
Rolling resistance configuration	2010	Truck Low	Flat 1
	Phase 1	Truck Low	Flat 1
	Moderate	Truck Medium	Flat 1
	Advanced	Truck High 1	Steep 2
	Long Term	Truck High 1	Steep 2
Mass configuration	2010	Truck Low	Flat 1
	Phase 1	Truck Low	Flat 1
	Moderate	Truck Medium	Flat 1
	Advanced	Truck High 1	Steep 2
	Long Term	Truck High 1	Steep 2

See US EPA and NHTSA, 2011b

Figure 2 is a graphic depiction of the technology learning curve, which shows that after 20 years of production, direct costs are assumed to be about 53% lower than their initial low-volume cost. Note that this does not translate to a 53% decline in total costs as the bulk of indirect costs do not decline with learning. Putting these components together, the technologies' direct costs, which per Figure 2 decline over time, are summed with the indirect warranty and indirect nonwarranty costs (from Table 3) to determine the total cost as follows.

$$TC_{year} = DMC_{base} \bullet LF_{year} + DMC_{base} \bullet ICF_{non\text{-}warranty} + DMC_{base} \bullet LF_{year} \bullet ICF_{warranty}$$

Where:
LF = learning factor (see Table 4 and Figure 2)
ICF = indirect cost factor (see Tables 3 and 4)
base = base year
year = evaluation

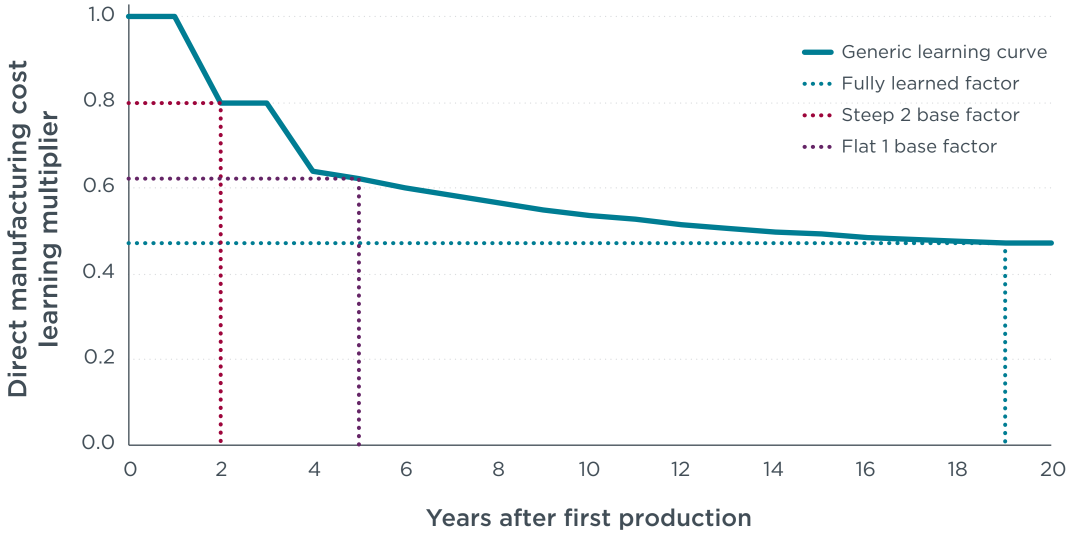

Figure 2. Direct manufacturing cost learning curve and base factors for technology cost reductions over time

Although the basic learning curve is technology independent, the position of a particular technology on the curve is not. In other words, for a given technology some portion of learning may have already occurred and thus learning between "now" and some point in the future will be less (or substantially less) than implied by assuming that future learning always starts at year zero (i.e., the first year of production).

Two starting points are assumed for technologies in this study, denoted as Steep 2 and Flat 1. Technologies associated with Steep 2 learning are assumed to begin learning at two years after first production, or at the beginning of the second steep learning cycle. This point is depicted by the dotted red line in Figure 2. For such technologies, fully learned direct manufacturing costs will be about 41% lower after 18 years than their assumed baseline DMC. Technologies associated with Flat 1 learning are assumed to begin learning at five years after first production, or at the beginning of the second flat (3% per year) learning cycle. This point is depicted by the dotted violet line in Figure 2. For such technologies, fully learned direct manufacturing costs will be about 24% lower after 15 years than their assumed baseline DMC. The base DMC learning assignments for the technologies included in this study are presented in Table 4.

In reviewing the cost effectiveness and economic payback data presented later in the report, it is important to recognize that more aggressive learning assumptions increase cost effectiveness and reduce technology payback periods. In recognition of this, this study generally relies on conservative learning assumptions, applying flat curve learning to all but the most advanced road load technologies. The Flat 1 learning data are consistent with assumptions used by the EPA and NHTSA for the Phase 1 heavy-duty rulemaking, and this study applies this same Flat 1 assumption to substantially more advanced technologies than are considered in the Phase 1 rule, so assumed direct cost reductions may be underestimated. In cases where the EPA and NHTSA assumed two cycles of steep learning (for example, advanced aerodynamic drag reductions), this study assumes only one and extends this same assumption to only the most advanced rolling resistance and mass reductions. If less conservative learning assumptions were employed, the cost effectiveness of associated fuel efficiency technologies as detailed in the following sections of this report would improve accordingly.

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 where data are 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 expressed in terms of retail price equivalent (RPE) with no indication of associated direct manufacturing costs are converted to a DMC-equivalent cost for this study by assuming an RPE markup factor of 50% (i.e., RPE = DMC × 1.5). In cases where explicit RPE factors are provided, those factors are used directly to calculate DMC.

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 used. These sources are:

- A 2010 study on medium- and heavy-duty truck fuel efficiency conducted by the National Research Council (NRC, 2010).
- A 2009 study on medium- and heavy-duty vehicle fuel efficiency conducted by TIAX LLC in support of the National Research Council study (Kromer et al., 2009).
- 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 (US EPA and NHTSA, 2011b).
- A 2010 study on technologies to reduce greenhouse gas emissions from heavy-duty vehicles conducted by ICF International in support of the EPA and NHTSA Phase 1 rulemaking (Browning et al., 2010).

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. These secondary sources include:

- A 2009 study on low carbon technologies for heavy-duty vehicles conducted by Ricardo for the UK Department of Transport (Ricardo, 2009).
- A 2011 study on greenhouse gas emissions from heavy-duty vehicles conducted by Ricardo for the European Commission (Ricardo, 2011).

- A 2014 study on heavy-duty trailer fuel efficiency technology and cost conducted by the International Council on Clean Transportation (Sharpe et al., 2014).
- A 2009 study on long-haul tractor-trailer fuel consumption and CO_2 emissions conducted by the Northeast States Center for a Clean Air Future, the International Council on Clean Transportation, Southwest Research Institute, and TIAX LLC (Northeast States Center for a Clean Air Future 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. The above data sources are valid in reflecting the applicable technologies that have been under development, and have made technical advances toward market readiness, since their publication. These data sources are too numerous to list here, but are referenced as appropriate in the technology discussions that follow. Certainly each of these targeted sources is as critical to this report as the broader scope sources identified here.

KEY ECONOMIC ASSUMPTIONS

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

Fuel price. Analysis is conducted for three different fuel price scenarios representing low, best estimate, and high fuel prices. All three estimates are derived from the EIA's *2014 Annual Energy Outlook* (US EIA, 2014a), which forecasts diesel fuel prices through 2040 under best estimate, low, and high oil price scenarios. Because the focus of this study is on the period 2020 to 2030, the average diesel fuel price rounded to the nearest 10 cents for that 11-year period is calculated for each oil price scenario, and converted from EIA's 2012 dollars to the 2014 year dollars used in this study.

The resulting estimates of $3.10, $4.10, and $5.40 per gallon are used for the low, best estimate, and high fuel price scenarios associated with this study. The difference between the minimum and maximum EIA fuel prices during the 11-year period is 10, 55, and 53 cents per gallon for the low, best estimate, and high fuel price scenarios respectively, so average estimates are reasonably representative of fuel prices expected throughout the period. While there have been dramatic declines in fuel prices over the last few months of 2014, it is important to recognize that the period associated with this analysis is 2020 and beyond. At this time, it is expected that recent price declines will have only a minor effect, if any, on long-term fuel price trends so that no adjustments to the EIA forecast data are made in response to the observed short-term price variability.

Discount rate. Analysis is conducted for three different discount rates: 3%, 7%, and 10% (see OMB, 1992). Because 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 are assumed to accrue immediately and are not discounted, or financed, in any way. Conversely, any associated fuel savings are discounted in accordance with the stated rates beginning in the year immediately following technology adoption.

Vehicle miles of travel (VMT). The rate at which fuel savings accrue depends on both the assumed discount rate and accumulated VMT by age. Age dependent VMT data for long-haul tractor-trailers are taken from the EPA and NHTSA Phase 1 rulemaking for heavy-duty vehicles (US EPA and NHTSA, 2011b). The basic assumption from the rulemaking data is that tractors are driven approximately 133,000 miles in the first year of tractor ownership, and then VMT per year drops over time with vehicle age. It is important to note that these EPA and NHTSA data include consideration of the survival rates for tractor-trailers and therefore reflect the fleet-weighted average VMT for all tractor-trailers. Such consideration is important in assuring that the derived VMT function is the appropriate metric for determining fleet-average fuel savings, as opposed to the fuel savings for a non-average long-lived tractor-trailer.

This VMT-by-age relationship reflects how high tractor activity is in the early years of tractor ownership, whereby about half of the average 1.2 million lifetime miles are driven in the first 5 years of ownership. Per-vehicle VMT-by-age is assumed to be constant from 2014 through 2030. Potential per-vehicle VMT growth factors were evaluated, but ultimately set to unity based on an analysis of EPA Motor Vehicle Emission Simulator (MOVES) heavy-duty truck population and VMT data (US EPA, 2014). While heavy-duty vehicle VMT, as encoded in MOVES, is assumed to grow over time — it grows at a rate that is substantially identical to the growth rate of the heavy-duty vehicle population — per-vehicle VMT remains constant. It is important to recognize that assuming constant per-vehicle VMT over time is conservative from an economic analysis standpoint as aggregate fuel savings increase with assumed mileage.

VMT elasticity. VMT 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 increase in fuel economy, results in a net reduction in operating costs. An elastic relationship between operating costs and VMT assumes that a fraction of any operating cost savings will be spent on increased travel. This effect is sometimes called the rebound effect.

Various estimates of the magnitude of this elasticity have been developed. This study uses the estimate developed by the EPA and NHTSA for the Phase 1 heavy-duty vehicle rulemaking, namely a -0.05% change in VMT per 1% change in operating costs (US EPA and NHTSA, 2011b). Generally, this represents a relatively inelastic response to changes in operating costs and, as indicated in the EPA and NHTSA discussion surrounding their assumed value, there is considerable associated uncertainty. However, long-haul tractor-trailer operation is likely to have a relatively insignificant level of discretionary driving, which would be expected to be quite sensitive to fuel cost. On the other hand, non-discretionary driving in the sector is subject to myriad influences that are either independent of trucking costs (e.g., costs of alternative transportation modes) or subject to considerably more sources of influence than trucking costs alone (e.g., the total demand for freight). Given those parameters, the magnitude of the EPA and NHTSA elasticity estimate appears reasonable.

It is important to recognize the effect VMT elasticity can have on different economic impact metrics. Aggregate fuel and fuel cost savings will decline with increasing VMT elasticity as some of the savings that would have accrued had VMT not increased will be redeemed for additional driving, incurring costs that would not otherwise have been incurred. Although not estimated in this cost analysis, the same effect will occur with regard to greenhouse gas emissions. Conversely, increasing VMT reduces the time period over which technology costs are recouped, leading to shorter time-based payback periods.

In effect, technology costs can be equated to a specific number of miles by dividing cost by dollars per mile fuel savings. As VMT elasticity increases, the time period required to accumulate this "payback mileage" is compressed. Beyond the point where increased mileage exceeds the mileage that would have otherwise been accumulated if VMT were inelastic, all savings become negative. However, as long as this point is beyond the payback mileage, the time required to accumulate the payback mileage will be decreased under a more elastic VMT scenario. The effect is minor for the VMT elasticity assumed in this study, but could be significant under higher elasticity scenarios.

Operating cost breakdown. Because VMT elasticity is expressed in terms of operating costs and potential fuel efficiency standards affect (at least on a first order basis) only the vehicle purchase price and fuel cost components, it is necessary to estimate the share of those components with regard to total operating costs. This study relies on a breakdown of dollar-per-mile operating costs developed by the EPA and NHTSA for the Phase 1 heavy-duty vehicle rulemaking (US EPA and NHTSA, 2011b; see Figure 9-1). This operating cost distribution indicates that fuel costs account for 40.2% of total operating costs, assuming a 2008 fuel price of $4.79 per gallon; truck purchase costs account for 11.9% of total operating costs; and other components (e.g., repair and maintenance, insurance, tires, licensing and permits, tolls, driver pay, driver benefits, and driver bonuses) account for 47.9% of total operating costs. This study adjusts this distribution to account for differences in the base distribution fuel price and the three fuel price scenarios evaluated in this study. The resulting adjusted distributions, as presented in Table 5, are used as the basis for determining all VMT elasticity effects in this study.

Table 5. Distribution of long-haul operating costs at varying fuel prices

Distribution component	At 2008 fuel price $4.79/gallon	At EIA low 2020 to 2030 $3.10/gallon	At EIA mid 2020 to 2030 $4.10/gallon	At EIA high 2020 to 2030 $5.40/gallon
Fuel cost	40.2%	28.3%	34.3%	40.8%
Truck purchase	11.9%	14.3%	13.1%	11.8%
Other	47.9%	57.4%	52.6%	47.4%
Aggregate	100.0%	100.0%	100.0%	100.0%

Baseline tractor and trailer prices. To estimate the VMT 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 $137,500 (2014 dollars) and baseline trailer price is taken as $25,000 (2014 dollars) based on publicly available market data. The baseline tractor is a 2015 Mack sleeper with a 13-liter MP8 engine (CommercialTruckTrader.com, 2014a), consistent with the baseline vehicle characteristics of this study. The baseline trailer is a standard 53-foot dry van trailer (CommercialTruckTrader.com, 2014b).

Trailers per tractor. Based on data developed by TIAX (Kromer et al., 2009), it is estimated that there are three long-haul trailers in operation for every tractor. Therefore, this study incorporates trailer technology costs by multiplying the per-trailer costs by a factor of three to account for the fact that three trailers will need to be improved for every improved tractor. We note more recent data by Sharpe et al. (2013) finds an average of 2.4 trailers per tractor, thereby making this report's trailer-specific costs conservative.

Technology package real-world fuel economy. All fuel economy impact estimates are taken directly from Delgado and Lutsey (2015), as summarized previously in Figure 1. Generally, fuel economy achieved in actual practice is somewhat lower than that achieved over standardized regulatory driving cycles. Recognizing this, Delgado and Lutsey (2015) developed fuel economy estimates for standardized regulatory cycles and a real-world highway cycle based on approximately 120 miles of long-haul interstate travel from Wheeling, West Virginia, to Columbus, Ohio, including variable grade effects. All fuel economy data subjected to economic analysis in this study is based on the latter real-world cycle.

INDIVIDUAL TECHNOLOGY COSTS

Technology costs form the basis of all economic analysis for 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. Through this research, it is readily apparent that a considerable range of estimates is available with regard to the cost of a given technology. In an effort to capture the potential impact of such variation, a two-path approach is employed in this study, essentially reflecting “best estimate high” and “best estimate low” costs. These should not be confused with minimum and maximum costs. This is not an attempt to capture the highest and lowest cost estimates for a technology, but rather to capture the uncertainty surrounding best estimate costs. Outlier cost estimates on either the high or low side are not included in the analysis conducted for this study.

In a general but definitely not universal sense, the approach can be thought of as comprising NRC-equivalent costs (NRC, 2010) on the high side and EPA-equivalent costs (US EPA and NHTSA, 2011b) on the low side. Together these two sources represent the most robust compendia of currently available heavy-duty vehicle and engine technology cost estimates, and thus serve as primary-level data sources for this study.

The NRC cost estimates usually exceed those of the EPA and NHTSA, so NRC cost estimates more often end up defining best estimate high costs and EPA and NHTSA estimates more often end up defining best estimate low costs. This generality, however, is really nothing more than a convenient labeling convention as there are instances where the cost estimates of the two sources are inverted in magnitude and thus get assigned counter to the generality, or where costs derived from a secondary-level source are defining for a particular technology. Regardless of source, best estimate high costs will always equal or exceed best estimate low costs, and best estimate high costs for technology packages will always consist of the sum of component best estimate high costs and vice versa. In no case are package costs derived from the integration of best estimate high costs for one or more component technologies and best estimate low costs for one or more component technologies. All high and low cost distinctions are carried through from individual technology to technology package cost estimates.

Engine technology. The various engine technology packages from the simulation modeling (as identified in Section II) are treated on an aggregate basis (i.e., analogous to an individual technology) in this study. The TIAX study (Kromer et al., 2009) commissioned in support of the NRC heavy-duty vehicle technology study (NRC, 2010) includes cost estimates for four engine technology packages, including baseline, that are within 2% (or one percentage point) of the peak BTE values associated with the Delgado and Lutsey (2015) modeled technology packages (see Table 1). The only technology package without a TIAX/NRC counterpart is the long-term (55% peak BTE) engine technology package.

To estimate the TIAX/NRC-equivalent cost of the long-term engine technology package, the cost of the four available packages, with turbocompounding and WHR technology cost removed, as applicable, is regressed against peak BTE with a correlation coefficient of 0.97 to derive a "without WHR" engine cost. This represents a modest but reasonable extrapolation given the fact that the non-WHR components of the long-term package are expected to reflect continuing evolutionary advancements of existing technology, and that the cost of such advancements for the preceding packages demonstrated a strong correlation.

The long-term engine package cost must also include the cost of improved WHR technology. To estimate this additional cost, an average of low and high WHR cost estimates is developed. On the low side, WHR cost is estimated as unchanged from that of the preceding engine package. The high side estimate is developed by regressing the cost of the four available engine packages, with turbocompounding and WHR technology cost included as applicable, against peak BTE with a correlation coefficient of 0.94 to derive a "with WHR" engine cost. Subtracting the estimated without WHR engine cost derived above yields a WHR-only cost estimate.

Because WHR system improvements are expected to be an integral component of the long-term engine package, there is little doubt that WHR costs will increase above those of the preceding engine package. However, the with WHR regression-based estimate is believed to overestimate the cost increase, as it is derived using an approach that does not recognize the step-change nature of the movement from conventional turbocharging to turbocharging plus turbocompounding to turbocharging plus WHR. The impacts of these step changes are manifest as overestimates of the cost change associated with any one waste heat technology alone. To compensate for this overestimate, the cost of long-term WHR for this study is estimated as the arithmetic average of the low side (i.e., no cost increase) and high side (i.e., regression-based cost increase) estimates.

The EPA and NHTSA cost estimates for the Phase 1 heavy-duty vehicle rulemaking (US EPA and NHTSA, 2011b) also include an increased engine efficiency technology package. This package is estimated to have a peak BTE of 48.2%, which would make it roughly equivalent to the 2020 engine package of this study. However, because the EPA and NHTSA cost analysis is based on expected 2017 engine technology, this study assumes the developed cost estimates are more comparable to the 2017 engine package of both this study and TIAX/NRC. By comparing the EPA and NHTSA costs to the corresponding costs for the comparable TIAX/NRC package, cost ratios for non-WHR and WHR components are developed. These ratios are then applied to the costs for the remaining TIAX/NRC engine packages to develop EPA-equivalent costs for the packages. It is important to note that were this comparison conducted on the basis of the higher cost equivalent-BTE engine package, the developed EPA-equivalent costs would have been significantly lower than estimated for this study.

Although many sources were assessed, the TIAX/NRC-based and EPA-based engine technology cost estimates are used as this study's best estimate high and best estimate low costs, respectively. Actual developed costs are included in summary Table 7 that appears at the end of this section.

Drive configuration. Although costs for 6x2 drive technology are not included in the NRC heavy-duty vehicle technology study, they are included in the underlying TIAX study commissioned by the NRC (Kromer et al., 2009). These costs are used directly for this study as the best estimate high costs. Alternative cost estimates are obtained from a North American Council for Freight Efficiency (NACFE) report on 6x2 technology

(NACFE, 2014). NACFE estimates a substantial premium under current low volume production, but notes that "OEMs and 6x2 suppliers/manufacturers are in wide agreement that, within a few years, 6x2 configurations will be approximately cost-neutral."

Low volume premiums are due to the need for a larger gear set, the addition of load-shifting electronics, higher cost traction control componentry, and custom made dead axles. NACFE believes that as production increases, these additional costs will come down to the point where they are fully offset by savings due to the elimination of inter-axle prop shafts, the inter-axle differential, and the dead axle gear set and axle shafts. Based on this assessment, this study uses a zero increment high production volume cost estimate as the best estimate low cost for 6x2 drive technology. Specific developed costs are included in summary Table 7 at the end of this section.

Transmission technology. The TIAX study (Kromer et al., 2009) commissioned in support of the NRC heavy-duty vehicle technology study (NRC, 2010) includes cost estimates for AMT transmission technology. No equivalent costs are estimated for the Phase 1 heavy-duty vehicle rulemaking, as transmission improvements are not expected to result from the rule. Alternative estimates for AMT technology costs are derived from two Ricardo studies conducted in Europe (Ricardo, 2009 and Ricardo, 2011). The technology costs from the two Ricardo studies are wildly different, with the 2011 study estimating costs three times those of the 2009 study. This study relies directly on the 2011 Ricardo study costs for best estimate high AMT costs. AMT best estimate low costs are taken directly from TIAX/NRC. The Ricardo 2009 study estimates for AMT technology are not used for any analysis in this study.

Cost estimates for heavy-duty truck DCT technology are not generally available in the literature. As a result, DCT cost estimates are derived in this study. The basis for this derivation is comparative production cost data for various transmission designs as published by Zeroshift (Heath and Child, 2007). Although the Zeroshift data present cost estimates for 5- and 6-speed transmissions relative to a conventional 5-speed manual transmission, it is believed that the relative costs of the various designs would be applicable for higher speed transmissions as long as an equivalent speed relationship is maintained. Thus, both best estimate low and best estimate high costs for DCT technology are estimated by applying the Zeroshift ratio of DCT to AMT costs to the developed AMT cost estimates for tractor-trailers. Specific developed costs are included in summary Table 7.

Hybrid technology. The TIAX study (Kromer et al., 2009) commissioned in support of the NRC heavy-duty vehicle technology study (NRC, 2010) includes cost estimates for hybrid technology, namely 50 kW parallel. An ICF study (Browning et al., 2010) commissioned in support of the EPA and NHTSA Phase 1 heavy-duty vehicle rulemaking includes cost estimates for the same hybrid technology. The ICF cost estimate is identical to the upper end of the range of costs estimated by TIAX, so this cost is used as the best estimate high cost for this study. The best estimate low cost for this study is set at the midpoint of the TIAX cost estimate range. Specific developed costs are included in summary Table 7.

Engine downsizing. Information on the cost impacts of engine downsizing in the heavy-duty sector is not generally available. Nevertheless, reducing engine displacement should result in some cost savings due to a reduction in materials and, if applicable, parts count. Because the levels of downsizing evaluated in this study are not sufficient to promote fundamental engine configuration changes, such as a reduction in cylinder count, no associated part count reductions are anticipated. The cost savings due to reduced material demand are estimated by first estimating the average per-pound cost of materials and applying the derived cost to the weight savings associated with engine downsizing.

This study uses a baseline engine weight of 2,676 pounds, FleetOwner.com's 2014 estimate for a Mack MP8-505 engine, which is consistent with the baseline engine used for this study. Engine weight changes attributable to downsizing by reducing the baseline engine weight are estimated at 268 pounds for a 10% displacement reduction and 401 pounds for a 15% displacement reduction.

The average per-pound cost of materials is estimated at $1.45. This estimate is derived by adjusting the baseline tractor cost of $137,500 (see "Key economic assumptions," above) to an equivalent direct manufacturing cost by assuming a 50% markup and multiplying the resulting DMC by the estimated parts fraction of cost. The parts fraction of tractor DMC is estimated from detailed data developed through light-duty vehicle teardown analysis (FEV, 2012). Although the teardown work is applicable to a light-duty vehicle, the determined relationship (albeit at differing absolute cost levels) between parts and vehicle DMC should be reasonably representative of the corresponding relationship for other vehicles. Applying this relation to the baseline tractor DMC and dividing by the baseline tractor weight yields an estimate for the average per-pound cost of materials. The baseline tractor weight is estimated as the assumed unladen tractor-trailer weight from this study's technology modeling, 32,500 pounds, minus the unladen weight of a standard 53-foot dry van trailer, which is estimated at 14,400 pounds for this study (McGuire).

The $1.45 derived average per-pound cost of materials is quite consistent with the $1.32 per-pound cost from the detailed light-duty vehicle teardown analysis and provides some validation of the cross-sector applicability of the parts-to-vehicle DMC ratio. It is also possible to calculate per-pound costs for the light-duty engine system and detailed engine components from the FEV teardown work. For the engine system as a whole, the per-pound DMC is $2.30, while that for the cylinder block is $1.96. Both are substantially higher than the vehicle-average per-pound cost, which is not surprising given that the use of less expensive materials will be biased toward non-engine components. Nevertheless, given the uncertainty associated with applying light-duty vehicle data to the heavy-duty sector, this study bases all downsizing costs (i.e., savings) on the more conservative vehicle-average per-pound cost of $1.45, applying the same per-pound cost to generate both best estimate high and best estimate low net costs. Specific developed costs are included in summary Table 7.

Aerodynamic drag reduction. As described in Section II, the Delgado and Lutsey (2015) aerodynamic drag reductions are characterized by five distinct "bins," with reductions ranging from 0%-50%. Costing of drag reduction technology is somewhat more complex than engine- and powertrain-related technology due to the fact that technology can be applied to the tractor, the trailer, or both. This study develops its aerodynamic technology costs from TIAX/NRC, ICF/EPA, and Sharpe et al. (2014) study costs. Both the TIAX study (Kromer et al., 2009) commissioned in support of the NRC heavy-duty vehicle technology study (NRC, 2010) and the ICF study (Browning et al., 2010) commissioned in support of the EPA and NHTSA Phase 1 heavy-duty vehicle rulemaking (US EPA and NHTSA, 2011b) include cost estimates for various tractor and trailer aerodynamic drag reduction technologies. TIAX/NRC assumes a higher baseline drag coefficient than either ICF/EPA or Delgado and Lutsey (2015), but nonetheless evaluates reductions ranging from 0%-30% for the tractor and 0%-24% for the trailer. ICF/EPA evaluates reductions ranging from 0%-37% for the tractor and 0%-20% for the trailer. Also, Sharpe et al. (2014) include cost estimates for trailer drag reductions ranging from 0%-25%.

The cost data from each of these studies are independently regressed, in that separate relations are developed for each study against drag reduction to derive generalized cost versus drag reduction relations. This allows cost to be estimated for any drag reduction within the range associated with the underlying cost data. Taking cost data for each combination of explicitly evaluated tractor and trailer data points, it is then possible to adjust the associated drag and cost data to match one or more of the drag reduction levels from this study's technology assumptions.

To reflect the emerging drag reduction practice, technology is applied to both tractors and trailers on an incremental basis. First, tractors' aerodynamic drag levels are matched to aerodynamic drag coefficients evaluated in the ICF/EPA study. In effect, this initially assigns to each drag reduction level tractors with drag characteristics that do not alone reach the overall drag reduction level; therefore, additional aerodynamic improvements are then assigned to the trailers. These tractors are then paired with various trailer aerodynamic packages, and the tractor and trailer package that results in the closest agreement with the associated overall drag reduction level is selected as the aerodynamic technology package for costing purposes. Trailer drag characteristics are then adjusted using the developed regressions so that the selected package characteristics exactly match the associated drag reduction level.

For the moderate and advanced drag reduction levels, this does not result in a least cost solution, instead increasing costs by a factor of two to three relative to costs that would be associated with tractor-only technologies. For the long term package, there is only one tractor package that could possibly facilitate compliance with the drag reduction level, so that the net cost with any trailer package, once adjusted to achieve the assumed aerodynamic reduction level, is identical. Thus, the long term technology package remains a least cost solution.

Except for the long term tractor package, both tractor and trailer cost estimates based on TIAX/NRC, ICF/EPA, and Sharpe et al. (2014) data are of similar magnitude. TIAX/NRC costs for the long term tractor are considerably higher. Although similar, TIAX/NRC tractor costs for the less advanced drag packages are slightly lower than those of ICF/EPA. For all packages requiring trailer drag reduction, Sharpe et al. (2014) trailer costs are slightly lower than those of ICF/EPA. Therefore, to maintain a best estimate high and best estimate low approach to costs, this study combines the ICF/EPA tractor costs with the Sharpe et al. (2014) costs to create one estimate and uses the combined TIAX/NRC tractor and trailer costs as a second estimate. The lower of these two estimates is defined as the best estimate low cost and the higher of the two is defined as the best estimate high cost. Specific developed costs are included in summary Table 7.

Rolling resistance reduction. The approach used to estimate rolling resistance reduction costs is quite similar to that for aerodynamic drag. As described in Section II, the starting point is the tractor-trailer simulation analysis' five distinct bins for rolling resistance reductions, with associated reductions ranging from 0%-35%. As with drag reduction, the costing of rolling resistance reduction technology is somewhat more complex than engine- and powertrain-related technology due to the fact that technology can be applied to the tractor, the trailer, or both.

Both the TIAX study (Kromer et al., 2009) commissioned in support of the NRC heavy-duty vehicle technology study (NRC, 2010) and the ICF study (Browning et al., 2010) commissioned in support of the EPA and NHTSA Phase 1 heavy-duty vehicle rulemaking (US EPA and NHTSA, 2011b) include cost and associated rolling resistance reduction estimates for tractor and trailer rolling resistance reduction technologies. However, TIAX/

NRC assumes a second generation of rolling resistance reduction that is not reflected in the ICF/EPA data. The "maximum technology" rolling resistance characteristics included in the TIAX/NRC study are about 2% better than the characteristics required to achieve reductions consistent with the most advanced rolling resistance reduction technology package in this study, so cost and associated rolling resistance reduction data are available for the full range of assumed reductions.

Unlike aerodynamic drag, this study does not assume that rolling resistance reduction technology is continuous with regard to available reductions, or more accurately, composed of sufficiently differing technology options that can effectively be combined to create a pseudo-continuum. Due to the limited rolling resistance reduction options available — combinations of baseline dual tires, low rolling resistance (LRR) dual tires, next generation LRR (NG-LRR) dual tires, single wide LRR tires, and single wide NG-LRR tires — it is more appropriate to construct distinct tractor and trailer technology packages from these options and then estimate the market shares of each package required to attain the applicable rolling resistance reduction levels. In terms of decreasing rolling resistance, the specific technology packages considered are: (1) baseline duals on tractor and trailer, (2) LRR duals on tractor only, (3) LRR duals on tractor and trailer, (4) LRR single wides on tractor only, (5) LRR single wides on tractor and trailer, (6) NG-LRR duals on tractor and trailer, (7) NG-LRR single wides on tractor only, and (8) NG-LRR single wides on tractor and trailer.

As with aerodynamic drag, it is possible to assign the rolling resistance technologies on a least-cost basis. While not inherently incorrect, such an approach results in a bias toward maximum tractor-based technology due to the economic requirement that three trailers be improved for every tractor. Given a desire to more accurately reflect the emerging rolling resistance reduction market that is expected to apply technology to both tractors and trailers on an evolutionary basis, the technology packages defined above are treated in a stepwise fashion as the assumed rolling resistance reduction increases. Specifically, the market shares presented in Table 6 are used to match the rolling resistance reduction levels assumed in this study.

Table 6. Rolling resistance improvement technology distribution

Technology package	On tractor	On trailer	RR change	Market Shares				
				2010	Phase 1	Moderate	Advanced	Long Term
Base duals	Yes	Yes	0.0%	100.0%	13.3%			
LRR duals	Yes	No	-10.4%		86.7%	20.0%		
LRR duals	Yes	Yes	-13.8%			30.5%		
LRR SW	Yes	No	-16.1%			20.0%		
LRR SW	Yes	Yes	-23.3%			20.0%		
NG-RR duals	Yes	Yes	-19.5%			9.5%	16.3%	
NG-LRR SW	Yes	No	-29.0%				50.0%	20.4%
NG-LRR SW	Yes	Yes	-36.5%				33.7%	79.6%
Net Market Share				100.0%	100.0%	100.0%	100.0%	100.0%
Net Rolling Resistance Change				0.0%	-9.0%	-16.0%	-30.0%	-35.0%

RR = rolling resistance, LRR = low rolling resistance, SW = single wide tires, NG = next generation

The net cost for each rolling resistance reduction technology level is the market share-weighted average of the component technology costs. Cost data from TIAX/NRC are used as reported. However, cost data from ICF/EPA are problematic in two areas. First, the estimated cost for aluminum wheels is wildly inconsistent with corresponding estimates developed by others. Because conversion to aluminum wheels is typically considered to be an integral component of the conversion from dual to single wide wheels, the cost of the conversion is included in the cost of low rolling resistance single wide technology. Second, the ICF/EPA cost for low rolling resistance dual tires is wildly different with regard to tractor and trailer applications. The cost for tractor applications is quite consistent with corresponding costs developed by others. However, the per-tire cost for trailers is nearly four times the ICF/EPA estimated cost for a low rolling resistance tractor drive axle tire and nearly twice the ICF/EPA estimated cost of a low rolling resistance tractor steer axle tire. This study adjusts for such inconsistencies by using the ICF/EPA per-tire drive axle low rolling resistance tire costs for both the tractor drive axles and all trailer axles, and by substituting the TIAX/NRC costs for low rolling resistance single wide tires for those developed by ICF/EPA. The TIAX/NRC and adjusted ICF/EPA cost estimates are used as the best estimate high and best estimate low costs, respectively, for this study. Actual developed costs are included in summary Table 7.

Weight reduction. Weight reduction cost estimation poses a unique challenge. While the efficiency technology simulation analysis addresses weight reduction in terms of five distinct bins, with curb weight reductions ranging from 0%-17%, these nominal reductions are actually technology package dependent. This is due to the fact that most fuel efficiency technologies include an inherent weight effect that must be added to the nominal weight reduction level to determine a net weight reduction target. Thus, weight reduction costs must be developed on a technology package basis.

The weight reduction effect of individual technologies or technology pseudo-packages, in the case of engine and aerodynamic drag technology, is primarily taken from the TIAX study (Kromer et al., 2009) commissioned in support of the NRC heavy-duty vehicle technology study (NRC, 2010). Exceptions are 6x2 drive technology, the long-term engine technology package, and DCT transmission technology, for which estimates are not developed by TIAX, and the weight effect of engine downsizing, which is estimated explicitly in the technology costing analysis.

The weight effect of 6x2 drive technology is taken from an article in *Heavy Duty Trucking* (Berg, 2013). The long-term engine technology package is estimated to be weight neutral relative to the next most advanced engine package because the expected compliance route for the long-term package is the continued optimization of systems included in the next most advanced engine package. The weight effects of DCT transmission technology are taken from an FEV technical paper (Hellenbroich and Rosenburg, 2009) comparing the weight of AMT technology with an equivalent DCT. The weight ratio from this paper is applied to the TIAX-estimated AMT weight effect to derive an equivalent weight effect for DCT technology. All estimated weight effects are included in summary Table 7.

On a nominal basis, this study’s weight reduction levels range from zero to 5,525 pounds. When the effects of other added fuel efficiency technology are considered, the net required reduction ranges as high as 6,100 pounds. TIAX/NRC includes cost estimates for weight reductions as high as 3,000 pounds. ICF/EPA includes minimal data on weight reduction, essentially including analysis for only aluminum wheels (which would provide for weight reduction on the order of up to 500 pounds for a single wide configuration). Thus, it is necessary to use supplemental data to derive cost estimates for the full range of required reductions.

Data from the European Aluminium Association provide estimated costs for heavy-duty truck reductions as great as 6,000 pounds (EAA, 2014). The US Department of Energy (US DOE, 2013) has established heavy-duty vehicle targets and costs for weight reductions as high as 9,000 pounds. Although the targets extend through 2050, the 2030 target roughly corresponds to the most advanced technology level of the tractor-trailer simulation study. Additionally, detailed data developed by FEV (FEV, 2012) on weight reduction potential in the light-duty sector is available. Although not directly applicable to tractor-trailers, the exhaustive and detailed nature of this data is quite informative with regard to validating and elaborating upon some of the observed differences in weight reduction cost estimates.

For light-duty vehicles, the FEV data show that when fully learned, a 19% reduction in baseline (2010-era) vehicle weight can nominally be achieved at a net cost of -28 cents per pound. When adjusted for current learning, the net cost (DMC) in 2014 is 79 cents per pound, declining to -10 cents per pound by 2030. These costs reflect a fully integrated weight reduction strategy that evaluates all vehicle and engine components as an integrated package, while fully maintaining performance and structural integrity. The value of the fully integrated approach is apparent when the costs associated with specific systems and limited integration are examined. For example, the 2014 cost for reductions to the engine and body structure in isolation is $6.33 per pound if secondary mass reduction effects are not considered, and $2.76 per pound if secondary effects are considered. Thus, if weight reduction costs are based on the engine and body structure only, costs can be expected to be 3.5 times higher than an approach that examines all vehicle components. If secondary reductions in the weight and body structure system are not considered, a cost multiple of eight is observed. Clearly, there are large differences in cost associated with differences in the scope of weight reduction evaluations.

The FEV light-duty vehicle data also help to explain some of the differences in secondary mass reduction potential that are claimed in the literature. If only the engine and body structure system is considered, secondary mass reductions equal 79% of primary reductions. However, if the scope of primary reductions is extended to include closures, bumpers, and suspension, brake, and fuel system components, secondary mass reductions decline to 25% of primary reductions as systems with less secondary reduction potential are directly evaluated. Finally, if the scope of mass reduction evaluation is extended to all vehicle systems and components, the secondary mass reduction potential declines to 16%. Thus, quite expectedly, the scope of primary mass reduction evaluation strongly influences secondary mass reduction potential, and it is expected that this explains much of the observed differential in various estimates of secondary mass reduction potential.

Interestingly, if the percentage mass reduction potential and cost from the FEV light-duty vehicle study is applied to the heavy-duty tractor curb weight, the resulting data point agrees quite closely with both European Aluminium Association and DOE mass reduction data. Moreover, if this same approach is employed using only FEV engine and body structure data without secondary mass reduction, the resulting data point agrees quite closely with the TIAX/NRC data. When secondary mass reductions are considered, the engine and body structure data agree well with the European Aluminium Association and DOE mass reduction data. In short, when extrapolated to the heavy-duty sector, the light-duty weight reduction data not only agree well with the heavy-duty sector-specific data, but also appear to provide a basis for explaining a substantial portion of observed differences. Figure 3 graphically depicts these relationships.

Also depicted in Figure 3 is an extrapolation of the TIAX/NRC cost estimates through the full range of weight reductions required to achieve this study's technology levels. A trend line is also plotted through the single extrapolated light-duty vehicle data point that includes all vehicle systems and components, but excludes secondary mass reduction. The slope of this trend line is set by maintaining the ratio of the TIAX/NRC cost estimate to the extrapolated light-duty vehicle estimate across the full range of weight reductions. Given the general agreement of this trend line with both the European Aluminium Association and DOE mass reduction data, it would be reasonably appropriate to use the underlying equation to develop best estimate low weight reduction costs for this study. However, given the extrapolated nature of the light-duty vehicle data and the target nature of the DOE data, a more conservative approach is undertaken wherein the average of the TIAX/NRC trend and the extrapolated light-duty vehicle trend (as depicted in Figure 3) is used as the basis for best estimate low costs. The extrapolated TIAX/NRC trend is used directly as the basis for best estimate high costs.

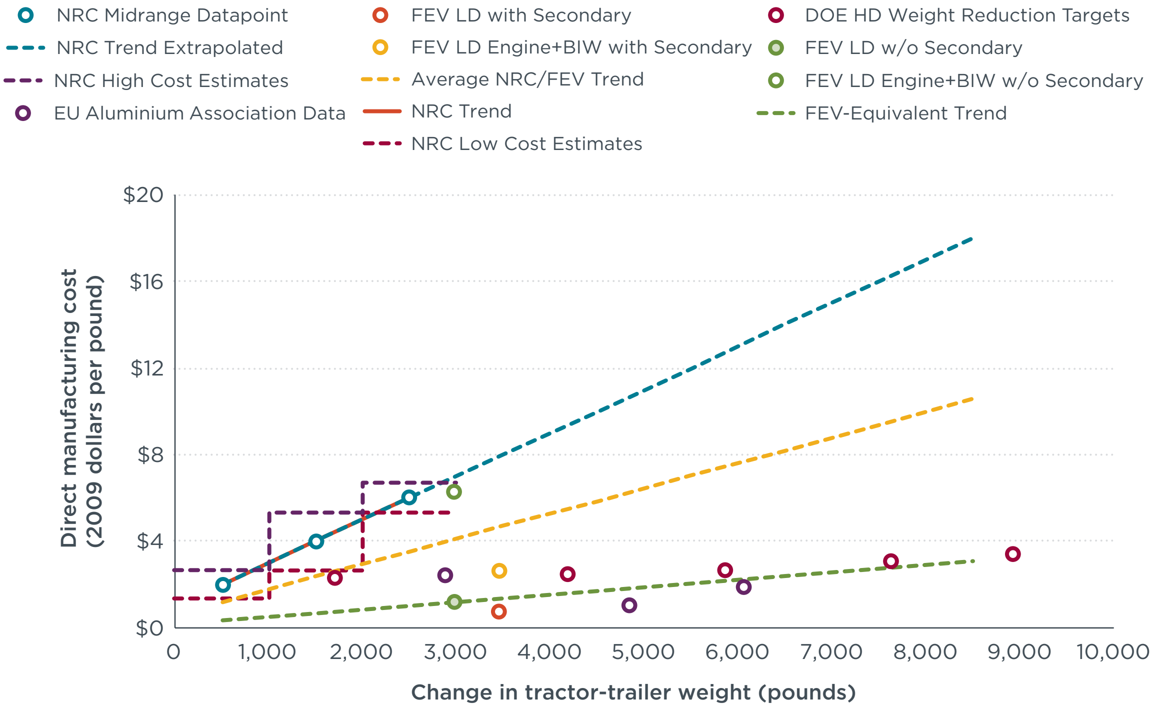

Figure 3. Tractor-trailer weight reduction data

Figure 4 depicts the resulting cost functions, converted to the same thousand pound step function basis as the underlying TIAX/NRC data. Based on the analysis described above, it is believed that the developed mass reduction costs do not include consideration of secondary mass reduction. Therefore, it is necessary to account for both the mass reduction effect and cost savings of available secondary reductions to properly estimate net mass reduction cost. Based on the FEV light-duty vehicle data described above, this study assumes a secondary mass reduction potential of 25% of primary mass reduction for the tractor, and no secondary mass reduction potential for the trailer due to the limited structural and secondary componentry that would not be otherwise targeted for mass reduction. With regard to the cost savings of secondary mass reduction, this study uses the same per-pound cost savings used for evaluating engine downsizing, $1.45, determined as described in the engine downsizing discussion above.

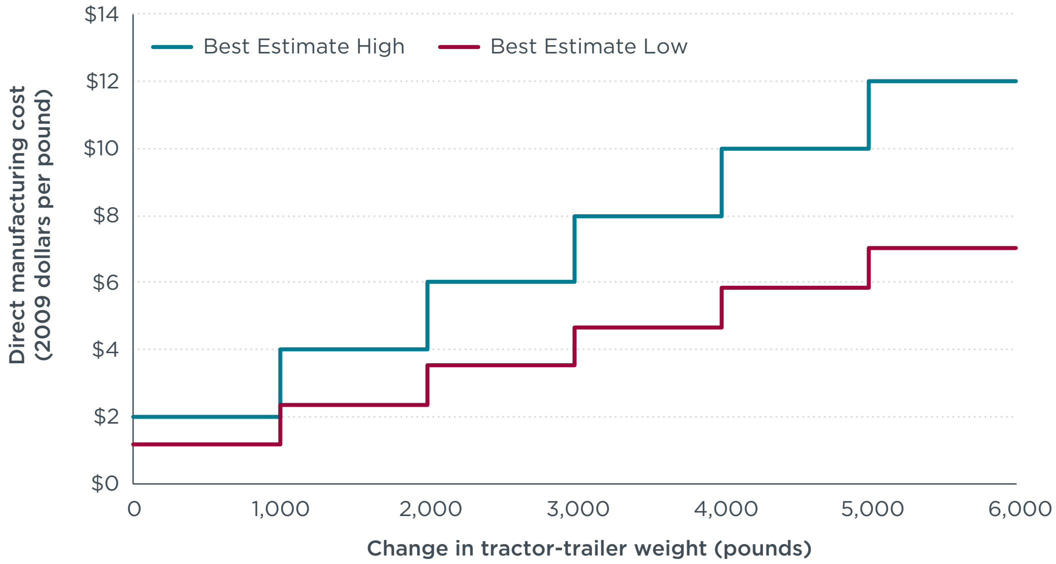

Figure 4. Tractor-trailer weight reduction-to-cost functions

Finally, because of the difference in secondary mass reduction potential and the three-to-one weighting of trailer versus tractor costs, it is necessary to estimate the fraction of required mass reduction that will be allocated to the tractor and the trailer. To accomplish this allocation, the gross required weight reduction is first calculated as the targeted weight reduction level plus the weight effects of all technology included in the evaluated package. This gross weight reduction is processed through a five-step iteration based on the DOE weight reduction targets (US DOE, 2013), which express five levels of increasingly stringent mass reduction, with individual targets for both tractors and trailers established at each level. The gross weight reduction is disaggregated into a tractor and trailer component by allocating the DOE target level tractor and trailer components for each succeeding level of mass reduction until the overall gross reduction is achieved. At each step in the five-step process, tractor weight reduction targets are allocated first.

For example, if a 1,000-pound reduction is required and the target reductions for the first two levels of reduction are 500 pounds and 1,100 pounds for the tractor and 200 pounds and 400 pounds for the trailer, then the allocation function would first assign 500 pounds to the tractor, then 200 pounds to the trailer, then 300 pounds to the tractor, for a net reduction of 800 pounds from the tractor and 200 pounds from the trailer. All of the required trailer-based mass reductions are costed on a primary reduction basis (as no secondary reduction potential is assumed for the trailer). Trailer costs are then multiplied by the requisite three-to-one weighting factor. Primary tractor-based reductions are assumed to equal gross tractor-based reductions divided by 1.25, based on the assumed 25% secondary reduction potential for the tractor.

Other fixed costs. In developing cost estimates for the Phase 1 heavy-duty vehicle rulemaking (US EPA and NHTSA, 2011b), certain fixed costs primarily related to engine research and development are not included in either the DMC or indirect cost multipliers. Instead these costs are allocated as a separate consideration and, therefore, should be accounted for in this study as well because the study relies on the same ICMs employed for the Phase 1 rule. 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 technology package.

The EPA and NHTSA express fixed costs for the Phase 1 heavy-duty vehicle rulemaking on a per-vehicle basis by dividing total estimated costs by annual heavy-duty vehicle sales. This has the effect of spreading the fixed costs for heavy-duty tractor engine manufacturers across a wider sales base than is appropriate for this study. This study follows the basic Phase 1 approach, but considers only costs and sales specific to the tractor-trailer sector. This results in a per-vehicle cost estimate of $473 for the engine technology associated with the Phase 1 rulemaking, defined as 2017 engine technology in this study. To derive estimates for other levels of engine technology, this study scales fixed costs on the basis of estimated engine technology DMC. In other words, the ratio of per-vehicle costs for the Phase 1 (2017) engine technology to the DMC for the Phase 1 (2017) engine is applied to the DMC of all other engine technology packages to derive corresponding per-vehicle fixed cost estimates for each engine technology package. The EPA and NHTSA estimate that the period of fixed cost recovery is five years and that assumption is maintained in this study. Because the investment and recovery periods for engine technology packages beyond Phase 1 (2017) will be different than the period for Phase 1 (2017) technology, fixed cost estimates for engine technology packages beyond Phase 1 (2017) are expressed relative to a 2017 base, while fixed costs for 2017 technology are expressed relative to 2010 baseline technology.

The NRC heavy-duty vehicle technology study used as a primary reference for this study includes fixed cost recovery as an integral component of developed cost estimates. However, that recovery is an inherent element of the NRC indirect cost accounting and this study adjusts all NRC cost estimates to a DMC basis to ensure consistent indirect cost accounting for all evaluated cost data. As a result, NRC fixed cost accounting is removed from its cost estimates and is therefore addressed explicitly in this study in the same manner as all other cost estimates (i.e., as a fraction of engine technology package costs).

Individual technology cost summary. Based on the approaches described above, direct manufacturing and indirect costs were compiled for each of the technologies evaluated in this study. Table 7 summarizes the total cost of each individual technology, excluding weight reduction costs. The total costs are summarized for evaluation years 2014, 2020, 2025, and 2030, showing the effect of learning on technology costs over time. The results are shown for both best estimate low and best estimate high costs. The total composite configuration estimates in the bottom rows in the table include three trailers per tractor, as assumed throughout this report.

Table 7. Individual technology weight change and total best estimate low and high cost (direct plus indirect) for 2014, 2020, 2025, and 2030

Technology		Weight change (lb)	Best estimate low total cost (2014 dollars)				Best estimate high total cost (2014 dollars)			
			2014	2020	2025	2030	2014	2020	2025	2030
Engine configuration	2010	0	$0	$0	$0	$0	$0	$0	$0	$0
	2017	50	$1,235	$1,074	$972	$947	$3,214	$2,795	$2,528	$2,463
	2020	50	$1,884	$1,650	$1,467	$1,431	$5,583	$4,891	$4,348	$4,241
	2020+WHR	350	$6,780	$5,962	$5,149	$5,024	$12,028	$10,577	$9,135	$8,913
	Long Term	350	$7,519	$6,612	$5,710	$5,571	$14,184	$12,473	$10,772	$10,510
Drive configuration	6 × 4	0	$0	$0	$0	$0	$0	$0	$0	$0
	6 × 2	-400	$0	$0	$0	$0	$201	$175	$158	$154
Transmission configuration	Manual	0	$0	$0	$0	$0	$0	$0	$0	$0
	AMT	80	$4,097	$3,563	$3,223	$3,140	$5,060	$4,400	$3,981	$3,878
	DCT	104	$5,735	$5,024	$4,467	$4,357	$7,083	$6,205	$5,516	$5,381
Hybrid technology	No	0	$0	$0	$0	$0	$0	$0	$0	$0
	Yes	400	$20,047	$17,629	$15,225	$14,855	$22,275	$19,588	$16,917	$16,505
Relative engine size	100%	0	$0	$0	$0	$0	$0	$0	$0	$0
	90%	-268	-$502	-$439	-$391	-$381	-$502	-$439	-$391	-$381
	85%	-401	-$750	-$657	-$584	-$570	-$750	-$657	-$584	-$570
Tractor aerodynamic configuration	2010	0	$0	$0	$0	$0	$0	$0	$0	$0
	Phase 1	250	$1,487	$1,296	$1,165	$1,136	$1,671	$1,456	$1,310	$1,276
	Moderate	250	$1,487	$1,296	$1,165	$1,136	$1,671	$1,456	$1,310	$1,276
	Advanced	250	$2,066	$1,817	$1,589	$1,550	$2,365	$2,080	$1,819	$1,775
	Long Term	350	$4,624	$3,608	$2,888	$2,763	$7,508	$5,859	$4,690	$4,487
Trailer aerodynamic configuration	2010	0	$0	$0	$0	$0	$0	$0	$0	$0
	Phase 1	0	$0	$0	$0	$0	$0	$0	$0	$0
	Moderate	200	$516	$450	$404	$394	$1,045	$910	$819	$798
	Advanced	400	$1,468	$1,291	$1,129	$1,102	$3,548	$3,120	$2,728	$2,662
	Long Term	700	$3,048	$2,378	$1,904	$1,821	$7,731	$6,033	$4,829	$4,620
Tractor rolling resistance configuration	2010	0	$0	$0	$0	$0	$0	$0	$0	$0
	Phase 1	0	$172	$150	$135	$131	$209	$182	$164	$160
	Moderate	-150	$489	$430	$376	$367	$517	$454	$397	$388
	Advanced	-320	$833	$650	$520	$498	$847	$661	$529	$506
	Long Term	-380	$952	$742	$594	$569	$952	$742	$594	$569
Trailer rolling resistance configuration	2010	0	$0	$0	$0	$0	$0	$0	$0	$0
	Phase 1	0	$0	$0	$0	$0	$0	$0	$0	$0
	Moderate	-80	$218	$191	$167	$163	$245	$215	$188	$184
	Advanced	-130	$327	$255	$204	$195	$342	$267	$214	$204
	Long Term	-300	$714	$557	$446	$426	$714	$557	$446	$426

Table 8 presents a summary of the fixed cost estimates used in this study. Estimated fixed cost is added to every evaluated technology package on the basis of the included engine technology. Although tabulated in terms of 2009 dollars, as that is the basis used for the underlying EPA and NHTSA cost estimates, all cost data are converted to 2014 dollars when applied in this study. All fixed costs are assumed to apply for a five-year period that begins in 2014 for Phase 1 (2017) engine technology and 2020 for all other engine technology packages.

Weight reduction technology is not included in Table 7 due to the fact that the magnitude, and therefore the cost, of required reduction is technology package dependent. For this reason, the specific cost of associated weight reduction is presented in the next section that defines technology package costs. Table 9 summarizes the developed per-pound weight reduction cost estimates in the step function format of the underlying NRC data. The cost base for each step is the accumulated cost associated with all preceding steps. Figure 4 above, presents the same step functions graphically.

Table 8. Per-vehicle fixed cost estimates (2009 dollars)

Engine configuration	Best estimate low	Best estimate high	Recovery period begins
2010	$0	$0	not applicable
2017	$473	$1,232	2014
2020	$202	$769	2020
2020+WHR	$1,870	$2,925	2020
Long Term	$2,126	$3,670	2020

Note: 2017 cost relative to 2010. All others relative to 2017

Table 9. Weight reduction cost functions (2009 dollars)

Weight reduction (lb)		Best estimate low		Best estimate high	
Lower limit	Upper limit	DMC base	DMC slope	DMC base	DMC slope
0	1000	$0	$1.18	$0	$2.00
1000	2000	$1,180	$2.35	$2,000	$4.00
2000	3000	$3,530	$3.52	$6,000	$6.00
3000	4000	$7,050	$4.69	$12,000	$8.00
4000	5000	$11,740	$5.86	$20,000	$10.00
5000	6000	$17,600	$7.04	$30,000	$12.00

TECHNOLOGY PACKAGE COSTS

Costs are evaluated for 12 technology packages, as analyzed in the tractor-trailer simulation modeling. These packages cover a wide range of fuel economy reflecting a 5.3 miles per gallon (mpg) baseline and extending to a maximum of 11.6 mpg, as measured over a real-world long-haul cycle that includes grade. The entirety of this range reflects up to a 54% reduction in per-ton-mile fuel consumption from the 2010 baseline tractor-trailer. Table 10 presents a summary of the technologies included in each package as well as the package description used for reference purposes in various data tables and results presented in this report. These match the technology packages presented in Figure 1 above.

Table 10. Technology package definitions

Technology classification	Individual technology	Technology package [a]											
		1	2	3	4	5	6	7	8	9	10	11	12
Engine configuration	2010	X											
	2017		X	X	X	X							
	2020						X	X	X				
	2020+WHR									X	X		
	Long Term											X	X
Drive configuration	6 × 4	X	X	X									
	6 × 2				X	X	X	X	X	X	X	X	X
Transmission configuration	Manual	X	X	X									
	AMT				X	X							
	DCT						X	X	X	X	X	X	X
Hybrid technology	No	X	X	X	X	X	X	X	X	X	X	X	
	Yes												X
Relative engine size	100%	X	X	X	X	X	X	X					
	90%								X	X	X	X	X
Road load configuration	2010	X	X										
	Phase 1			X	X								
	Moderate					X	X						
	Advanced							X	X	X			
	Long Term										X	X	X
Fuel economy (mpg)		5.3	5.8	6.4	6.6	6.9	7.5	8.4	8.5	8.9	10.2	11.0	11.6

[a] Technology packages defined as

1 Baseline 2010 tractor-trailer
2 Add 2017 engine (45.8% BTE)
3 Reduce road load (Net 16% aerodynamic drag, 9% rolling resistance, 2% mass)
4 Add 6×2 drive and AMT
5 Reduce road load (Net 20% aerodynamic drag, 16% rolling resistance, 7% mass)
6 Add 2020 engine (49% BTE) and DCT
7 Reduce road load (Net 30% aerodynamic drag, 10% rolling resistance, 14% mass)
8 Downsize engine 10%
9 Add Waste Heat Recovery (52% BTE)
10 Reduce road load (Net 50% aerodynamic drag, 35% rolling resistance, 17% mass)
11 Add post-2020 engine (55% BTE)
12 Add hybrid (60% efficiency regeneration)

Table 11 presents the weight reduction cost estimates associated with each technology package. The table summarizes the best estimate low and best estimate high total (i.e., direct manufacturing plus indirect) costs for the base year 2014 and evaluation years 2020, 2025, and 2030.

Table 11. Total weight reduction technology best estimate low and high cost (direct plus indirect) for 2014, 2020, 2025, and 2030

Technology	Weight change (lb)	Best estimate low total cost (2014 dollars)				Best estimate high total cost (2014 dollars)			
		2014	2020	2025	2030	2014	2020	2025	2030
Tractor-Based Weight Reduction Costs									
Baseline 2010 tractor-trailer	0	$0	$0	$0	$0	$0	$0	$0	$0
Add 2017 engine (45.8% BTE)	50	$40	$35	$31	$31	$81	$70	$63	$61
Reduce road load (Net 16% Aero, 9% RR, 2% Mass) [nominal 2017 tractor-trailer]	950	$764	$665	$598	$583	$1,530	$1,333	$1,198	$1,168
Add 6×2 drive and AMT	630	$506	$441	$397	$387	$1,014	$884	$795	$775
Reduce road load (Net 20% Aero, 16% RR, 7% Mass)	1,793	$2,285	$2,009	$1,757	$1,714	$4,374	$3,846	$3,363	$3,282
Add 2020 Engine (49% BTE) and DCT	1,817	$2,337	$2,055	$1,797	$1,753	$4,469	$3,929	$3,436	$3,353
Reduce road load (Net 30% Aero, 30% RR, 14% Mass)	3,208	$6,829	$5,329	$4,266	$4,081	$12,590	$9,824	$7,864	$7,524
Downsize engine 10%	2,940	$5,823	$4,543	$3,637	$3,480	$10,793	$8,422	$6,741	$6,450
Add Waste Heat Recovery (52% BTE)	3,240	$6,949	$5,423	$4,341	$4,153	$12,804	$9,991	$7,998	$7,652
Reduce road load (Net 50% Aero, 35% RR, 17% Mass)	3,982	$10,059	$7,849	$6,283	$6,011	$18,331	$14,304	$11,450	$10,955
Add post-2020 engine (55% BTE)	3,982	$10,059	$7,849	$6,283	$6,011	$18,331	$14,304	$11,450	$10,955
Add hybrid (60% efficiency regen.)	4,209	$11,227	$8,761	$7,013	$6,709	$20,393	$15,913	$12,738	$12,187
Trailer-Based Weight Reduction Costs (Single Trailer)									
Baseline 2010 tractor-trailer	0	$0	$0	$0	$0	$0	$0	$0	$0
Add 2017 engine (45.8% BTE)	0	$0	$0	$0	$0	$0	$0	$0	$0
Reduce road load (Net 16% Aero, 9% RR, 2% Mass) [nominal 2017 tractor-trailer]	0	$0	$0	$0	$0	$0	$0	$0	$0
Add 6×2 drive and AMT	0	$0	$0	$0	$0	$0	$0	$0	$0
Reduce road load (Net 20% Aero, 16% RR, 7% Mass)	432	$693	$609	$533	$520	$1,175	$1,033	$903	$881
Add 2020 Engine (49% BTE) and DCT	432	$693	$609	$533	$520	$1,175	$1,033	$903	$881
Reduce road load (Net 30% Aero, 30% RR, 14% Mass)	1,296	$2,789	$2,176	$1,742	$1,666	$4,734	$3,694	$2,957	$2,829
Downsize engine 10%	1,296	$2,789	$2,176	$1,742	$1,666	$4,734	$3,694	$2,957	$2,829
Add Waste Heat Recovery (52% BTE)	1,296	$2,789	$2,176	$1,742	$1,666	$4,734	$3,694	$2,957	$2,829
Reduce road load (Net 50% Aero, 35% RR, 17% Mass)	1,699	$4,197	$3,275	$2,621	$2,508	$7,130	$5,564	$4,454	$4,261
Add post-2020 engine (55% BTE)	1,699	$4,197	$3,275	$2,621	$2,508	$7,130	$5,564	$4,454	$4,261
Add hybrid (60% efficiency regen.)	1,872	$4,801	$3,746	$2,999	$2,869	$8,159	$6,367	$5,096	$4,876
Tractor Plus Population-Adjusted Trailer Weight Reduction Costs (Three Trailers)									
Baseline 2010 tractor-trailer	0	$0	$0	$0	$0	$0	$0	$0	$0
Add 2017 engine (45.8% BTE)	50	$40	$35	$31	$31	$81	$70	$63	$61
Reduce road load (Net 16% Aero, 9% RR, 2% Mass) [nominal 2017 tractor-trailer]	950	$764	$665	$598	$583	$1,530	$1,333	$1,198	$1,168
Add 6×2 drive and AMT	630	$506	$441	$397	$387	$1,014	$884	$795	$775
Reduce road load (Net 20% Aero, 16% RR, 7% Mass)	2,225	$4,364	$3,837	$3,355	$3,274	$7,898	$6,944	$6,072	$5,926
Add 2020 Engine (49% BTE) and DCT	2,249	$4,416	$3,882	$3,395	$3,313	$7,993	$7,027	$6,145	$5,997
Reduce road load (Net 30% Aero, 30% RR, 14% Mass)	4,504	$15,195	$11,856	$9,491	$9,080	$26,791	$20,905	$16,734	$16,010
Downsize engine 10%	4,236	$14,188	$11,071	$8,862	$8,479	$24,994	$19,503	$15,612	$14,936
Add Waste Heat Recovery (52% BTE)	4,536	$15,315	$11,950	$9,566	$9,152	$27,006	$21,073	$16,869	$16,139
Reduce road load (Net 50% Aero, 35% RR, 17% Mass)	5,681	$22,648	$17,673	$14,147	$13,535	$39,722	$30,996	$24,812	$23,738
Add post-2020 engine (55% BTE)	5,681	$22,648	$17,673	$14,147	$13,535	$39,722	$30,996	$24,812	$23,738
Add hybrid (60% efficiency regen.)	6,081	$25,630	$19,999	$16,009	$15,317	$44,871	$35,013	$28,028	$26,815

BTE=brake thermal efficiency; AMT=automated manual transmission; DCT=dual clutch transmission; Aero=aerodynamic drag; RR=rolling resistance; Mass=tractor-trailer curb mass

Table 12 presents the aggregate cost estimates associated with each technology package. The cost results in the table include both best estimate low and best estimate high total (i.e., direct manufacturing plus indirect) costs for base year 2014 dollars and evaluation years 2020, 2025, and 2030. In essence these are the aggregated costs of all the non-weight reduction technologies (from Table 7), plus fixed costs (from Table 8, as applicable) and weight reduction technology costs (from Table 11). Included in these costs are the technologies for one tractor and three trailers. The costs shown are from 2010 baseline technology, and as indicated, the nominal 2017 baseline technology package is estimated to approximately cost $3,000-$6,000 in the 2020-2025 time frame. These total cost estimates are the basis for all economic analysis undertaken in this study. As shown, the technology costs are based on a 2010 baseline tractor-trailer, upon which the engine data and tractor-trailer efficiency simulation data were based. In addition, the third technology package shown in the table represents an estimated nominal 2017 tractor-trailer that meets the Phase 1 efficiency standard requirements. As shown, the vast majority of the additional technology costs — more than 90% — from the 2010 baseline go beyond the Phase 1 nominal 2017 efficiency level.

Table 12. Total technology package best estimate low and high cost (direct plus indirect) for tractor and three trailers in 2014, 2020, 2025, and 2030

Technology	Best estimate low total cost (2014 dollars)				Best estimate high total cost (2014 dollars)			
	2014	2020	2025	2030	2014	2020	2025	2030
Baseline 2010 tractor-trailer	$0	$0	$0	$0	$0	$0	$0	$0
Add 2017 engine (45.8% BTE)	$1,768	$1,109	$1,003	$977	$4,579	$2,865	$2,591	$2,525
Reduce road load (Net 16% Aero, 9% RR, 2% Mass) [nominal 2017 tractor-trailer]	$4,151	$3,185	$2,870	$2,797	$7,909	$5,765	$5,200	$5,067
Add 6×2 drive and AMT	$7,991	$6,523	$5,892	$5,741	$12,655	$9,891	$8,936	$8,707
Reduce road load (Net 20% Aero, 16% RR, 7% Mass)	$14,367	$12,122	$10,807	$10,537	$23,714	$19,599	$17,466	$17,030
Add 2020 Engine (49% BTE) and DCT	$16,212	$14,417	$12,585	$12,276	$26,916	$24,387	$20,895	$20,381
Reduce road load (Net 30% Aero, 30% RR, 14% Mass)	$31,098	$25,847	$21,533	$20,807	$54,541	$45,878	$37,930	$36,667
Downsize engine 10%	$29,590	$24,622	$20,514	$19,825	$52,243	$44,037	$36,417	$35,213
Add Waste Heat Recovery (52% BTE)	$35,613	$31,553	$24,899	$24,091	$60,700	$53,542	$42,460	$41,086
Reduce road load (Net 50% Aero, 35% RR, 17% Mass)	$51,521	$43,326	$33,903	$32,610	$92,327	$76,935	$60,339	$58,000
Add post-2020 engine (55% BTE)	$52,260	$44,243	$34,464	$33,157	$94,483	$79,607	$61,977	$59,597
Add hybrid (60% efficiency regen.)	$75,289	$64,198	$51,552	$49,794	$121,906	$103,212	$82,110	$79,179

Technology costs include one tractor and three trailers; BTE=brake thermal efficiency; AMT=automated manual transmission; DCT=dual clutch transmission; Aero=aerodynamic drag; RR=rolling resistance; Mass=tractor-trailer curb mass

IV. ECONOMIC FINDINGS

This section presents basic economic metrics associated with the total cost estimates for the evaluated technology packages as presented in Table 12. Specific investigated metrics consist of the payback period associated with each technology package; the lifetime cost or, more accurately, savings associated with each technology 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 cost associated with each technology package. The lifetime cost of each technology package is defined as the lifetime cost savings that accrue due to the decreased fuel use associated with each technology package minus the fuel cost associated with any increase in VMT due to operating cost elasticity minus the increased capital cost of the applicable technology package. Both the payback period and lifetime cost are measured relative to baseline tractor-trailer fuel economy and cost. The marginal cost of long-haul tractor-trailer technology is measured as the effective cost in dollars per gallon of fuel saved for the next increment of fuel economy, and essentially measures the cost effectiveness of the technology required to produce that next fuel economy increment. Marginal costs expressed in dollars per gallon saved can be readily compared to 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 (3%, 7%, and 10%) and three fuel price scenarios ($3.10, $4.10, and $5.40 per gallon).

As indicated in the preceding section of this report, technology cost estimates are developed for all calendar years between 2020 and 2030. Accordingly, economic metrics can be developed and presented for each 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 — 2020 and 2025. Evaluation year 2020 is the worst case year for the period 2020 through 2030 as technology costs for 2020 will be higher than those for all other years. Thus evaluation for 2020 will produce the least favorable economic picture of the evaluated technology packages. Evaluation year 2025 represents the midrange year and provides a representative indication of median-level economic metrics for the larger 11-year period.

TECHNOLOGY PACKAGE PAYBACK PERIODS

Table 13, for best estimate low technology costs, and Table 14, for best estimate high technology costs, present the economic payback periods for the 2020 and 2025 evaluation years. Due to the effect of learning on technology costs, payback periods are generally lower in 2025 than 2020. As shown, discount rate is directly related to payback, but due to quick payback and the high VMT in the first several years of tractor use in the long-haul sector, the net effect of differential discount rates on estimated payback for the evaluated technology packages is minor. Also shown, fuel price is inversely related to payback, with higher fuel prices resulting in shorter payback periods, as more savings accrue for each gallon of fuel that is saved. Due to continued technology cost learning, payback periods beyond 2025 are shorter than those presented for 2025.

Table 13. Technology package payback periods (years) for best estimate low costs

Evaluation year	**2020**	**2020**	**2020**	**2020**	**2020**	**2020**	**2020**	**2020**	**2020**
Discount rate	**3%**	**3%**	**3%**	**7%**	**7%**	**7%**	**10%**	**10%**	**10%**
Fuel cost per gallon	**$3.10**	**$4.10**	**$5.40**	**$3.10**	**$4.10**	**$5.40**	**$3.10**	**$4.10**	**$5.40**
Baseline 2010 tractor-trailer	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Add 2017 engine (45.8% BTE)	0.2	0.1	0.1	0.2	0.1	0.1	0.2	0.1	0.1
Reduce road load (Net 16% Aero, 9% RR, 2% Mass) [nominal 2017 tractor-trailer]	0.3	0.2	0.1	0.3	0.2	0.1	0.3	0.2	0.1
Add 6×2 drive and AMT	0.4	0.3	0.3	0.4	0.3	0.3	0.4	0.3	0.3
Reduce road load (Net 20% Aero, 16% RR, 7% Mass)	0.7	0.5	0.4	0.7	0.5	0.4	0.7	0.5	0.4
Add 2020 Engine (49% BTE) and DCT	0.6	0.5	0.4	0.6	0.5	0.4	0.6	0.5	0.4
Reduce road load (Net 30% Aero, 30% RR, 14% Mass)	0.9	0.7	0.5	0.9	0.7	0.5	0.9	0.7	0.5
Downsize engine 10%	0.8	0.6	0.5	0.8	0.6	0.5	0.8	0.6	0.5
Add Waste Heat Recovery (52% BTE)	1.0	0.8	0.6	1.0	0.8	0.6	1.0	0.8	0.6
Reduce road load (Net 50% Aero, 35% RR, 17% Mass)	1.2	0.9	0.7	1.2	0.9	0.7	1.2	0.9	0.7
Add post-2020 engine (55% BTE)	1.1	0.8	0.6	1.1	0.8	0.6	1.1	0.8	0.6
Add hybrid (60% efficiency regen.)	1.6	1.2	0.9	1.6	1.2	0.9	1.6	1.2	0.9
Evaluation year	**2025**	**2025**	**2025**	**2025**	**2025**	**2025**	**2025**	**2025**	**2025**
Discount rate	**3%**	**3%**	**3%**	**7%**	**7%**	**7%**	**10%**	**10%**	**10%**
Fuel cost per gallon	**$3.10**	**$4.10**	**$5.40**	**$3.10**	**$4.10**	**$5.40**	**$3.10**	**$4.10**	**$5.40**
Baseline 2010 tractor-trailer	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Add 2017 engine (45.8% BTE)	0.2	0.1	0.1	0.2	0.1	0.1	0.2	0.1	0.1
Reduce road load (Net 16% Aero, 9% RR, 2% Mass) [nominal 2017 tractor-trailer]	0.2	0.2	0.1	0.2	0.2	0.1	0.2	0.2	0.1
Add 6×2 drive and AMT	0.4	0.3	0.2	0.4	0.3	0.2	0.4	0.3	0.2
Reduce road load (Net 20% Aero, 16% RR, 7% Mass)	0.6	0.5	0.3	0.6	0.5	0.3	0.6	0.5	0.3
Add 2020 Engine (49% BTE) and DCT	0.6	0.4	0.3	0.6	0.4	0.3	0.6	0.4	0.3
Reduce road load (Net 30% Aero, 30% RR, 14% Mass)	0.8	0.6	0.4	0.8	0.6	0.4	0.8	0.6	0.4
Downsize engine 10%	0.7	0.5	0.4	0.7	0.5	0.4	0.7	0.5	0.4
Add Waste Heat Recovery (52% BTE)	0.8	0.6	0.5	0.8	0.6	0.5	0.8	0.6	0.5
Reduce road load (Net 50% Aero, 35% RR, 17% Mass)	0.9	0.7	0.5	0.9	0.7	0.5	0.9	0.7	0.5
Add post-2020 engine (55% BTE)	0.9	0.6	0.5	0.9	0.6	0.5	0.9	0.6	0.5
Add hybrid (60% efficiency regen.)	1.3	0.9	0.7	1.3	0.9	0.7	1.3	0.9	0.7

BTE=brake thermal efficiency; AMT=automated manual transmission; DCT=dual clutch transmission; Aero=aerodynamic drag; RR=rolling resistance; Mass=tractor-trailer curb mass

Table 14. Technology package payback periods (years) for best estimate high costs

Evaluation year	**2020**	**2020**	**2020**	**2020**	**2020**	**2020**	**2020**	**2020**	**2020**
Discount rate	**3%**	**3%**	**3%**	**7%**	**7%**	**7%**	**10%**	**10%**	**10%**
Fuel cost per gallon	**$3.10**	**$4.10**	**$5.40**	**$3.10**	**$4.10**	**$5.40**	**$3.10**	**$4.10**	**$5.40**
Baseline 2010 tractor-trailer	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Add 2017 engine (45.8% BTE)	0.5	0.4	0.3	0.5	0.4	0.3	0.5	0.4	0.3
Reduce road load (Net 16% Aero, 9% RR, 2% Mass) [nominal 2017 tractor-trailer]	0.5	0.3	0.3	0.5	0.3	0.3	0.5	0.3	0.3
Add 6×2 drive and AMT	0.7	0.5	0.4	0.7	0.5	0.4	0.7	0.5	0.4
Reduce road load (Net 20% Aero, 16% RR, 7% Mass)	1.1	0.8	0.6	1.1	0.8	0.6	1.1	0.8	0.6
Add 2020 Engine (49% BTE) and DCT	1.1	0.8	0.6	1.1	0.8	0.6	1.1	0.8	0.6
Reduce road load (Net 30% Aero, 30% RR, 14% Mass)	1.7	1.3	0.9	1.7	1.3	0.9	1.8	1.3	0.9
Downsize engine 10%	1.6	1.2	0.9	1.6	1.2	0.9	1.6	1.2	0.9
Add Waste Heat Recovery (52% BTE)	1.8	1.3	1.0	1.9	1.4	1.0	1.9	1.4	1.0
Reduce road load (Net 50% Aero, 35% RR, 17% Mass)	2.2	1.6	1.2	2.3	1.7	1.2	2.4	1.7	1.2
Add post-2020 engine (55% BTE)	2.1	1.6	1.2	2.2	1.6	1.2	2.2	1.6	1.2
Add hybrid (60% efficiency regen.)	2.8	2.0	1.5	2.9	2.0	1.5	3.0	2.1	1.5
Evaluation year	**2025**	**2025**	**2025**	**2025**	**2025**	**2025**	**2025**	**2025**	**2025**
Discount rate	**3%**	**3%**	**3%**	**7%**	**7%**	**7%**	**10%**	**10%**	**10%**
Fuel cost per gallon	**$3.10**	**$4.10**	**$5.40**	**$3.10**	**$4.10**	**$5.40**	**$3.10**	**$4.10**	**$5.40**
Baseline 2010 tractor-trailer	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Add 2017 engine (45.8% BTE)	0.4	0.3	0.3	0.4	0.3	0.3	0.4	0.3	0.3
Reduce road load (Net 16% Aero, 9% RR, 2% Mass) [nominal 2017 tractor-trailer]	0.4	0.3	0.2	0.4	0.3	0.2	0.4	0.3	0.2
Add 6×2 drive and AMT	0.6	0.5	0.3	0.6	0.5	0.3	0.6	0.5	0.3
Reduce road load (Net 20% Aero, 16% RR, 7% Mass)	1.0	0.7	0.6	1.0	0.7	0.6	1.0	0.7	0.6
Add 2020 Engine (49% BTE) and DCT	0.9	0.7	0.5	0.9	0.7	0.5	0.9	0.7	0.5
Reduce road load (Net 30% Aero, 30% RR, 14% Mass)	1.4	1.0	0.8	1.4	1.0	0.8	1.4	1.0	0.8
Downsize engine 10%	1.3	0.9	0.7	1.3	0.9	0.7	1.3	0.9	0.7
Add Waste Heat Recovery (52% BTE)	1.4	1.0	0.8	1.4	1.0	0.8	1.4	1.0	0.8
Reduce road load (Net 50% Aero, 35% RR, 17% Mass)	1.7	1.3	0.9	1.7	1.3	0.9	1.8	1.3	0.9
Add post-2020 engine (55% BTE)	1.6	1.2	0.9	1.6	1.2	0.9	1.7	1.2	0.9
Add hybrid (60% efficiency regen.)	2.1	1.5	1.1	2.2	1.6	1.1	2.2	1.6	1.1

BTE=brake thermal efficiency; AMT=automated manual transmission; DCT=dual clutch transmission; Aero=aerodynamic drag; RR=rolling resistance; Mass=tractor-trailer curb mass

The payback periods for all evaluated technology packages for low and high costs, over the varying economic assumptions and over the 2020 and 2025 evaluation years, are less than three years. Figure 5 depicts the payback periods calculated for the 2025 evaluation year under the best (low discount rate, high fuel price) and worst (high discount rate, low fuel price) case conditions evaluated in this study. As shown, the technology packages for the 2025 evaluation year all have payback periods of 2.2 years or less due to fuel savings that significantly outweigh initial technology purchase costs. Even under the least advantageous conditions of high technology cost, low fuel price, and high discount rate, the most advanced technology packages that deliver 10 mpg or greater have payback periods of 1.4 to 2.2 years. These same technology packages generally deliver 0.5 to 0.7 year payback periods for high fuel price, low technology cost, and low discount rate assumptions. The more moderate technology packages, as shown in the figure, deliver worst-case payback periods of 1.5 years or less and best-case payback periods of 0.5 years or less. To provide some context for these payback period results, although practices vary widely, it is a generally held industry practice for fleets to operate tractors for four to six years as a typical ownership cycle and seek payback periods within two years for technology investments (Roeth et al., 2013). This topic is evaluated further below.

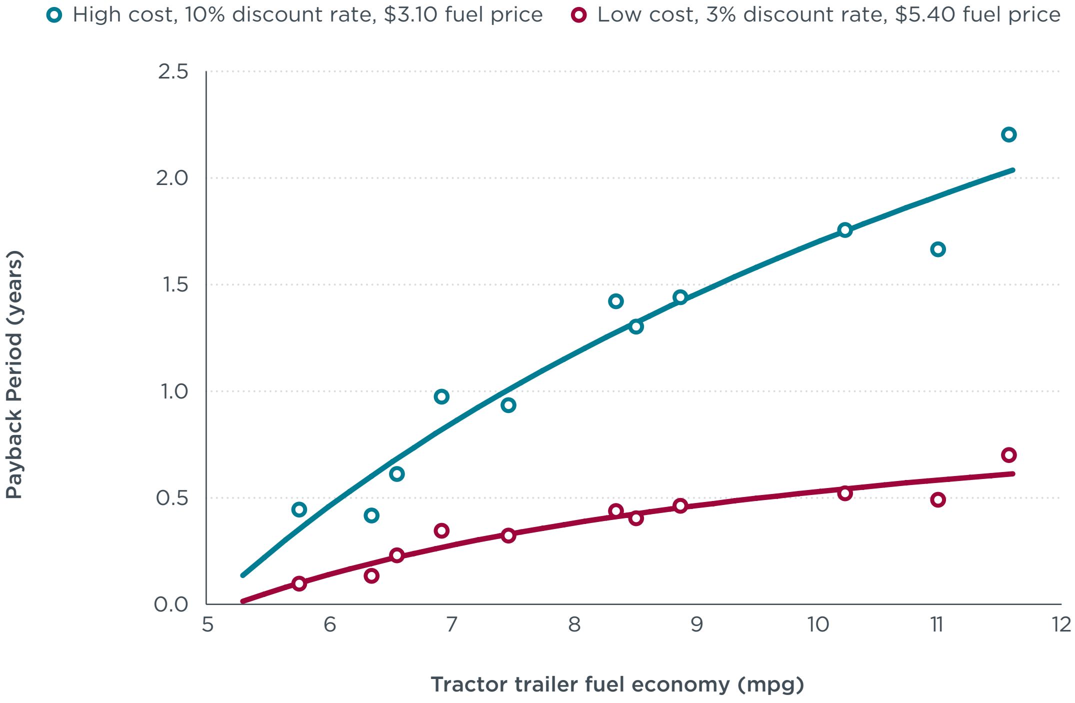

Figure 5. Tractor-trailer efficiency technology package payback periods for 2025 under varying technology cost and economic assumptions

LIFETIME SAVINGS ESTIMATES

Table 15 and 16 present the net lifetime savings associated with each technology package in evaluation years 2020 and 2025. The best estimate low technology costs are shown in Table 15 while Table 16 has the best estimate high technology costs. These estimates represent the net savings to vehicle owners based on the lifetime discounted fuel savings minus the initial technology costs relative to an unimproved baseline tractor-trailer. These results also account for the fuel expenditure of additional driving due to VMT elasticity but without assuming any economic benefit for that additional driving.

For a maximum efficiency technology package in 2025, the net savings range from $174,000-$500,000 for best estimate low technology cost and $144,000-$470,000 for best estimate high technology cost. These levels of fuel savings indicate that the most advanced efficiency technology packages investigated result in lifetime fuel savings that are approximately three times the initial technology cost — under high technology costs, low future fuel prices, and high discount rate — and up to 18 times the initial technology cost under low technology cost, high future fuel prices, and low discount rate. Under the middle economic assumptions for fuel price and discount rate, the efficiency technology package through 10% engine downsizing (i.e., at 8.5 mpg) offers seven to 11 times greater fuel-saving benefits than cost. Under the middle economic assumptions, the most advanced technology package offers four to seven times greater benefits than costs.

For additional context, compared to the baseline tractor price, assumed to be $137,500 in this study, this means the efficiency technology investment not only pays for itself, but also pays for the unimproved tractor as well. If the tractor and three trailers, assumed in this study to be priced at $25,000 each, are considered, the technology investment is not only fully repaid, but also covers a minimum of 60%-100% of the unimproved capital expenditure of the tractor and trailers.

Table 15. Technology package net lifetime savings for best estimate low technology costs, for varying evaluation year, discount rate, fuel price

Evaluation year	2020	2020	2020	2020	2020	2020	2020	2020	2020
Discount rate	**3%**	**3%**	**3%**	**7%**	**7%**	**7%**	**10%**	**10%**	**10%**
Fuel cost per gallon	**$3.10**	**$4.10**	**$5.40**	**$3.10**	**$4.10**	**$5.40**	**$3.10**	**$4.10**	**$5.40**
Baseline 2010 tractor-trailer	$0	$0	$0	$0	$0	$0	$0	$0	$0
Add 2017 engine (45.8% BTE)	$43,476	$57,691	$76,097	$34,895	$46,374	$61,238	$30,533	$40,621	$53,684
Reduce road load (Net 16% Aero, 9% RR, 2% Mass) [nominal 2017 tractor-trailer]	$91,614	$121,869	$161,061	$73,369	$97,801	$129,450	$64,093	$85,565	$113,380
Add 6×2 drive and AMT	$104,036	$139,329	$185,050	$82,758	$111,258	$148,179	$71,940	$96,987	$129,435
Reduce road load (Net 20% Aero, 16% RR, 7% Mass)	$123,252	$166,483	$222,495	$97,197	$132,108	$177,340	$83,952	$114,633	$154,384
Add 2020 Engine (49% BTE) and DCT	$154,208	$208,100	$277,941	$121,754	$165,273	$221,673	$105,255	$143,502	$193,068
Reduce road load (Net 30% Aero, 30% RR, 14% Mass)	$187,050	$255,147	$343,424	$146,075	$201,066	$272,353	$125,245	$173,573	$236,223
Downsize engine 10%	$195,740	$266,240	$357,638	$153,328	$210,260	$284,067	$131,768	$181,801	$246,666
Add Waste Heat Recovery (52% BTE)	$203,795	$279,109	$376,756	$158,499	$219,318	$298,171	$135,472	$188,922	$258,221
Reduce road load (Net 50% Aero, 35% RR, 17% Mass)	$238,750	$329,107	$446,297	$184,461	$257,427	$352,063	$156,862	$220,988	$304,157
Add post-2020 engine (55% BTE)	$259,069	$356,278	$482,377	$200,692	$279,192	$381,021	$171,016	$240,005	$329,496
Add hybrid (60% efficiency regen.)	$253,631	$355,508	$487,669	$192,460	$274,730	$381,455	$161,363	$233,665	$327,459
Evaluation year	**2025**	**2025**	**2025**	**2025**	**2025**	**2025**	**2025**	**2025**	**2025**
Discount rate	**3%**	**3%**	**3%**	**7%**	**7%**	**7%**	**10%**	**10%**	**10%**
Fuel cost per gallon	**$3.10**	**$4.10**	**$5.40**	**$3.10**	**$4.10**	**$5.40**	**$3.10**	**$4.10**	**$5.40**
Baseline 2010 tractor-trailer	$0	$0	$0	$0	$0	$0	$0	$0	$0
Add 2017 engine (45.8% BTE)	$43,580	$57,794	$76,200	$35,000	$46,478	$61,341	$30,637	$40,725	$53,788
Reduce road load (Net 16% Aero, 9% RR, 2% Mass) [nominal 2017 tractor-trailer]	$91,924	$122,178	$161,369	$73,679	$98,111	$129,759	$64,405	$85,876	$113,689
Add 6×2 drive and AMT	$104,657	$139,948	$185,666	$83,380	$111,879	$148,798	$72,564	$97,610	$130,056
Reduce road load (Net 20% Aero, 16% RR, 7% Mass)	$124,547	$167,774	$223,781	$98,496	$133,403	$178,631	$85,253	$115,931	$155,679
Add 2020 Engine (49% BTE) and DCT	$156,014	$209,900	$279,736	$123,565	$167,080	$223,475	$107,069	$145,312	$194,874
Reduce road load (Net 30% Aero, 30% RR, 14% Mass)	$191,309	$259,395	$347,660	$150,345	$205,327	$276,603	$129,520	$177,840	$240,481
Downsize engine 10%	$199,797	$270,286	$361,673	$157,395	$214,318	$288,116	$135,839	$185,865	$250,722
Add Waste Heat Recovery (52% BTE)	$210,370	$285,667	$383,296	$165,089	$225,894	$304,733	$142,070	$195,508	$264,795
Reduce road load (Net 50% Aero, 35% RR, 17% Mass)	$248,076	$338,412	$455,580	$193,805	$266,755	$361,373	$166,216	$230,327	$313,481
Add post-2020 engine (55% BTE)	$268,754	$365,943	$492,020	$210,395	$288,879	$390,691	$180,728	$249,703	$339,179
Add hybrid (60% efficiency regen.)	$266,161	$368,014	$500,149	$205,013	$287,263	$393,967	$173,927	$246,212	$339,987

BTE=brake thermal efficiency; AMT=automated manual transmission; DCT=dual clutch transmission; Aero=aerodynamic drag; RR=rolling resistance; Mass=tractor-trailer curb mass

Table 16. Technology package net lifetime savings for best estimate high technology costs, for varying evaluation year , discount rate, fuel price

Evaluation year	**2020**	**2020**	**2020**	**2020**	**2020**	**2020**	**2020**	**2020**	**2020**
Discount rate	**3%**	**3%**	**3%**	**7%**	**7%**	**7%**	**10%**	**10%**	**10%**
Fuel cost per gallon	**$3.10**	**$4.10**	**$5.40**	**$3.10**	**$4.10**	**$5.40**	**$3.10**	**$4.10**	**$5.40**
Baseline 2010 tractor-trailer	$0	$0	$0	$0	$0	$0	$0	$0	$0
Add 2017 engine (45.8% BTE)	$41,752	$55,974	$74,387	$33,165	$44,649	$59,519	$28,800	$38,893	$51,961
Reduce road load (Net 16% Aero, 9% RR, 2% Mass) [nominal 2017 tractor-trailer]	$89,077	$119,341	$158,543	$70,823	$95,263	$126,920	$61,544	$83,022	$110,844
Add 6×2 drive and AMT	$100,722	$136,027	$181,760	$79,433	$107,943	$144,874	$68,611	$93,666	$126,122
Reduce road load (Net 20% Aero, 16% RR, 7% Mass)	$115,889	$159,144	$215,182	$89,812	$124,743	$169,995	$76,556	$107,254	$147,024
Add 2020 Engine (49% BTE) and DCT	$144,379	$198,300	$268,174	$111,898	$155,441	$211,867	$95,385	$133,653	$183,242
Reduce road load (Net 30% Aero, 30% RR, 14% Mass)	$167,272	$235,423	$323,758	$126,248	$181,283	$252,616	$105,393	$153,760	$216,451
Downsize engine 10%	$176,566	$247,117	$338,570	$134,108	$191,080	$264,932	$112,523	$162,593	$227,497
Add Waste Heat Recovery (52% BTE)	$182,068	$257,437	$355,143	$136,722	$197,585	$276,486	$113,669	$167,158	$236,500
Reduce road load (Net 50% Aero, 35% RR, 17% Mass)	$205,488	$295,919	$413,188	$151,132	$224,158	$318,857	$123,499	$187,677	$270,903
Add post-2020 engine (55% BTE)	$224,044	$321,326	$447,502	$165,603	$244,161	$346,053	$135,893	$204,933	$294,479
Add hybrid (60% efficiency regen.)	$214,973	$316,926	$449,168	$153,734	$236,065	$342,855	$122,602	$194,958	$288,809
Evaluation year	**2025**	**2025**	**2025**	**2025**	**2025**	**2025**	**2025**	**2025**	**2025**
Discount rate	**3%**	**3%**	**3%**	**7%**	**7%**	**7%**	**10%**	**10%**	**10%**
Fuel cost per gallon	**$3.10**	**$4.10**	**$5.40**	**$3.10**	**$4.10**	**$5.40**	**$3.10**	**$4.10**	**$5.40**
Baseline 2010 tractor-trailer	$0	$0	$0	$0	$0	$0	$0	$0	$0
Add 2017 engine (45.8% BTE)	$42,021	$56,242	$74,654	$33,435	$44,918	$59,787	$29,070	$39,162	$52,230
Reduce road load (Net 16% Aero, 9% RR, 2% Mass) [nominal 2017 tractor-trailer]	$89,632	$119,895	$159,095	$71,381	$95,819	$127,474	$62,102	$83,579	$111,399
Add 6×2 drive and AMT	$101,662	$136,963	$182,692	$80,376	$108,883	$145,811	$69,555	$94,608	$127,062
Reduce road load (Net 20% Aero, 16% RR, 7% Mass)	$117,989	$161,238	$217,268	$91,919	$126,844	$172,091	$78,666	$109,359	$149,124
Add 2020 Engine (49% BTE) and DCT	$147,822	$201,733	$271,595	$115,350	$158,885	$215,301	$98,842	$137,103	$186,684
Reduce road load (Net 30% Aero, 30% RR, 14% Mass)	$175,119	$243,249	$331,561	$134,115	$189,133	$260,448	$113,270	$161,622	$224,296
Downsize engine 10%	$184,091	$254,622	$346,054	$141,651	$198,608	$272,442	$120,076	$170,132	$235,021
Add Waste Heat Recovery (52% BTE)	$193,018	$268,359	$366,035	$147,697	$208,538	$287,415	$124,658	$178,127	$247,447
Reduce road load (Net 50% Aero, 35% RR, 17% Mass)	$221,913	$312,307	$429,537	$167,590	$240,586	$335,254	$139,974	$204,126	$287,324
Add post-2020 engine (55% BTE)	$241,505	$338,750	$464,888	$183,096	$261,625	$363,486	$153,403	$222,417	$311,936
Add hybrid (60% efficiency regen.)	$235,882	$337,794	$469,993	$174,680	$256,978	$363,733	$143,567	$215,894	$309,714

BTE=brake thermal efficiency; AMT=automated manual transmission; DCT=dual clutch transmission; Aero=aerodynamic drag; RR=rolling resistance; Mass=tractor-trailer curb mass

Assumptions related to future economic conditions, namely the fuel savings discount rate and fuel price, play a significant role in determining absolute lifetime savings from the tractor-trailer efficiency technologies. Figure 7 graphically depicts the best case — associated with best estimate low costs, a low discount rate, and high fuel price — and worst case — associated with best estimate high costs, a high discount rate, and low fuel price — lifetime fuel savings estimates for the 2025 evaluation year. The figure shows that the economic factors (i.e., fuel price, discount rate) play a far larger role than high and low best estimate technology costs in determining the overall benefits from 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 benefit-cost evaluation, when compared to the effect of the economic factors.

Figure 6. Net lifetime savings from tractor-trailer fuel efficiency technologies for 2025 under varying technology cost, discount rate, and fuel price (2014 dollars)

FIRST-USER SAVINGS ESTIMATES

As another indicator of the potential attractiveness of the initial technology purchase, first-user fuel savings for tractor-trailers with the various efficiency technology packages are also estimated. Company tractor ownership practices vary quite widely. Companies tend to operate their new long-haul tractors less than 10 years, and the generally cited conventional wisdom is that new long-haul tractors are held for four to six years. Based on reporting of commercial tractor transactions by the National Automobile Dealers Association (2014), the average 2014 used late-model sleeper tractor transaction involves a seven-year-old tractor that has accrued about 700,000 miles. In addition, Roeth et al. (2013) report that typical ownership cycles for long-haul tractors are four to six years. This analysis conservatively assumes a five-year initial tractor ownership period for evaluating average first-user fuel-saving impacts.

The results for first-user discounted net fuel savings (i.e., discounted fuel savings minus technology costs) are summarized in Table 17. These net fuel savings are based on five-year ownership, ignoring all fuel savings that would otherwise accrue during the remaining useful life of the tractors. The net discounted fuel savings for best estimate low technology costs are shown in the top half of Table 17, while the bottom half presents savings for best estimate high technology costs. As tabulated, the fuel savings for the first-owner are a substantial part of the overall lifetime savings that are presented above. This is largely due to the fact that the average tractor accrues more than half of its lifetime mileage in the first five years of operation.

The efficiency technology package that reduces fuel consumption by 38% through 10% engine downsizing has a cost of $21,000-$36,000 in 2025 and offers $100,000-$194,000 in discounted fuel savings during the first five years of operation, depending on economic assumptions. As shown in Table 17, this efficiency package results in a net benefit of $64,000-$174,000 over the first five years of operation. These estimated benefits to the first technology user are three to nine times greater than the upfront technology cost.

The most advanced technology package, with a 54% fuel consumption reduction and a cost of $52,000-$82,000 for the tractor and three trailers, results in $145,000-$280,000 in fuel savings during the first five years of operation. It therefore delivers a net benefit of $63,000-$229,000 during those five years, providing benefits to the first technology owner that are two to five times higher than costs.

Table 17. Technology package first-owner net savings for best estimate high and low technology costs, for varying discount rate, fuel price for 2025 evaluation year

Discount rate	3%	3%	3%	7%	7%	7%	10%	10%	10%
Fuel cost per gallon	**$3.10**	**$4.10**	**$5.40**	**$3.10**	**$4.10**	**$5.40**	**$3.10**	**$4.10**	**$5.40**
Best estimate low technology cost									
Baseline 2010 tractor-trailer	$0	$0	$0	$0	$0	$0	$0	$0	$0
Add 2017 engine (45.8% BTE)	$21,662	$28,888	$38,245	$20,246	$27,021	$35,794	$19,310	$25,787	$34,173
Reduce road load (Net 16% Aero, 9% RR, 2% Mass) [nominal 2017 tractor-trailer]	$45,321	$60,701	$80,625	$42,311	$56,731	$75,410	$40,320	$54,105	$71,961
Add 6×2 drive and AMT	$50,308	$68,249	$91,491	$46,798	$63,618	$85,409	$44,477	$60,556	$81,386
Reduce road load (Net 20% Aero, 16% RR, 7% Mass)	$58,003	$79,979	$108,451	$53,706	$74,309	$101,003	$50,863	$70,559	$96,077
Add 2020 Engine (49% BTE) and DCT	$73,126	$100,520	$136,023	$67,773	$93,456	$126,742	$64,233	$88,785	$120,604
Reduce road load (Net 30% Aero, 30% RR, 14% Mass)	$86,670	$121,283	$166,155	$79,912	$112,364	$154,432	$75,443	$106,465	$146,680
Downsize engine 10%	$91,486	$127,321	$173,780	$84,491	$118,088	$161,645	$79,865	$111,982	$153,620
Add Waste Heat Recovery (52% BTE)	$94,706	$132,984	$182,616	$87,236	$123,124	$169,656	$82,295	$116,602	$161,084
Reduce road load (Net 50% Aero, 35% RR, 17% Mass)	$109,448	$155,372	$214,937	$100,494	$143,551	$199,396	$94,573	$135,733	$189,118
Add post-2020 engine (55% BTE)	$119,684	$169,092	$233,186	$110,056	$156,379	$216,470	$103,689	$147,971	$205,415
Add hybrid (60% efficiency regen.)	$109,965	$161,744	$228,918	$99,877	$148,423	$211,401	$93,206	$139,613	$199,816
Best estimate high technology cost									
Baseline 2010 tractor-trailer	$0	$0	$0	$0	$0	$0	$0	$0	$0
Add 2017 engine (45.8% BTE)	$20,089	$27,318	$36,678	$18,672	$25,450	$34,226	$17,735	$24,215	$32,604
Reduce road load (Net 16% Aero, 9% RR, 2% Mass) [nominal 2017 tractor-trailer]	$43,010	$58,395	$78,323	$39,999	$54,423	$73,107	$38,008	$51,796	$69,657
Add 6×2 drive and AMT	$47,289	$65,235	$88,483	$43,777	$60,603	$82,398	$41,455	$57,539	$78,375
Reduce road load (Net 20% Aero, 16% RR, 7% Mass)	$51,396	$73,382	$101,867	$47,095	$67,708	$94,414	$44,251	$63,956	$89,485
Add 2020 Engine (49% BTE) and DCT	$64,876	$92,283	$127,799	$59,519	$85,214	$118,512	$55,976	$80,540	$112,371
Reduce road load (Net 30% Aero, 30% RR, 14% Mass)	$70,379	$105,014	$149,909	$63,614	$96,086	$138,178	$59,140	$90,182	$130,419
Downsize engine 10%	$75,683	$111,540	$158,021	$68,682	$102,299	$145,877	$64,052	$96,188	$137,846
Add Waste Heat Recovery (52% BTE)	$77,251	$115,552	$165,208	$69,774	$105,683	$152,238	$64,830	$99,157	$143,660
Reduce road load (Net 50% Aero, 35% RR, 17% Mass)	$83,150	$129,104	$188,701	$74,189	$117,273	$173,147	$68,262	$109,448	$162,861
Add post-2020 engine (55% BTE)	$92,305	$141,742	$205,867	$82,669	$129,019	$189,139	$76,297	$120,604	$178,075
Add hybrid (60% efficiency regen.)	$79,549	$131,358	$198,564	$69,452	$118,026	$181,034	$62,775	$109,209	$169,441

BTE=brake thermal efficiency; AMT=automated manual transmission; DCT=dual clutch transmission; Aero=aerodynamic drag; RR=rolling resistance; Mass=tractor-trailer curb mass

MARGINAL COST OF TECHNOLOGY

Both payback period and lifetime savings provide important insights into the economic viability of the evaluated technology packages. However, because 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 successive, 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 to baseline technology, but to the technologies that are adopted before it. This study evaluates marginal costs in terms of the cost investment per gallon of fuel saved. Marginal costs in terms of dollars per gallon can be readily compared to actual, or more accurately, 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 since it is cheaper to pay for fuel than to invest in additional technology.

To undertake the marginal cost analysis, technology costs for 2020 and 2025 are analyzed in terms of their associated discounted lifetime gallons of fuel saved. The data for efficiency technology package cost and the discounted lifetime fuel savings are analyzed at the bounding conditions, which are the conditions that produce the highest and lowest marginal cost estimates. Because high fuel prices have the greatest elasticity effects, they decrease the quantity of fuel saved 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. This study uses both 2020 and 2025 evaluation years in the marginal cost analysis to capture technology cost differentials. Minimum fuel quantity savings are coupled with the higher 2020 technology costs and maximum fuel savings are coupled with the lower 2025 technology costs. Other combinations of fuel savings and costs will produce marginal cost estimates for 2020-2025 that lie between those presented in this report.

Marginal cost curves, as presented in Figure 7, are developed from the lifetime discounted fuel savings data. For the most advanced technology package included in this study, which has an associated real-world cycle fuel economy of 11.6 mpg, the marginal cost of technology ranges from $1.06 per gallon of fuel saved under high savings, low cost conditions to $2.75 per gallon 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 fuel prices of $3.10-$5.40 per gallon expected between 2020 and 2030.

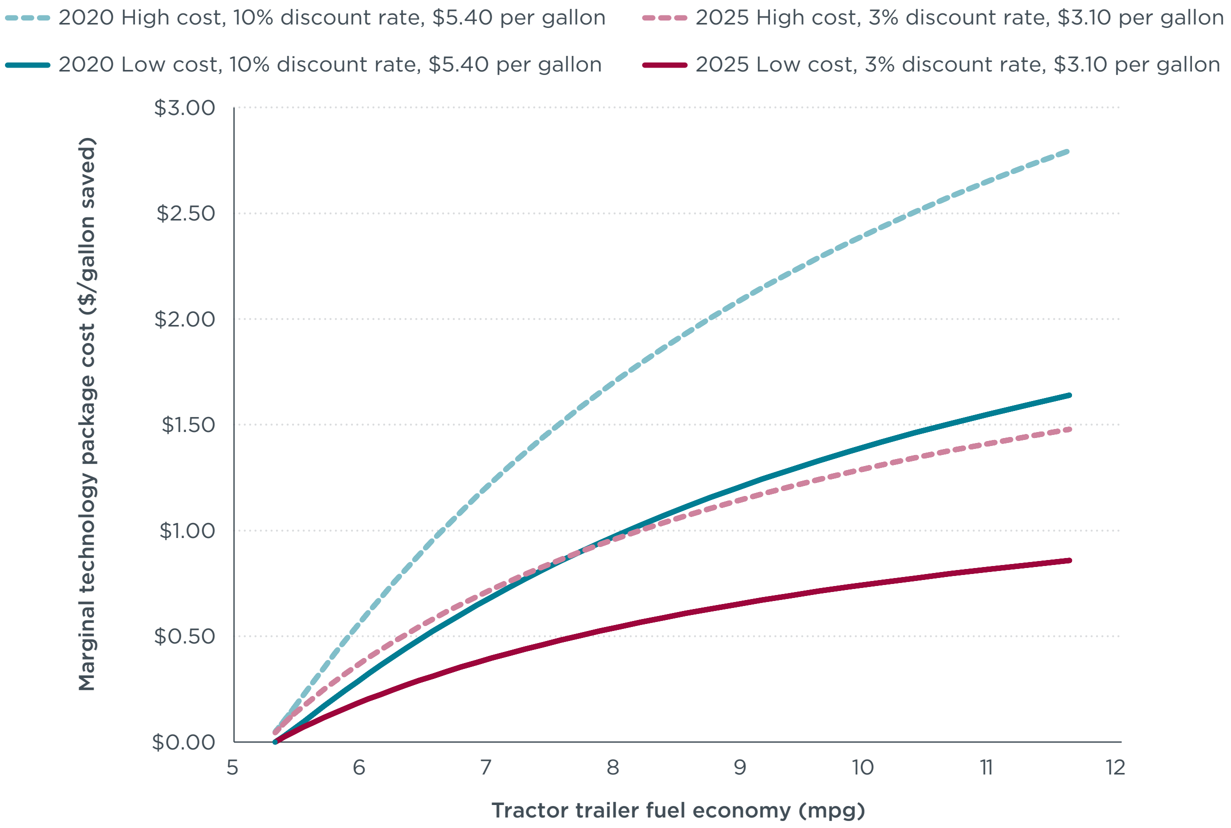

Figure 7. Best and worst case marginal cost per gallon saved for efficiency technology for 2020-2025 (2014 dollars)

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 2020-2030 time frame. The specific technology packages evaluated in the study, based on tractor-trailer simulation modeling from Delgado and Lutsey (2015), are presented in Figure 1 of this report. In total, the packages generate fuel economy increases that provide greater than a doubling of tractor-trailer fuel economy, corresponding to per-mile fuel consumption reductions of more than 50%. On a nondiscounted basis, the most advanced of the packages offers potential lifetime savings of more than 125,000 gallons 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. To provide a broader indication of potential technology costs, the study evaluates two cost estimates for each technology, representing low and high best estimate costs based on the range of data that are available in the research literature. 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 indicates that there are available and emerging technology options to dramatically and cost-effectively increase new long-haul tractor-trailer efficiency.

ECONOMIC FINDINGS

The primary finding of the study is that, due to high technology availability and extensive lifetime mileage, substantial improvements are available to cost effectively increase long-haul tractor-trailers efficiency. While upfront technology 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 three trailers per common industry practice, costs approximately $210,000, and additional efficiency technology costs were assessed incrementally from this baseline.

Available efficiency technologies, in a package that offers a per-mile tractor-trailer fuel consumption reduction of 38%, are estimated to have incremental technology costs in 2025 that include $1,100-$4,000 for the engine, $4,500-5,700 for the transmission, $1,600-$1,800 in tractor aerodynamics, $3,600-$6,700 in tractor lightweighting, $1,100-$2,700 in trailer aerodynamics, and $1,700-$3,000 in trailer lightweighting. These costs are estimated from a 2010 reference tractor-trailer for the year 2025, based on best available cost data and conventional technology learning assumptions. The range of potential lifetime fuel savings for these moderate efficiency packages is $156,000-$382,000 per tractor-trailer, depending on discount rate and fuel price assumptions.

The most advanced technology package offers a 54% per-mile fuel consumption reduction and is estimated to have incremental technology costs in 2025 that include $5,300-$10,400 for the engine, $4,500-$5,700 for the transmission, $2,900-$4,700 in tractor aerodynamics, $7,000-$12,700 in tractor lightweighting, $15,000-$17,000 for a hybrid system, $1,900-$4,800 in trailer aerodynamics, and $3,000-$5,100 in trailer lightweighting. This most advanced technology package generates $226,000-$552,000 in lifetime fuel savings per tractor-trailer, depending on economic assumptions for the future fuel price and the discount rate.

Figure 10 graphically depicts the breakdown of costs for the most advanced technology package in 2025. The technology costs in the figure are the average of low and high best estimate costs, as developed for one tractor and three trailers. A representative baseline long-haul tractor, with three trailers per common industry practice, as analyzed here, costs approximately $210,000. The advanced technology package shown in the figure delivers a real-world tractor-trailer fuel economy of 11.6 mpg, more than double the 2010 baseline technology performance. For this most advanced technology package, the efficiency component costs are distributed among the powertrain, tractor, trailer, and hybrid systems. On average, total vehicle costs increase by about 31% when all technologies are included.

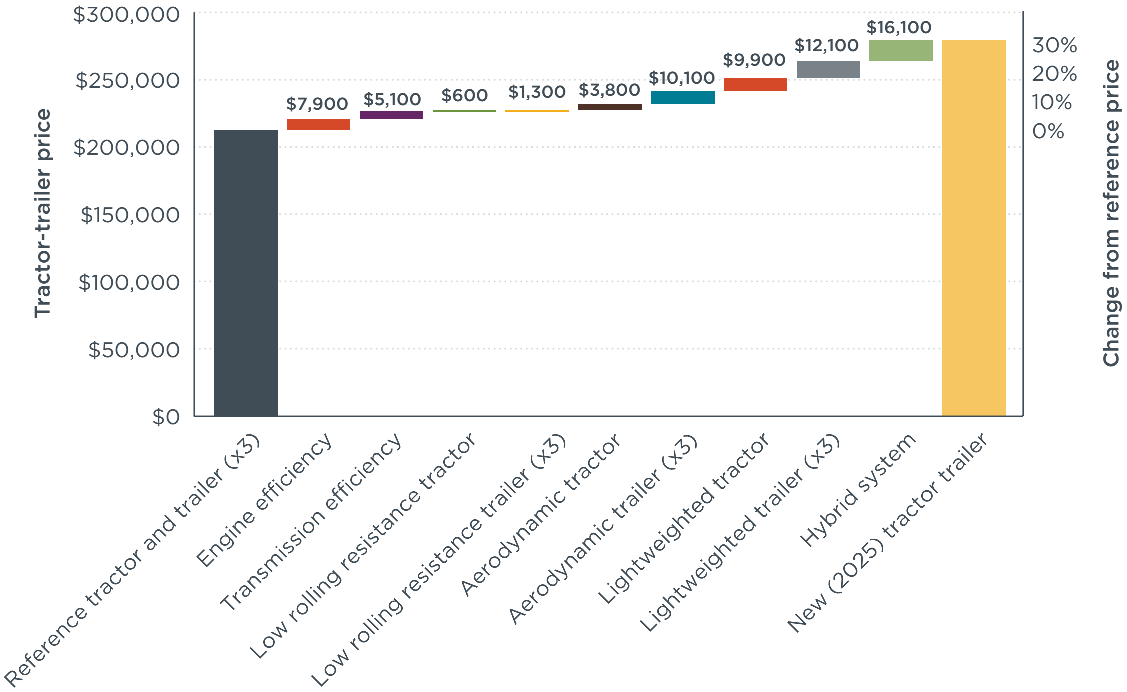

Figure 8. Tractor-trailer technology cost increase from 2010 baseline technology for the most advanced efficiency technology package in 2025 (2014 dollars), based on one tractor and three trailers

One key insight from this analysis is that a large fraction of the total potential technology costs for the most advanced technology packages are in the advanced lightweighting technology and the long-haul hybrid system. Including all of the technologies except for lightweighting and hybridization, the total tractor-trailer costs would increase by approximately 14%, based on the midpoint between the low and high technology costs. Examining such technology packages, the results indicate that for a 10 mile-per-gallon tractor-trailer, there would be $9,000-$14,000 in additional cost on the tractor and $1,000-$2,700 per trailer above the 2017 baseline technology

Figure 9 shows the estimated fuel consumption reductions and the associated payback periods for evaluated technology packages in 2025. Moving down the figure, the data represent the sequential addition of more advanced efficiency technologies. The figure depicts how the average estimate of the payback periods evaluated in this analysis 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 conditions for fuel prices ranging from $3.10-$5.40 per gallon, and discount rates ranging from 3%-10%. Payback periods for the moderate technology packages, offering up to a 38% per-mile fuel consumption reduction, are generally less than a year. The most advanced technology packages, with 50% or greater fuel consumption reduction, result in 0.9-1.3 year payback periods for the average economic assumptions.

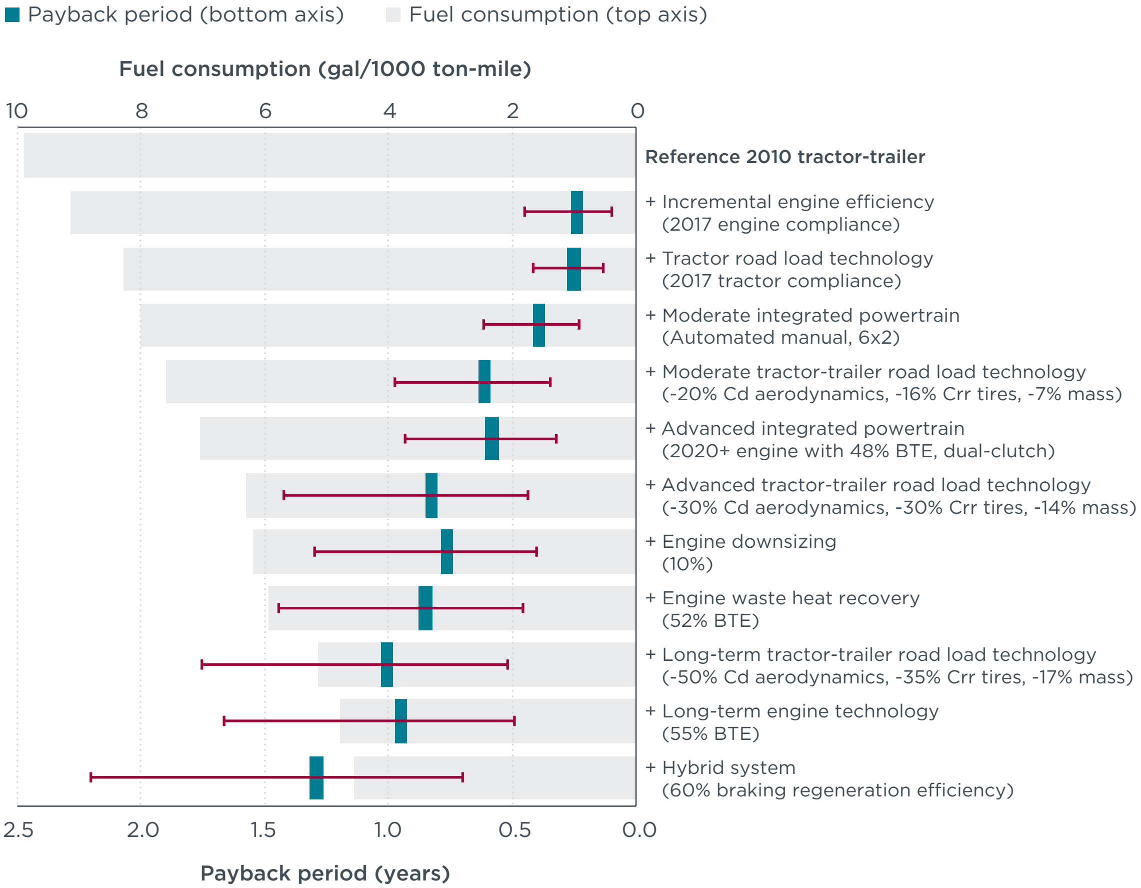

Figure 9. Fuel consumption impacts and associated 2025 payback periods for tractor-trailer efficiency technologies

Substantial net lifetime savings representing discounted fuel savings minus technology costs accrue for all evaluated technology packages, with savings increasing more rapidly than technology costs for the full range of evaluated technology. For moderate packages yielding 38% per-mile fuel consumption reduction, discounted savings after technology payback range from $136,000-$362,000 per-tractor depending on evaluation year, discount rate, fuel price, and whether best estimate low or best estimate high costs are considered. The most advanced technology packages offer per-mile fuel consumption reductions of up to 54% and discounted savings after technology payback ranging from $174,000-$500,000 per tractor. These potential fuel savings largely accrue to the first owner of the tractor, due to high mileage accrual that is typically more than 100,000 per year in the first several years of ownership. Our analysis of a typical five-year ownership cycle indicates that approximately half the lifetime fuel savings would fall to the first tractor owner.

The marginal cost of all technology packages — under all technology cost, discount rate, and fuel price scenarios — is cost effective for fuel prices expected in the 2020-2030 time frame. Under worst case evaluation conditions, namely a high discount rate and 2020 costs, the marginal cost of the most advanced technology package is less than $3.00 per gallon of fuel saved for best estimate high costs. The marginal cost of the technology packages is less than $2.00 per gallon of fuel saved for best estimate low costs. These compare with the EIA (2014) average and low fuel price cases that are approximately $3.10 and $4.10 per gallon over the 2020-2030 time frame.

POLICY DISCUSSION AND RECOMMENDATIONS

The results of this cost analysis reinforce the policy implications of its companion technology study (i.e., Delgado and Lutsey, 2015). 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 here would require technology-forcing regulations to drive them into the marketplace. 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 applicable technologies, state-of-the-art understanding of technologies' effectiveness through modeling, and rigorous cost evaluation as conducted here.

With the US government set to establish heavy-duty vehicle 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 well beyond the levels associated with the Phase 1 heavy-duty vehicle rulemaking that, for long-haul tractor-trailers, applies to model year 2014 to 2017 vehicles and engines.

More specifically, the findings from this study point to several policy implications related to US greenhouse gas emission and efficiency standards for 2020 and beyond.

(1) *Available efficiency technologies for tractor-trailers have fuel savings that greatly exceed up-front technology costs.* The findings indicate that available tractor-trailer efficiency technologies can reduce per-mile fuel consumption by 38% from baseline 2010 technology, or by about 25% from 2017, the final year of the adopted standards, and deliver payback periods to tractor-trailer users that are generally within one year for base-case economic assumptions. Based on technology availability and the attractive cost-effectiveness to end users, this level of efficiency technology can be widely deployed in the 2020-2025 time frame.

(2) *Emerging advanced efficiency technologies over the long-term offer more substantial fuel savings and attractive payback periods.* This study's findings indicate that technology packages with long-term road load and engine technologies can achieve, in the 2025-2030 time frame, at least 50% per-mile fuel consumption reduction from baseline 2010 technology, or at least 40% from 2017. For these advanced technology pathways, the payback periods from the fuel savings are less than 1.5 years for base-case economic assumptions. Technology-forcing standards and sufficient lead-time would be needed to promote the development and deployment of these advanced efficiency technologies in the 2025 time frame.

(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 of $3.10 per gallon through 2030, the attractive payback findings in this study are robust. The more advanced technology packages, with 48%-54% fuel consumption reduction, have payback periods of 1.4-2.2 years when high technology costs, high discount rates, and low fuel prices are assumed. The attractive and robust payback period findings indicate that there are prevailing market barriers, and increasingly stringent tractor-trailer efficiency standards are warranted.

(4) *Tractor-trailer efficiency technologies offer first-user fuel savings that greatly exceed the increased upfront capital costs.* Examining typical first tractor users' discounted future fuel savings, available efficiency technologies that reduce fuel consumption by 38% offer $100,000-$194,000 in discounted fuel savings and result in benefits that are three to nine times greater than the upfront technology cost, depending on the economic assumptions. The most advanced emerging technology package, offering a 54% fuel consumption reduction for new 2025 tractor-trailers, results in $145,000-$281,000 in fuel savings, or two to five times higher benefits than costs. When including full tractor lifetime benefits, beyond the typical five years of operation by the first user, the benefit-to-cost ratio is even greater. The high benefit-to-cost ratio points to a clear opportunity for efficiency standards to simultaneously mitigate climate-related emissions, provide overall economic benefits, and offer an attractive investment for fleets.

A number of issues remain beyond the scope of this current 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, while this study does not evaluate or take credit for fuel use reductions that might accrue through reductions in vehicle idling and hoteling, some of the evaluated technologies promote or facilitate such reductions. Thus, there is significant potential for an integrated idle reduction program that is not investigated in this study. Another key area for follow-on research would be to investigate tractor-trailer technology packages that exclude advanced lightweighting and hybrid systems, which are found to have the highest costs. Such work could help pinpoint an optimal technology point where most of the efficiency technology can be applied, but where capital costs are minimized.

This 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. Questions such as how this modeling might inform or relate to the technology potential for tractor-trailers in other major vehicle markets that are on the verge of developing standards (e.g., Europe, China) remain open. Interactions among efficiency technologies, technologies to control conventional air pollution, and their costs are not investigated. In addition, the impacts of efficiency technologies on non-fuel operating and maintenance costs have not been analyzed.

While this study is focused on tractor-trailer technology cost-effectiveness in the US context, the implications extend well beyond the immediate US regulatory dialogue for 2020 and beyond. The manufacturers and suppliers that are developing the efficiency technologies evaluated in this study could further leverage their investments by deploying the same technologies at greater volume globally. And companies might be prompted to do just that. China, Canada, and Japan have already adopted some form of efficiency or greenhouse gas standards for heavy-duty vehicles and are working toward their next phase of regulations. India, Mexico, South Korea, and the European Union are also investigating new heavy-duty vehicle efficiency policies. As a result, heavy-duty vehicle efficiency technology and policy advancements could be greatly leveraged in the years ahead.

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