



HEAVY-DUTY VEHICLES IN CHINA

COST-EFFECTIVENESS OF FUEL-EFFICIENCY AND CO₂ REDUCTION TECHNOLOGIES FOR LONG-HAUL TRACTOR-TRAILERS IN THE 2025-2030 TIMEFRAME

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ACKNOWLEDGMENTS

This project was supported by Energy Foundation China and Aspen Global Change Institute. The authors thank Ma Dong, Boyong Wang, and Rachel Muncrief for their critical input and reviews of the report.

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ABBREVIATIONS AND ACRONYMS

AMT	Automated Manual Transmission
BIC	Best-in-Class
BMEP	Brake Mean Effective Pressure
BTE	Brake Thermal Efficiency
CATARC	China Automotive Technology & Research Center
C_d	Coefficient of Drag
$C_d A$	Aerodynamic Drag Area (Vehicle frontal area times C_d)
CFLP	China Federation of Logistics Purchasing
CO_2	Carbon Dioxide
C_{rr}	Coefficient of Rolling Resistance
C-WTVC	A version of the World Harmonized Vehicle Cycle adapted to the China
DCT	Dual Clutch (automated manual) Transmission
DE	Diesel Engine
DMC	Direct Manufacturing Cost
DOE	Department of Energy (United States)
DPF	Diesel Particulate Filter
EC	European Commission
EGR	Exhaust Gas Recirculation
EPA	Environmental Protection Agency (United States)
GE	Gasoline Engine
HDV	Heavy-Duty Vehicle
ICCT	The International Council on Clean Transportation
IC	Indirect Cost
ICM	Indirect Cost Multiplier
kg	kilogram(s)
km	kilometer(s)
kW	kilowatt(s)
L	liter(s)
L/100 km	liters per hundred kilometers
m	meter(s)
MCC	China Ministry of Commerce
MEE	Ministry of Ecology and Environment
MIIT	Ministry of Industry and Information Technology
m^2	square meters
NBSC	National Bureau of Statistics of China
NO_x	Oxides of Nitrogen
NPV	Net Present Value
NRC	National Research Council (United States)
OMB	Office of Management and Budget (United States)
ORC	Organic Rankine Cycle WHR technology
rpm	revolutions per minute
SAE	Society of Automotive Engineers
SCR	Selective Catalytic Reduction
S2	Stage 2
S3	Stage 3
TC	Total (retail level) Cost, $TC = DMC + IC$.
VGT	Variable Geometry Turbocharger
VKT	Vehicle Kilometers of Travel
WHR	Waste Heat Recovery (specifically Organic Rankine Cycle technology)

EXECUTIVE SUMMARY

Ongoing technology and policy developments point to the potential for more-efficient new freight trucks. Major markets such as the United States, Canada, China, Japan, and most recently India have adopted heavy-duty vehicle (HDV) standards for carbon dioxide (CO₂), a substantial step toward improving efficiency. While these efforts represent positive first steps, there is potential for accelerated deployment into the freight market of substantially more effective existing and emerging efficiency technology. This study assesses the future costs of advanced long-haul tractor-trailer technologies as an input into the China policy dialogue on HDV efficiency and CO₂ standards. Specifically, the study investigates the costs associated with the technologies evaluated by the International Council on Clean Transportation (ICCT) in a companion study. The companion study relies on simulation modeling to investigate the technology potential for reducing tractor-trailer fuel consumption.

The fundamental approach in this assessment involves deriving technology costs from the best available data on HDV and engine technologies to assess the cost effectiveness of increasingly efficient tractor-trailer technology packages. Economic impact metrics are investigated, including investment payback periods, lifetime fuel savings, and the marginal costs associated with various technology packages under a range of economic assumptions. Such assumptions include three discount rates—4%, 7%, and 10%—and three diesel fuel prices per liter—¥4.50, ¥7.00, and ¥9.00—expressed in 2016 yuan. The evaluated efficiency technology packages include per-kilometer fuel-consumption and CO₂ reductions in 2030 of as much as 51% relative to a 2015-era baseline Stage 2 tractor-trailer. The packages include individual technology options that address engine and powertrain efficiency, vehicle road load, waste energy recovery, and hybridization. All economic calculations include a ratio of 1.045 trailers for each tractor because the population of trailers to be equipped with fuel-consumption reduction technology exceeds the number of tractors.

The primary finding of this study is that substantial improvements are available to cost-effectively increase long-haul tractor-trailer efficiency in China. This reflects wide-ranging technology availability and extensive lifetime mileage. While upfront technology and net present value maintenance costs can be significant, the economic return more than justifies an investment in efficiency for the entire range of cases investigated. A representative baseline long-haul tractor with 1.045 trailers costs approximately ¥422,700 in 2016 yuan. Available efficiency technology packages offering moderate fuel-consumption reductions of as much as 35% are projected to cost ¥117,300–¥130,300 in 2025–2030 based on best-available cost data and conventional technology learning assumptions. The potential discounted lifetime fuel savings for these moderate efficiency packages range from ¥478,400–¥1,215,050 per tractor-trailer, depending on discount rate and fuel price assumptions. The most advanced technology package offers a 51% distance-specific fuel-consumption reduction and is estimated to cost ¥326,000–¥333,400 in 2025–2030. But this package would generate lifetime fuel savings of ¥698,900–¥1,775,100 per tractor-trailer. For the most advanced technology package, the efficiency component costs are roughly equally distributed among the powertrain, a hybrid system, the tractor, and the trailer.

Figure ES-1 depicts the estimated fuel-consumption reductions and associated payback periods for evaluated technology packages in 2030. Moving down the figure, the data represent the sequential addition of more advanced efficiency technologies. The average payback periods estimated in this study generally increase with more advanced technology packages. The “whiskers” of each payback band reflect the range of payback periods across high and low technology cost estimates and varying economic assumptions for diesel fuel prices ranging from ¥4.50–¥9.00 per liter and discount rates ranging from 4%–10%. Payback periods for the moderate technology packages, offering reductions of as much as 35% in fuel consumption, are generally 1.3 years or less. The most advanced technology packages, with 37% or greater reductions in fuel consumption, result in payback periods of 1.4–2.4 years under average economic assumptions.

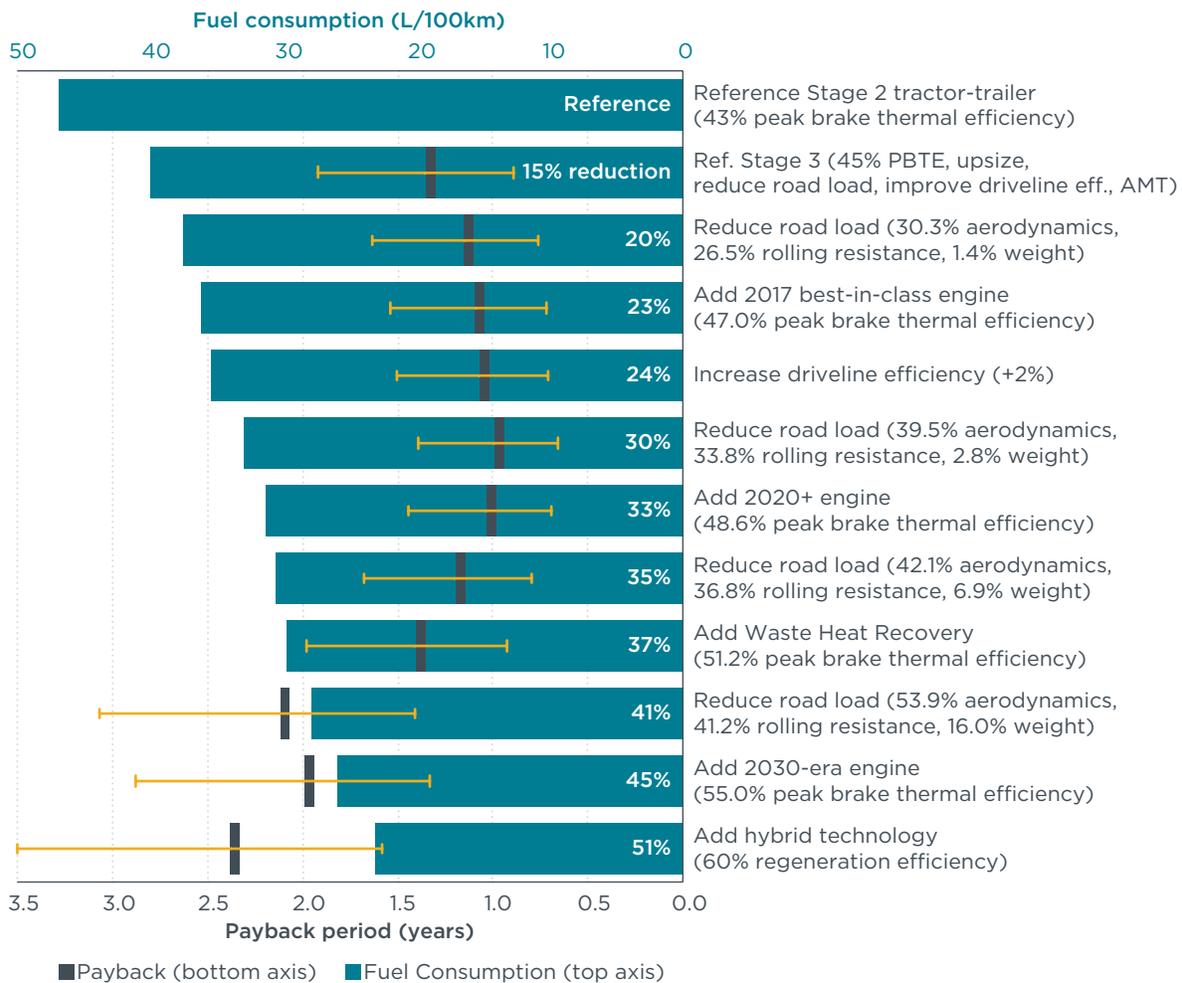


Figure ES-1. Cumulative fuel-consumption impacts and associated 2030 payback periods for tractor-trailer efficiency technologies

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

1. Available efficiency technologies for long-haul tractor-trailers offer fuel savings that greatly exceed the upfront costs of technology and maintenance.

Findings indicate that available tractor-trailer efficiency technology can reduce

distance-based fuel consumption and CO₂ emissions by 35% from baseline 2015 Stage 2 technology and deliver payback periods to tractor-trailer owners that are generally within 1.3 years or less. Fuel savings from these packages exceed increased technology costs by a factor of 3–12, depending on evaluated economic conditions. Based on technology availability, this level of efficiency technology can be widely deployed in the 2020–2025 timeframe.

2. ***Emerging advanced efficiency technologies offer more substantial fuel savings and more attractive payback periods over the long term.*** Study findings indicate that technology packages with long-term road load and engine technologies in the post-2025 timeframe can achieve a 51% reduction in fuel consumption and CO₂ emissions from baseline 2015 Stage 2 technology. For these advanced-technology pathways, the payback periods from fuel savings are less than 2.4 years under average economic assumptions. Technology-forcing standards and sufficient lead time would be needed to promote the development and deployment of these advanced technologies post-2025.
3. ***Tractor-trailer efficiency technologies' attractive payback periods persist even in the event of higher technology costs and low fuel prices.*** Based on this study's investigation of varying technology costs and economic assumptions, including an average fuel price as low as ¥4.50 per liter through 2030, the attractive payback findings in this study are robust. The more advanced technology packages, delivering 37%–51% reductions in fuel consumption and CO₂ emissions, have payback periods of 0.9–4.0 years, even assuming high technology costs, high discount rates, and low fuel prices. Payback would occur even sooner if less conservative but still reasonable assumptions for vehicle kilometers of travel (VKT) and technology cost are employed. The attractive and robust payback-period findings indicate that there are prevailing market barriers to technology introduction, warranting the introduction of stringent tractor-trailer efficiency standards.
4. ***Tractor-trailer efficiency technologies offer first-owner fuel savings that greatly exceed the increased upfront capital and maintenance costs.*** For typical first owners of a tractor, available efficiency technologies that reduce fuel consumption by 35% offer ¥126,300–¥653,000 in discounted fuel savings over the first five years of ownership and result in benefits that are 2–7 times greater than the upfront technology and maintenance costs, depending on economic assumptions. The most advanced emerging technology package, offering a 51% reduction in fuel consumption for new 2030 tractor-trailers, would result in ¥310,500–¥954,100 in fuel savings, exceeding costs by 1.2–5.0 times. When taking into account the savings over a tractor's entire lifetime, beyond the typical five years of first-owner operation, the benefit-to-cost ratio is even greater. This points to a clear opportunity for efficiency standards to simultaneously mitigate climate-related emissions, provide overall economic benefits, and offer an attractive return on investment for fleets. Benefits increase further under less conservative but still reasonable VKT and technology-cost assumptions.

While this study focuses on the cost-effectiveness of tractor-trailer technology in China, the implications are not limited by geography. The manufacturers and suppliers that are developing efficiency technologies could leverage their investments by deploying the same technologies at greater volume globally. Establishing stringent HDV standards in a market the size of China can play a key role in advancing global market opportunities.

I. INTRODUCTION

Rapid growth in road freight activity is placing significant burdens on the supporting infrastructure and the environment (Agenbroad, Creyts, Mullaney, Song, and Wang, 2016). China is the world's largest producer of heavy-duty vehicles (HDVs), which account for about 5% of the on-road vehicle fleet but consume more than a third of total transport energy demand. China's net crude oil imports total more than \$100 billion annually. Fuel use in the road freight sector is expected to quadruple by 2030 from 2010, and the contribution of the road freight sector to total carbon emissions in China is expected to increase from 6% in 2010 to 18% by 2030. China's transport sector accounts for 10.8% of global CO₂ emissions from transport. Such trends are incompatible with China's goals for reducing carbon emissions.

In early 2018, the Ministry of Industry and Information Technology (MIIT) finalized the third stage (Stage 3) of China's heavy-duty vehicle fuel consumption standards which will go into effect in mid-2019. The previous two stages, Stage 1 "Industry Standard", and Stage 2 "National Standard" were implemented in mid-2012 and mid-2014 respectively (Delgado, 2016). Although a good step, such standards are not sufficient to promote the adoption of available fuel-consumption reduction technology or to counteract the negative impacts on climate change and energy security. In early 2018, the Ministry of Environmental Protection (MEP) was reconstituted as the Ministry of Ecology and Environment (MEE) and now have new authority with respect to climate change and greenhouse gas (GHG) emissions reduction policies. Currently, it is uncertain if MIIT will promulgate Stage 4 fuel consumption standards or if MEE will implement a first-ever HDV GHG regulation. The development and implementation of more stringent CO₂ standards for HDVs can help China achieve its carbon-reduction targets as well as incentivize research and development of new fuel-efficiency technologies.

Evaluation of the fuel-saving potential of different HDV technologies is a fundamental step in the development of effective HDV CO₂ standards. A recently published ICCT paper (Delgado, Rodríguez, and Muncrief, 2018) uses vehicle simulation modeling analysis to evaluate the level of fuel-consumption reduction that can be achieved in the European freight transportation sector in the 2020–2030 timeframe. A similar assessment was internally performed by the ICCT specifically for the Chinese market (Delgado, 2018). This paper serves as a companion to that simulation modeling, adding an assessment of the cost-effectiveness of long-haul tractor-trailer technology. Specifically, this study takes the fuel-consumption results of the companion tractor-trailer simulation work (Delgado, 2018) as a given, develops estimates of future costs for the evaluated technologies, and derives associated economic estimates for consumer payback and lifetime fuel savings.

The potential of technology options for reducing CO₂ emissions from HDVs has been investigated in a substantial number of studies over the past several years. A listing and synopsis of this work is available in two study reports previously prepared by the ICCT for the U.S. and EU markets (Meszler, Lutsey, and Delgado, 2015; Meszler, Delgado, Rodríguez, and Muncrief, 2018). This study and its underlying Delgado (2018) simulation model study are intended to serve as companion studies to the previous U.S. and EU work by expanding the scope of the technology review and cost analysis to the Chinese road freight market. The underlying simulation modeling technology assessment evaluates the fuel-efficiency potential of available and emerging technologies expected to be

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

The tractor-trailer simulation modeling methodology was documented in detail in the ICCT's assessment for the EU (Delgado et al., 2018). Readers are referred to that report for detailed information, but Figure 1 below presents a summary of the China-specific modeling results (Delgado, 2018) that serve as the basis for this study. As depicted, evaluated technology packages provide for fuel-consumption reductions ranging from zero to 51% relative to a 2015 Stage 2 compliant baseline tractor-trailer, as estimated for the C-WTVC driving cycle (Zheng, 2013).

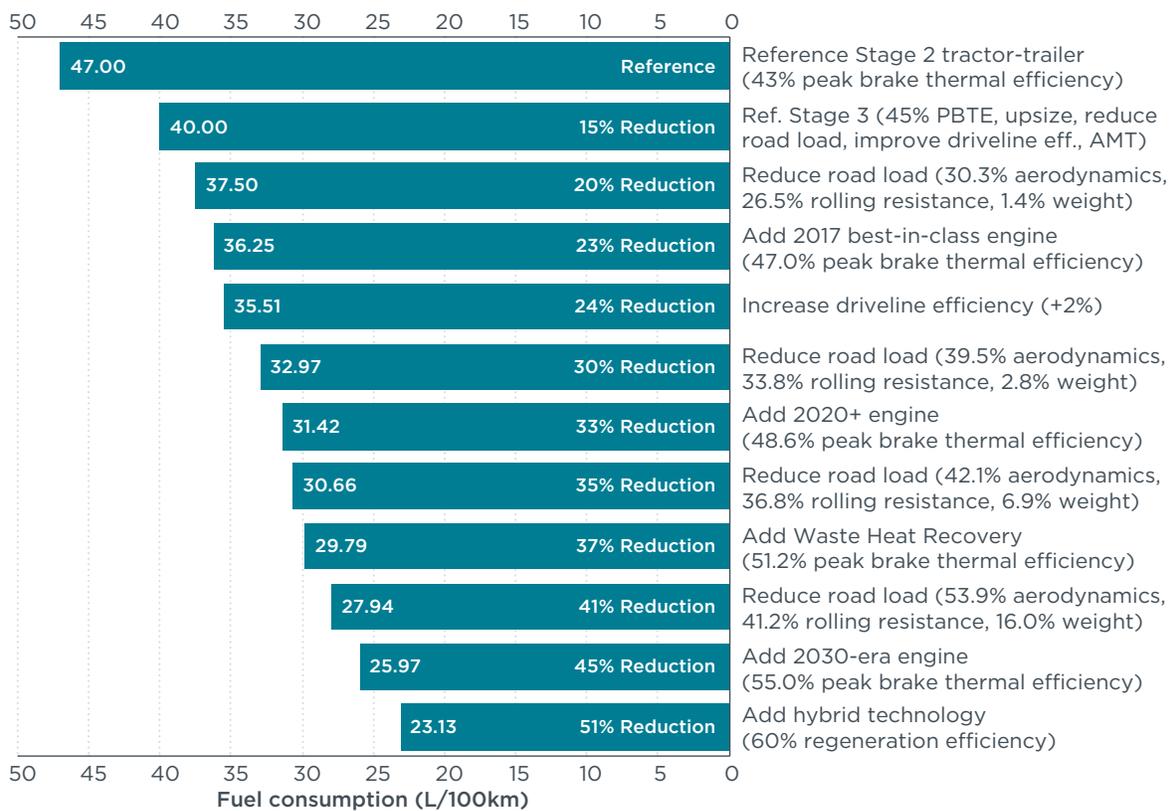


Figure 1. Potential cumulative fuel-consumption reduction from selected tractor-trailer efficiency technologies in China in the 2020–2030 timeframe (Delgado et al., 2018)

Baseline tractor-trailer characteristics are as follows:

Tractor Curb Weight	9,000 kg
Trailer Curb Weight	7,000 kg
Tractor-Trailer Gross Combined Weight	49 tonnes
Maximum Payload	33.0 tonnes
Modeled Payload	33.0 tonnes
Axle Configuration	6×4
Engine Displacement	10.0 liters
Fueling System	1600-1800 bar common rail
Turbocharger	Single-stage, fixed geometry
Peak Cylinder Pressure	~180 bar
Maximum BMEP	23.3 bar
Maximum Torque	1540 Nm
Engine Output	250 kW (Rated)
Engine Brake Thermal Efficiency	43.0% (Peak)
Engine Brake Thermal Efficiency	41.3% (Average over the C-WTVC cycle)
Emissions Certification	China V
Aftertreatment System	SCR+DPF
Transmission	10 Speed MT
Transmission Gear Ratios	14.9, 11.6, 9.0, 7.0, 5.6, 4.4, 3.4, 2.6, 2.0, 1.6, 1.3, 1.0
Rear Axle Ratio	4.11
Tire Size	12R22.5 Tractor (×10) 12R22.5 Trailer (×12)
Aerodynamic Drag Coefficient	0.76
Tractor-Trailer Drag Area	10 m ²
Aerodynamic Drag Area	7.6 m ²
Tire Rolling Resistance	6.8 kg/tonne
Accessory Demand	1.4 kW

The primary objective of this study is to evaluate the cost and cost-effectiveness of available and emerging long-haul tractor-trailer efficiency technologies evaluated in the underlying ICCT simulation modeling study (Delgado, 2018) for application in China in the 2020–2030 timeframe. The fundamental approach for the cost assessment is to derive best-estimate costs from existing research on heavy-duty vehicle and engine technologies and use these derived cost estimates to calculate economic impact metrics that offer the opportunity to assess the viability of the fuel-efficiency technologies. Vehicle and engine technologies and their associated fuel-efficiency impacts are taken as given in the underlying simulation modeling study. This follow-on study relies on previous government, industry, academic, and independent consulting research to quantify costs in the tractor-trailer market, as well as a range of conventional economic assumptions to evaluate impacts on tractor-trailer operators.

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

II. VEHICLE EFFICIENCY TECHNOLOGY BACKGROUND

There are three fundamental means of improving the fuel efficiency of a vehicle. Fuel demand can be lowered by: (1) reducing the amount of energy required to move a vehicle, (2) decreasing the energy losses associated with the conversion and transmission of the chemical energy stored in fossil fuels to the tractive energy delivered to a vehicle's drive wheels, and (3) by capturing and reusing energy that is lost during non-tractive events such as braking. This study analyzes technologies in each of these fuel-efficiency categories, as defined in the companion tractor-trailer simulation modeling study. A brief description of each of the evaluated technologies follows.

VEHICLE ROAD LOAD TECHNOLOGY

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

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

Low rolling-resistance tires. The rolling resistance of tires represents a significant contributor to overall road load power requirements and fuel use. The dissipation of energy from the flexing of tire sidewalls and heat generation during tire revolution varies with tire design and is proportional to tractor-trailer weight and speed. Many HDV tire suppliers and developers offer products with increasingly lower rolling resistance.

Weight reduction. The energy required to induce a given motion, overcoming rolling resistance and road grade, is directly related to tractor-trailer weight. Using lightweight materials and improved design to reduce weight can affect efficiency either directly in terms of reduced fuel consumption for a given load or by increasing payload capacity, which increases load-specific fuel efficiency. The net effect of either is increased energy efficiency. The potential for lightweighting in tractor-trailers is significant. Optimized computer-aided engineering approaches can maximize reductions by evaluating tractor, trailer, and powertrain design as an integrated system. Such an approach will enable the optimized design not only of individual parts, but also of associated systems and subsystems to capture the synergies of component weight reductions.

Road load technology packages. The variety of approaches available for improving road load characteristics makes it difficult to set defined technology pathways. Instead, a series of increasingly efficient technology packages are evaluated in the technology simulation modeling undertaken to estimate fuel consumption rates. The specific levels of road load technology evaluated are summarized in Table 1. It should be noted that tractor-trailer test procedures in China require the vehicle test weight to be maintained at the gross (vehicle plus cargo) weight of the tractor-trailer combination. Any reduction in curb weight is assumed to be fully offset by an increase in cargo weight, resulting in no change in kilometer-specific fuel consumption. Curb weight reductions do, however, generate load-specific fuel consumption improvements, reducing fuel consumed per unit of payload weight.

Table 1. Road load definition

Vehicle configuration	Curb weight change	Drag coefficient change	Rolling resistance change
Baseline Stage 2	0.0%	0.0%	0.0%
Baseline Stage 3	0.0%	-21.1%	-11.8%
Incremental	-1.4%	-30.3%	-26.5%
Moderate	-2.8%	-39.5%	-33.8%
Advanced	-6.9%	-42.1%	-36.8%
Long Term	-16.0%	-53.9%	-41.2%
Vehicle configuration	Curb weight (kg)	Drag area (C _d A) (m ²)	Rolling resistance (kg/tonne)
Baseline Stage 2	16,000	7.6	6.8
Baseline Stage 3	16,000	6.0	6.0
Incremental	15,776	5.3	5.0
Moderate	15,552	4.6	4.5
Advanced	14,896	4.4	4.3
Long Term	13,440	3.5	4.0

ENGINE TECHNOLOGY

Six distinct levels of diesel heavy-duty engine improvement, generally classified in terms of peak brake thermal efficiency (BTE), are shown in Table 2. The first two classifications reflect the baseline engine performance currently observed (Stage 2) and expected (Stage 3) in China in the absence of specific fuel-consumption requirements. Best-in-class engine technology for the 2017-era is technology that is currently in use on advanced engines in the United States and the European Union. The remaining three classifications reflect increasingly more efficient engines, expected to be available beginning in 2020. The underlying efficiency technologies that enable the evaluated level of performance are described below.

Table 2. Engine efficiency definitions

Engine configuration	Peak brake thermal efficiency ^a (BTE)	Waste heat recovery system
Stage 2 Baseline	43.0%	None
Stage 3 Baseline	45.0%	None
2017 Best-in-Class	47.0%	None
2020	48.6%	Turbo Compounding
2020+WHR	51.2%	Organic Rankine Cycle
Long Term	55.0%	Organic Rankine Cycle

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

Engine friction reduction. Engine efficiency is affected by frictional losses and the churning of lubricating oil in bearings, valve trains, and piston-cylinder interfaces. Friction reduction provides direct brake work efficiency gains.¹ Available and emerging efficiency technologies to reduce losses include improved piston ring designs, better low-viscosity lubricants, and low-friction coatings and surface finishes.

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

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

On-demand engine accessories. Engine and vehicle accessories including the water pump, oil pump, fuel injection pump, air compressor, power steering pump, cooling fan, alternator, and air conditioning compressor are traditionally gear or belt driven. These auxiliary loads, or parasitic losses, tend to increase with engine speed. Decoupling accessories from the engine when their operation is not needed, operating them at optimal speeds, or harnessing 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 and disengage the accessories, variable-speed electric motors, and variable-flow pumps.

¹ Brake work is a measure of the amount of energy that an engine makes available at the crankshaft and which can subsequently be used to perform required functions such as moving a vehicle. For a given fuel input, engine efficiency increases as brake work increases.

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, because of 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 technology to reduce pumping, exhaust, and coolant losses. For example, enhanced NO_x aftertreatment systems allow for higher engine-out NO_x levels, thus enabling efficiency-biased calibration of fuel injection timing and combustion parameters as well as reduced EGR.

Turbocharger system improvement. Turbocharging technology uses exhaust energy to increase intake pressure, improving volumetric efficiency. Efficient turbocharging increases engine power density and facilitates efficient EGR. Advanced turbocharger designs have the potential to reduce pumping, exhaust, and coolant losses. These designs are 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 for efficient intake boosting.

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

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

Although turbo compounding and ORC systems—as well as conventional turbochargers—are designed to capture otherwise wasted heat energy, these technologies are treated separately in this analysis to distinguish associated cost and efficiency impacts. Unless otherwise specified, WHR is intended to signify an ORC system, and turbo compounding is referred to explicitly. There are many WHR systems under development that are configured in different ways, as seen for example in U.S. Department of Energy (DOE) SuperTruck demonstration projects (Delgado and

Lutsey, 2014). In this analysis, a WHR system without turbo compounding is assumed. Conventional and emerging intake pressurization turbochargers are treated as an integral component of all diesel engine packages.

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

Engine downsizing. Vehicle improvements that reduce road load power requirements may shift the operational speed and load characteristics of an engine to lower efficiency regions. Generally, any resulting reduction in performance can be offset by downsizing, or reducing the displacement of the engine, forcing operation at higher load, which generally corresponds with higher efficiency. Vehicle performance can be maintained at pre-downsizing levels through a combination of road load power requirement reductions in conjunction with various other engine and transmission efficiency technologies. However, baseline tractor-trailer engines in China are generally smaller and reflect reduced performance relative to their U.S. and EU counterparts. It is expected that this distinction will diminish over the near term as tractor-trailer engine displacement in China is likely to increase. In recognition, this study assumes that Stage 3 engine technology will reflect a displacement that is 20% larger than that of Stage 2 engine technology, and that more advanced engine technology packages, such as 2017 best-in-class and beyond, will reflect a displacement that is 40% larger than that of Stage 2 engine technology. To avoid conflating this expected market adjustment, this study assumes no independent level of engine downsizing.

Engine technology packages. It is difficult to treat engine technologies individually without assuming explicit and inflexible technology pathways. That is because of the variety of approaches available for improving engine efficiency as well as associated interrelationships among not only the technologies but also their associated loss mechanisms. The efficiency technology pathways for this analysis are based on six levels of net engine efficiency as described earlier in this section (see Table 2). The “Stage 2 baseline” engine technology package is a representative, average-technology engine currently produced for the Chinese market, with specific design parameters as delineated in Section I. The “Stage 3 baseline” engine technology package is a representative, average-technology, engine common in the U.S. and EU markets in the 2015 timeframe and expected to be widely available in the Chinese Stage 3 market. The “2017 best-in-class” engine technology package represents technology currently available on advanced U.S. and EU engines, and includes such component technology as a higher compression ratio, higher injection pressure, a reduction in EGR rates, and improved accessory management.

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

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

TRANSMISSION AND DRIVELINE TECHNOLOGY

Transmission and driveline technology have the potential to reduce tractor-trailer energy use in several ways. Increased internal efficiency of transmission and driveline componentry reduces frictional losses incurred during the transmission of energy from the engine to the wheels, resulting in direct increases in net tractive efficiency. Advanced technologies involving improved controls and integrated transmission-engine strategies can result in powertrain optimization, increasing the time that the engine is able to operate at high-efficiency speed and load conditions.

As in the United States and unlike in the European Union, dual drive-axle and conventional manual transmission tractors are common in China.

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 (6×2). Independent of other influences, the increased deployment of single-drive axle, or 6×2, drivelines is driven by their ability to cost-effectively increase efficiency and reduce weight. The 6×2 configuration increases driveline efficiency by greatly reducing gearing-related energy losses through the use of only one drive axle as the second axle in the conventional tandem axle configuration becomes a non-powered or “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. This study does not, however, consider such systems to be viable in the long-haul tractor-trailer market in China as regulatory requirements impose a reduced payload capacity on single-drive axle tractors. As a result, all simulated tractor-trailer combinations are 6×4, dual-drive axle configurations.

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 performed by the 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, potential improvements include optimized gearing, such as 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 and one for even gears. This design enables uninterrupted shifting, reducing engine power excursions and increasing the time an engine operates under high-efficiency conditions. DCT technology enables greater downspeeding than AMT technology, but this gives rise to engine design considerations. To maintain equivalent power at lower speed, the engine needs to operate at higher torque and in-cylinder pressure, and turbochargers need to be matched for lower compressor speed and higher mass flow requirements. Other considerations related to downspeeding include increased heat transfer, increased in-cylinder pressures, and torsional vibration. Although DCT is an available technology in the long-haul market, none of the technology packages analyzed in this study include a DCT.

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

III. ANALYSIS OF EFFICIENCY TECHNOLOGY COST

While the long-haul tractor-trailer simulation modeling underlying this study (Delgado et al., 2018) provides insight into the fuel-efficiency impacts of potential technologies, this study provides additional assessment of the cost-effectiveness of those technologies. This analysis evaluates best-estimate technology costs, based on a review and synthesis of existing technology cost data reported by a Chinese market analyst and in recent scientific, consulting, and government literature on tractor-trailer efficiency technology. The following discussion summarizes data sources and the approach to technology cost estimating.

APPROACH TO COST-DATA PROCESSING

For this study, cost data developed for an earlier fuel-efficiency study of long-haul tractor-trailers in the European Union (Meszler et al., 2018) was updated to reflect the tractor-trailer market in China using cost data developed by a Chinese market analyst (China Cost Study, 2018). Generally, the China-specific data represent specific discrete technology applications that do not lend themselves directly to a comprehensive multi-step technology analysis such as that undertaken in this study. Using the more-comprehensive EU cost data, this study adjusts for all levels of a specific technology by the ratio of the developed China costs to the corresponding EU costs. For example, the ratio of the China cost estimate for an X% aerodynamic drag reduction to the EU cost estimate for that same level of reduction is applied across the full range of evaluated aerodynamic drag reductions to develop a comprehensive China-specific aerodynamic drag reduction cost curve. Of course, cost estimates for discrete technologies such as switching from a manual to an automated manual transmission could be based directly on data from the China cost study, but adjustments were made in some cases as described in more detail below even for such discrete technologies. These adjustments were implemented to ensure that cost estimates for the China market were never less than cost estimates for the EU market. In other words, if the cost from the China cost study exceeded the estimated EU cost, the China-specific cost was used directly; if it did not, the cost from the China cost study was replaced by the estimate for the EU. The higher cost estimate was used without exception in an effort to provide conservative cost-effectiveness estimates.

Unless otherwise specified, all presented cost data are expressed in terms of 2016 yuan renminbi (¥). To compare China cost-study data with previously developed EU estimates, currency conversions are calculated using annual average exchange rates (X-Rates, 2018).² When necessary for comparison purposes, yuan-based cost estimates are converted for other years using consumer price indices from the National Bureau of Statistics of China (NBSC, 2018).

China study cost data are expressed in terms of direct manufacturing cost (DMC), which reflects the cost of materials and labor required to produce and assemble technology componentry and represents the cost of a component to the vehicle or engine manufacturer. The raw cost estimates do not account for indirect costs associated with items such as research and development, overhead, marketing and distribution, and profit markups. To account for such costs in this study, indirect cost multipliers (ICMs)

² Monthly averages are converted to annual averages by weighting each monthly average by the number of days in the month.

are applied to the DMCs to estimate indirect costs (ICs) and calculate total costs (TCs) for each technology, so that TC equals DMC plus IC. Total costs are generally equivalent to the expected impact on retail prices associated with a particular technology. However, manufacturers' actual pricing strategies may include influences that extend beyond specific technology cost—for example, adjustments designed to promote the sales of a specific technology or model.

This DMC/IC/TC costing methodology is structurally identical to the methodology used by the EPA to support its Phase 1 and 2 HDV efficiency standards (EPA, 2016) and similar to U.S. light-duty vehicle rulemakings. The methodology has been subjected to rigorous development and review and has been used by the ICCT to support previous vehicle analyses, including the EU tractor-trailer study from which comparative cost data are derived for this analysis. A previous ICCT-commissioned study (Kolwich, 2013) found that U.S.-derived indirect cost estimates were generally consistent—within 10% plus or minus—with EU indirect costs during the early years of technology introduction, but substantially overestimated EU and probably U.S. indirect costs beginning about five years after technology introduction. Projected 2025-era indirect costs were found to be overestimated by a factor of about five on average, so that the use of U.S. data could result in substantial IC overestimation. It is expected that this is no less true in the China market, so applied indirect-cost multipliers are likely to be conservative because they lead to cost overestimates.

Given the conservative approach of using the U.S.-derived data directly, the indirect cost multipliers developed in support of the U.S. Phase 2 rulemaking as presented in Table 3 are used for this study. Indirect costs vary with the complexity of the technology and are estimated to range from 15%–75% of direct manufacturing costs. Generally, technology that is either currently marketed or a moderate improvement on current technology is assumed to be of low complexity. Technologies that are still under development but are expected to be commercially available in the long term are assigned higher-complexity ICMs. As also depicted in Table 3, ICMs are established on a separate basis for warranty-related and non-warranty costs under the assumption that warranty-related costs decline with direct costs over time, while the non-warranty costs remain a function of baseline direct costs, with a single step change when production changes from near to long term. For a given technology, this study assumes the same level of complexity as assumed by the EPA for technologies included in the engineering analysis conducted by the agency for the Phase 2 HDV CO₂ rulemaking (EPA, 2016).

Table 3. Indirect cost multipliers used to convert from efficiency-technology direct manufacturing cost to total, retail cost

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

See U.S. Phase 2 HDV CO₂ rulemaking document (EPA, 2016) for more information.

Table 4 lists the specific ICM complexity-level assignments assumed in this study. Generally, successive technology levels represent progressively increasing stringency. The “High 2” complexity level, generally reflective of revolutionary technology such as dedicated electric propulsion, is not included in this study. Note also that the assignments in Table 4 include three technologies that are assigned gasoline-engine ICMs. No diesel-engine ICMs are included in the EPA reference document for these technologies, but this is not problematic because the gasoline ICMs are generally higher than their diesel counterparts (see Table 3). Consequently, the effect is conservative in that indirect cost estimates will be higher than would be derived using an ICM for diesel-engine technology.

This study also assumes that the direct manufacturing costs of technology are subject to reduction over time as manufacturers gain design and production experience. Consistent with the approach for ICMs, this study applies a series of technology-specific learning curves established by the EPA for its Phase 2 HDV CO₂ rulemaking (EPA, 2016). Table 4 includes the applicable learning curve assignments for each technology. All of the learning curves are variations on an underlying general design that assumes newly introduced low production-volume technology will undergo two or more cycles of “steep” learning in which costs decline by 20% after each successive two years of production. This is followed by a relatively flatter experience period that assumes typically five years of 3% annual cost reductions, followed by five years of 2% annual cost reductions. After five more years of 1% annual cost reductions, DMCs are assumed to stabilize.

Table 4. Technology indirect cost and learning curve assignments

Technology Type	Component Technology Assignments from U.S. Phase 2 HDV CO ₂ Rule	Assigned Learning Curve			Assigned ICM		
		Type	Curve No.	Base Year	Focus ^a	Level	Near-Term End
Engine technology	Aftertreatment Improvements - Level 1	Flat	2	2014	DE	Low	2022
	Aftertreatment Improvements - Level 2	Flat	2	2014	DE	Low	2024
	Cylinder Head Improvements - Level 1	Flat	2	2014	DE	Low	2022
	Cylinder Head Improvements - Level 2	Flat	13	2021	DE	Low	2027
	EGR Cooler - Level 1	Flat	2	2014	GE	Low	2022
	EGR Cooler - Level 2	Flat	13	2021	GE	Low	2027
	Fuel Injector Improvements - Level 1	Flat	2	2014	DE	Low	2022
	Fuel Injector Improvements - Level 2	Flat	13	2021	DE	Low	2027
	Fuel Pump Improvements - Level 1	Flat	2	2014	DE	Low	2022
	Fuel Pump Improvements - Level 2	Flat	13	2021	DE	Low	2027
	Fuel Rail Improvements - Level 1	Flat	2	2014	DE	Low	2022
	Fuel Rail Improvements - Level 2	Flat	13	2021	DE	Low	2027
	Oil Pump Improvements - Level 1	Flat	2	2014	DE	Low	2022
	Oil Pump Improvements - Level 2	Flat	13	2021	DE	Low	2027
	Piston Improvements - Level 1	Flat	2	2014	DE	Low	2022
	Piston Improvements - Level 2	Flat	13	2021	DE	Low	2027
	Turbocharger Efficiency - Level 1	Flat	2	2014	DE	Low	2022
	Turbocharger Efficiency - Level 2	Flat	13	2021	DE	Low	2027
	Turbo Compounding - Level 1	Flat	2	2014	DE	Low	2022
	Turbo Compounding - Level 2	Flat	13	2021	DE	Low	2027
	Valve train Friction Improvements - Level 1	Flat	2	2014	DE	Low	2022
	Valve train Friction Improvements - Level 2	Flat	13	2021	DE	Low	2027
	Variable Valve Timing	Flat	8	2015	GE	Medium	2018
Waste Heat Recovery	Steep	14	2021	HDV	Medium	2027	
Water Pump Improvements - Level 1	Flat	2	2014	DE	Low	2022	
Water Pump Improvements - Level 2	Flat	13	2021	DE	Low	2027	
Tractor Aerodynamic drag technology	Aerodynamic Drag Improvements - Level 3	Flat	2	2014	HDV	Low	2022
	Aerodynamic Drag Improvements - Level 4	Steep	4	2014	HDV	Low	2022
	Aerodynamic Drag Improvements - Level 5	Steep	4	2014	HDV	Medium	2025
	Aerodynamic Drag Improvements - Level 6	Steep	4	2014	HDV	Medium	2025
	Aerodynamic Drag Improvements - Level 7	Steep	4	2014	HDV	Medium	2025
Trailer Aerodynamic drag technology	Aerodynamic Drag Improvements - Level 3	Flat	2	2014	HDV	Low	2018
	Aerodynamic Drag Improvements - Level 4	Flat	2	2014	HDV	Low	2018
	Aerodynamic Drag Improvements - Level 5	Flat	2	2014	HDV	Low	2018
	Aerodynamic Drag Improvements - Level 6	Flat	2	2014	HDV	Low	2018
	Aerodynamic Drag Improvements - Level 7	Flat	2	2014	HDV	Low	2018
	Aerodynamic Drag Improvements - Level 8	Flat	2	2014	HDV	Low	2018

Tractor-Trailer Rolling resistance technology	Low Rolling Resistance Tires - Level 1	Flat	2	2014	HDV	Low	2022
	Low Rolling Resistance Tires - Level 2	Flat	2	2014	HDV	Low	2022
	Low Rolling Resistance Tires - Level 3	Flat	12	2018	HDV	Medium	2025
	Low Rolling Resistance Tires - Level 4	Flat	13	2021	HDV	Medium	2028
	Low Rolling Resistance Tires - Level 5	Flat	13	2021	HDV	Medium	2031
Tractor, weight reduction technology	Weight Reduction - Short Term	Flat	2	2014	HDV	Low	2022
	Weight Reduction - Medium Term	Flat	2	2014	HDV	Medium	2022
Trailer, weight reduction technology	Weight Reduction - Short Term	Flat	2	2014	HDV	Low	2022
	Weight Reduction - Medium Term	Flat	2	2014	HDV	Medium	2022
Hybrid technology	Parallel Hybrid	Steep	15	2014	HDV	High1	2024
Downsizing, downspeeding	Right Sized Engine	None	1	2014	HDV	Low	2010
	Axle Downspeed	Flat	12	2018	HDV	Low	2022
Transmission technology	Automated Manual Transmission	Flat	12	2018	HDV	Medium	2022
Driveline technology	High Efficiency Axle	Flat	12	2018	HDV	Low	2022
	High Efficiency Gearbox	Flat	13	2021	HDV	Low	2022

^a The focus parameter indicates the type of ICM that is applicable (DE=diesel engine, GE=gasoline engine, HDV=heavy-duty vehicle). See Table 3. See also U.S. Phase 2 HDV CO2 rulemaking document (EPA, 2016) for more information.

More-mature technologies will reflect a flatter curve as their periods of steep cost decline have occurred in the past. Less-mature technologies may reflect one or more periods of steep cost decline before moderating. Warranty-related indirect costs decline with direct costs and are thus inherently tied to the same learning curve. Non-warranty indirect costs are more fixed and are tied to baseline direct costs, not subject to learning. Such indirect costs do undergo a step reduction as technology ages from near to long term (see Tables 3 and 4) in recognition of the full recovery of some fixed-cost components. However, it should be reiterated that the ICCT-commissioned indirect-cost study (Kolwicz, 2013) found EPA-based long-term indirect costs to be greatly overestimated. Thus, use of the U.S. data is likely to result in conservatively high estimates of indirect costs.

Figure 2 depicts the subset of EPA learning curves used in this study (see the learning curve assignments listed in Table 4). As indicated, these curves range from the perfectly flat learning of curve 1 with no cost reductions over time to the significant learning reflected in curve 4, where 2030-era direct manufacturing costs decline to about 47% of baseline DMC. Note that this does not translate to a 53% decline in total costs as the bulk of indirect costs are non-warranty in nature and do not decline with learning. In all cases, the baseline direct costs estimated for this study apply in the earliest year for which the DMC multiplier is unity.³ Thus, the largest 2030-era cost adjustment is the 0.47

³ The baseline direct cost year for most currently available technologies is 2014, meaning that the baseline direct costs assumed for such technologies in this study are applicable to that year. For more advanced technologies, the baseline direct cost year is some future year. Waste heat recovery technology, for example, has a baseline cost year of 2021. For such technologies, direct costs in years prior to the baseline cost year will be greater than estimated baseline direct costs. Although this study presents summary costs only for years 2025 and later, there are a number of figures that show individual technology costs in both 2014 and 2030 to illustrate the degree and impact of assumed learning.

DMC multiplier of learning curve 4. Most technologies reflect 2030-era multipliers in the range of 0.73-0.81 (learning curves 2 and 13).

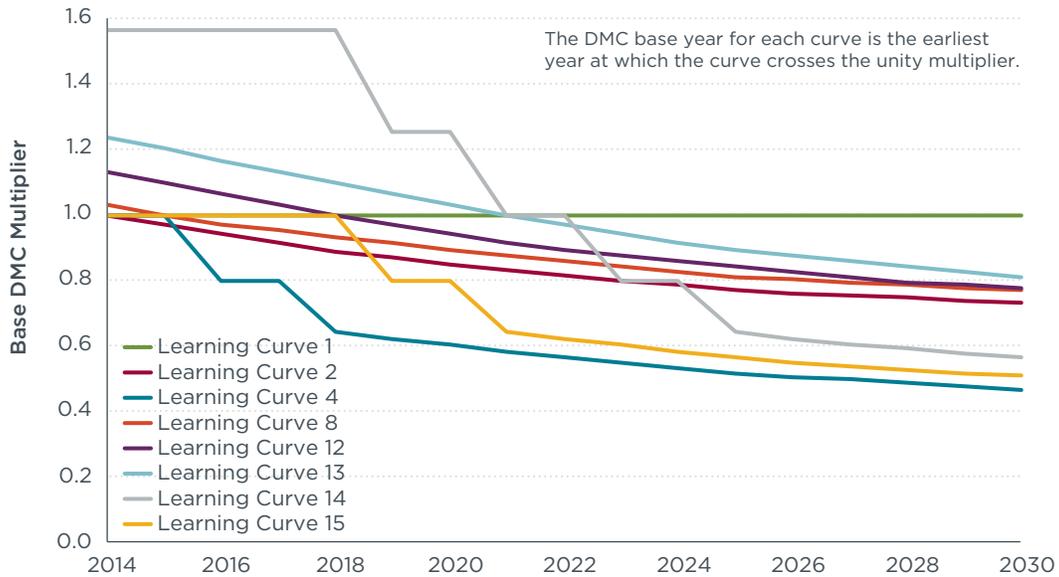


Figure 2. Direct manufacturing cost learning curves for technology cost reductions over time

Two specific adjustments were made to the EPA learning curves for this study. First, the U.S. curves reflect learning only through 2027. The curves are extended through 2030 by analyzing the year-over-year changes of each U.S. curve and extending the pattern through years 2028, 2029, and 2030. The maximum year-over-year adjustment applied for any of the curve extensions is 2%, with adjustments of 1% and zero for curves that have expended their allocated number of 2% and 1% adjustments.⁴ Second, learning curve 15, used for hybrid technology, is created for this study from the U.S. hybrid technology learning curve 11. Curves 15 and 11 reflect identical learning, but curve 15 is shifted in time to reflect a 2015 baseline DMC, whereas curve 11 assumes a 2021 baseline. The hybrid vehicle costs used in this study are developed specifically from 2015-era cost data and are treated accordingly. The adjusted curve results in projected cost reductions that closely match battery and motor cost reductions estimated independently by the ICCT (Wolfram & Lutsey, 2016).

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

⁴ As previously discussed, learning curves are based on a certain number of years in which 3%, 2%, and 1% cost reductions are assumed. The terminology “expended” means that the number of allocated cost-reduction years for one of the percentage changes has been reached and the curve is extended by shifting to the next lower percentage change assumption.

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

Where:

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

OVERVIEW OF DATA SOURCES

The primary source of cost data for this analysis is the proprietary and confidential HDV technology cost study for China (China Cost Study, 2018). The China cost study, commissioned by the ICCT, was performed by a leading independent Chinese market analyst. Although the analyst has held the ICCT to a strict confidentiality agreement, the provided cost estimates have been validated through comparison with corresponding cost estimates derived in support of previous ICCT analyses for the United States and the European Union. Moreover, to ensure that all cost estimates used are conservative in the sense that they are highly unlikely to underestimate costs, this study applies the China market analysis cost estimates only when they equal or exceed estimates previously developed for the United States or the European Union. When the U.S. or EU estimates are higher, they are used in place of the estimates from the China market analysis.

A substantial number of data sources underlie the U.S. and EU tractor-trailer technology-cost estimates previously developed by the ICCT (Meszler et al., 2018; Meszler, Lutsey, and Delgado, 2015). Those sources are incorporated into this study through the use of the associated data for validation purposes. Interested readers can consult the referenced documents for a detailed description of the underlying data sources. Generally, these data sources reflect a substantial number of government, industry, and independently funded economic and engineering analyses, all conducted over the past several years.

KEY ECONOMIC ASSUMPTIONS

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

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

evaluation year reflects the timing when the most advanced technology packages are expected to be commercially available and the year when standards of equivalent stringency could be implemented.

Diesel fuel price. Analysis is conducted for three diesel fuel price scenarios, representing low, best estimate, and high levels. All three estimates are derived from an analysis of historic China diesel fuel prices, in conjunction with projected changes in crude oil prices. Historic fuel prices for China are taken from several sources, including the Gold600.com price quote network (Gold600, 2018), GlobalPetrolPrices.com (GPP, 2018), and the World Bank diesel fuel price database (World Bank, 2018). For data reported at the provincial level of detail, population data from the National Bureau of Statistics of China (NBSC, 2011) are used to generate a national average price. Based on these data, the average per-liter diesel fuel price for China at the end of 2017 was ¥6.50 in 2016 yuan as throughout this study. Observed prices ranged from $\pm 20\%$ of the average, so the lowest observed per-liter price was about ¥5.00 and the highest, ¥8.00.

Real oil price forecasts (World Bank, 2017a; World Bank, 2017b) are used to derive commodity price-change factors for all years from 2017 through 2030. These factors are then applied to diesel commodity prices to derive price forecasts through 2030. Based on these data, the average diesel fuel price between 2020 and 2030 is expected to be about 8% higher than the 2017 price, or about ¥7.00 per liter on average. Based on the currently observed price range, low estimates for the future average fuel price estimate would be about ¥5.50 and the high, ¥8.50. To incorporate a factor of safety, the study expands the future potential price range to ¥4.50 to ¥9.00.

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

Economic analysis in this study is based on three real discount rates: 4%, 7%, and 10%. The 4% rate reflects an assumed social discount rate and is the rate recommended in the European Union for regulatory impact assessment (EC, 2017). The 7% rate reflects the financial discount rate recommended for application in U.S. regulatory analyses (OMB, 1992). The 10% scenario is intended to reflect an upper-bound financial assumption.

Vehicle kilometers of travel (VKT). The rate at which fuel savings accrue is dependent on both the assumed discount rate and accumulated VKT. Data from a number of sources was reviewed for this analysis. The China Federation of Logistics Purchasing (CFLP) estimates annual average VKT for all road freight, including rigid trucks and both short- and long-haul tractor-trailers, at about 48,000 km, with efficient performers accumulating up to 182,500 km annually (CFLP, 2016). Other researchers indicate annual average VKT estimates for heavy-duty trucks in China ranging from 50,000 km–90,000 km (Yu and Yu, 2008; Huo, Zhang, He, Yao, and Wang, 2012; Lang et al. 2012; Lang, Cheng, Zhou, Zhang, and Wang, 2014; Lang et al. 2016). In a 2017 report, the China Automotive Technology & Research Center developed a distribution of VKT in the road-freight sector that implies an annual average accumulation of about 100,000 km (CATARC, 2017). Finally, the market analyst that performed the China cost study

supporting this analysis interviewed several large tractor-trailer operators and estimated annual VKT ranging from 120,000 km–300,000 km, with a mean value of about 200,000 km (China Cost Study, 2018).

None of the available references are ideal. The VKT estimates from the China cost study are the only estimates that target the specific freight segment addressed in this analysis. However, sample size is limited and biased toward large operators. Conversely, the other available estimates are biased downward through the inclusion of vehicles other than tractor-trailers as well as the inclusion of both short- and long-haul operations. Given these limitations, this study assumes an annual average VKT for long-haul tractor-trailer operations of 100,000 km. This reflects the high end of the annual VKT range of all freight operators but is below the low end of the large long-haul tractor-trailer operator range. This should serve as a reasonable and probably conservative, on the low side, estimate of annual average long-haul VKT as such operations most certainly contribute inordinately to the average VKT estimates for all freight operators, which themselves range as high as 100,000 km.

Although this study assumes that average VKT does not vary with time, it is still necessary to account for the fact that the number of tractors in service does decline with age. The age distribution of road tractors in service in China is subject to significant uncertainty. Age distributions from four researchers indicate freight vehicles surviving for as few as 11 years and as long as 17 years, with uncorrelated median ages ranging from 6 to 11 years (Huo et al. 2012; Li et al., 2015; Hao, Wang, Ouyang, and Cheng, 2011; China Cost Study, 2018). It is likely that some of the differences are related to the types of freight vehicles included in the research sample. Fortunately, there are regulatory restrictions on tractor-trailer age in China that eliminate much of the uncertainty. In 2013, the China Ministry of Commerce (MCC) issued requirements mandating the scrapping of all road tractors after 15 years (MCC, 2013). Based on this restriction, an average tractor age distribution was developed by averaging the distributions from the four referenced data sources and forcing the average to zero after 15 years. Figure 3 shows the resulting distribution as well as comparative distributions from the United States and the European Union (Meszler et al., 2018). The mandatory scrapping age in China results in considerable differences between the age distributions of tractors in China, the European Union, and the United States. While the U.S. fleet exhibits a median age of 20 years, that of the EU is 12 years and China, 10. The relatively abbreviated lifetime of tractors in China can serve to limit the economic attractiveness of new technology to vehicle owners by decreasing the period to accrue return on investment.

The tractor survival distribution curve from Figure 3 is combined with the annual average VKT estimate of 100,000 km to create the survival-weighted VKT curve shown in Figure 4. Also shown are the corresponding curves for the United States and the European Union (Meszler et al., 2018). This survival-weighted VKT curve represents the average lifetime VKT accrual for a road tractor in China and is used for all economic analysis in this study. As one would expect, the differential survival rates (as shown in Figure 3), carry over to the survival-weighted VKT curve. Average lifetime VKT in China of 1 million km is very similar to that of the European Union's 1.05 million km but only about one-third of the 2.88 million km in the United States. Table 5 presents a summary of key VKT statistics derived from Figure 4.

Finally, per-vehicle VKT is assumed to be constant throughout the forecast period of this study. While per-vehicle VKT growth is possible, previous work in the United States

has suggested that VKT growth is more closely linked to vehicle population growth and that per-vehicle activity is relatively unaffected. This is a conservative assumption from an economic perspective as payback periods decrease and aggregate fuel savings increase with rising VKT.

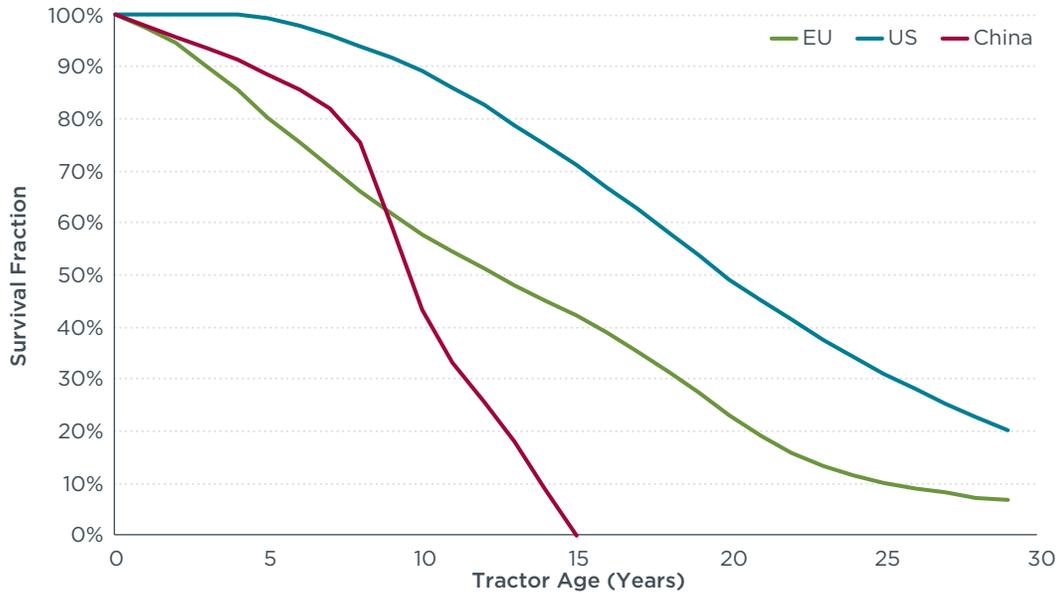


Figure 3. Tractor Survival Curves

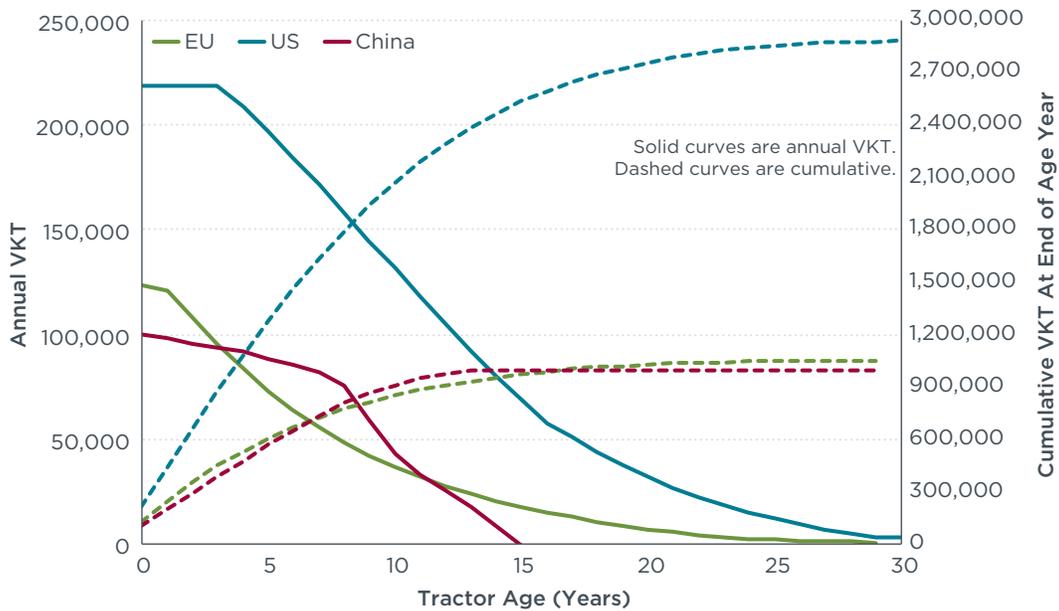


Figure 4. Survival-Weighted VKT for a Tractor (Average Tractor VKT)

Table 5. Key VKT Statistics

Parameter	China	EU	U.S.
Survival-weighted lifetime VKT (millions)	1.00	1.05	2.88
Median lifetime (years)	9.6	12.4	19.8
Maximum lifetime (years)	15	30	30
99% VKT accumulation lifetime (years)	15	24	26
Survival-weighted VKT after 5 Years (millions)	0.48	0.53	1.08
5-year fraction of lifetime VKT	47.9%	50.5%	37.6%
Survival-weighted VKT after 10 Years (millions)	0.87	0.81	1.94
10-year fraction of lifetime VKT	87.1%	77.4%	67.2%

Baseline tractor and trailer prices. To derive an estimate of the net change in truck purchase price due to additional technology investment, it is necessary to assume baseline vehicle costs. For this study, baseline tractor price is taken as ¥360,000 and baseline trailer price as ¥60,000, based on data collected for the China cost study (China Cost Study, 2018). That baseline tractor price is for a new 49 tonne DET45L 6×4 tractor. The baseline trailer price is for a new 3-axle, 12-tire trailer. Baseline tractor and trailer price assumptions are used solely to determine the percentage change in vehicle capital costs and have no influence on the economic cost-effectiveness of evaluated technology, which is dependent on the cost of the technology and the fuel savings.

Trailers per tractor. Based on the China cost study, it is estimated that there are 1.045 long-haul trailers in operation for every long-haul tractor (China Cost Study, 2018). Although this figure is substantially close to a ratio of 1:1, it is carried through the economic analysis so that all per-trailer costs in this study are inflated by a factor of 1.045 to account for the fact that 1.045 trailers will need to be upgraded for every improved tractor. Unless otherwise stated, the terminology tractor-trailer in the context of economic return on investment means a theoretical combination unit consisting of one tractor and 1.045 trailers.

Technology package real-world fuel consumption. All fuel-consumption impact estimates in this study are taken directly from the underlying ICCT simulation modeling assessment (Delgado et al., 2018), as summarized in Figure 1. Fuel consumption during real-world driving can be somewhat different from that achieved over standardized regulatory driving cycles, but this is less of an issue for long-haul tractor-trailers because of their more-standardized and quasi-steady state operating characteristics, predominantly reflecting high-speed highway driving. As a result, this study assumes that real-world fuel consumption is equal to that estimated in the underlying modeling assessment.

INDIVIDUAL TECHNOLOGY COSTS

Technology costs form the basis of all economic analysis in this study. As indicated in Section I, the technology cost assessment is based on a review of existing research on heavy-duty vehicles and engines. As is the case with any study that evaluates future conditions, there is a level of uncertainty associated with study estimates. In a similar economic study of long-haul tractor-trailer fuel economy in the United States (Meszler, Lutsey, and Delgado, 2015), effort was made to capture the potential impact of such uncertainty by analyzing both “best-estimate high” and “best-estimate low” costs. Since the performance of that study, a considerable body of additional research has

been reported to support regulatory programs for HDVs that have evolved beyond their nascent stages. Primary among these are the extensive cost data included in support of the U.S. Phase 2 CO₂ control program for HDVs (EPA, 2016), as well as data included in several recent EU-focused studies (Hill et al., 2015; Dünnebeil et al., 2015; Norris and Escher, 2017). This growth in the body of research associated with the cost of HDV technology is synthesized in the recent long-haul tractor-trailer cost-effectiveness evaluation conducted for the EU market (Meszler et al., 2018). In recognition of this evolution, the EU cost-effectiveness study was based on a single set of best-estimate costs, and this study continues that approach. That does not mean that all cost-estimate uncertainty has been resolved, but rather that sufficient research has now been conducted to allow the range of best-estimate costs to be reliably narrowed. While future refinement of cost estimates will continue as technologies evolve and become mainstream, this section presents the current best-estimate costs, as refined for the Chinese market and used in this study.

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

The approach to estimating engine technology costs in the China market builds on the approach employed for the recent long-haul tractor-trailer cost-effectiveness evaluation conducted for the EU market (Meszler et al., 2018). Interested readers are referred to that study documentation for a detailed discussion of the methodology employed. While engine technology costs specific to the Chinese market were developed independently in the China cost study (China Cost Study, 2018), the developed costs are not sufficient to produce the requisite BTE-based cost curve. To surmount this limitation, discrete costs developed in the China cost study were compared with corresponding discrete cost estimates from the EU study. This was performed independently for combustion engine-specific and WHR technology. Based on this discrete cost comparison, costs in the China market were estimated to be 1.463 times those of the European Union for combustion engine-specific technology and 0.567 times those of the European Union for WHR technology. However, as EU study costs are taken as the minimum technology costs in this study, the WHR cost adjustment factor was taken as unity and EU-specific costs for WHR were employed without change. If the estimated China-specific cost of WHR technology were employed, the technology would be economically more cost-effective than reported in this study. The net cost for all engine configurations that include WHR technology reflects the sum of both basic combustion engine improvements and WHR.

Figure 5 presents a comparison of unadjusted engine technology costs from the EU cost-effectiveness study and the corresponding engine technology costs employed in

this study. Although presented as quasi-continuous functions, it should be recognized that the presented “curves” are actually based only on the six presented discrete data points so that actual inflection points may not be accurately reflected because the costs between the indicated data points might be lesser or greater than the depicted “curves” would imply. Note also that Figure 5 depicts data developed for two years, 2014 and 2030. The difference between these two years is that 2014 illustrates baseline cost data and 2030 illustrates equivalent data adjusted for learning throughout the intervening period. The intent is to show the range of baseline and future costs of the associated technology. This same approach is employed throughout the study for various evaluated technologies. Developed engine-technology cost estimates are also presented in summary Table 8 appearing at the end of this section.

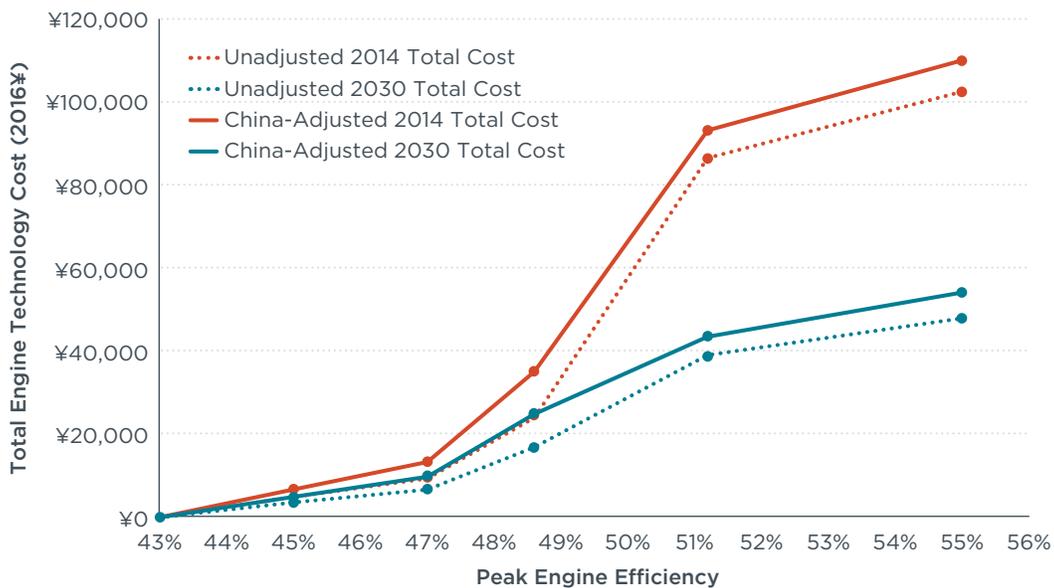


Figure 5. Engine Technology Costs

Transmission technology. This study includes a baseline tractor equipped with a manual transmission. Since the EU study included only AMT-equipped tractors, no associated cost for the technology was included in the EU study report. However, costs for the technology were developed during the EU cost estimation process and do serve as the basis for comparison with AMT costs in the China cost study. As was the case with WHR technology, the cost of AMT technology in the China market was estimated to be 33% lower than the cost estimated for the European Union. Therefore, as with WHR technology, the cost-adjustment factor for China was reset to unity and EU-estimated costs were used directly. If the estimated China-specific cost of AMT technology were employed, the technology would be economically more cost-effective than reported in this study. The developed AMT cost estimates are presented in Table 8.

Driveline technology. The cost of driveline efficiency improvement in the China market as estimated in the China cost study was compared with costs developed for the EU cost-effectiveness study. China market costs were estimated to be 10% lower than projected EU costs. As a result, the China cost adjustment was set to unity and EU-estimated costs were used directly in this study. If the estimated China-specific cost of improved driveline technology were employed, the technology would be

economically more cost-effective than found in this study. The driveline improvement costs are included in Table 8.

Hybrid technology. The cost of hybrid technology in the China market as estimated in the China cost study was compared with costs developed for the EU cost-effectiveness study. For the level of hybrid electric vehicle (HEV) system efficiency assumed in the simulation modeling underlying this study, costs in the China market were estimated to be 22% higher than costs estimated for the European Union. Consequently, all HEV costs estimated for the EU study have been increased by 22% for this study. As with other technologies, HEV costs are expected to decline over time with learning and increased production volume, as shown in Table 8.

Engine downsizing/downspeeding. Engine downsizing was included in the EU tractor-trailer technology cost-effectiveness study but is not considered in this study for China. The primary reason has nothing to do with the effectiveness of downsizing as a fuel-consumption reduction strategy, but rather a recognition that baseline tractor-trailer engines in China are much smaller than their EU and U.S. counterparts and that closing of this gap is likely over the next several years. This study assumes that Stage 3 engines will have a displacement 20% larger than that of the Stage 2 engine technology that serves as the baseline for this study. The analysis also assumes that more advanced engine technology packages will have a displacement 40% larger than that of Stage 2 technology. To avoid conflating this expected market adjustment with a simultaneous “downsizing” technology, this study assumes no independent level of engine downsizing and thus includes no costs for such technology.

Neither does the study include costs associated with the expected upsizing of China engines over the next several years. This upsizing is expected to occur regardless of any fuel-consumption requirements so that associated costs are similarly independent of such requirements. While tractor purchasers may indeed be subject to cost increases from engine upsizing, any such effects reflect influences beyond the scope of this study. As a result, no upsizing cost is assessed for the larger engines evaluated in this study. It is, however, important to recognize that although such costs are treated as zero, the fuel-consumption effects of upsizing are explicitly considered, resulting in reduced cost-effectiveness estimates relative to those that would accrue in a constant or downsized engine market. Since any fuel-consumption requirements would be imposed in a market that is subject to these confounding—and from a fuel-consumption standpoint, counterproductive— influences, it is important that their effects on fuel consumption be explicitly considered. This study does that. So, while upsizing costs are not considered, the effects of expected upsizing on tractor-trailer fuel consumption are explicitly included in the fuel-consumption estimates that are the basis for the economic evaluation reported in this study

It is also important to note that China is in the process of moving from China V to China VI emission standards (Yang and He, 2018). The fuel-consumption effects of this move are similarly considered in the simulation modeling estimates that underlie this economic evaluation. As in the case with engine upsizing, the cost effects of this transition are not considered as they accrue independently of any fuel-consumption requirements.

Aerodynamic drag reduction. The China cost study (China Cost Study, 2018) estimated costs for various aerodynamic drag technologies. These costs were aggregated to develop discrete cost estimates for three levels of aerodynamic drag reduction. These were 55% lower than corresponding costs estimated for the recent EU long-haul

tractor-trailer cost effectiveness study (Meszler et al., 2018). As a result, the China cost adjustment was set to unity and EU-estimated costs were used directly in this study. If the estimated China-specific cost of improved aerodynamic drag-reduction technology were employed, the technology would be economically more cost-effective than this study finds. The drag reduction costs used are presented in Figure 6 and included in Table 8. Note that the unadjusted EU and adjusted China cost curves overlaid each other since the China cost adjustment factor was reset to unity.

This study covers six levels of aerodynamic drag, with drag areas dropping from a baseline of 7.0 m² to 6.0 m², 5.3 m², 4.6 m², 4.4 m², and 3.5 m². These levels can be achieved through a wide range of tractor and trailer combinations, with improvement paths ranging from tractor-centric to trailer-dominant improvement, and every potential path in between.⁵ For this study, the improvement path is structured to match that assumed in the ICCT simulation modeling study: concurrent tractor and trailer improvements with initial modifications focusing on modest tractor improvements and first-step trailer improvements such as side skirts and gap reducers, culminating in advanced, integrated, tractor and trailer drag reduction technology. Since the ratio of trailers to tractors in China is relatively close to unity, the effect of selecting an aerodynamic drag improvement path that favors tractors over trailers, or vice versa, is muted relative to a market where a higher ratio of trailers is observed (such as the United States, where the ratio is 3 trailers per tractor). The net cost of trailer-based improvements scales directly with this ratio, so there is considerable economic sensitivity with regard to potential regulatory costs.

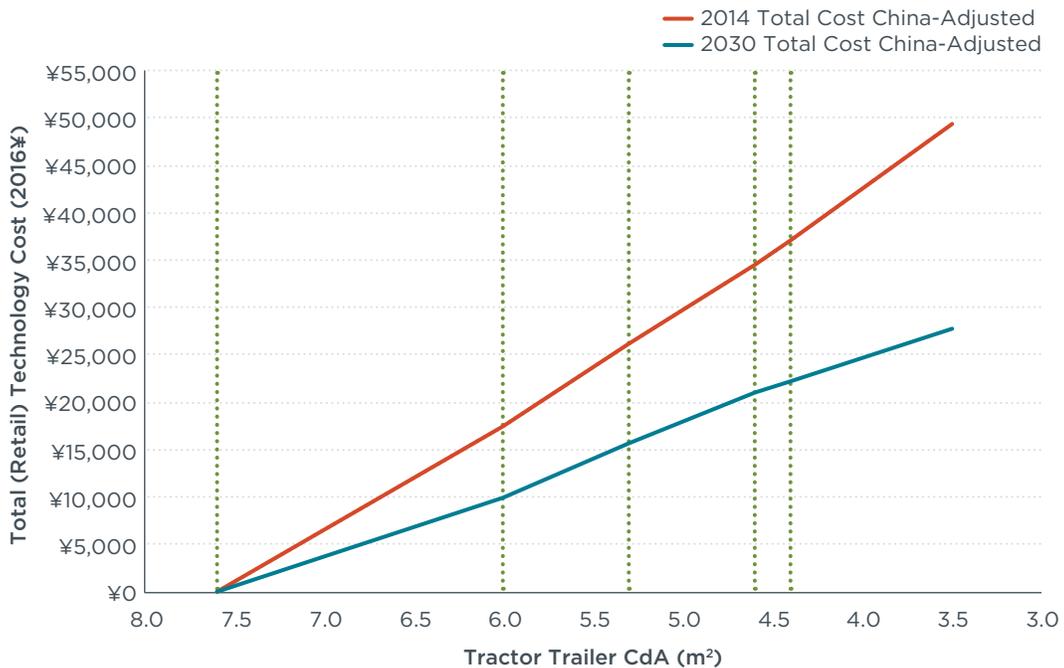


Figure 6. Aerodynamic drag technology cost curves (1.045 trailers per tractor)

⁵ Note that neither tractor nor trailer-dominant improvements can reach all of the performance levels evaluated in this study. These approaches simply signify an initial focus. At some point trailer improvements will be required under a tractor-centric approach and vice versa.

Rolling-resistance reduction. Estimated costs for three levels of rolling-resistance reduction technology in the China cost study (China Cost Study, 2018) were 66% higher than corresponding costs estimated for the recent EU long-haul tractor-trailer cost-effectiveness study (Meszler et al., 2018). Based on this relationship, EU-based costs across the full range of evaluated rolling-resistance reduction were adjusted by a factor of 1.66 to derive the full range of cost estimates used in this study. As shown in Figure 7, these costs apply to rolling-resistance values ranging from 6.8 kg/tonne to 4.0 kg/tonne.



Figure 7. Rolling resistance technology cost curves (1.045 trailers per tractor)

Even though the ICCT simulation modeling includes six levels of rolling resistance for the combined tractor-trailer unit, only three levels of rolling resistance tires are considered: energy efficiency class C tires with an assumed coefficient of rolling resistance (C_{rr}) of 6.0 kg/tonne, efficiency class B tires with an assumed C_{rr} of 5 kg/tonne, and efficiency class A tires with an assumed C_{rr} of 4 kg/tonne.⁶ The combination of these three tires across the steer, drive, and trailer axles results in the six levels of performance modeled by the ICCT. Thus, costs are developed for the three tire classes and weighted by tire count (2 steer tires, 8 drive tires, and 12 trailer tires) to determine the net cost for each of the six technology packages.

One additional weighting factor is included in the net package cost calculation. Trailer tires are weighting by a factor of 1.045 to reflect the ratio of trailers to tractors in China. This factor accounts for the fact that multiple trailers will need to be equipped for every tractor to ensure that in-use performance is equivalent to that modeled.

⁶ The assumed C_{rr} for all three classes of tires reflects the upper bound energy efficiency of the class. Class C tires are certified to have a rolling resistance of 5 kg/tonne to 6 kg/tonne. Class B tires are certified to have a rolling resistance of 4 kg/tonne to 5 kg/tonne. Class A tires are certified to have a rolling resistance of 4 kg/tonne or less.

Finally, ICCT simulation modeling assumes that tires are properly inflated at all times. The use of technologies such as tire pressure monitoring or automatic tire inflation systems is not assumed and, therefore, the costs of such systems are not considered in this study. Table 8 presents developed rolling-resistance reduction costs.

Weight reduction. Estimated costs for three levels of weight reduction in the China cost study (China Cost Study, 2018) were 38% higher than corresponding costs estimated for the recent EU long-haul tractor-trailer cost-effectiveness study (Meszler et al., 2018). Based on this relationship, EU-based costs across the full range of evaluated weight reduction were adjusted by a factor of 1.38 to derive the full range of cost estimates used in this study.

Several aspects related to the evaluation of weight are important to an understanding of how such reductions were integrated into this study. First, because other technologies can include an inherent weight effect, either adding to or reducing vehicle weight, these effects must be addressed in one of two ways. One is to include any additional weight effects in the cost of targeted net weight reductions. The other is to adjust simulation modeling of fuel-consumption estimates to include the incremental weight effects of a technology so that costs can be developed independent of such effects. This study employs the second approach, and all fuel-consumption estimates have been adjusted to account for all technology weight effects.

Second, it is necessary to distribute the target weight reductions between the tractor and trailer. This is more important in markets outside China where the ratio of trailers to tractors is substantially greater than 1:1, but it is a consideration for any tractor-trailer weight-reduction analysis. This study assumes that 38.3% of all weight reduction is allocated to the tractor and 61.7% to the trailer. This split is based on a detailed analysis of weight-reduction potential for EU tractor-trailers (Hill et al., 2015; Norris and Escher, 2017) and is used in this study because of a lack of data specific to the market in China. With the trailer-to-tractor ratio in China not substantially different from unity, the effect of this assumption on weight-reduction costs is minor.

Third, this study assumes that there is no secondary weight-reduction potential in the tractor-trailer market. Secondary weight-reduction opportunities accrue because as the weight of a vehicle is reduced, the structural demand on materials also declines, allowing for further or secondary design changes and weight reduction. These secondary weight reductions often deliver cost savings. However, such opportunities are limited in the tractor-trailer market as such vehicles are designed to accommodate a specific total weight regardless of tractor-trailer curb weight. In other words, as the curb weight of the tractor-trailer declines, the weight of allowable payload increases so that total design weight is unchanged. Thus, structural components must continue to accommodate the same design weight regardless of vehicle curb weight, and the opportunity for secondary weight reduction is accordingly limited.

Finally, fuel consumption regulations in China mandate that the test weight for tractor-trailers is fixed at maximum allowable weight. The test weight for a 49 tonne-class tractor-trailer is 49 tonnes regardless of whether tractor-trailer curb weight is reduced. Thus, from a testing standpoint, China dictates that 100% of any curb weight reduction be offset by an equal increase in payload weight. This effectively eliminates 100% of the per-kilometer fuel-consumption benefits of weight-reduction technology. While fuel consumption per payload tonne-km is reduced as more payload

is transported per unit of distance, it is not clear what fraction of tractor-trailer operators will take advantage of this potential. In cases where payload is volume limited, an operator has no potential to increase payload weight and will, therefore, gain a per-kilometer fuel-consumption reduction for any curb weight reduction, regardless of vehicle-testing requirements. Conversely, weight-limited operators could indeed increase payload to offset weight reductions, but the specific fraction of operations that will do so is unknown. This study makes a worst-case accounting of per-kilometer fuel-consumption impacts, assuming that there is no per-kilometer benefit associated with weight reduction while substantial cost is nonetheless incurred. For volume-limited operators and weight-limited operators that do not fully offset curb weight reductions, weight-reduction technology will be economically more cost-effective than estimated in this study.

Developed weight reduction costs are presented in Table 8.

Other fixed costs. There are certain fixed costs that are not accounted for in either direct or indirect costs. These are primarily related to compliance-demonstration and engine research and development. Those costs instead are allocated as a separate consideration and, to the extent they would apply in China, should be accounted for in this study. Compliance-related costs are excluded from this study,⁷ but engine research and development costs are included. To accommodate an accurate assessment of these costs, this study treats “fixed costs” as a distinct “technology,” the cost of which is included in every evaluated, non-baseline technology package. Based on the previous EU study (Meszler et al., 2018) this study estimates fixed costs as 15.1% of incremental engine technology costs and assumes that such costs are recovered over a four-year period. Table 6 shows the estimated fixed costs and the years they are assumed to be incurred.

Table 6. Per-vehicle fixed-cost estimates (2016¥)

Engine configuration	Fixed cost	Recovery period
Stage 2 Baseline		not applicable
Stage 3 Baseline	¥752	2018-2021
Stage 3 Best-In-Class	¥1,504	2018-2021
2020	¥3,947	2020-2023
2020+WHR	¥7,313	2022-2025
Long Term	¥8,999	2025-2028

Maintenance impacts. A number of the technologies evaluated in this study carry impacts independent of initial cost differentials. This study treats such post-purchase costs as maintenance items and accounts for their impact by calculating their initial cost equivalent and adding that estimate to explicit initial vehicle purchase costs. The initial cost equivalent is the net present value (NPV) of all applicable maintenance impacts for a given evaluation year. Generally, this can be thought of as the sum of money that would have to be escrowed on the day of initial purchase to fund the incremental costs of all combined maintenance impacts without additional investment over the lifetime

⁷ Certainly some level of compliance cost would be applicable, but given the uncertainty associated with the form, stringency, reporting, and oversight requirements of a China standard, this study does not attempt to quantify such costs. Nevertheless, it is expected that such costs would be modest on a per-vehicle basis.

of an affected tractor-trailer. The magnitude of the escrow investment is equal to the lost opportunity cost, were the same funds put to alternative use. NPV estimation requires knowledge of the magnitude and timing of a stream of future payments and the assumption of an effective discount rate to convert future payments into initial cost equivalents. As discussed earlier, this study evaluates economic impacts under three discounting scenarios: 4%, 7%, and 10%.

The timing of maintenance costs is determined based on assumed frequency in terms of the number of kilometers accumulated between maintenance events and the survival-weighted activity distribution described above and summarized in Figure 4. The NPV of lifetime maintenance is then calculated by summing the discounted cost of each event.

Five technologies are assumed in this study to impose incremental maintenance costs: low-viscosity engine oil, low rolling-resistance tires, waste heat recovery systems, high-efficiency axle lubricant, and hybrid system battery replacement. All associated maintenance intervals are set at the same values employed in the previous EU tractor-trailer study⁸ (Meszler et al., 2018).

The cost per maintenance event for low-viscosity engine oil, WHR, and high-efficiency axle lubricant are taken from the previous EU tractor-trailer study and are set at ¥770 for low-viscosity oil vs. ¥648 for conventional oil, ¥2,076 for WHR, and ¥692 for the axle lubricant. Although these costs are likely to decline in real terms with learning, they are held constant for this analysis. Replacement hybrid-system battery costs are set at the battery costs estimated to be applicable for new vehicles sold in China in the study evaluation years 2025 and 2030. These costs are estimated as described above for hybrid technology and are not assumed to decline beyond the effects of learning, even though replacement events will occur years after initial vehicle purchase. The costs for replacement of low rolling-resistance tires are similarly estimated in that they are set at the low rolling-resistance technology cost estimated for new vehicles sold in China in study evaluation years 2025 and 2030. As with the hybrid batteries, the costs are not assumed to exhibit any further learning after the study evaluation year even though replacement events will occur years after initial vehicle purchase.

Table 7 summarizes the resulting NPV of incremental maintenance costs estimated for this study.

8 Maintenance intervals for low-rolling resistance tires is 300,000 km, for WHR system is 160,000 km, for high-efficiency axle lubricant is 800,000 km, for low-viscosity engine oil is 55,000 km. Hybrid battery replacement interval is 400,000 km.

Table 7. Nominal per-vehicle maintenance cost impacts (NPV 2016¥)

Technology/configuration		2025 evaluation year			2030 evaluation year		
		Discount rate			Discount Rate		
		4%	7%	10%	4%	7%	10%
Low-viscosity engine oil		-¥1,988	-¥1,790	-¥1,631	-¥1,988	-¥1,790	-¥1,631
Low rolling-resistance tires/tractor	S2 Baseline	¥0	¥0	¥0	¥0	¥0	¥0
	S3 Baseline	¥5,564	¥4,803	¥4,194	¥5,332	¥4,603	¥4,019
	Incremental	¥6,691	¥5,776	¥5,043	¥5,943	¥5,130	¥4,479
	Moderate	¥6,691	¥5,776	¥5,043	¥5,943	¥5,130	¥4,479
	Advanced	¥7,040	¥6,077	¥5,307	¥6,136	¥5,297	¥4,625
	Long Term	¥7,312	¥6,312	¥5,511	¥6,298	¥5,437	¥4,747
Low rolling-resistance tires/trailer	S2 Baseline	¥0	¥0	¥0	¥0	¥0	¥0
	S3 Baseline	¥6,677	¥5,764	¥5,033	¥6,398	¥5,523	¥4,823
	Incremental	¥8,367	¥7,223	¥6,307	¥7,314	¥6,314	¥5,513
	Moderate	¥8,774	¥7,574	¥6,613	¥8,109	¥7,000	¥6,112
	Advanced	¥8,774	¥7,574	¥6,613	¥8,109	¥7,000	¥6,112
	Long Term	¥8,774	¥7,574	¥6,613	¥8,109	¥7,000	¥6,112
Waste heat reduction		¥9,751	¥8,481	¥7,461	¥9,751	¥8,481	¥7,461
High-efficiency axle lubricant		¥431	¥353	¥291	¥431	¥353	¥291
Hybrid battery		¥7,362	¥6,311	¥5,464	¥6,807	¥5,835	¥5,052

Individual technology cost summary. Based on the approaches described above, direct manufacturing and indirect costs are compiled for each of the technologies evaluated in this study. Table 8 summarizes the total cost of each individual technology, excluding independently accounted-for fixed costs that do not vary over time and maintenance costs as reported in Tables 6 and 7. Total costs are summarized for years 2015, 2020, 2025, and 2030, showing the effect of learning on technology costs over time. The total composite configuration estimates in the bottom rows of the table include a weighting factor of 1.045 trailers per tractor. All other trailer estimates are per-trailer.

Table 8. Individual technology costs (2016¥ direct plus indirect) for 2015, 2020, 2025, and 2030

Technology		2015	2020	2025	2030
Engine configuration	China V	¥0	¥0	¥0	¥0
	China VI	¥6,480	¥5,673	¥5,086	¥4,758
	China VI BIC	¥12,961	¥11,347	¥10,173	¥9,517
	2020+	¥34,191	¥30,076	¥26,776	¥24,785
	2020+WHR	¥92,994	¥77,703	¥50,273	¥43,434
	Long Term	¥110,179	¥92,484	¥61,756	¥53,850
Weight configuration/ tractor	Baseline S2	¥0	¥0	¥0	¥0
	Baseline S3	¥0	¥0	¥0	¥0
	Incremental	¥1,236	¥1,106	¥977	¥936
	Moderate	¥3,973	¥3,580	¥3,079	¥2,958
	Advanced	¥15,884	¥14,311	¥12,311	¥11,824
	Long Term	¥57,833	¥52,108	¥44,823	¥43,050
Weight configuration/ trailer	Baseline S2	¥0	¥0	¥0	¥0
	Baseline S3	¥0	¥0	¥0	¥0
	Incremental	¥631	¥565	¥499	¥478
	Moderate	¥2,744	¥2,472	¥2,126	¥2,042
	Advanced	¥16,242	¥14,634	¥12,588	¥12,090
	Long Term	¥85,281	¥76,838	¥66,097	¥63,482
Aerodynamic configuration/ tractor	Baseline S2	¥0	¥0	¥0	¥0
	Baseline S3	¥17,275	¥12,385	¥10,748	¥9,842
	Incremental	¥19,888	¥14,027	¥12,274	¥11,024
	Moderate	¥22,501	¥15,669	¥13,800	¥12,206
	Advanced	¥25,252	¥17,399	¥15,406	¥13,451
	Long Term	¥37,632	¥25,181	¥22,637	¥19,052
Aerodynamic configuration/ trailer	Baseline S2	¥0	¥0	¥0	¥0
	Baseline S3	¥0	¥0	¥0	¥0
	Incremental	¥5,837	¥5,032	¥4,614	¥4,421
	Moderate	¥11,094	¥9,564	¥8,770	¥8,403
	Advanced	¥11,094	¥9,564	¥8,770	¥8,403
	Long Term	¥11,094	¥9,564	¥8,770	¥8,403
Rolling resistance configuration/ tractor	Baseline S2	¥0	¥0	¥0	¥0
	Baseline S3	¥2,893	¥2,587	¥2,287	¥2,191
	Incremental	¥3,409	¥3,020	¥2,750	¥2,442
	Moderate	¥3,409	¥3,020	¥2,750	¥2,442
	Advanced	¥3,594	¥3,176	¥2,894	¥2,522
	Long Term	¥3,816	¥3,367	¥3,005	¥2,588

Technology		2015	2020	2025	2030
Rolling resistance configuration/trailer	Baseline S2	¥0	¥0	¥0	¥0
	Baseline S3	¥3,472	¥3,105	¥2,744	¥2,630
	Incremental	¥4,246	¥3,754	¥3,439	¥3,006
	Moderate	¥4,579	¥4,040	¥3,606	¥3,333
	Advanced	¥4,579	¥4,040	¥3,606	¥3,333
	Long Term	¥4,579	¥4,040	¥3,606	¥3,333
Composite weight, aerodynamic, and rolling resistance/ tractor + trailer ^a	Baseline S2	¥0	¥0	¥0	¥0
	Baseline S3	¥23,796	¥18,216	¥15,903	¥14,782
	Incremental	¥35,730	¥27,924	¥24,938	¥22,664
	Moderate	¥49,129	¥39,069	¥34,784	¥32,005
	Advanced	¥78,081	¥64,395	¥56,698	¥52,695
	Long Term	¥204,779	¥175,168	¥152,469	¥143,293
Driveline configuration	Base S2 Efficiency	¥0	¥0	¥0	¥0
	Base S3 Efficiency	¥2,552	¥2,234	¥1,910	¥1,750
	High Efficiency	¥6,727	¥5,893	¥5,069	¥4,666
Transmission	Manual	¥0	¥0	¥0	¥0
	AMT	¥36,422	¥32,201	¥27,540	¥25,787
Hybrid technology	No	¥0	¥0	¥0	¥0
	Yes	¥143,506	¥121,894	¥82,634	¥76,404

^a Includes a weighting factor of 1.045 trailers per tractor. Individual trailer technology costs are per-unit.

TECHNOLOGY PACKAGE COSTS

Costs are evaluated for 12 technology packages, as analyzed in the ICCT long-haul tractor-trailer simulation modeling. These packages cover a wide range of fuel consumption, reflecting a baseline of 47.0 liters per hundred kilometers (L/100 km) and extending to a minimum of 23.13 L/100 km, as measured over the C-WTVC driving cycle. The entirety of this range reflects as much as a 51% reduction in per-kilometer fuel consumption from the 2015 Stage 2 baseline tractor-trailer. Table 9 presents a summary of the technologies included in each package as well as an associated package description that is used for reference purposes in various data tables and results presented in this report. The order and composition of the presented technology packages matches the order and composition of the packages included in the ICCT simulation modeling as presented in Figure 1.

Table 9. Technology package definitions

Component Technologies		Technology Package ^a											
		1	2	3	4	5	6	7	8	9	10	11	12
Engine configuration	China V	X											
	China VI		X	X									
	China VI BIC				X	X	X						
	2020+							X	X				
	2020+WHR									X	X		
	Long Term											X	X
Road load configuration	Baseline S2	X											
	Baseline S3		X										
	Incremental			X	X	X							
	Moderate						X	X					
	Advanced								X	X			
	Long Term										X	X	X
Engine Size	Baseline	X											
	1.2×Baseline		X	X									
	1.4×Baseline				X	X	X	X	X	X	X	X	X
Driveline configuration	Base S2 Efficiency	X											
	Base S3 Efficiency		X	X	X								
	High Efficiency					X	X	X	X	X	X	X	X
Transmission	Manual	X											
	AMT		X	X	X	X	X	X	X	X	X	X	X
Hybrid technology	No	X	X	X	X	X	X	X	X	X	X	X	
	Yes												X
Fuel consumption (L/100 km)		See technology package definitions in note a.											

^a Technology packages defined as:

- (47.00 L/100 km) Reference (baseline) Stage 2 tractor-trailer (43.0% peak brake thermal efficiency engine)
- (40.00 L/100 km) Reference Stage 3 tractor-trailer (45.0% peak brake thermal efficiency engine; reduced road load from baseline: 21.1% aerodynamic drag, 11.8% rolling resistance, 0% weight; upsize engine by 20%; increase driveline efficiency by 1%; replace manual transmission with AMT)
- (37.50 L/100 km) Reduce road load (from baseline: 30.3% aerodynamic drag, 26.5% rolling resistance, 1.4% weight)
- (36.25 L/100 km) Add China VI best-in-class engine (47.0% peak brake thermal efficiency)
- (35.51 L/100 km) Increase driveline efficiency (+2%)
- (32.97 L/100 km) Reduce road load (from baseline: 39.5% aerodynamic drag, 33.8% rolling resistance, 2.8% weight)
- (31.42 L/100 km) Add 2020+ engine (48.6% peak brake thermal efficiency)
- (30.66 L/100 km) Reduce road load (from baseline: 42.1% aerodynamic drag, 36.8% rolling resistance, 6.9% weight)
- (29.79 L/100 km) Add Waste Heat Recovery (51.2% peak brake thermal efficiency)
- (27.94 L/100 km) Reduce road load (from baseline: 53.9% aerodynamic drag, 41.2% rolling resistance 16.0% weight)
- (25.97 L/100 km) Add long term (2030-era) engine (55.0% peak brake thermal efficiency)
- (23.13 L/100 km) Add hybrid technology (60% regeneration efficiency)

Table 10 shows the aggregate cost estimates associated with each technology package. Presented costs represent total, or direct manufacturing plus indirect, retail-level costs for base year 2015 and evaluation years 2020, 2025, and 2030. The costs are the aggregate of individual technology costs from Table 8 and fixed costs from Table 6. Included are the technology costs for one tractor and 1.045 trailers. These total retail-level cost estimates plus maintenance-cost impacts are the basis for all economic analysis undertaken in this study. Maintenance NPV costs are not included in this table as they are sensitive to the discount rate associated with each economic analysis

scenario. Scenario-specific costs, including maintenance NPV costs, are presented in Table 11 for economic analysis years 2025 and 2030. All costs presented in Tables 10 and 11 are incremental to a 2015-era baseline Stage 2 tractor-trailer.

Table 10. Total, retail technology package costs (2016¥ direct plus indirect) for 2015, 2020, 2025, and 2030

Technology Package		Evaluation year			
		2015	2020	2025	2030
1	Reference Stage 2 Tractor-Trailer (43% Peak BTE)	¥0	¥0	¥0	¥0
2	Ref Stage 3 (45% PBTE, Upsize, Reduce RL, DL, AMT)	¥69,251	¥59,077	¥50,439	¥47,078
3	Reduce RL (30.3% Aero, 26.5% RR, 1.4% Weight)	¥81,184	¥68,784	¥59,474	¥54,960
4	Add Stage 3 BIC Engine (47.0% Peak BTE, Upsize)	¥87,665	¥75,210	¥64,561	¥59,719
5	Increase Driveline Efficiency (+2%)	¥91,840	¥78,868	¥67,720	¥62,634
6	Reduce RL (39.5% Aero, 33.8% RR, 2.8% Weight)	¥105,239	¥90,013	¥77,566	¥71,975
7	Add 2020+ Engine (48.6% Peak BTE)	¥126,470	¥111,185	¥94,169	¥87,243
8	Reduce RL (42.1% Aero, 36.8% RR, 6.9% Weight)	¥155,422	¥136,511	¥116,083	¥107,933
9	Add Waste Heat Recovery (51.2% Peak BTE)	¥214,224	¥180,191	¥146,893	¥126,582
10	Reduce RL (53.9% Aero, 41.2% RR, 16.0% Weight)	¥340,922	¥290,964	¥242,664	¥217,180
11	Add 2030-Era Engine (55.0% Peak BTE)	¥358,107	¥305,745	¥255,833	¥227,596
12	Add Hybrid Technology (60% Regen Efficiency)	¥501,613	¥427,639	¥338,467	¥304,000

Technology costs include one tractor and 1.045 trailers; BTE=brake thermal efficiency; Ref=reference; PBTE=peak BTE; Upsize=upsized engine; DL=driveline efficiency improvement; RL=road load; Aero=aerodynamic drag; RR=rolling resistance; Weight=tractor-trailer curb weight; BIC=best-in-class

Table 11. Total, retail technology package plus NPV of incremental maintenance costs (2016¥ direct plus indirect) for 2025 and 2030 evaluation years under varying discount rates and fuel prices (costs are insensitive to fuel price).

Evaluation Year	2025								
	4%			7%			10%		
Discount Rate	4%			7%			10%		
Fuel Cost (¥/liter)	¥7.00	¥4.50	¥9.00	¥7.00	¥4.50	¥9.00	¥7.00	¥4.50	¥9.00
Reference Stage 2 Tractor-Trailer (43% Peak BTE)	¥0	¥0	¥0	¥0	¥0	¥0	¥0	¥0	¥0
Ref Stage 3 (45% PBTE, Upsize, Reduce RL, DL, AMT)	¥62,680	¥62,680	¥62,680	¥61,006	¥61,006	¥61,006	¥59,666	¥59,666	¥59,666
Reduce RL (30.3% Aero, 26.5% RR, 1.4% Weight)	¥74,532	¥74,532	¥74,532	¥72,472	¥72,472	¥72,472	¥70,824	¥70,824	¥70,824
Add Stage 3 BIC Engine (47.0% Peak BTE, Upsize)	¥79,619	¥79,619	¥79,619	¥77,559	¥77,559	¥77,559	¥75,911	¥75,911	¥75,911
Increase Driveline Efficiency (+2%)	¥83,209	¥83,209	¥83,209	¥81,072	¥81,072	¥81,072	¥79,361	¥79,361	¥79,361
Reduce RL (39.5% Aero, 33.8% RR, 2.8% Weight)	¥93,462	¥93,462	¥93,462	¥91,269	¥91,269	¥91,269	¥89,514	¥89,514	¥89,514
Add 2020+ Engine (48.6% Peak BTE)	¥108,077	¥108,077	¥108,077	¥106,082	¥106,082	¥106,082	¥104,485	¥104,485	¥104,485
Reduce RL (42.1% Aero, 36.8% RR, 6.9% Weight)	¥130,341	¥130,341	¥130,341	¥128,298	¥128,298	¥128,298	¥126,663	¥126,663	¥126,663
Add Waste Heat Recovery (51.2% Peak BTE)	¥170,902	¥170,902	¥170,902	¥167,588	¥167,588	¥167,588	¥164,934	¥164,934	¥164,934
Reduce RL (53.9% Aero, 41.2% RR, 16.0% Weight)	¥266,944	¥266,944	¥266,944	¥263,594	¥263,594	¥263,594	¥260,909	¥260,909	¥260,909
Add 2030 Era Engine (55.0% Peak BTE)	¥280,113	¥280,113	¥280,113	¥276,763	¥276,763	¥276,763	¥274,078	¥274,078	¥274,078
Add Hybrid Technology (60% Regen Efficiency)	¥370,109	¥370,109	¥370,109	¥365,707	¥365,707	¥365,707	¥362,176	¥362,176	¥362,176
Evaluation Year	2030								
	4%			7%			10%		
Discount Rate	4%			7%			10%		
Fuel Cost (¥/liter)	¥7.00	¥4.50	¥9.00	¥7.00	¥4.50	¥9.00	¥7.00	¥4.50	¥9.00
Reference Stage 2 Tractor-Trailer (43% Peak BTE)	¥0	¥0	¥0	¥0	¥0	¥0	¥0	¥0	¥0
Ref Stage 3 (45% PBTE, Upsize, Reduce RL, DL, AMT)	¥58,808	¥58,808	¥58,808	¥57,204	¥57,204	¥57,204	¥55,919	¥55,919	¥55,919
Reduce RL (30.3% Aero, 26.5% RR, 1.4% Weight)	¥68,217	¥68,217	¥68,217	¥66,404	¥66,404	¥66,404	¥64,952	¥64,952	¥64,952
Add Stage 3 BIC Engine (47.0% Peak BTE, Upsize)	¥72,976	¥72,976	¥72,976	¥71,163	¥71,163	¥71,163	¥69,711	¥69,711	¥69,711
Increase Driveline Efficiency (+2%)	¥76,322	¥76,322	¥76,322	¥74,431	¥74,431	¥74,431	¥72,917	¥72,917	¥72,917
Reduce RL (39.5% Aero, 33.8% RR, 2.8% Weight)	¥86,458	¥86,458	¥86,458	¥84,458	¥84,458	¥84,458	¥82,857	¥82,857	¥82,857
Add 2020+ Engine (48.6% Peak BTE)	¥99,738	¥99,738	¥99,738	¥97,936	¥97,936	¥97,936	¥96,494	¥96,494	¥96,494
Reduce RL (42.1% Aero, 36.8% RR, 6.9% Weight)	¥120,621	¥120,621	¥120,621	¥118,793	¥118,793	¥118,793	¥117,330	¥117,330	¥117,330
Add Waste Heat Recovery (51.2% Peak BTE)	¥149,021	¥149,021	¥149,021	¥145,923	¥145,923	¥145,923	¥143,440	¥143,440	¥143,440
Reduce RL (53.9% Aero, 41.2% RR, 16.0% Weight)	¥239,781	¥239,781	¥239,781	¥236,661	¥236,661	¥236,661	¥234,160	¥234,160	¥234,160
Add 2030 Era Engine (55.0% Peak BTE)	¥250,197	¥250,197	¥250,197	¥247,077	¥247,077	¥247,077	¥244,576	¥244,576	¥244,576
Add Hybrid Technology (60% Regen Efficiency)	¥333,408	¥333,408	¥333,408	¥329,316	¥329,316	¥329,316	¥326,032	¥326,032	¥326,032

Technology costs include one tractor and 1.045 trailers; BTE=brake thermal efficiency; Ref=reference; PBTE=peak BTE; Upsize=upsized engine; DL=driveline efficiency improvement; RL=road load; Aero=aerodynamic drag; RR=rolling resistance; Weight=tractor-trailer curb weight; BIC=best-in-class

Figure 8 summarizes total technology costs, direct plus indirect, including the NPV of maintenance-cost impacts associated with the evaluated efficiency technology packages. The figure shows basic cost curves for the 2025 evaluation year under a 4% discount rate and the 2030 evaluation year under a 10% discount rate. The 2025 curve reflects maximum costs incurred in the 2025–2030 timeframe, while the 2030 curve reflects minimum incurred costs. Only maintenance costs are affected by the discount rate and, to avoid clutter, Figure 8 shows costs for only the highest and lowest maintenance-cost impact scenarios. Cost curves for other maintenance-cost impact scenarios and other evaluation years between 2025 and 2030 lie between the two depicted curves.

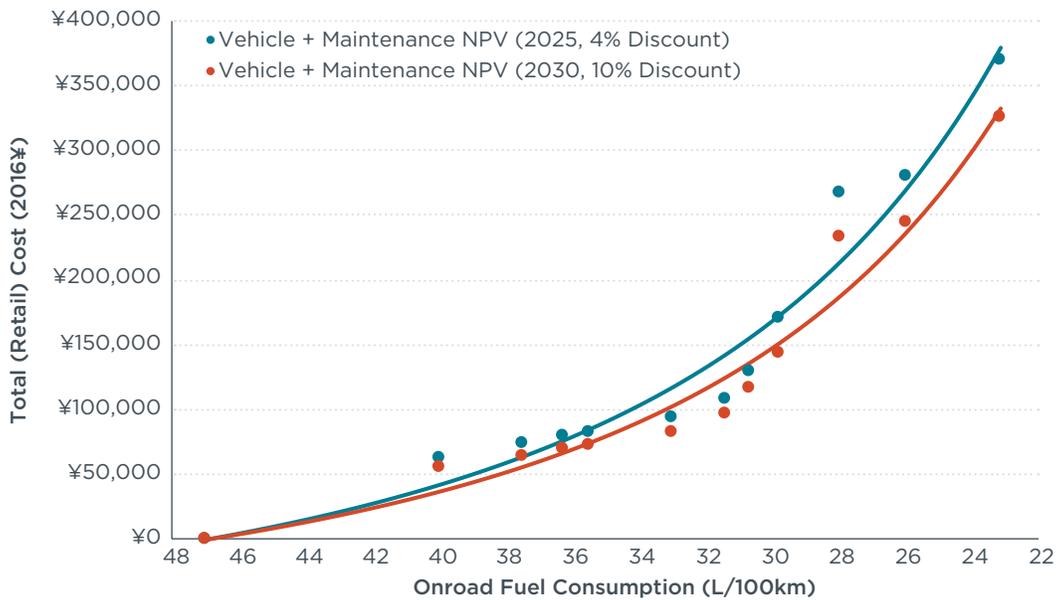


Figure 8. Summary of total technology package costs versus tractor-trailer fuel consumption for evaluation years 2025 and 2030

As shown in Figure 8, efficiency packages that attain 31 L/100 km by 2025 cost about ¥130,500 per tractor-trailer, including the effects of an assumption of 1.045 trailers per tractor. Such packages reflect about a 35% reduction in per-kilometer fuel consumption relative to the baseline 2015-era Stage 2 tractor-trailer. Also shown in the figure are the costs of achieving more advanced efficiency technology levels. To achieve efficiency levels as low as 23 L/100 km, a 51% per-kilometer fuel consumption reduction, 2025 costs range up to ¥370,000 per tractor-trailer, assuming 1.045 trailers per tractor.

IV. ECONOMIC FINDINGS

This section presents basic economic metrics associated with the total cost estimates for the evaluated technology packages presented in Table 11. Specific metrics consist of the payback period associated with each technology package, the lifetime savings associated with each package, and the marginal cost of long-haul tractor-trailer technology. The payback period is defined as the time required to recover the increased capital and NPV of future maintenance costs associated with each technology package. The lifetime cost of each technology package is defined as the lifetime cost savings that accrue because of the decreased fuel use associated with each technology package, minus the increased capital and NPV of future maintenance costs of the applicable technology package. The payback period and the lifetime cost are measured relative to baseline Stage 2 tractor-trailer fuel consumption and cost. The marginal cost of long-haul tractor-trailer technology is measured as the effective cost in yuan per liter of fuel saved for the next increment of fuel efficiency, and essentially measures the cost-effectiveness of the technology required to produce that next increment of fuel-consumption reduction. Marginal costs expressed in yuan per liter saved can be readily compared with expected fuel prices to determine the cost-effective level of technology. As discussed in Section III above, all economic metrics are evaluated under three discount rate scenarios—4%, 7%, and 10%—and three fuel-price scenarios—¥7.00, ¥4.50, and ¥9.00 per liter.

As indicated in the preceding section, technology cost estimates are developed for all calendar years between 2020 and 2030. Accordingly, economic metrics can be developed and presented for any of the years in this range. However, when each potential evaluation year is combined with three discount rate and three fuel price scenarios, a total of 99 separate measures of each economic metric for each technology package are generated. In the interest of simplifying both the presentation and clarity of findings, all economic metrics are presented for two evaluation years only, 2025 and 2030. Evaluation year 2025 represents the midrange year and provides a representative indication of median-level economic metrics for the larger 11-year period. Given the lead time that would be required for any newly adopted HDV control program to achieve the stringent fuel-consumption reductions reflected in the more advanced technology packages evaluated in this study, it is unlikely that such reductions would be required earlier than 2025.

This should not be interpreted as encouraging extended adoption delay as it is critical for standards to be put into effect as soon as possible to establish a glide path toward the stringent standards required to deliver reductions of the levels associated with the advanced technology packages considered in this study. The 2030 evaluation year reflects the timing during which the most advanced technology packages are expected to be commercially available and therefore reflects the year in which standards of equivalent stringency could be implemented.

TECHNOLOGY PACKAGE PAYBACK PERIODS

Table 12 presents the economic payback periods for the 2025 and 2030 evaluation years. Because of the effect of learning on technology costs, payback periods are generally shorter in 2030 than in 2025. Both the NPV of maintenance impacts and fuel savings are inversely related to the assumed discount rate so that the effects of discount rate on costs and savings largely offset. The quick payback, due to high VKT, in the first several years of tractor-trailer use in the long-haul sector also serves to limit the impact of differential discount rates on estimated payback, since no discount is applied during the first year of operation. As is also shown, fuel price is inversely related to payback, with higher fuel prices resulting in shorter payback periods.

Table 12. Technology package payback periods in years

Evaluation Year	2025								
Discount Rate	4%			7%			10%		
Fuel Cost (¥/liter)	¥7.00	¥4.50	¥9.00	¥7.00	¥4.50	¥9.00	¥7.00	¥4.50	¥9.00
Reference Stage 2 Tractor-Trailer (43% Peak BTE)	n/a								
Ref Stage 3 (45% PBTE, Upsize, Reduce RL, DL, AMT)	1.3	2.1	1.0	1.3	2.0	1.0	1.2	2.0	0.9
Reduce RL (30.3% Aero, 26.5% RR, 1.4% Weight)	1.1	1.8	0.9	1.1	1.8	0.8	1.1	1.7	0.8
Add Stage 3 BIC Engine (47.0% Peak BTE, Upsize)	1.1	1.7	0.8	1.0	1.7	0.8	1.0	1.6	0.8
Increase Driveline Efficiency (+2%)	1.0	1.6	0.8	1.0	1.6	0.8	1.0	1.6	0.8
Reduce RL (39.5% Aero, 33.8% RR, 2.8% Weight)	1.0	1.5	0.7	0.9	1.5	0.7	0.9	1.5	0.7
Add 2020+ Engine (48.6% Peak BTE)	1.0	1.6	0.8	1.0	1.6	0.8	1.0	1.5	0.7
Reduce RL (42.1% Aero, 36.8% RR, 6.9% Weight)	1.1	1.8	0.9	1.1	1.8	0.9	1.1	1.8	0.9
Add Waste Heat Recovery (51.2% Peak BTE)	1.4	2.3	1.1	1.4	2.3	1.1	1.4	2.3	1.1
Reduce RL (53.9% Aero, 41.2% RR, 16.0% Weight)	2.1	3.3	1.6	2.1	3.4	1.6	2.1	3.5	1.6
Add 2030 Era Engine (55.0% Peak BTE)	2.0	3.2	1.5	2.0	3.2	1.5	2.0	3.3	1.5
Add Hybrid Technology (60% Regen Efficiency)	2.3	3.7	1.8	2.3	3.9	1.8	2.3	4.0	1.8
Evaluation Year	2030								
Discount Rate	4%			7%			10%		
Fuel Cost (¥/liter)	¥7.00	¥4.50	¥9.00	¥7.00	¥4.50	¥9.00	¥7.00	¥4.50	¥9.00
Reference Stage 2 Tractor-Trailer (43% Peak BTE)	n/a								
Ref Stage 3 (45% PBTE, Upsize, Reduce RL, DL, AMT)	1.2	1.9	0.9	1.2	1.9	0.9	1.2	1.9	0.9
Reduce RL (30.3% Aero, 26.5% RR, 1.4% Weight)	1.0	1.6	0.8	1.0	1.6	0.8	1.0	1.6	0.8
Add Stage 3 BIC Engine (47.0% Peak BTE, Upsize)	1.0	1.5	0.8	0.9	1.5	0.7	0.9	1.5	0.7
Increase Driveline Efficiency (+2%)	0.9	1.5	0.7	0.9	1.5	0.7	0.9	1.5	0.7
Reduce RL (39.5% Aero, 33.8% RR, 2.8% Weight)	0.9	1.4	0.7	0.9	1.4	0.7	0.8	1.4	0.7
Add 2020+ Engine (48.6% Peak BTE)	0.9	1.4	0.7	0.9	1.4	0.7	0.9	1.4	0.7
Reduce RL (42.1% Aero, 36.8% RR, 6.9% Weight)	1.1	1.7	0.8	1.0	1.7	0.8	1.0	1.7	0.8
Add Waste Heat Recovery (51.2% Peak BTE)	1.3	2.0	1.0	1.2	2.0	0.9	1.2	2.0	0.9
Reduce RL (53.9% Aero, 41.2% RR, 16.0% Weight)	1.8	3.0	1.4	1.8	3.0	1.4	1.8	3.1	1.4
Add 2030 Era Engine (55.0% Peak BTE)	1.7	2.8	1.3	1.7	2.8	1.3	1.7	2.9	1.3
Add Hybrid Technology (60% Regen Efficiency)	2.1	3.3	1.6	2.1	3.4	1.6	2.1	3.5	1.6

Technology costs include one tractor and 1.045 trailers; BTE=brake thermal efficiency; Ref=reference; PBTE=peak BTE; Upsize=upsized engine; DL=driveline efficiency improvement; RL=road load; Aero=aerodynamic drag; RR=rolling resistance; Weight=tractor-trailer curb weight; BIC=best-in-class

The payback periods for evaluated technology packages, over all the varying economic assumptions and over the 2025 and 2030 evaluation years, are all less than four years. Figure 9 depicts payback period as a continuous function. Note that the continuous regression-based function omits the two technology packages represented by the open markers in the figure. This omission is because the technology package simulation modeling did not include an underlying cost-effectiveness consideration, so the order of the evaluated packages was not rigorously established. This results in a less-than-optimum progression from one technology package to the next. The effects of non-optimization can be statistically ignored as in this study, but this is not a statistical anomaly. The same optimization will occur in practice as the most cost-effective technologies are adopted first.

Figure 9 focuses on best- and worst-case paybacks. The lower-cost evaluation year, 2030, reflects best-case conditions with low discounting and high fuel-price assumptions maximizing the value of fuel savings. The higher-cost evaluation year, 2025, reflects worst-case conditions with high discounting and low fuel price assumptions that minimize the value of fuel savings.

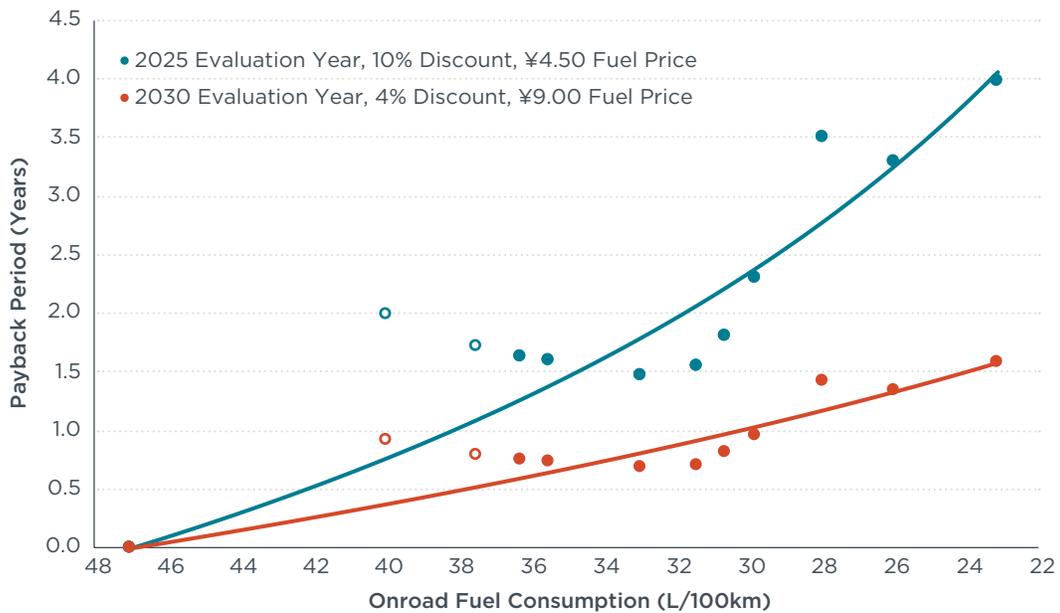


Figure 9. Tractor-trailer efficiency technology package payback periods under varying technology cost and economic assumptions

As shown, worst-case payback periods are estimated to be four years or less for fuel-consumption rates as low as 23 L/100 km because of fuel savings that significantly outweigh initial technology purchase and incremental maintenance costs. These same technology packages generally deliver payback periods of 0.7-1.6 years for best-case cost and economic assumptions. The more moderate technology packages deliver payback periods of one year or less under any reasonable set of economic assumptions. Note that although practices vary widely, all of the estimated payback periods fall well within the four- to six-year typical initial ownership period

for road tractor fleets, and nearly all satisfy the typical desire to achieve payback on technology investment within two years (China Cost Study, 2018; Roeth, Kircher, Smith, and Swim, 2013). This first-owner issue is evaluated further below.

As discussed in Section III above, primary economic findings are based on a number of conservative assumptions with regard to VKT and technology cost. If less conservative assumptions were employed, technology payback periods would be even shorter.

LIFETIME SAVINGS ESTIMATES

Table 13 presents the net lifetime savings associated with each technology package in the evaluation years 2025 and 2030. These estimates represent the net savings to vehicle owners, based on lifetime discounted fuel savings minus initial technology and discounted lifetime maintenance costs relative to an unimproved baseline Stage 2 tractor-trailer. For a maximum-efficiency technology package in 2025, the net savings range from ¥337,000–¥1,405,000, rising to ¥373,000–¥1,442,000 by 2030. The fuel savings for the most advanced efficiency technology packages investigated are at least 1.9 times the initial technology cost under high technology costs, low future fuel prices, and a high discount rate, and up to 5.3 times the initial technology cost under low technology cost, high future fuel prices, and a low discount rate. Compared with the baseline tractor price of ¥360,000 assumed in this study, this means that the technology investment not only pays for itself but also pays for no less than 93% and as much as 400% of the unimproved tractor as well. If the tractor and 1.045 trailers are considered, with each trailer assumed to be priced at ¥60,000, not only is the technology investment fully repaid, but no less than 79% and as much as 340% of the unimproved capital expenditure for the tractor and trailers is also covered.

Table 13. Technology package net lifetime savings for varying evaluation years, discount rates, and fuel prices (2016¥)

Evaluation Year	2025								
	4%			7%			10%		
Discount Rate	¥7.00	¥4.50	¥9.00	¥7.00	¥4.50	¥9.00	¥7.00	¥4.50	¥9.00
Fuel Cost (¥/liter)	¥7.00	¥4.50	¥9.00	¥7.00	¥4.50	¥9.00	¥7.00	¥4.50	¥9.00
Reference Stage 2 Tractor-Trailer (43% Peak BTE)	¥0	¥0	¥0	¥0	¥0	¥0	¥0	¥0	¥0
Ref Stage 3 (45% PBTE, Upsize, Reduce RL, DL, AMT)	¥342,184	¥197,589	¥457,859	¥296,066	¥168,541	¥398,087	¥259,154	¥145,290	¥350,245
Reduce RL (30.3% Aero, 26.5% RR, 1.4% Weight)	¥475,216	¥278,877	¥632,286	¥412,381	¥239,219	¥550,910	¥362,087	¥207,476	¥485,776
Add Stage 3 BIC Engine (47.0% Peak BTE, Upsize)	¥541,905	¥319,932	¥719,483	¥470,598	¥274,827	¥627,214	¥413,523	¥238,725	¥553,361
Increase Driveline Efficiency (+2%)	¥581,404	¥344,042	¥771,294	¥505,088	¥295,745	¥672,562	¥444,004	¥257,088	¥593,537
Reduce RL (39.5% Aero, 33.8% RR, 2.8% Weight)	¥717,828	¥428,081	¥949,625	¥624,253	¥368,710	¥828,688	¥549,355	¥321,188	¥731,889
Add 2020+ Engine (48.6% Peak BTE)	¥793,324	¥471,395	¥1,050,867	¥688,914	¥404,987	¥916,056	¥605,343	¥351,833	¥808,151
Reduce RL (42.1% Aero, 36.8% RR, 6.9% Weight)	¥814,670	¥477,166	¥1,084,673	¥705,160	¥407,497	¥943,291	¥617,507	¥351,732	¥830,127
Add Waste Heat Recovery (51.2% Peak BTE)	¥824,312	¥468,879	¥1,108,659	¥710,147	¥396,670	¥960,928	¥618,770	¥338,876	¥842,685
Reduce RL (53.9% Aero, 41.2% RR, 16.0% Weight)	¥835,327	¥441,659	¥1,150,262	¥708,562	¥361,363	¥986,320	¥607,099	¥297,096	¥855,102
Add 2030 Era Engine (55.0% Peak BTE)	¥936,099	¥501,737	¥1,283,588	¥795,883	¥412,795	¥1,102,353	¥683,655	¥341,608	¥957,293
Add Hybrid Technology (60% Regen Efficiency)	¥1,010,562	¥517,465	¥1,405,039	¥851,984	¥417,094	¥1,199,895	¥725,064	¥336,764	¥1,035,704
Evaluation Year	2030								
Discount Rate	4%			7%			10%		
Fuel Cost (¥/liter)	¥7.00	¥4.50	¥9.00	¥7.00	¥4.50	¥9.00	¥7.00	¥4.50	¥9.00
Reference Stage 2 Tractor-Trailer (43% Peak BTE)	¥0	¥0	¥0	¥0	¥0	¥0	¥0	¥0	¥0
Ref Stage 3 (45% PBTE, Upsize, Reduce RL, DL, AMT)	¥346,056	¥201,462	¥461,731	¥299,869	¥172,343	¥401,889	¥262,900	¥149,036	¥353,991
Reduce RL (30.3% Aero, 26.5% RR, 1.4% Weight)	¥481,531	¥285,192	¥638,601	¥418,450	¥245,288	¥556,979	¥367,959	¥213,348	¥491,648
Add Stage 3 BIC Engine (47.0% Peak BTE, Upsize)	¥548,548	¥326,575	¥726,127	¥476,994	¥281,224	¥633,611	¥419,722	¥244,924	¥559,560
Increase Driveline Efficiency (+2%)	¥588,291	¥350,929	¥778,181	¥511,729	¥302,386	¥679,203	¥450,447	¥263,531	¥599,980
Reduce RL (39.5% Aero, 33.8% RR, 2.8% Weight)	¥724,832	¥435,085	¥956,629	¥631,064	¥375,520	¥835,499	¥556,011	¥327,844	¥738,545
Add 2020+ Engine (48.6% Peak BTE)	¥801,663	¥479,734	¥1,059,206	¥697,060	¥413,133	¥924,202	¥613,334	¥359,824	¥816,142
Reduce RL (42.1% Aero, 36.8% RR, 6.9% Weight)	¥824,389	¥486,885	¥1,094,392	¥714,665	¥417,001	¥952,796	¥626,840	¥361,065	¥839,460
Add Waste Heat Recovery (51.2% Peak BTE)	¥846,192	¥490,759	¥1,130,539	¥731,812	¥418,335	¥982,594	¥640,264	¥360,370	¥864,179
Reduce RL (53.9% Aero, 41.2% RR, 16.0% Weight)	¥862,490	¥468,822	¥1,177,424	¥735,494	¥388,296	¥1,013,253	¥633,848	¥323,845	¥881,851
Add 2030 Era Engine (55.0% Peak BTE)	¥966,014	¥531,653	¥1,313,503	¥825,569	¥442,481	¥1,132,039	¥713,157	¥371,110	¥986,795
Add Hybrid Technology (60% Regen Efficiency)	¥1,047,262	¥554,166	¥1,441,740	¥888,375	¥453,486	¥1,236,287	¥761,208	¥372,908	¥1,071,848

Technology costs include one tractor and 1.045 trailers; BTE=brake thermal efficiency; Ref=reference; PBTE=peak BTE; Upsize=upsized engine; DL=driveline efficiency improvement; RL=road load; Aero=aerodynamic drag; RR=rolling resistance; Weight=tractor-trailer curb weight; BIC=best-in-class

Assumptions related to future economic conditions—fuel price and fuel savings discount rate—play a significant role in determining absolute lifetime savings from the tractor-trailer efficiency technologies. Figure 10 depicts generalized relations for lifetime fuel-savings estimates in the best case—with low costs, a low discount rate, and a high fuel price—and the worst case—with high costs, a high discount rate, and a low fuel price. As shown, the economic factors of fuel price and discount rate play a large role in determining the overall benefits associated with the deployment of efficiency technology. The short payback period for even the most advanced technology package essentially ensures that technology cost is a relatively small factor in the overall cost-benefit evaluation, as compared with the effects of the economic assumptions.



Figure 10. Net lifetime savings from tractor-trailer fuel-efficiency technologies for varying technology cost, discount rate, and fuel price (2016¥)

As discussed in Section III above, primary economic findings are based on a number of conservative assumptions with regard to VKT and technology cost. If less conservative assumptions were employed, net lifetime savings would be even greater because of the larger fuel savings associated with higher levels of VKT and reduced technology costs.

FIRST-OWNER SAVINGS ESTIMATES

As another indicator of the potential attractiveness of the initial technology purchase is the net savings from the tractor-trailer efficiency technology packages that accrue to a vehicle's first owner. These are discounted fuel savings minus technology and incremental maintenance costs. Tractor ownership practices vary widely, but most companies tend to operate new long-haul tractors less than 10 years. Conventional wisdom is that such tractors are held for four to six years before resale (China Cost Study, 2018; Roeth et al., 2013). For evaluating first-owner impacts, this analysis assumes a five-year initial tractor ownership period.

Table 14 presents estimated first-owner net savings. These are based only on the first five years of ownership, ignoring all fuel savings that accrue during the remaining

useful life of the tractor-trailer. The savings for the first owner are a substantial part of the overall lifetime savings. This is largely because the average tractor accrues half of its lifetime mileage in the first five years. This should not be surprising given that the median survival-weighted tractor age in China is only 9.6 years (see Table 5). Recognize also that first-owner savings are likely to be underestimated in this study for two reasons. One is that first-owner savings are constrained by the conservative VKT and technology-cost assumptions that are employed. The other is that the study assumes constant average VKT over time when it is likely that VKT declines on a year-over-year basis throughout a tractor's lifetime, so that average VKT over the first five years of a tractor's life is higher than average VKT over the next five years.

Moderate efficiency-technology package 8 reduces fuel consumption by 35%, based on upsized 2020 engine, high-efficiency driveline, and advanced road load technology. The package costs ¥111,700–¥121,000⁹ and offers ¥294,800–¥653,000 in discounted fuel savings during the first five years, depending on economic assumptions. This delivers benefits to the first owner that are 2.4–5.8 times greater than the upfront technology and incremental maintenance costs. As shown in Table 14, this package results in a net benefit of ¥174,400–¥540,800 over the five years. The most advanced technology package, with a 51% reduction in fuel consumption and a cost of ¥315,300–¥352,500, results in ¥430,700–¥954,100 in fuel savings during the first five years. The first owner reaps benefits that are 1.2–3.0 times greater than the costs. The net benefit delivered during the first five years is ¥80,200–¥637,000, as shown in Table 14.

⁹ These costs are slightly lower than those presented in previous sections of this report as they include maintenance effects only through the first five years of operation.

Table 14. Technology package first-owner net lifetime savings for varying evaluation years, discount rates, and fuel prices (2016¥)

Evaluation Year	2025								
	4%			7%			10%		
	Discount Rate	4%			7%			10%	
Fuel Cost (¥/liter)	¥7.00	¥4.50	¥9.00	¥7.00	¥4.50	¥9.00	¥7.00	¥4.50	¥9.00
Reference Stage 2 Tractor-Trailer (43% Peak BTE)	¥0	¥0	¥0	¥0	¥0	¥0	¥0	¥0	¥0
Ref Stage 3 (45% PBTE, Upsize, Reduce RL, DL, AMT)	¥162,713	¥84,996	¥224,886	¥151,814	¥78,078	¥210,803	¥142,053	¥71,884	¥198,189
Reduce RL (30.3% Aero, 26.5% RR, 1.4% Weight)	¥230,524	¥124,997	¥314,946	¥215,695	¥115,572	¥295,793	¥202,412	¥107,132	¥278,636
Add Stage 3 BIC Engine (47.0% Peak BTE, Upsize)	¥264,016	¥144,710	¥359,460	¥247,211	¥134,015	¥337,767	¥232,157	¥124,437	¥318,333
Increase Driveline Efficiency (+2%)	¥284,016	¥156,439	¥386,078	¥266,025	¥144,982	¥362,859	¥249,908	¥134,721	¥342,059
Reduce RL (39.5% Aero, 33.8% RR, 2.8% Weight)	¥352,857	¥197,125	¥477,443	¥330,837	¥183,080	¥449,042	¥311,110	¥170,501	¥423,597
Add 2020+ Engine (48.6% Peak BTE)	¥385,524	¥212,495	¥523,948	¥361,018	¥196,849	¥492,352	¥339,061	¥182,835	¥464,043
Reduce RL (42.1% Aero, 36.8% RR, 6.9% Weight)	¥386,922	¥205,522	¥532,043	¥361,222	¥189,112	¥498,911	¥338,197	¥174,412	¥469,225
Add Waste Heat Recovery (51.2% Peak BTE)	¥377,790	¥186,752	¥530,620	¥351,079	¥169,825	¥496,082	¥327,144	¥154,658	¥465,133
Reduce RL (53.9% Aero, 41.2% RR, 16.0% Weight)	¥339,461	¥127,873	¥508,732	¥309,809	¥109,057	¥470,410	¥283,238	¥92,198	¥436,071
Add 2030 Era Engine (55.0% Peak BTE)	¥387,533	¥154,073	¥574,300	¥354,744	¥133,240	¥531,946	¥325,363	¥114,574	¥493,993
Add Hybrid Technology (60% Regen Efficiency)	¥389,628	¥124,600	¥601,651	¥352,612	¥101,156	¥553,776	¥319,442	¥80,150	¥510,875

Evaluation Year	2030								
	4%			7%			10%		
	Discount Rate	4%			7%			10%	
Fuel Cost (¥/liter)	¥7.00	¥4.50	¥9.00	¥7.00	¥4.50	¥9.00	¥7.00	¥4.50	¥9.00
Reference Stage 2 Tractor-Trailer (43% Peak BTE)	¥0	¥0	¥0	¥0	¥0	¥0	¥0	¥0	¥0
Ref Stage 3 (45% PBTE, Upsize, Reduce RL, DL, AMT)	¥166,260	¥88,543	¥228,433	¥155,351	¥81,615	¥214,340	¥145,581	¥75,412	¥201,716
Reduce RL (30.3% Aero, 26.5% RR, 1.4% Weight)	¥235,694	¥130,166	¥320,116	¥220,828	¥120,705	¥300,927	¥207,512	¥112,232	¥283,735
Add Stage 3 BIC Engine (47.0% Peak BTE, Upsize)	¥269,513	¥150,208	¥364,957	¥252,672	¥139,476	¥343,228	¥237,585	¥129,865	¥323,760
Increase Driveline Efficiency (+2%)	¥289,757	¥162,181	¥391,819	¥271,730	¥150,687	¥368,565	¥255,580	¥140,392	¥347,730
Reduce RL (39.5% Aero, 33.8% RR, 2.8% Weight)	¥358,963	¥203,230	¥483,548	¥336,914	¥189,157	¥455,119	¥317,160	¥176,551	¥429,647
Add 2020+ Engine (48.6% Peak BTE)	¥392,964	¥219,935	¥531,388	¥368,429	¥204,261	¥499,764	¥346,447	¥190,220	¥471,428
Reduce RL (42.1% Aero, 36.8% RR, 6.9% Weight)	¥395,643	¥214,243	¥540,764	¥369,912	¥197,801	¥507,600	¥346,857	¥183,072	¥477,885
Add Waste Heat Recovery (51.2% Peak BTE)	¥398,672	¥207,634	¥551,502	¥371,929	¥190,675	¥516,932	¥347,966	¥175,480	¥485,954
Reduce RL (53.9% Aero, 41.2% RR, 16.0% Weight)	¥365,556	¥153,968	¥534,826	¥335,869	¥135,118	¥496,471	¥309,268	¥118,228	¥462,101
Add 2030 Era Engine (55.0% Peak BTE)	¥416,380	¥182,921	¥603,148	¥383,558	¥162,054	¥560,760	¥354,146	¥143,357	¥522,776
Add Hybrid Technology (60% Regen Efficiency)	¥424,982	¥159,954	¥637,005	¥387,909	¥136,454	¥589,074	¥354,688	¥115,396	¥546,121

Technology costs include one tractor and 1.045 trailers; BTE=brake thermal efficiency; Ref=reference; PBTE=peak BTE; Upsize=upsized engine; DL=driveline efficiency improvement; RL=road load; Aero=aerodynamic drag; RR=rolling resistance; Weight=tractor-trailer curb weight; BIC=best-in-class

MARGINAL COST OF TECHNOLOGY

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

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

To undertake the marginal cost analysis, technology costs for 2025 and 2030 are first expressed in terms of their estimated discounted lifetime liters of fuel saved.¹⁰ The relationship between efficiency technology package cost and discounted lifetime fuel savings is depicted in Figure 11. The data presented in the figure are limited to bounding conditions producing the highest and lowest marginal cost estimates. The highest discount rates define the lowest fuel quantity savings, while low discount rates define the highest fuel quantity savings. This study uses 2025 and 2030 evaluation years in the marginal cost analysis to capture technology cost differentials. Minimum fuel quantity savings are coupled with the higher, or 2025, technology costs, and maximum fuel savings are coupled with the lower, or 2030, technology costs. Other combinations of fuel savings and costs will produce marginal cost estimates for the 2025–2030 period that lie between those presented. Note that the continuous regression-based function omits the two technology packages represented by the open markers in the figure. This omission is because the technology package simulation modeling did not include an underlying cost-effectiveness consideration, so the order of the evaluated packages was not rigorously established. This results in a less-than-optimum progression from one technology package to the next. The effects of non-optimization can be statistically ignored as in this study, but this is not a statistical anomaly as the same optimization will occur in practice as the most cost-effective technologies are adopted first.

¹⁰ Discounting future saved fuel volume is equivalent to discounting the value of the saved fuel volume under a fixed fuel price. The discounted value of future fuel savings is equal to the liters of fuel saved (V) times the price per liter (P) times the applicable discount rate (D). Given the capital cost of a technology package (C), the fuel price required to offset that cost is determinable by setting C equal to $V \times P \times D$ and solving for P as $C / (V \times D)$, where $V \times D$ is the discounted volume of fuel saved. In short, the fuel price required to recoup a technology investment is a function of the discounted volume of fuel saved. It is also easily seen that the value of saved fuel is identical whether one discounts savings (S) directly, or applies a specified fuel price to already-discounted saved fuel volume ($V \times D$). S equals $P \times V \times D$ directly, which is exactly the same as $P \times (V \times D)$. Discounting fuel volume is functionally identical to discounting fuel savings.



Figure 11. Technology package cost and discounted lifetime fuel savings for best-and worst-case economic assumptions

Marginal cost curves, as presented in Figure 12, are developed from the lifetime discounted fuel savings functions presented in Figure 11. For the most advanced technology package included in this study, which has an associated fuel consumption of 23.1 L/100 km, the marginal cost of technology ranges from ¥3.94 per liter of fuel saved under high-savings, low-cost conditions to ¥5.58 per liter of fuel saved under low-savings, high-cost conditions. Thus, the full slate of technology packages evaluated in this study are marginally cost-effective given the nominal and high fuel prices expected between 2020 and 2030 of ¥7.00 and ¥9.00 per liter. Under the lowest evaluated fuel price of ¥4.50 per liter, the full slate of technology packages is cost-effective under high-savings, low-cost economic conditions, or 2030 costs with low discount rate, but it falls outside the cost-effective limit under the low-savings, high-cost conditions, or 2025 costs and high discount rate. Under low-savings, high-cost conditions, the minimum fuel consumption that is marginally cost-effective at a fuel price of ¥4.50 per liter is 26.6 L/100 km, representing a per-kilometer reduction of 43% from the 2015 Stage 2 baseline.

As is the case for all presented economic metrics, the marginal cost-effectiveness estimates are based on a number of conservative assumptions with regard to VKT and technology cost, as discussed in Section III above. If less conservative assumptions were employed, technology would become cost effective, and it is likely that the full slate of technology packages would be cost-effective under even the most optimistic fuel-price assumptions.

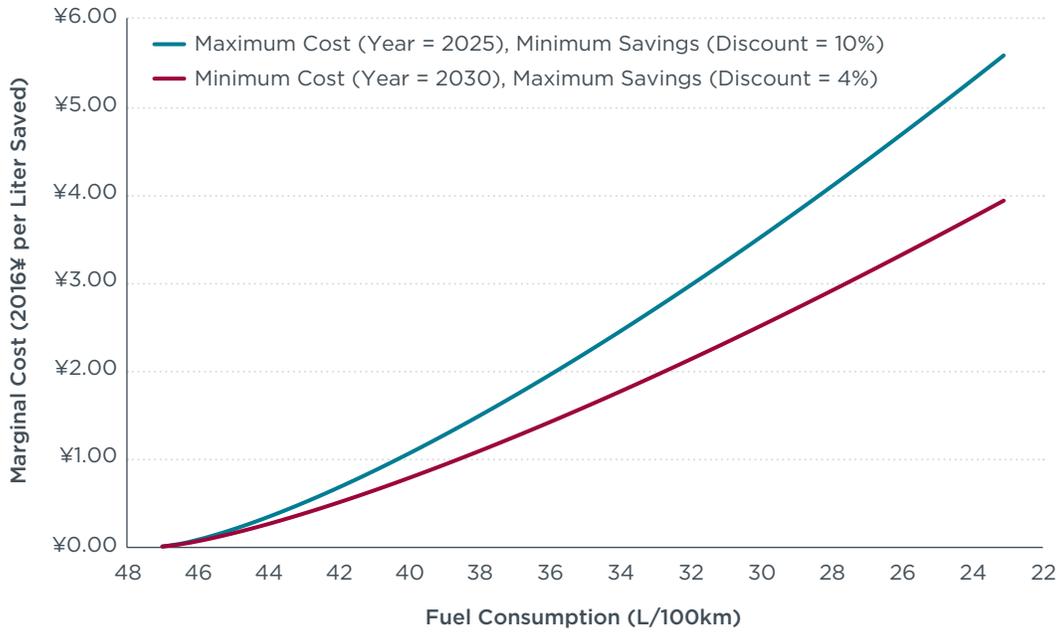


Figure 12. Best- and worst-case marginal cost per liter of fuel saved in the 2025–2030 timeframe

V. CONCLUSIONS

This study evaluates the cost impacts of long-haul tractor-trailer CO₂ reduction and efficiency technology packages that are emerging and could become widely deployed in the 2020–2030 timeframe in China. The specific technology packages evaluated in the study, based on ICCT tractor-trailer simulation modeling (Delgado et al., 2018), are presented in Figure 1. In total, the packages generate per-kilometer fuel consumption and CO₂ reductions of as much as 51%. On a non-discounted but survival-weighted basis, the most advanced of the packages offers potential lifetime savings of more than 238,000 liters of diesel fuel per equipped tractor-trailer.

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

ECONOMIC FINDINGS

Upfront costs for individual technologies and technology packages can be significant. Moderate efficiency technology packages, based on technologies largely available in the market, offer per-kilometer fuel-consumption reductions of as much as 35% and are estimated to cost ¥117,300–¥130,300 in the 2025–2030 timeframe based on best available cost data and conventional technology learning assumptions. The most advanced technology package, based on emerging technologies, offers a 51% per-kilometer reduction in fuel consumption and is estimated to cost ¥326,000–¥333,400 per new combination tractor-trailer in 2030. All cost estimates assume 1.045 trailers are equipped for every tractor. A representative baseline long-haul tractor with 1.045 trailers, as implied by China population statistics, costs about ¥422,700. On average, total vehicle costs increase by about 29% for the moderate package and by about 78% for the most advanced efficiency package.

Figure 13 depicts the breakdown of costs for the most advanced technology package in 2030. The presented technology costs are the average of minimum and maximum estimated costs, as developed for one tractor and 1.045 trailers. The advanced technology package shown in the figure delivers a tractor-trailer fuel consumption of 23.1 L/100 km, providing a 51% per-kilometer reduction in fuel consumption relative to the 2015 baseline Stage 2 technology package. For this most advanced technology package, the efficiency component costs are roughly equally distributed among the powertrain, the hybrid system, the tractor, and the trailer.

Figure 14 shows the estimated fuel-consumption reductions and the associated payback periods for evaluated technology packages in 2030. Moving down the figure, the data represent the generally sequential addition of more advanced efficiency technologies. The figure depicts how the average estimate of the payback periods evaluated in this analysis generally increases with more advanced technology packages. The “whiskers” of each payback band reflect the range of payback periods across high and low technology cost estimates under varying economic assumptions for fuel prices ranging from ¥4.50–¥9.00 per liter and discount rates ranging from 4%–10%. Payback periods for the moderate technology packages, offering as much as a 35% per-kilometer fuel-consumption reduction, are generally 1.3 years or less.

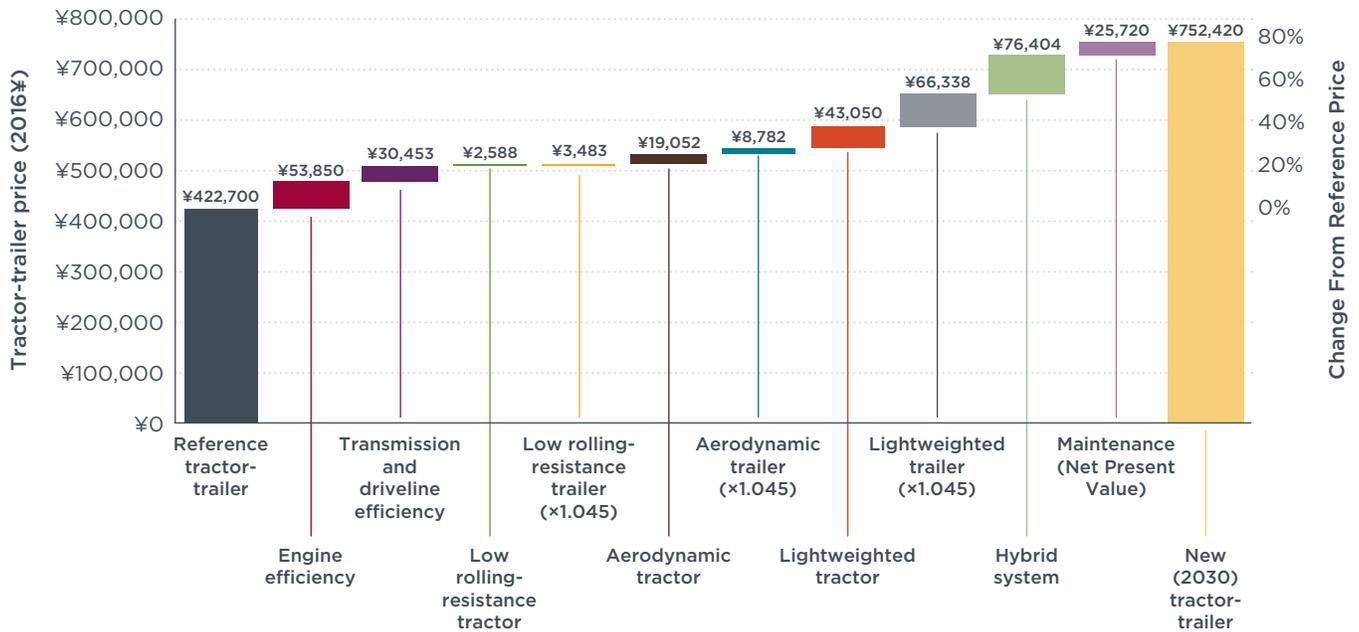


Figure 13. Tractor-trailer technology cost increase for the most advanced efficiency technology package in 2030 (1.045 trailers per tractor)

The most advanced technology packages, with 37% or greater reductions in fuel consumption, result in payback periods of 1.4–2.4 years for average economic assumptions. Although attractive, these payback estimates are based on conservative cost and VKT assumptions and would be shorter for a less conservative but still reasonable set of assumptions.

The discounted fuel savings over the average tractor-trailer lifetime greatly exceed the associated upfront technology and net present value maintenance costs of the efficiency packages. The potential discounted lifetime fuel savings for the moderate 35% per-kilometer fuel-consumption reduction technology package range from ¥478,400–¥1,215,050 per tractor-trailer, depending on discount rate and fuel-price assumptions. This compares with technology costs of ¥117,300–¥130,300. The most advanced technology package offers a 51% per-kilometer fuel-consumption reduction and is estimated to cost ¥326,000–¥333,400, resulting in ¥698,900–¥1,775,100 of lifetime fuel savings per tractor-trailer.

Substantial net lifetime savings accrue for all evaluated technology packages, with savings increasing more rapidly than technology costs for the full range of evaluated technology. For the moderate, 35% per-kilometer fuel consumption reduction packages, discounted savings range from ¥351,700–¥1,094,400 per tractor-trailer depending on evaluation year, discount rate, and fuel price. For the most advanced, 51% reduction in per-kilometer fuel consumption packages, discounted savings range from ¥372,900–¥1,441,700 per tractor-trailer. These fuel savings largely accrue to the first owner of the tractor, because of high mileage typically averaging an estimated 100,000 km per year in the first several years of ownership. The analysis of a typical five-year ownership cycle indicates that approximately half of the lifetime fuel savings

would fall to the first owner.¹¹ Under less conservative cost and VKT assumptions, net savings would be even greater.

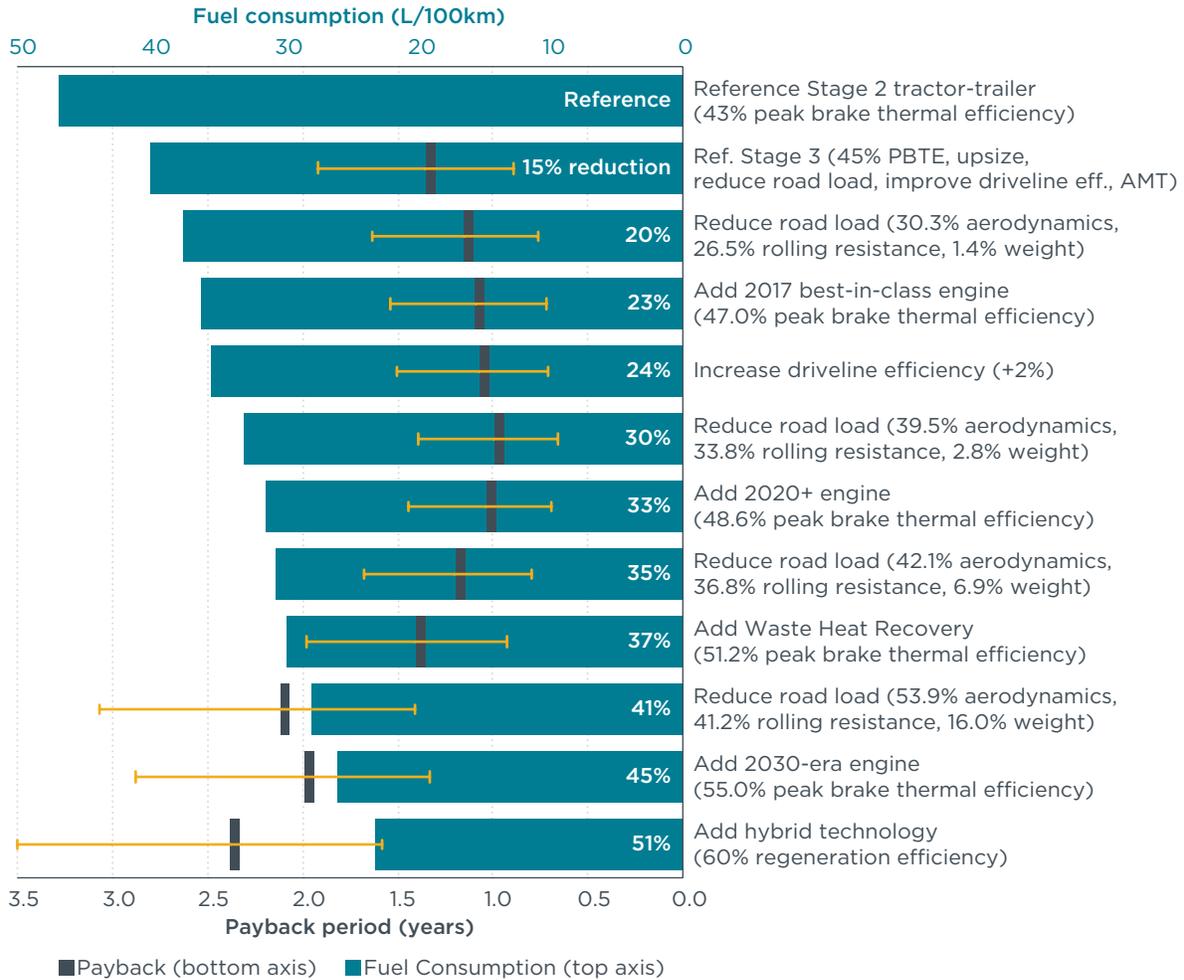


Figure 14. Fuel-consumption impacts and associated 2030 payback periods for tractor-trailer efficiency technologies

All technology packages are marginally cost-effective under all evaluated technology cost and discount rate scenarios for fuel prices expected in the 2020–2030 timeframe, with the exception of the most advanced technology packages under worst-case evaluation conditions of high discount rate, 2025 technology costs, and a fuel price of ¥4.50 per liter. Under such conditions, the marginal cost of the most advanced technology package is about ¥5.58 per liter, below the nominal fuel price estimate of ¥7.00 per liter and the high estimate of ¥9.00 but above the low estimate of ¥4.50. Under best-case conditions, the marginal cost of the most advanced technology package is about ¥3.94 per liter, well below all fuel price estimates. Moreover, although the marginal cost of the most advanced technology package exceeds the lowest expected fuel price under worst-case evaluation conditions, significant fuel-consumption reductions of at least 43% on a per-kilometer basis continue to be marginally cost-

¹¹ Vehicle lifetime for this study is defined on a 15-year survival-weighted basis. The associated median age of tractors is 9.6 years.

effective under such conditions. Under less conservative cost and VKT assumptions, marginal cost effectiveness would be further improved.

POLICY DISCUSSION AND RECOMMENDATIONS

The findings from this technology cost and payback investigation generally show that there is substantial potential to cost-effectively reduce CO₂ emissions and increase long-haul tractor-trailer efficiency in China. Regulatory stringency levels for the potential next stage of fuel consumption standards and/or first-ever greenhouse gas standards for heavy-duty vehicles in China, would ideally be predicated upon available technology, state-of-the-art understanding of technology effectiveness through modeling, and rigorous cost evaluation as conducted in this study. Key findings include:

1. ***Available efficiency technologies for long-haul tractor-trailers offer fuel savings that greatly exceed up-front technology and maintenance impact costs.*** Findings indicate that available tractor-trailer efficiency technology can reduce per-kilometer fuel consumption and CO₂ emissions by 35% from baseline 2015 Stage 2 fuel-consumption standard technology and deliver payback periods to tractor-trailer owners that are generally within 1.3 years or less. Fuel savings from these packages exceed increased technology costs by a factor of 3–12, depending on evaluated economic conditions. Based on technology availability and attractive cost-effectiveness to end users, this level of efficiency technology can be widely deployed in the 2020–2025 timeframe.
2. ***Emerging advanced efficiency technologies offer more substantial fuel savings and attractive payback periods over the long term.*** Study findings indicate that technology packages with long-term road load and engine technologies can achieve, in the post-2025 timeframe, a 51% per-kilometer reduction in fuel consumption and CO₂ emissions from baseline 2015 Stage 2 technology. For these advanced technology pathways, the payback periods from fuel savings are less than 2.4 years under average economic assumptions. Technology-forcing standards¹² and sufficient lead time would be needed to promote the development and deployment of these advanced efficiency technologies post-2025.
3. ***Tractor-trailer efficiency technologies' attractive payback periods persist even in the event of higher technology costs and low fuel prices.*** Based on this study's investigation of varying technology costs and economic assumptions—including an average fuel price as low as ¥4.50 per liter through 2030—the attractive payback findings in this study are robust. The more advanced technology packages, delivering a 37%–51% per-kilometer fuel-consumption and CO₂ emissions reduction, have payback periods of 0.9–4.0 years even when high technology costs, high discount rates, and low fuel prices are assumed. Payback would occur even sooner if less conservative, but still reasonable, VKT and technology-cost assumptions were employed. The attractive and robust payback period findings indicate that there are prevailing market barriers to technology introduction, warranting increasingly stringent tractor-trailer efficiency standards.

¹² A technology-forcing standard generally requires the development and commercialization of technologies that would otherwise be unlikely to be introduced into the market. In contrast, a technology-tracking standard accelerates the market adoption of current off-the-shelf technologies with low adoption rates.

4. Tractor-trailer efficiency technologies offer first-owner fuel savings that greatly exceed the increased upfront capital and maintenance impact costs. Examining typical first tractor owners' discounted future fuel savings, available efficiency technologies that reduce fuel consumption by 35% offer ¥126,300–¥653,000 in discounted fuel savings and result in benefits that are 2–7 times greater than the upfront technology and maintenance impact costs, depending on economic assumptions. The most advanced emerging technology package, offering a 51% fuel consumption reduction for new 2030 tractor-trailers, results in ¥310,500–¥954,100 in fuel savings, benefits that exceed costs by 1.2–5.0 times. When full tractor lifetime benefits are considered, the benefit-to-cost ratio is even greater, pointing to a clear opportunity for efficiency standards to simultaneously mitigate climate-related emissions, provide overall economic benefits, and offer an attractive investment for fleets. Positive benefits increase further under less conservative, but still reasonable, VKT and technology-cost assumptions.

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

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

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