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EFFICIENCY TECHNOLOGY POTENTIAL FOR HEAVY-DUTY DIESEL VEHICLES IN THE UNITED STATES THROUGH 2035

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EXECUTIVE SUMMARY

Heavy-duty vehicles in the United States are subject to increasingly stringent fuel efficiency and greenhouse gas standards. Set by the Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration, the current Phase 2 standards extend through model year 2027. Most heavy-duty vehicles on the road today are powered by diesel-fueled internal combustion engines and no existing national policy requires a change in this status quo.

This analysis considers the potential for technologies to improve the efficiency of internal combustion engine vehicles beyond the Phase 2 standards and out to model year 2035. We focus on two key vehicle segments: Class 8 high-roof sleeper cab tractor trucks and Class 6–7 multipurpose vocational vehicles. Drawing on previous ICCT and EPA analysis, recent literature, and the latest SuperTruck achievements, we simulate efficiency technologies using the EPA's Greenhous Gas Emissions Model (GEM). We estimate technology costs relative to low-cost compliance with the Phase 2 standard.

For both vehicle segments, engine efficiency improvements deliver the largest efficiency benefits. Low rolling resistance tires, idle reduction technologies, and tractor-trailer aerodynamic improvements are also significant but we assume some of these advances are already deployed to achieve low-cost compliance in model year 2027. For the Class 8 tractor-trailer, we identify cost-effective potential for a 29% increase in fuel economy and a 24% decrease in per ton-mile CO_2 emissions compared to Phase 2 standards, at a marginal cost of $5,200. Adding mild hybridization and transmission-enabled strategies like engine downspeeding and downsizing, which require more than two years to recoup upfront costs, increases per ton-mile efficiency gains by 10 percentage points and brings the marginal cost up to $29,300. However, the efficiency benefits of these more expensive technologies are largely erased if trailer technologies are removed, which lowers fuel economy from 13.8 to 12.1 mpg. For the Class 6–7 vocational vehicle, we identify potential for a 44% increase in fuel economy and a 34% decrease in per ton-mile CO_2 emissions from Phase 2. This technology package has a marginal cost of $15,400 relative to the standard and a cumulative payback period of less than two years.

With the entrance of zero-emission vehicles into the heavy-duty market, future standards may consider the technology potential for both conventional and zero-emission powertrains to reduce greenhouse gas emissions. Given the long lifetime of heavy-duty vehicles, fuel efficiency standards for new diesel vehicles cast a long shadow. Achieving ambitious climate targets requires that the last generations of internal combustion engine vehicles be as fuel-efficient and low-emitting as possible.

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INTRODUCTION

Heavy-duty vehicles were responsible for one-quarter of transport sector greenhouse gas emissions in the United States in 2019, with more than 99% of CO_2-equivalent emissions emitted directly as CO_2 (U.S. Environmental Protection Agency, 2021). These vehicles, defined as trucks and buses with a gross vehicle weight rating greater than 8,500 pounds, serve a range of commercial vehicle segments from last-mile delivery and refuse pickup to intercity busing and long-haul trucking.

The U.S. Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA), referred to as “the agencies” in this paper, have historically regulated heavy-duty vehicles with increasingly stringent fuel efficiency and greenhouse gas standards. The first phase of these regulations took effect in model year 2014 and set separate standards for engine and chassis manufacturers (Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles, 2011). By model year 2017, the overall efficiency of heavy-duty vehicles was required to improve by 6–23% from a 2010 baseline, with the highest percentage improvements required for Class 8 sleeper cab tractors and the lowest for Class 2b–8 vocational vehicles (Sharpe, 2011). The second and most recent phase of these regulations updated the simulation model used for vehicle certification, added a separate standard for trailers, and required further efficiency improvements for engines and vehicles starting in model year 2021 (Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles—Phase 2, 2016). By model year 2027, these Phase 2 standards will require efficiency improvements of 12–27% from a 2017 baseline.

Figure 1 shows currently adopted Phase 1 and 2 vehicle efficiency standards for two representative vehicle segments, Class 8 high-roof sleeper cab tractor trucks and Class 6–7 multipurpose vocational vehicles, measured in grams of CO_2 per ton-mile (gCO_2/ton-mi). The regulations also specify equivalent standards for fuel consumption, measured in gallons per 1000 ton-miles (gal/1000 ton-mi), using a conversion factor of 10,180 grams of CO_2 per gallon of diesel. The baseline and standards for Phase 1 are not directly comparable to those for Phase 2, which reflect more refined transmission and engine modeling, the inclusion of road grade in drive cycles, and updated aerodynamic test procedures and default trailer settings.

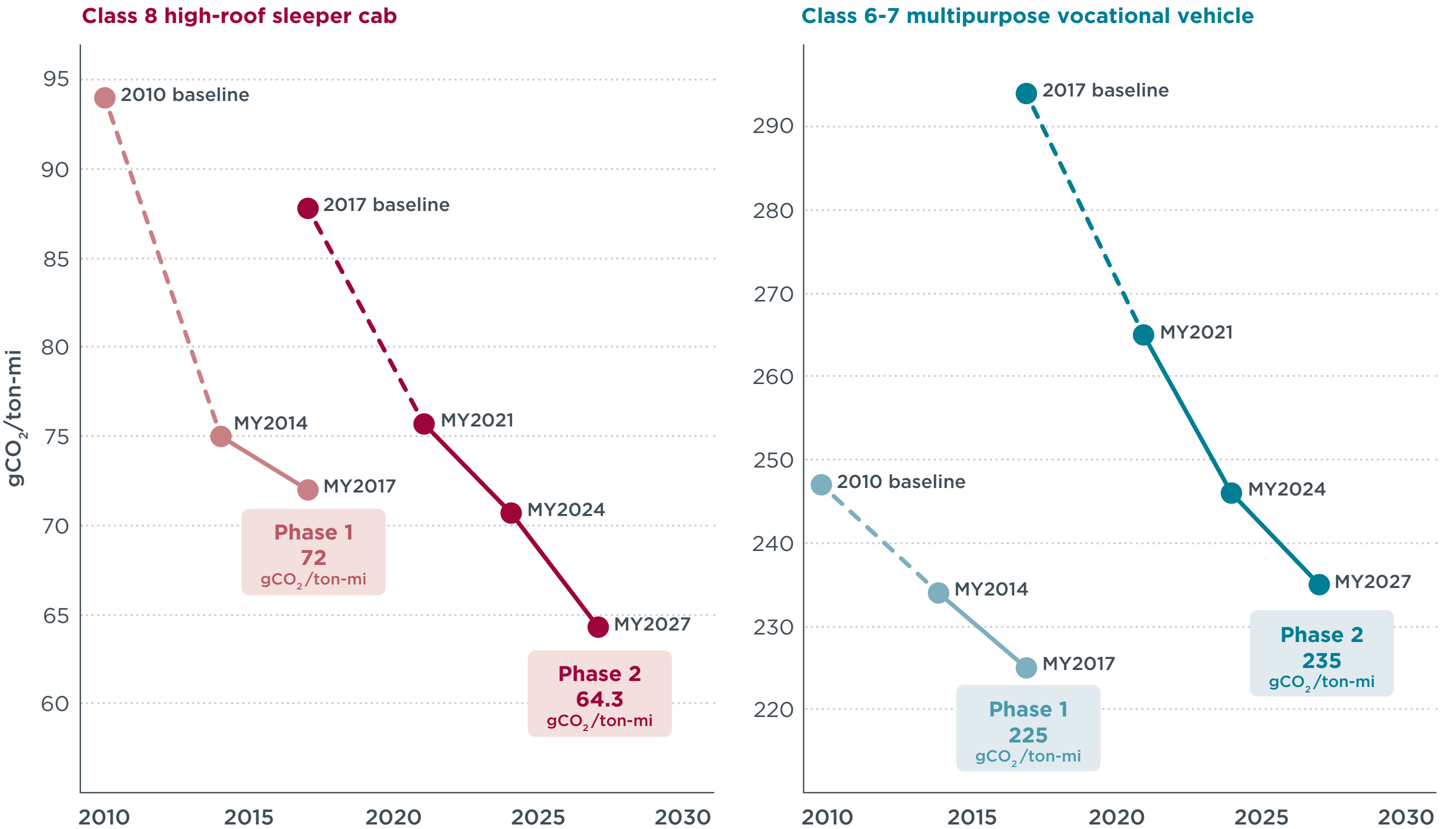

Figure 1. Phase 1 and 2 vehicle efficiency standards for Class 8 high-roof sleeper cab tractor trucks and Class 6–7 multipurpose vocational vehicles. The difference between the 2017 standard in Phase 1 and the 2017 baseline in Phase 2 reflects upgrades to the Greenhouse Gas Emissions Model (GEM), which are detailed in the model documentation and which we have summarized above.

Heavy-duty vehicles (HDVs) have historically been powered by internal combustion engines, which is reflected in the regulatory structure of current fuel efficiency standards. With growing global momentum for a transition to zero-emission technology, future standards may consider the technology potential for both conventional and zero-emission powertrains (Office of Transportation and Air Quality U.S. Environmental Protection Agency, 2021). This analysis focuses on the technology potential remaining for diesel HDVs, as they currently represent more than 99% of the fleet and no existing national policy requires a change in this status quo. Subsequent analyses will evaluate the technology potential, costs, and regulatory considerations for zero-emission HDVs.

Previous ICCT and EPA analyses identified the potential for cost-effective emissions reductions beyond those required for compliance in model year 2027 (Delgado & Lutsey, 2015; Meszler et al., 2015; U.S. EPA, 2015). Using the EPA's Greenhouse Gas Emissions Model (GEM), we build on these earlier analyses to estimate the efficiency technology potential for heavy-duty diesel vehicles out to model year 2035, focusing on the two representative vehicle segments shown in Figure 1 (U.S. Environmental Protection Agency, 2016). We evaluate the cost-effectiveness of each efficiency technology by considering the cost per percent reduction in fuel consumption and the payback period, or the time required to recoup upfront costs with fuel savings. For each vehicle segment, we project efficiency improvements and marginal costs for a single real-world vehicle in model years 2027 and 2035. We compare this technology potential to the Phase 2 standard for model year 2027, which is based on projected fleet-average technology adoption rates.

In the following sections, we first describe our vehicle simulation modeling tools and baseline vehicle parameters. We then consider the efficiency technologies that could be deployed in model year 2027 and 2035 vehicles, and subsequently evaluate their cost-effectiveness, primarily by extending cost estimates provided in the Phase 2 regulatory documents. We conclude by presenting technology packages that represent incremental improvements in vehicle efficiency in order of technology cost-effectiveness and by comparing our results to current Phase 2 standards and previous ICCT analysis.

MODELING TOOLS

The Greenhouse Gas Emission Model (GEM) is the EPA's regulatory model for certifying medium- and heavy-duty vehicle fuel consumption and CO_2 emissions. The tool is used both by the agency to develop greenhouse gas emission standards and by manufacturers to demonstrate compliance with these standards. The model was initially developed during the Phase 1 rulemaking and was updated for the Phase 2 regulation. In this analysis, we use GEM P2v3.5.1, which includes several improvements to the version first published with the Phase 2 rulemaking. Table 1 shows the baseline powertrain configuration we use in GEM for each vehicle segment.

Table 1. Baseline powertrain settings for Class 8 high-roof sleeper cabs and Class 6–7 multipurpose vocational vehicles in this study.

	Class 8 high-roof sleeper cab	Class 6–7 multipurpose vocational vehicle
Engine	15-liter, 455 hp compression-ignition	7-liter, 270 hp compression-ignition
Idle speed	600 revolutions per minute	750 revolutions per minute
Transmission	Manual, 10-speed	Automatic, 6-speed
Transmission gear ratios	12.8, 9.25, 6.76, 4.90, 3.58, 2.61, 1.89, 1.38, 1.00, 0.73	3.102, 1.8107, 1.4063, 1.0, 0.7117, 0.61
Rear axle ratio	3.70	5.29
Loaded tire size	512 revolutions per mile	557 revolutions per mile

In GEM, vehicle efficiency is calculated as a weighted average over three specific drive cycles: the California Air Resources Board's heavy heavy-duty diesel truck (HHDDT) transient cycle and two constant speed 55-mph and 65-mph cycles with variable road grade (GEM 55 mph and GEM 65 mph). For vocational vehicles,[1] efficiency is additionally weighted over two idle cycles, representing idling while parked and while in traffic. These drive and idle cycle weightings for the two vehicle segments we analyze here are listed in Table 2, adding up to 100%.

1 Vocational vehicles are a broad category of heavy-duty vehicles, including those vehicles not categorized as Class 2b-3 pickup trucks and vans or as Class 7-8 combination tractors. They include vehicles such as larger vans and trucks, utility bucket trucks, refuse trucks, and urban buses.

Table 2. GEM parameters for Class 8 high-roof sleeper cabs with long dry box trailers and Class 6–7 multipurpose vocational vehicles in the Phase 2 regulation.

	Class 8 high-roof sleeper cab	Class 6–7 multipurpose vocational vehicle
Drive and idle cycles[a]	5% HHDDT transient 9% GEM 55 mph 86% GEM 65 mph	31% HHDDT transient 13% GEM 55 mph 13% GEM 65 mph 25% parked idle 17% drive idle
Curb weight	32,500 lbs (14,742 kg)	13,950 lbs (6,328 kg)
Payload	38,000 lbs (17,237 kg)	11,200 lbs (5,080 kg)
Total weight	70,500 lbs (31,978 kg)	25,150 lbs (11,408 kg)
Gear efficiency	100% for direct drive, 98% for high gears, 96% for low gears	99.5% for direct drive, 98% for other gears
Tire rolling resistance weighting	15% steer tires 42.5% drive tires 42.5% trailer tires	30% steer tires 70% drive tires
Default trailer settings	6 kg/t tire rolling resistance -0.3 m^2 delta C_dA for trailer skirt	—
Frontal area	10.4 m^2	5.4 m^2
Weight reduction distribution	One-third added to payload, two-thirds reduced from total vehicle weight	One-half added to payload, one-half reduced from total vehicle weight
Accessory power load	1.2 kW electrical 2.3 kW mechanical	0.9 kW electrical 1.6 kW mechanical

[a] Vocational vehicle cycle weights do not add up to 100% due to rounding.

The model is structured to implement certain efficiency technologies based on a set of underlying assumptions. All high-roof tractor-trailers are simulated with a 53-foot dry box van trailer, which includes aerodynamic side skirts as part of the default aerodynamic drag area (C_dA). The rolling resistance coefficient (C_{rr}) for tires is modeled as a weighted average of steer, drive, and trailer tire coefficients, with weighting factors varying by vehicle segment. In addition, lightweighting is implemented in GEM such that only part of the applied weight reduction decreases the total weight of the vehicle and the remainder serves to increase payload. This reflects two ways in which lightweighting may improve vehicle efficiency: first, by reducing the road load (decreased weight) and second, by reducing the total number of trips needed along a given route (increased payload). In GEM, an increase in payload delivers a greater per-ton-mile efficiency gain than an equivalent decrease in vehicle weight. In practice, however, the effectiveness of lightweighting depends heavily on whether a vehicle is weight- or space-limited.

Many efficiency technologies can be implemented directly based on user-provided input data, such as engine efficiency improvements, transmission type, axle ratios, aerodynamic drag, weight reduction, and neutral idle. For vocational vehicles, stop-start and automatic engine shutdown technology can also be implemented directly. Several other technologies are implemented indirectly by specifying technology improvement multipliers that are applied to the simulation results, such as tire pressure systems, accessory loads, predictive cruise control, and extended idle reduction. The Phase 2 rulemaking pre-defines improvement values for these technologies. We align with these values except when further advances are anticipated, and we note when this is the case.

Mild hybridization cannot be simulated directly in GEM. For tractor-trailers, efficiency improvements are derived from independent modeling and are applied as a post-processing factor. To calculate efficiency gains from regenerative braking energy as captured with a mild hybrid system, we employ Simcenter Amesim, a physics-based simulation tool that supports integrated assessment of vehicle performance. We use the tool to simulate a diesel vehicle that mimics the corresponding vehicle simulation in GEM. This simulation provides high resolution data on power demand and losses, from which we calculate the potential for recovery of braking losses based on a given battery capacity and power rating. For vocational vehicles, the agencies estimate efficiency savings from mild hybridization with engineering calculations. We conservatively apply this value, which is roughly comparable to our own simulations.

TECHNOLOGY IMPROVEMENTS

The EPA's current vehicle efficiency standards are technology-neutral, such that compliance can be demonstrated with a range of technology packages. The standards themselves are set by weighting the efficiency improvement associated with individual technologies by their projected fleet-wide adoption rates. We draw on previous ICCT analysis to define a low-cost technology package that achieves compliance with the model year 2027 standard in each segment (Sharpe et al., 2018). This allows us to compare efficiency improvements and cost-effectiveness beyond Phase 2 to a single, real-world vehicle. We compare this low-cost compliance scenario with the technology adoption assumed in the Phase 2 standards and then estimate technology potential out to model year 2035.

For Class 8 high-roof sleeper cabs, we include trailer efficiency technologies but highlight tractor-only technology potential in our results, with more detail in the Appendix. To compare with tractor and trailer standards, we use the GEM inputs specified in the Phase 2 rulemaking to simulate a single tractor-trailer representing both standards in model year 2027. This combined standard is 57.7 gCO_2/ton-mi, roughly 10% lower than the tractor standard.

TRACTOR-TRAILERS

The technology adoption rates for the Phase 2 standard in model year 2027 are shown in Table 3, alongside the technology packages assumed for low-cost compliance and our estimate of the technology potential out to 2035. These assumptions are described in more detail below. Figure 2 shows efficiency improvements by technology area in each modeling scenario, relative to the Phase 2 standard. Tractor-only efficiency improvements and a summary of the 2010 baseline for tractor-trailers can be found in the Appendix.

Table 3. Class 8 high-roof sleeper cab tractor-trailers technologies and adoption rates projected under the Phase 2 standard, compared to low-cost compliance in 2027 and our assumed technology potential in 2035. Technologies not considered in the Phase 2 rulemaking are highlighted in yellow. Tire rolling resistance levels and aerodynamics bins are listed in Table A1 in the Appendix.

	Phase 2 standard in 2027	Low-cost compliance in 2027	Technology potential in 2035
Engine			
2027 compliant engine (49% peak BTE)	X	X	
Advanced engine (55% peak BTE)			X
Transmission[a]			
Manual		X	
Automatic (with neutral idle)	30%		
Automated manual	50%		
Dual clutch	10%		X
1% gear efficiency improvement	70%		X
Top gear direct drive	50%	X	X
Mild hybrid (P0 configuration)			X
Transmission-enabled			
2.70 final drive ratio baseline		X	
2.31 final drive ratio	X		
1.96 final drive ratio			X
10% engine downsizing			X
Idle reduction			
Tamper-proof AESS		X	
Adjustable AESS	15%		
Adjustable AESS + diesel auxiliary power unit (APU)	40%		X
Adjustable AESS + battery APU	15%		
Adjustable AESS + automatic stop-start	15%		
Adjustable AESS + fuel operated heater	15%		
Driveline			
6x2 axle configuration[b]	30%	X	X
Baseline axle efficiency (93.5%)	20%		
Axle efficiency with low friction lubricants (95.4%)	80%	X	
Advanced axle efficiency (97%)			X

Tire rolling resistance[c]	Phase 2 Steer	Phase 2 Drive	Phase 2 Trailer	Low-cost Steer	Low-cost Drive	Low-cost Trailer	Tech. potential Steer	Tech. potential Drive	Tech. potential Trailer
Baseline	5%	5%							
Level 1	10%	10%							
Level 2	50%	50%	5%						
Level 3	35%	35%		X	X	X			
Level 4			95%						
Level 5							X	X	X
Model input (C_{rr})	*5.6 kg/t*	*5.8 kg/t*	*4.8 kg/t*	*4.9 kg/t*	*5.0 kg/t*	*5.1 kg/t*	*4.0 kg/t*	*4.1 kg/t*	*4.2 kg/t*
Vehicle weighted-average C_{rr}	*5.3 kg/t*			*5.0 kg/t*			*4.1 kg/t*		

Aerodynamics	Phase 2 Tractor	Phase 2 Trailer	Low-cost Tractor	Low-cost Trailer	Tech. potential Tractor	Tech. potential Trailer
Bin III	20%					
Bin IV	30%					
Bin V	50%	30%	X			X
Bin VI		70%		X	X	
Bin VII						
Model input (C_dA)	*5.3 m²*	*-1.3 m² delta*	*4.9 m²*	*-1.4 m² delta*	*4.4 m²*	*-1.0 m² delta*

	Phase 2 standard in 2027	Low-cost compliance in 2027	Technology potential in 2035
Weight reduction			
Advanced lightweighting (2,700 lbs)			X
Intelligent controls			
Predictive cruise control	40%		
Advanced predictive cruise control			X
Accessories			
High efficiency or electric A/C	30%		X
Improved accessories (2 kW load reduction)	30%	X	X
Other technologies			
Tire pressure monitoring system	70%		
Automatic tire inflation system	30%	X	X

[a] Adoption rates of manual, automatic, automatic manual, and dual clutch transmission technologies do not add up to 100% in the Phase 2 rulemaking.
[b] Includes 300-pound weight reduction.
[c] In Phase 2, tire rolling resistance values are defined through Level 3 for steer and drive tires and Level 4 for trailer tires. Level 2 tires are the baseline for box trailers, while the baseline for steer and drive tires is named explicitly.

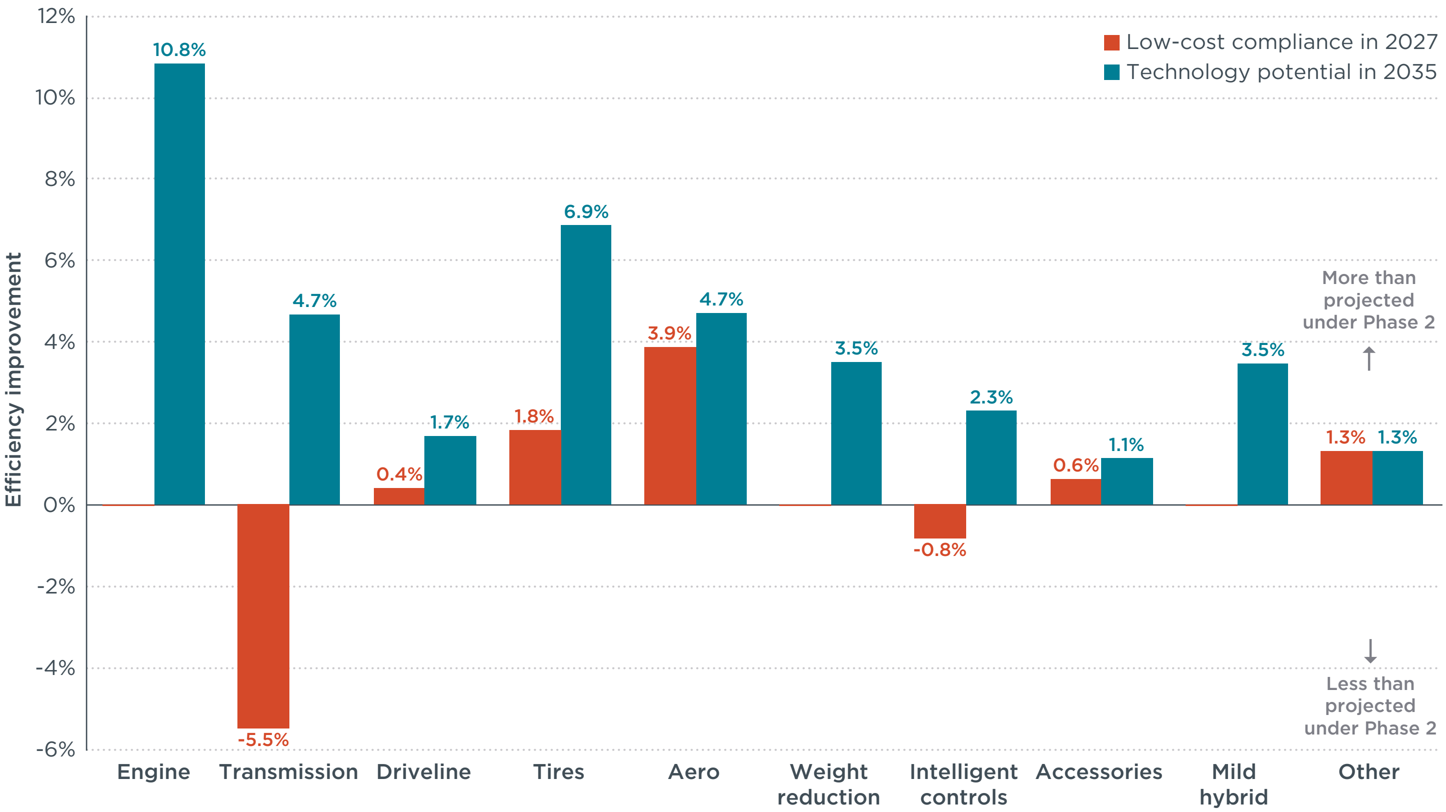

Figure 2. Tractor-trailer efficiency improvements by technology area for low-cost compliance in 2027 and technology potential in 2035, relative to Phase 2 standards.

Low-cost compliance in model year 2027

In an earlier cost analysis of the Phase 2 rulemaking, we identified an aero-focused technology package that delivered the lowest compliance costs for a Class 8 high-roof sleeper cab in model year 2027. However, this package included the most advanced aerodynamic technologies considered in the Phase 2 rulemaking for both tractors and trailers, corresponding to an aerodynamic drag area of 2.1 m^2, which may not be realistic. For this analysis we choose the second most cost-effective technology package, a tire-focused compliance strategy that included Level 3 tires and automatic tire inflation systems for both tractors and trailers. For trailers, the package also included Bin VI aerodynamics. For tractors, it included Bin V aerodynamics, a 6x2 axle configuration, top gear direct drive, a tamper-proof automatic engine shutdown system (AESS), and improved accessories. For the 6x2 configuration, we assume a weight reduction of 300 pounds. We additionally include axle efficiency improvements to achieve compliance in our simulations. This combined tractor-trailer technology package corresponds to a 6% reduction in the vehicle weighted-average tire rolling resistance coefficient compared to the adoption-weighted Phase 2 standard. With no adoption of more advanced transmission technologies, this technology area offers less efficiency improvement than projected under the standard. Collectively, this low-cost technology package delivers 56.7 gCO_2/ton-mi, an overcompliance of 1.8% in reference to our combined Phase 2 tractor-trailer standard for model year 2027.

Technology potential in model year 2035

Beyond model year 2027, we anticipate improvements in engine efficiency to achieve 55% peak brake thermal efficiency (BTE) for the Class 8 tractor-trailer, which has long been a target for the U.S. SuperTruck program and has been demonstrated by at least one of the SuperTruck 2 teams (Heavy Duty Trucking Staff, 2021). The largest engine efficiency gains are associated with advanced waste heat recovery systems.

We also include dual clutch transmission technology, which enables enhanced engine-transmission integration and further engine downspeeding compared to an automated manual transmission. In GEM, we assume that efficiency savings from enhanced power train integration are similar for both transmission types but employ a lower drive axle ratio to simulate additional downspeeding potential for dual clutch transmissions. We optimize downspeeding for fuel savings while maintaining engine performance, such that the speed-trace remains within 2 mph for more than 90% of the cycle time, as in previous ICCT work (Delgado & Lutsey, 2015). We find that 15% downspeeding from the model year 2027 standard delivers 1.9% fuel savings when paired with the advanced road load technologies outlined below. With top gear direct drive, this translates to a drive axle ratio of 1.96.

Dual clutch transmission technology also enables engine downsizing by reducing the torque reserve needed. Engine downsizing can improve vehicle efficiency by shifting engine operation toward a more efficient region, which we model in GEM by downscaling the engine map. Using the same performance criteria as above, we find that 10% engine downsizing maximizes fuel savings when paired with 15% downspeeding and the advanced road load technologies outlined below. We do not include any weight reduction associated with engine downsizing.

Other drivetrain technologies include improved transmission gear and axle efficiencies. We assume full adoption of transmission gear efficiency improvements considered in the Phase 2 rulemaking. We anticipate improvements in axle efficiency up to 97%, which could be achieved with advanced low viscosity lubricants.

As is being demonstrated by the SuperTruck 2 teams, advances in road load technologies—including tires, aerodynamics, and lightweighting—have the potential to deliver significant efficiency gains beyond Phase 2. We assume continued development of low rolling resistance tire technology out to 2035, with the vehicle weighted-average rolling resistance coefficient falling to 4.1 kilograms per tonne (kg/t), 23% lower than assumed in the combined tractor-trailer standards in 2027. This aligns with input from key industry stakeholders, SuperTruck 2 achievements, and previous ICCT analysis. For tractor-only technology potential, we assume GEM default trailer tire rolling resistance of 6 kg/t, bringing the weighted average to 4.9 kg/t.

Aerodynamic drag areas as low as 3.1 m^2 were reported as part of the SuperTruck 1 program and below 3.0 m^2 in SuperTruck 2 (National Academies of Sciences, Engineering, and Medicine, 2020; U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, n.d.-b). However, some of the aerodynamic improvements demonstrated in the SuperTruck program are possible due to the permanent pairing of the tractor and trailer, and we conservatively estimate a higher drag area of 3.4 m^2, or a drag coefficient of 0.33. This is roughly equivalent to the second-most advanced tractor aerodynamic bin and a trailer with side skirts and a boat tail. For tractor-only technology potential, we assume GEM default trailer aerodynamics, which raises aerodynamic drag by 0.7 m^2 compared to the combined tractor-trailer potential.

The Phase 2 tractor-trailer standards were not predicated on vehicle weight reduction or lightweighting. However, weight reductions of more than 4,000 pounds have been achieved by SuperTruck 1 and 2 project teams (National Academies of Sciences, Engineering, and Medicine, 2020; U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, n.d.-a). Several studies have reported fuel economy improvements ranging from 0.5% to 1% per 1,000-pound weight reduction for Class 8 tractor-trailers (National Academies of Sciences, Engineering, and Medicine, 2020; North American Council for Freight Efficiency, 2021). We model a total tractor-trailer weight reduction of 3,000 pounds, or a 9% reduction from the default GEM curb weight. This corresponds to a weight reduction of 2,700 pounds when combined with a 6x2 axle configuration and could be achieved with a shorter sleeper cab and frame, wide-base trailer tires, and the use of some aluminum components and other lightweight materials throughout the tractor and trailer. Since GEM assigns one-third of the total weight reduction to increased payload, these weight savings improve freight efficiency (i.e., gal/1000 ton-mi) by 1.3% per 1,000 pounds in our simulations. If we consider that the total vehicle weight is only reduced by two-thirds of the 2,700 pounds applied, fuel economy improves by 0.7% per 1,000 pounds of *realized* weight reduction compared to 0.4% per 1,000 pounds of *applied* weight reduction. For tractor-only technology potential, we remove 1,000 pounds of weight reduction, attributing this portion to trailer technologies.

Improvements in several other technologies may deliver efficiency improvements by 2035. We anticipate significant advances in predictive cruise control technology, with enhancements such as traffic prediction and cooperative control. Estimated efficiency improvements for these enhancements are as high as 13% but depend strongly on driving conditions: for cooperative control, much smaller efficiency improvements are associated with long separation distances, speed variation, and curved roads. (Zhai et al. 2020, Jia et al. 2021, and McAuliffe et al. 2018). We conservatively model an additional 1% efficiency gain beyond the 2% gain pre-defined in the Phase 2 rulemaking.

The electrification of accessories, known as e-accessories, is increasingly feasible with the adoption of 48-volt electrical systems. All five SuperTruck 2 project teams adopted 48-volt systems, enabling the electrification of power steering, coolant pumps, cooling fans, A/C compressors, and auxiliary power units (U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, n.d.-b). Efficiency improvements up to 1% each have been reported for electric coolant pumps and power steering (Kiesenhofer, 2021; National Academies of Sciences, Engineering, and Medicine, 2020). We conservatively model a total 1.5% efficiency gain from the baseline GEM configuration, or 1.1% compared to the Phase 2 standard, corresponding to full adoption of high efficiency A/C compressors and an additional 2 kW load reduction.

Mild hybrid technology has seen increasing adoption in several heavy-duty vehicle segments, led by transit bus operations and smaller urban delivery trucks. For tractor-trailers, hybridization primarily offers efficiency savings through the recovery of braking losses, known as regenerative braking. Several SuperTruck 2 project teams adopted mild hybrid systems, providing energy storage in addition to enabling further accessory electrification, with battery capacities up to 14 kWh (U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, n.d.-a, n.d.-b). Lombardi et al. (2020) modeled efficiency improvements upwards of 20% for a Class 8 tractor-trailer with a 28-kWh battery at 100 kW nominal power, over several drive cycles including the full FIGE and HHDDT cycles. In this analysis, we assume a P0 hybrid with a 10-kWh battery and 50 kW motor nominal power, allowing for a 60% state-of-charge swing. We estimate efficiency gains of 4.0% from regenerative braking, based on Amesim simulations weighted over the three GEM drive cycles. This estimate decreases slightly after accounting for the weight of the hybrid system, which we assume adds 500 pounds to the total vehicle weight.

VOCATIONAL VEHICLES

The technology adoption rates for the Phase 2 standard in model year 2027 are shown in Table 4, alongside the technology packages assumed for low-cost compliance and our estimate of the technology potential out to 2035. These assumptions are described in more detail below. Figure 3 shows efficiency improvements by technology area in each modeling scenario, relative to the Phase 2 standard.

Table 4. Class 6–7 multipurpose vocational vehicle technologies and adoption rates projected under the Phase 2 standard, compared to low-cost compliance in 2027 and our assumed technology potential in 2035. Technologies not considered in the Phase 2 rulemaking are highlighted in yellow. Tire rolling resistance levels and aerodynamics bins are listed in Table A1 in the Appendix.

	Phase 2 standard in 2027		Low-cost compliance in 2027		Technology potential in 2035	
Engine						
2027 compliant engine (43% peak BTE)	X		X			
Advanced engine (49% peak BTE)					X	
Transmission						
Automatic	X		X		X	
2 additional gears (8-speed)	20%					
Lock-up in 3rd	50%					
Lock-up in 1st	50%					
Advanced shift strategy	30%		X			
1% gear efficiency improvement	62%					
Bolt-on hybrid	6%					
Integrated mild hybrid with stop-start	8%				X	
Idle reduction						
Neutral idle	60%		X			
Stop-start	30%				(part of mild hybrid)	
Automatic engine shutdown	70%		X		X	
Driveline						
4x2 axle configuration	X		X		X	
5.29 drive axle ratio	X		X		X	
Baseline axle efficiency (89%)	70%		X			
Axle efficiency with low friction lubricants (93%)	30%					
Advanced axle efficiency (97%)					X	
Tire rolling resistance	**Steer**	**Drive**	**Steer**	**Drive**	**Steer**	**Drive**
Level 3v		100%				
Level 5v	100%		X	X		
Level 7v[a]					X	X
Model input (C_{rr})	*6.2 kg/t*	*6.9 kg/t*	*6.2 kg/t*	*6.2 kg/t*	*4.8 kg/t*	*4.8 kg/t*
Vehicle weighted-average C_{rr}	*6.7 kg/t*		*6.2 kg/t*		*4.8 kg/t*	
Aerodynamics						
Side skirts	0%				X	
Nose cone	0%				X	
Model input (C_dA)	*5.4 m^2*		*5.4 m^2*		*4.8 m^2*	
Weight reduction						
Aluminum wheels (150 lbs)	50%				X	
Advanced lightweighting (1,100 lbs)					X	
Accessories						
Improved accessories (0.4 kW load reduction)	15%					
Advanced accessories (0.8 kW load reduction)					X	
Other technologies						
Tire pressure monitoring system	80%		X		X	

[a] Phase 2 defined tire rolling resistance only through Level 5v.

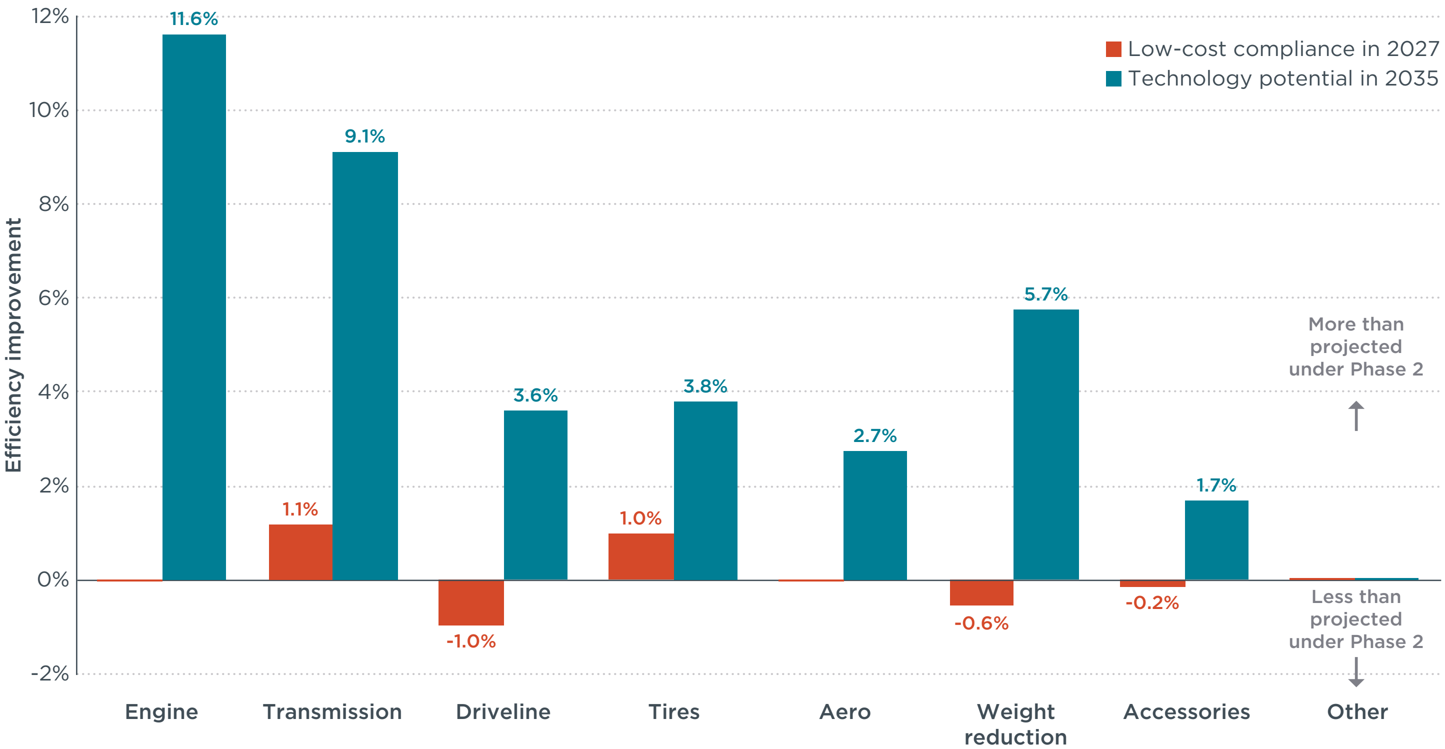

Figure 3. Vocational vehicle efficiency improvements by technology area for low-cost compliance in 2027 and technology potential in 2035, relative to the Phase 2 standard.

Lowest cost compliance in model year 2027

In an earlier cost analysis of the Phase 2 rulemaking, we identified a tire-focused technology package that delivered the lowest compliance costs for a Class 6–7 multipurpose vocational vehicle in model year 2027. This package included Level 5v tires and a tire pressure monitoring system as well as advanced shift strategy, automatic engine shutdown, and neutral idle technology. The package additionally included early torque converter lockup, which we exclude to reduce overcompliance in this analysis. This technology package corresponds to a 7.3% reduction in the vehicle weighted-average tire rolling resistance coefficient compared to the adoption-weighted Phase 2 standard. With no adoption of low friction lubricants, axle efficiency decreases by roughly 1 percentage point. Collectively, this low-cost technology package delivers 233 gCO_2/ton-mi, an overcompliance of 0.7% compared to the respective Phase 2 standard for model year 2027.

Technology potential in model year 2035

Beyond model year 2027, we anticipate further improvements in engine efficiency up to 49% peak BTE, comparable to the relative improvement we assume for tractor-trailers from model year 2027 to 2035. Achates Power recently developed a near-50% BTE engine targeting Class 8 trucks that meets California's low-NOx standards and has announced development of engine variants for medium-duty applications (Schreck, 2021). We do not consider automated manual transmissions, in alignment with the agencies who could not determine "a predictable level of improvement" over an automatic transmission (U.S. Environmental Protection Agency & U.S. DOT, 2016). As for the Class 8 tractor-trailer, we assume improvements in axle efficiency up to 97%.

Low rolling resistance tires and lightweighting are key road load reduction technologies for vocational vehicles. We anticipate advances in low rolling resistance tires beyond Level 5v, with the vehicle weighted-average rolling resistance coefficient falling to 4.8 kg/t, 28% lower than the adoption-weighted Phase 2 standard in model year 2027. This is less ambitious than that found in other ICCT analysis but represents a 3% annual reduction from the coefficient in our low-cost compliance vehicle in 2027 (Delgado et al., 2017).

Lightweighting generally delivers greater efficiency improvements for vocational vehicles than for tractor-trailers because their transient operations benefit more from curb weight reductions. Vocational vehicles are also expected to have more weight-sensitive payloads, and this is reflected in GEM, which assigns half of any simulated weight savings to payload increases compared to only one-third for tractor-trailers. Literature on lightweighting specific to medium-duty trucks is sparse, but two studies reported fuel economy improvements of 3–4% per 1,000-pound weight reduction for Class 5–7 trucks (Environmental Defense Fund, 2010; Wang et al., 2016). We model a total weight reduction of 1,250 pounds, or a 9% reduction from the default GEM curb weight. This corresponds to an additional 1,100 pounds of lightweighting beyond the aluminum wheels considered under Phase 2 and could be achieved with various lightweight material substitutes, such as for the frame, axle hubs, and driveshaft. In our simulations, these weight savings improve freight efficiency (i.e., gal/1000 ton-mi) by 4.9% per 1,000 pounds. If we consider that the total vehicle weight is only reduced by one-half of the 1,250 pounds applied, fuel economy improves by 1.5% per 1,000 pounds of *realized* weight reduction compared to 0.7% per 1,000 pounds of *applied* weight reduction.

Aerodynamic improvements deliver fewer benefits for vocational vehicles than for tractor-trailers, and therefore tend to be less cost-effective. No adoption of aerodynamic technologies was projected under the Phase 2 standards. One study reported an 8% efficiency benefit for a Class 6 box truck when equipped with side skirts and a front fairing, or nose cone (Ragatz & Thornton, 2016). We model the same 0.6 m^2 decrease in aerodynamic drag area, corresponding to a drag coefficient of 0.89.

Accessory electrification has the potential to deliver significant fuel savings in medium-duty applications. In the Phase 2 rulemaking, electrification of power steering and A/C compressors were assigned efficiency improvement values of 1% and 0.5%, respectively. The addition of high efficiency alternators and electric cooling fans could further increase accessory savings. We model a 2% efficiency gain from the baseline GEM configuration, corresponding to a total load reduction of 0.8 kW. Vocational vehicles with higher accessory loads may have larger potential improvement, which is not reflected in the default GEM configuration.

Transmission-enabled engine downspeeding and downsizing are less relevant for multipurpose vocational vehicles, which have more variable drive cycles and log fewer highway miles than long-haul trucks. In the Phase 2 rulemaking, the agencies considered several technologies for improving automatic transmissions in vocational vehicles, such as adding two more gears and enhancing driveline integration with the use of advanced shifting strategies and torque converter lockup in 1st gear instead of 3rd. However, an integrated mild hybrid with a P2 configuration—positioned between the engine and transmission—either precludes or incorporates many of the efficiency gains from these individual technologies.

For vocational vehicles, mild hybridization typically offers the largest efficiency savings through its stop-start functionality. Efficiency benefits also accrue from regenerative braking, and some may also incorporate torque assist during launch. A recent study reported a 22% efficiency improvement for a Class 6–7 urban vocational truck utilizing a mild hybrid system with stop-start (Dahodwala et al., 2021). In this analysis, we assume a 17.4% efficiency improvement for multipurpose vocational vehicles, the same as calculated by the agencies in the Phase 2 rulemaking. Estimated efficiency benefits from our own simulations in Amesim, weighted over the three GEM drive cycles, are roughly comparable. GEM does not provide a mechanism to simulate increases in vehicle weight that do not offset lightweighting, and we align with the agencies in not considering this as part of the integrated mild hybrid system.

TECHNOLOGY COST-EFFECTIVENESS

For each of the individual technology improvements described in the previous section, we assess the costs and cost-effectiveness from low-cost compliance in 2027 to the technology potential in model year 2035. We define a given technology's cost-effectiveness as its cost (in 2020 U.S. dollars) per percent reduction in fuel consumption, as measured in simulation. Unless otherwise noted, all technology costs in 2035 are estimated based on cost data in the Phase 2 rulemaking documents (U.S. Environmental Protection Agency & U.S. DOT, 2016).

TRACTOR-TRAILERS

When available, the cost data for tractor-trailer technologies are based on the Phase 2 Regulatory Impact Analysis, converted from 2013 to 2020 dollars. For those fuel-saving technologies not explicitly included in the Phase 2 rulemaking, our methodology and cost estimates are summarized in Table 5, with costs rounded to the nearest ten dollars. The methodology is described in more detail below.

Table 5. Marginal costs and methodology for tractor-trailer technologies in 2035 compared to the low-cost compliance vehicle in 2027. All other technology costs are sourced from the Phase 2 Regulatory Impact Analysis.

	Marginal cost relative to low-cost compliance in 2027 (2020$)	Methodology	Type
Engine efficiency	$8,200	Cost = [cost per % reduction, MY 2027] * 2 * 10.8%	Extended from Phase 2
Engine downsizing	-$690	Cost = [cost savings for 10% downsizing]	Adapted from Meszler et al. (2015)
Axle efficiency	$380	Cost = [cost of improvement from 93% to 95% efficiency] * 2	Extended from Phase 2
Low rolling resistance tires	$310	Cost = [cost of most advanced tire level in Phase 2] * 1.5	Extended from Phase 2
Lightweighting	$5,130	Cost = 2,700 lbs * ([Low cost per lb. for 3,240-lb. weight reduction] + [High cost per lb. for 3,240-lb. weight reduction]) / 2	Adapted from Meszler et al. (2015)
Advanced predictive cruise control	$1,680	Cost = [cost of predictive cruise control] * 2	Extended from Phase 2
Mild hybridization	$14,300	Cost = [cost of mild hybrid system for heavy heavy-duty vocational vehicle] * 1.1	Adapted from Phase 2 vocational cost

There are no cost estimates in the Phase 2 rulemaking for an engine that achieves 55% peak BTE. To estimate the cost of these engine efficiency improvements, we draw on the cost per percent fuel consumption reduction for the model year 2027 engine, which was roughly $350 per percent reduction. Efficiency improvements are expected to increase in cost as engines push up against thermodynamic limits, such that incremental improvements beyond model year 2027 would be more expensive on a cost per percent reduction basis. Based on conversations with the SuperTruck 2 project teams, there appears to be a large degree of uncertainty as to the cost of commercializing a 55% peak BTE engine. Given this uncertainty, we assume a two-fold increase in the model year 2027 cost per percent reduction. Multiplying this cost per percent reduction by the 10.8% fuel consumption reduction achieved by the 55% peak BTE engine over the regulatory cycle yields roughly $8,200. Figure A2 in the Appendix compares this cost per percent reduction in fuel consumption in 2035 to the cost estimate in 2017 and 2027 from the Phase 2 rulemaking.

Cost savings associated with engine downsizing are not included in the Phase 2 rulemaking, and we source these costs from Meszler et al. (2015). For improvements in axle efficiency up to 97%, we double the cost that the agencies estimated in the Phase 2 regulation to move from 93% to 95% efficiency.

We assume that a new tire technology bin is achieved for all tires by 2035, with costs that are 50% higher than the most advanced tire bin assumed in the Phase 2 rulemaking. For lightweighting, we estimate a per-pound cost based on the average of high- and low-cost scenarios for a 3,240-pound weight reduction in Meszler et al. (2015), multiplied by the 2,700 pounds applied in our analysis. For advances in predictive cruise control technology, we double the cost reported for predictive cruise control systems in the Phase 2 rulemaking.

We estimate the cost for a mild hybrid system for Class 8 tractor-trailers based on the agencies' cost estimates for Class 8 vocational vehicles, since hybridization was not considered in setting the stringency for tractor trucks in the Phase 2 regulation. Since tractor-trailers have more stringent durability requirements compared to vocational vehicles, we increase the cost by 10%.

Figure 4 shows the cumulative costs and percent reduction in fuel consumption as technologies are added to the vehicle in order of cost-effectiveness—i.e., technology areas are less cost-effective moving from left to right. Low rolling resistance tires are by far the most cost-effective technology area, with costs of about $60 per percent reduction in fuel consumption. Axle efficiency improvements (including 6x2 axles), advanced predictive cruise control, and aerodynamics are next in the cost-effectiveness ranking and provide fuel savings at a cost of $500 to $600 per percent reduction. Engine efficiency and accessory load reductions bring the total per-vehicle fuel savings to just over 20% at a cumulative cost of roughly $11,700. Curb weight reduction of 2,700 pounds pushes the total fuel consumption down by another 3 percentage points. The next technology progression includes a dual clutch transmission, 15% engine downspeeding, 10% engine downsizing, and a diesel auxiliary power unit (including engine automatic shutoff) which bring overall efficiency improvements to roughly 31% at a cost of nearly $22,000. A mild hybrid system is the least cost-effective technology included in our analysis and brings total fuel savings for the tractor-trailer to about 33% and total costs to roughly $53,000.

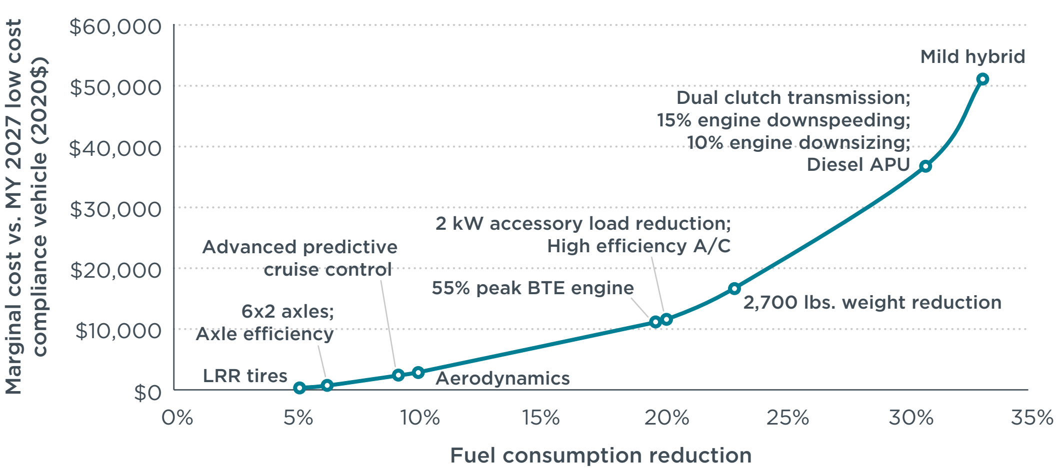

Figure 4. Cost curve of tractor-trailer efficiency technologies beyond the model year 2027 low-cost compliance Class 8 high-roof sleeper cab.

VOCATIONAL VEHICLES

Table 6 summarizes our methodology and cost estimates for fuel-saving technologies for multipurpose vocational vehicles. The methodology is described in more detail below. As for tractor-trailers, any technology costs not listed are sourced from the Phase 2 Regulatory Impact Analysis and costs are rounded to the nearest ten dollars.

Table 6. Marginal costs and methodology for Class 6–7 multipurpose vocational vehicle technologies in 2035 compared to the low-cost compliance vehicle in 2027. All other technology costs are sourced from the Phase 2 Regulatory Impact Analysis.

	Marginal cost relative to low-cost compliance in 2027 (2020$)	Methodology	Type
Engine efficiency	$3,030	Cost = [cost per % reduction, MY 2027] * 2 * 11.6%	Extended from Phase 2
Axle efficiency	$510	Cost = [cost of improvements from 90% to 93% efficiency] + [cost of tractor truck improvement from 93% to 97% efficiency]	Adapted from Phase 2 vocational and tractor truck costs
Low rolling resistance tires	$150	Cost = [cost of most advanced tire level in Phase 2] * 2	Extended from Phase 2
Aerodynamics	$930	Cost = [cost of side skirt for short van trailer] + [cost of nose cone]	Adapted from Phase 2 and NRC (2010)
Lightweighting	$2,190	Cost = 1,250 * ([Low cost per lb. for 3,240-lb. weight reduction] + [High cost per lb. for 3,240-lb. weight reduction]) / 2	Adapted from Meszler et al. (2015)
Accessory load reduction	$1,550	Cost = [cost for 0.4 kW load reduction] * 2	Extended from Phase 2

We estimate the costs of engine efficiency improvements using the same methodology as for the tractor truck engine. We again assume a two-fold increase in the cost per percent reduction in fuel consumption for the model year 2027 engine, which represents the complexity and added costs of pushing to higher peak BTE. Multiplying this cost per percent reduction by the 11.6% fuel consumption reduction achieved by the 49% peak BTE engine over the regulatory cycle yields roughly $3,000.

For improvements in axle technology, the Phase 2 rulemaking includes cost estimates to move from 90% to 93% efficiency for vocational vehicles. We use our tractor truck estimate from this study to account for additional costs to increase from 93% to 97% efficiency.

As with the tractor truck, we assume a new rolling resistance tire technology bin, with costs that are double that of the most advanced tire bin assumed in the Phase 2 rulemaking. Aerodynamic advancements are not considered for vocational vehicles in setting the stringency of the standards in the Phase 2 regulation. As such, we develop an estimate for an 11% reduction in aerodynamic drag by adding the cost of side skirts for a short box-trailer in the Phase 2 rulemaking to the estimated cost of a nose cone for a medium-duty box truck (National Research Council, 2010). For lightweighting, we use the same per-pound cost estimate derived from Meszler et al. (2015), multiplied by the 1,250 pounds applied in our vocational analysis. Finally, we double the cost of a 0.4 kW reduction in accessory loads to estimate the cost for a 0.8 kW load reduction.

Figure 5 shows the cumulative costs and percent reduction in fuel use as technologies are added to the vehicle in order of cost-effectiveness, as in Figure 4. As with tractor-trailers, low rolling resistance tires are the most cost-effective technology area we considered, with costs of about $40 per percent fuel consumption reduction. Axle efficiency improvements are also very cost-effective and provide efficiency improvements at roughly $100 per percent fuel consumption reduction. Advances in engine and aerodynamic technologies are clustered relatively closely, with each providing benefits at approximately $300 per percent reduction. Together, these technologies push efficiency improvements to over 20% compared to the model year 2027 baseline at a cumulative cost of roughly $4,700. At $340 per percent reduction, lightweighting for the vocational vehicle is much more cost-effective than for the tractor-trailer, which we estimate to cost approximately $1,500 per percent reduction. The addition of electrified and more efficient accessories, along with a hybrid-electric powertrain, brings overall fuel savings to 34% at a total cost of approximately $17,400.

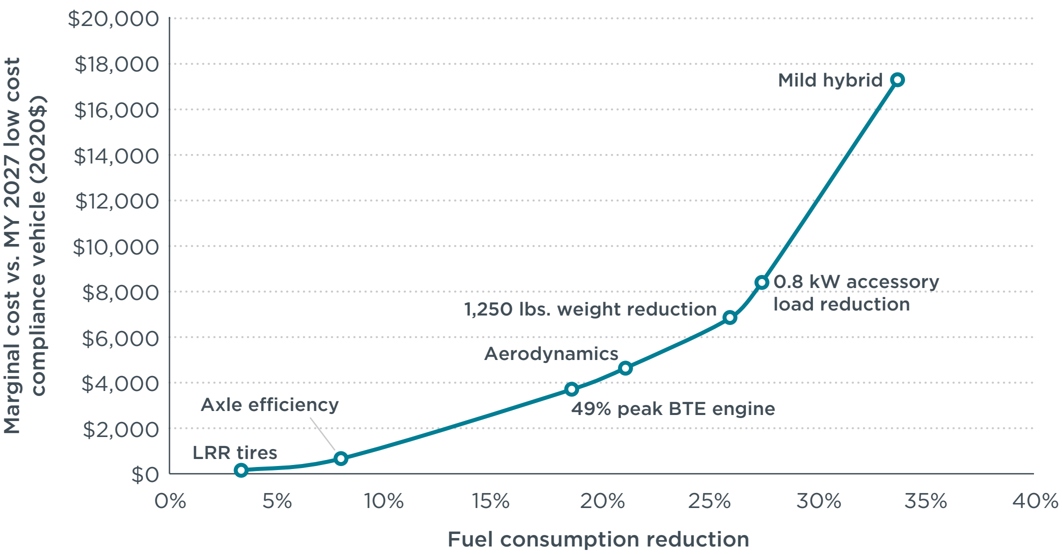

Figure 5. Cost curve of vocational vehicle efficiency technologies beyond the model year 2027 low-cost compliance Class 6–7 multipurpose vocational vehicle.

TECHNOLOGY PACKAGE RESULTS

We define several incremental technology packages for each vehicle based on deployment of technologies in order of cost-effectiveness, starting from the low-cost compliance scenario. For each of these packages, we derive the cumulative technology payback period using the cost estimates described in the previous section. Costs for individual technologies that make up each package are detailed in the Appendix, as well as a cost comparison to the Phase 2 standard in 2027.

Payback values for all technology packages are calculated using the same annual vehicle miles traveled as the agencies in the Phase 2 regulatory impact analysis. We also use 2035 diesel fuel prices from the 2021 Annual Energy Outlook (AEO)'s *Reference case* and a conservative 7% discount rate (U.S. Energy Information Administration, 2021). We additionally perform a sensitivity analysis with two bounding scenarios: (1) low fuel costs from AEO 2021 combined with a 10% discount rate and (2) high fuel costs from AEO 2021 with a 3% discount rate. The three AEO fuel price scenarios and payback results from this sensitivity analysis can be found in the Appendix.

TRACTOR-TRAILERS

Figure 6 shows vehicle efficiency improvements for each technology package compared to our combined Phase 2 tractor-trailer standard and low-cost compliance scenario in model year 2027. The payback period is shown relative to the low-cost compliance vehicle, which has compliance costs of approximately $4,200 compared to the roughly $15,800 that the agencies estimated as average compliance costs in model year 2027. The cumulative marginal costs and fuel consumption reductions for each incremental technology package are shown along with the two alternative payback period scenarios in Figure A3 in the Appendix.

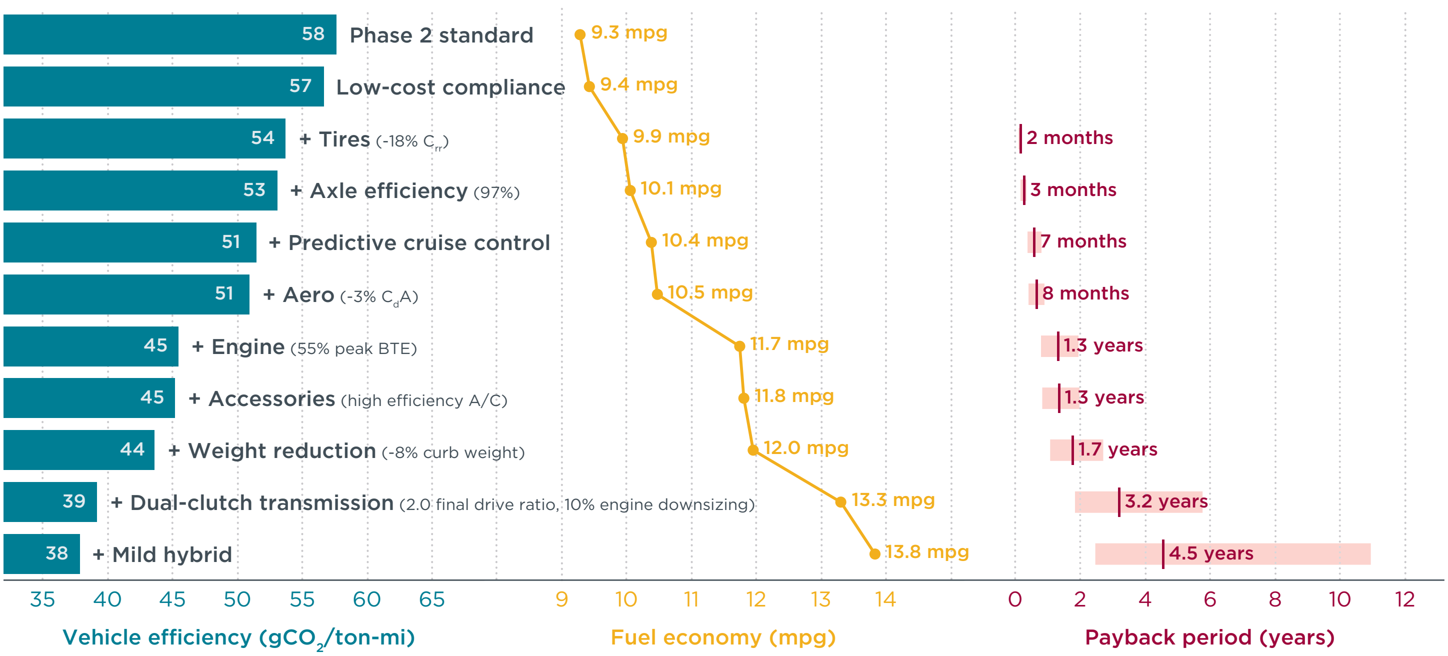

Figure 6. Vehicle efficiency, fuel economy, and payback period for incremental technology improvements from low-cost compliance with the Phase 2 standards for Class 8 high-roof sleeper cab tractor-trailers in model year 2027.

Beyond low-cost compliance with the Phase 2 standard, anticipated advances in tire rolling resistance would achieve the most cost-effective efficiency improvements. By reducing fuel use by more than 5% at a cost of roughly $300, tire advances are expected to recoup upfront costs in around 2 months. Together with improvements in axle efficiency, predictive cruise control, and aerodynamics—all with payback periods of less than one year—we project a 1 mile per gallon (mpg) increase in fuel economy and a 10% vehicle efficiency improvement. Engine and transmission technologies achieve some of the largest efficiency improvements, with each technology area raising fuel economy by roughly 1.3 mpg. Engine efficiency improvements are much more cost-effective, however, at about one-third the price of the transmission technology package. Mild hybrid technology offers a smaller 0.5 mpg fuel economy improvement at about two-thirds the price of the transmission technology package. Optimization of mild hybrid technology and additional accessory electrification not considered in our analysis have the potential to increase the fuel savings and cost-effectiveness of mild hybridization. In total, the efficiency technologies explored in this analysis deliver a 49% increase in fuel economy and a 34% decrease in per ton-mile CO_2 emissions from model year 2027 standards. This full technology potential has a marginal cost of $52,900 compared to low-cost compliance scenario, or $41,300 compared to the agencies' adoption-weighted compliance cost.

In both the Phase 1 and 2 regulations, the agencies set the stringency targets for tractor trucks such that the technology packages had payback values of two years or less. This two-year payback reflects the nature of the trucking market, in which a large percentage of fleets—particularly for-hire trucking companies—tend to have ownership cycles of four to six years. Taking the lower end of this range, a two-year payback would allow a fleet to recoup its investment in the first half of a vehicle's life and then receive a return on investment in the final two years of ownership. Excluding mild hybridization and transmission-enabled efficiency strategies like engine downspeeding and downsizing, all the technologies we modeled are projected to recoup costs within 2 years. At a marginal cost of $16,800 compared to low-cost compliance with the Phase 2 standard, this technology package delivers a 2.7 mpg, or 29%, increase in fuel economy and a 24% decrease in per ton-mile CO_2 emissions from model year 2027 standards. A model year 2035 vehicle with these technologies is projected to achieve a fuel economy of 12 mpg, doubling the 6-mpg fuel economy baseline for model year 2010 assumed in the Phase 1 rulemaking.

Previous ICCT analysis of efficiency technologies for tractor-trailers identified the potential to achieve a fuel economy of 11.6 mpg over a real-world highway cycle and 12.3 mpg over a 65-mph cycle with variable speed by 2030. In Figure 7, we compare the latter, with a drive cycle that bears more resemblance to the three GEM drive cycles, to both the full and two-year payback technology potential for 2035 identified in this analysis. We also show the combined Phase 2 tractor-trailer standards in 2027 and the EPA's projection of the best tractor-trailer in 2027 (U.S. EPA, 2015). Efficiency technologies assumed in this best tractor-trailer are summarized in Table A5 in the Appendix and include engine efficiency improvements to 49.8% peak BTE, an automated manual transmission with direct drive, and a 6x2 axle configuration.

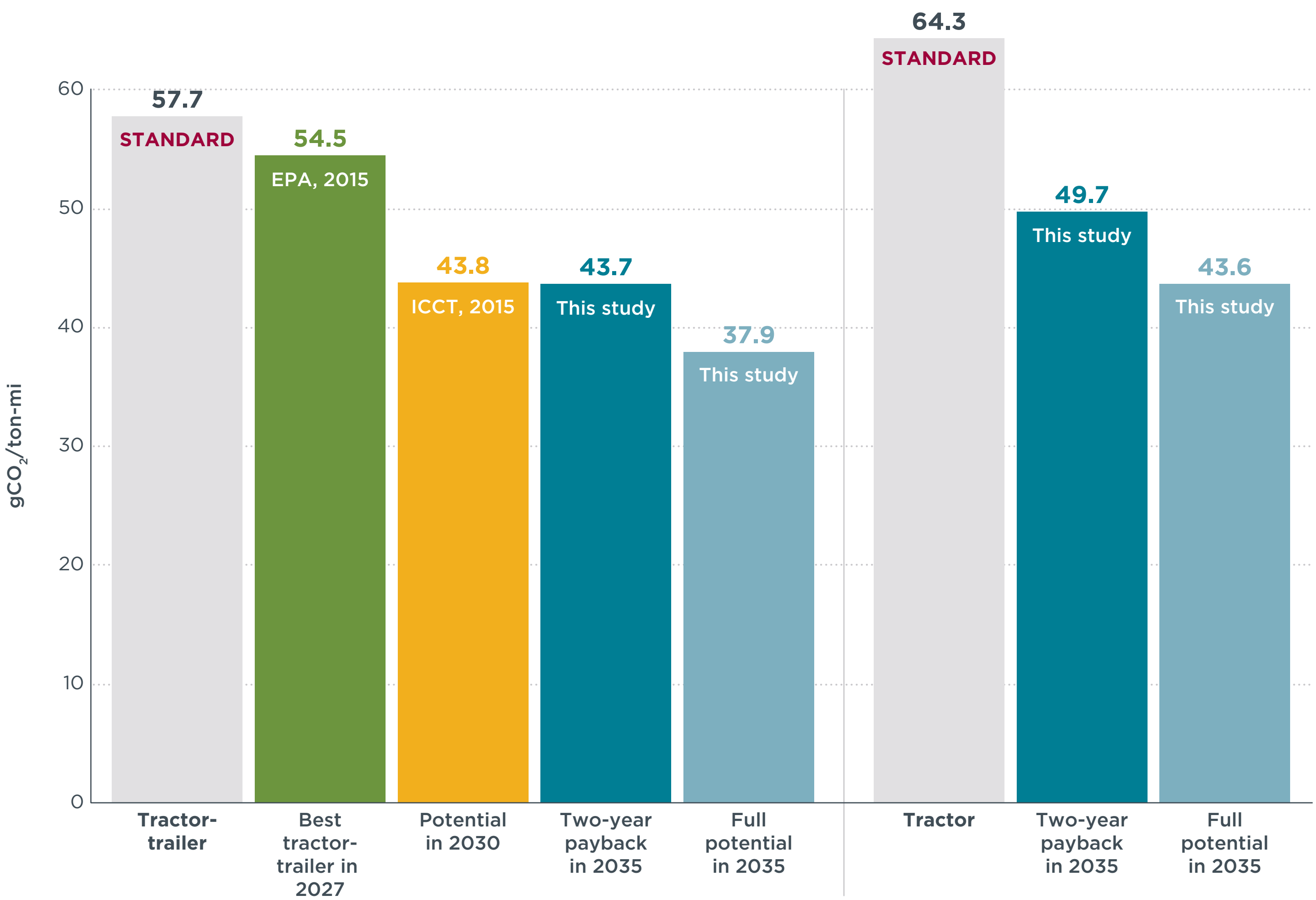

Figure 7. Tractor-trailer and tractor-only technology potential from this study compared to previous ICCT and EPA analysis, as well as Phase 2 standards. Values for fuel economy and payload can be found in the Appendix.

We separately compare tractor-only results from this analysis to the current Phase 2 tractor standard, given that Phase 2 trailer standards are currently suspended due to legal challenges from manufacturers (Motor & Equipment Manufacturers Association, n.d.). Our tractor-only simulations use the default GEM parameters for trailer tires and aerodynamics—namely 6 kg/t tire rolling resistance and -0.3 m^2 delta C_dA for trailer skirts—and exclude 1,000 pounds of lightweighting and trailer automatic tire inflation systems from the technology potential in 2035.

This comparison illustrates the untapped technology potential recognized by the EPA during the Phase 2 rulemaking process, with 6% lower per ton-mile CO_2 emissions than required under the combined tractor-trailer standards we simulated. It also shows how far the combined tractor-trailer results of our study go beyond previous ICCT analysis, with the potential for roughly 13% lower per-ton mile CO_2 emissions and 12% higher fuel economy. These results are not strictly comparable, however, given the use of a different vehicle simulation platform and different drive cycles in the earlier ICCT analysis. Still, our analysis simulates more substantial improvements in road load technology, including roughly 11% lower tire rolling resistance and roughly 7% lower aerodynamic drag area, as well as larger efficiency gains for mild hybrid technology and the consideration of e-accessories and intelligent controls. Compared to the Phase 2 standard in 2027, our analysis indicates potential for 24% (two-year payback) and 34% (full potential) reduction from the combined tractor-trailer standard we simulate.

As evidenced by the difference between combined tractor-trailer and tractor-only simulations, trailer technologies significantly improve fuel economy and vehicle efficiency. Trailers have significant untapped potential for aerodynamics and lightweighting, which has been demonstrated by the SuperTruck program. In our simulations, the inclusion of a trailer boat tail, rolling resistance tires comparable to steer and drive tires, an automatic tire inflation system, and an additional 1,000 pounds of lightweighting deliver 13% efficiency benefit. However, even without trailer technologies, we estimate tractor-only technology improvements with less than a two-year payback period could deliver 23% lower per-ton mile CO_2 emissions by 2035 compared to the Phase 2 tractor standard in 2027. This corresponds to a 27% increase in fuel economy from 8.3 to 10.6 mpg.

VOCATIONAL VEHICLES

Technology package results for vocational vehicles are shown in Figure 8, in order of cost-effectiveness and with the payback period shown relative to the low-cost compliance scenario. This low-cost vehicle has compliance costs of approximately $1,100 compared to the roughly $3,100 that the agencies estimated as average compliance costs in model year 2027. As with the tractor-trailer, cumulative marginal costs, fuel consumption reductions, and the two alternative payback period scenarios are shown in Figure A5 in the Appendix.

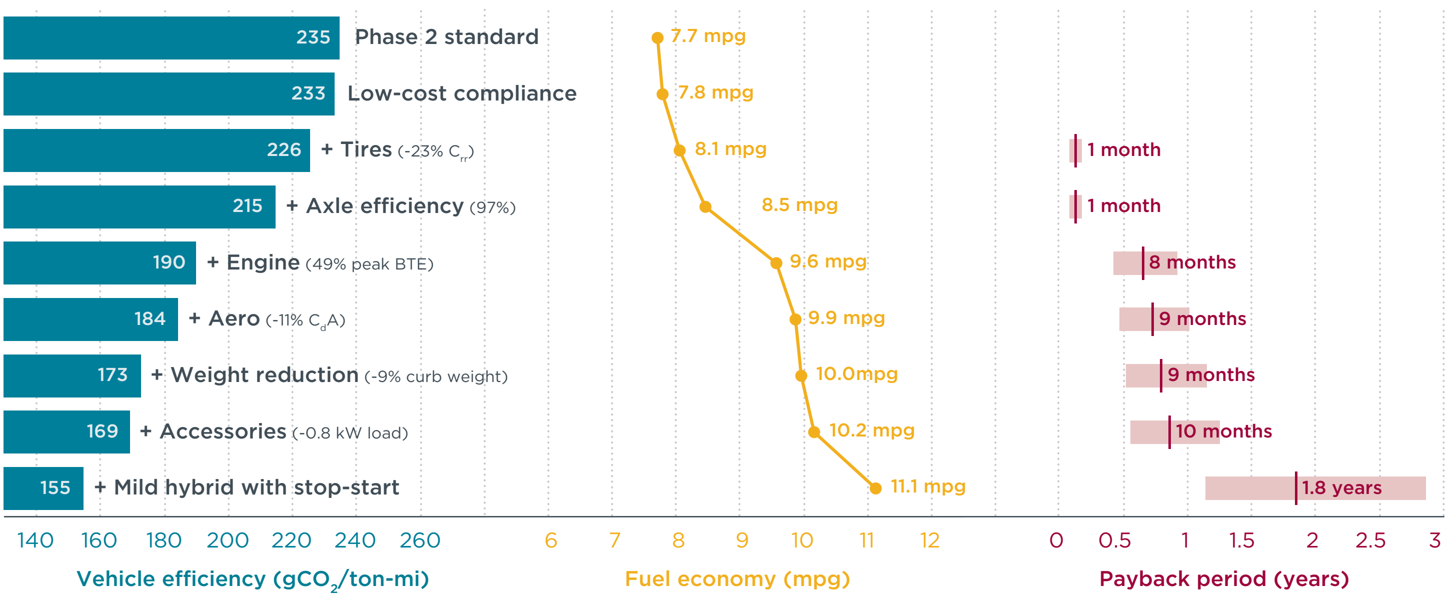

Figure 8. Vehicle efficiency, fuel economy, and payback period for incremental technology improvements from low-cost compliance with the Phase 2 standards for Class 6–7 multipurpose vocational vehicle standard in model year 2027.

The two most cost-effective technology improvements—low rolling resistance tires and axle efficiency—improve fuel economy by 0.7 mpg at an upfront cost of roughly $650 relative to the low-cost compliance vehicle. At such low cost, these technologies are expected to recoup upfront costs within a month or two. Engine efficiency improvements are the next most cost-effective technology and contribute the largest efficiency improvements, increasing fuel economy by 1.1 mpg and decreasing per ton-mile CO_2 emissions by nearly 12%. Mild hybridization is the most expensive technology we considered but offers significant fuel savings of 1 mpg, such that the cumulative payback period still falls within two years under the median cost scenario (7% discount rate, reference diesel cost).

Excluding mild hybrid technology, all the technologies we modeled are projected to recoup costs within 1 year in the median cost scenario. At a marginal cost of $8,500 compared to low-cost compliance with the Phase 2 standard, this technology package delivers a 2.5 mpg, or 32%, increase in fuel economy and a 28% reduction in per ton-mile CO_2 emissions from the model year 2027 standard. Adding mild hybrid technology brings the total cost to $17,400 compared to low-cost compliance scenario, or $19,400 compared to the adoption-weighted Phase 2 standards. We project this full technology package to deliver a 44% increase in fuel economy and a 34% decrease in per ton-mile CO_2 emissions from model year 2027 standards. A model year 2035 vehicle with these technologies is projected to achieve a fuel economy of 11.1 mpg, which is on par with cost-effective (i.e., two-year payback) tractor truck fuel economy when trailer technologies are excluded.

CONCLUSIONS

Driven by greenhouse gas emissions regulations, heavy-duty vehicles have become increasingly fuel efficient over the last decade. In this analysis, we identified the potential for further efficiency improvements beyond 2027, the last model year of the Phase 2 standards, and out to 2035. We focused on two representative vehicle segments, a Class 8 high-roof sleeper cab and a Class 6–7 multipurpose vocational vehicle. We summarize key takeaways below.

» **Tractor-trailer efficiency technologies could cost-effectively reduce per ton-mile CO_2 emissions by 24% from the Phase 2 standard.** This corresponds to a 29% improvement in fuel economy to 12 mpg. By definition, this cost-effective technology package would recoup upfront costs in less than 2 years. We estimate a marginal cost of $16,800 from the low-cost compliance scenario, or $5,200 from the agencies' average compliance cost with Phase 2 in 2027.

» **The full potential of tractor-trailer technologies could further reduce per ton-mile CO_2 emissions by 10 percentage points, to 34% below the Phase 2 standard.** Beyond the cost-effective technology package, full potential includes mild hybridization and transmission-enabled strategies like engine downspeeding and downsizing, which could increase fuel economy to 13.8 mpg. This adds a marginal cost of $24,100 onto the cost-effective package, with a full cost of $29,300 compared to the agencies' Phase 2 compliance costs. We estimate it would require nearly 5 years to recoup the upfront costs of this full technology package.

» **Estimated per ton-mile CO_2 emissions for tractors are 12–13% higher without trailer technologies.** This reduces efficiency gains by 10 percentage points, to 14% and 24% for cost-effective and full technology packages, respectively. Marginal costs are reduced by $2,000, such that trailer technologies would cost roughly $200 per percent reduction in fuel consumption compared to roughly $800 for engine efficiency improvements.

» **All the efficiency technologies we considered for vocational vehicles would recoup costs in under two years and could reduce per ton-mile CO_2 emissions by 34% from the Phase 2 standard.** This corresponds to a 44% improvement in fuel economy. We estimate a marginal cost of $17,400 from the low-cost compliance scenario, or $15,400 from the agencies' average compliance cost with Phase 2 in 2027.

» **Engine efficiency improvements deliver the largest efficiency benefits for both vehicle segments.** Low rolling resistance tires, idle reduction technologies, and tractor-trailer aerodynamic improvements are also substantial, but we assume some of these advances are already deployed to achieve low-cost compliance in model year 2027.

» **Low rolling resistance tires continue to offer the most cost-effective efficiency benefits; aerodynamics, engine efficiency, and axle efficiency also deliver cost-effective fuel savings for both vehicle segments.** This parallels previous ICCT analysis, which showed Phase 2 standards could be met most cost-effectively through the adoption of low rolling resistance tires, advanced aerodynamics, and engine efficiency improvements (Sharpe et al., 2016, 2018).

The long lifetime of heavy-duty vehicles means that many internal combustion engine trucks sold in 2035 could still be on the road in 2050. Current Phase 2 standards are expected to continue to improve fuel economy and decrease per ton-mile CO_2

emissions through model year 2027. With anticipated advances in vehicle efficiency technology, our analysis shows that substantial and cost-effective efficiency improvements could still be made beyond current standards.

While this analysis focused specifically on diesel-powered vehicles, zero-emission heavy-duty vehicles also have a vital role to play in decreasing fuel use and greenhouse gas emissions. In future work, we aim to explore how zero-emission vehicles can be integrated into the stringency requirements in the next phase of greenhouse gas emissions standards for commercial truck and buses. For the United States and other countries to achieve ambitious climate targets for the transportation sector by mid-century, it is critically important to accelerate the deployment of zero-emission vehicles and to ensure that the last generations of internal combustion vehicles are as fuel-efficient and low-emitting as possible.

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APPENDIX

Table A1. Tire rolling resistance levels and aerodynamic bins for high-roof sleeper cab tractor-trailers and vocational vehicles. Technology levels extending beyond the Phase 2 rulemaking are highlighted in yellow.

Tractor-trailers			
Tire rolling resistance (C_{rr}, kg/t)	Steer	Drive	Trailer
Baseline	7.8	8.1	—
Level 1	6.6	6.9	6.5
Level 2	5.7	6	6
Level 3	4.9	5	5.1
Level 4	4.3	4.5	4.7
Level 5	4.0	4.1	4.2
Aerodynamics (C_dA, m^2)	Tractor		Trailer delta
Bin I	≥6.9		0
Bin II	6.3-6.8		0.1
Bin III	5.7-6.2		0.4
Bin IV	5.2-5.6		0.7
Bin V	4.7-5.1		1
Bin VI	4.2-4.6		1.4
Bin VII	≤4.1		1.8
Vocational vehicles			
Tire rolling resistance (C_{rr}, kg/t)			
Level 1v	7.5-8.1		
Level 2v	7.0-7.49		
Level 3v	6.6-6.99		
Level 4v	6.3-6.59		
Level 5v	5.8-6.29		
Level 6v	5.2-5.79		
Level 7v	4.7-5.19		
Aerodynamics (C_dA, m^2)			
Skirt	-0.3		
Nose cone	-0.3		

Table A2. Model year 2010 baseline used in the Phase 1 rulemaking. Unlike Phase 2, the vocational vehicle baseline is not specific to an urban, regional, or multipurpose duty cycle.

	Class 8 high-roof sleeper cab	Class 6–7 vocational vehicle
Engine	45% peak BTE	40% peak BTE
Transmission	10-speed manual with direct drive	6-speed manual
Driveline	6x4 configuration 2.64 drive axle ratio 93.5% axle efficiency	4x2 configuration 3.36 drive axle ratio GEM default axle efficiency
Tire rolling resistance	7.2 kg/t weighted average	9 kg/t weighted average
Aerodynamics	7.3 m² C_dA	5.4 m² C_dA
Accessories	1.35 kW load	1.3 kW load

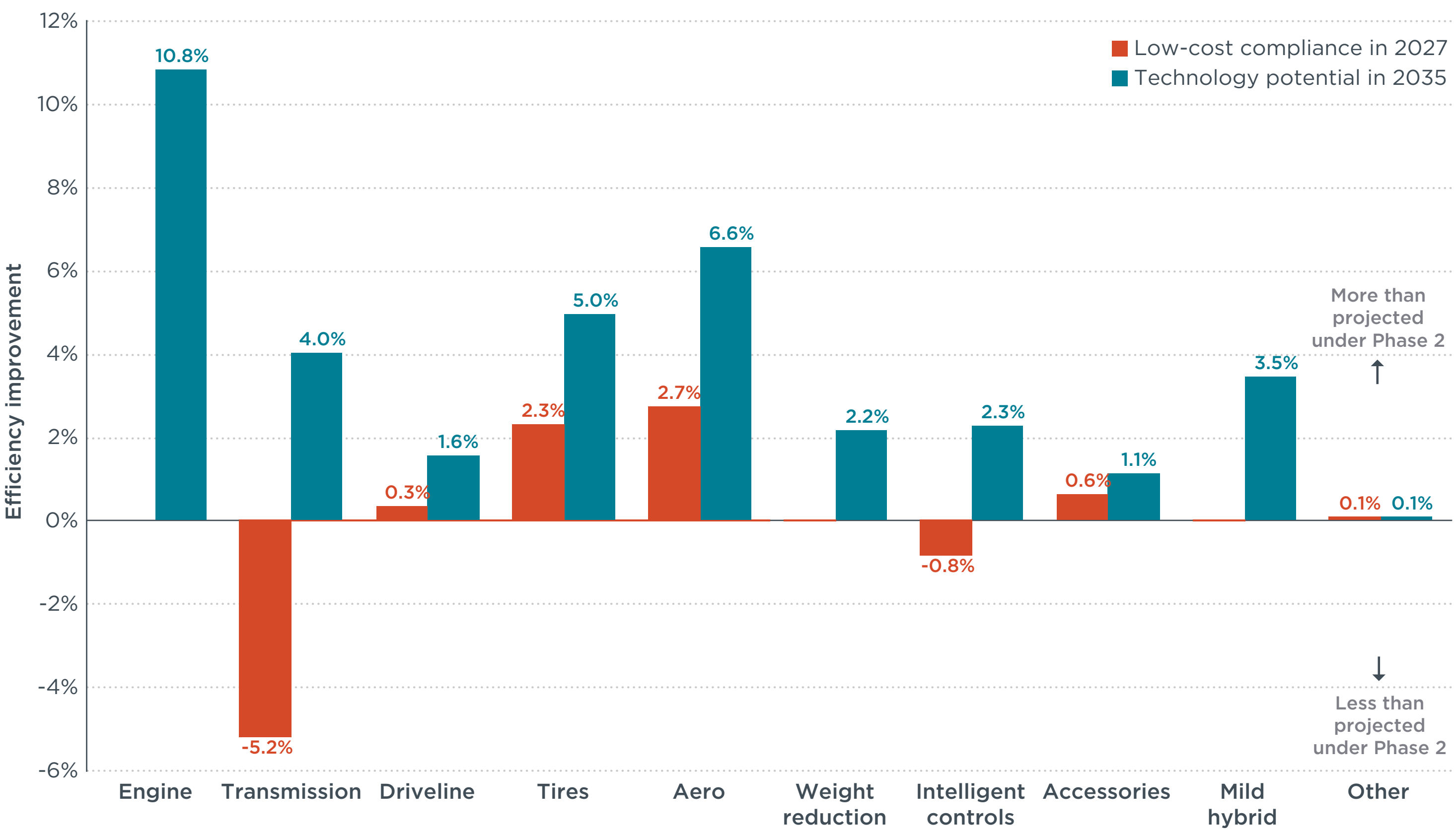

Figure A1. Vehicle efficiency improvements by technology area relative to the Phase 2 tractor standard, for low-cost compliance in 2027 and technology potential out to 2035. Transmission includes transmission-enabled downspeeding and downsizing, as well as idle reduction technologies; other includes tire pressure monitoring systems.

Table A3. Class 8 high roof sleep cab tractor technology adoption rates and costs for the Phase 2 model year 2027 standard, the low-cost compliance vehicle in model year 2027, and 2035 technology potential.

	Technology cost (2020$)	Adoption rates			Package costs (2020$)		
		MY 2027 standard	MY 2027 low-cost compliance	MY 2035 technology potential	MY 2027 standard	MY 2027 low-cost compliance	MY 2035 technology potential
Engine							
2027 compliant engine (49% peak BTE)	$1,726	100%	100%		$1,726	$1,726	$0
2027 compliant engine + WHR (50% peak BTE)	$5,751				$0	$0	$0
Advanced engine (55% peak BTE)	$8,198			100%	$0	$0	$9,933
15% engine downsizing	-$685			100%	$0	$0	-$685
Transmission							
Automatic (with neutral idle)	$13,347	30%			$4,004	$0	$0
Automated manual	$4,212	50%			$2,106	$0	$0
Dual clutch	$12,656	10%		100%	$1,445	$0	$14,453
1% gear efficiency improvement	$292	70%		100%	$204	$0	$292
Top gear direct drive	$0	50%	100%	100%	$0	$0	$0
Driveline							
6x2 axle configuration	$190	30%	100%	100%	$57	$190	$190
2.31 final drive ratio baseline		100%			$0	$0	$0
2.26 final drive ratio					$0	$0	$0
2.08 final drive ratio				100%	$0	$0	$0
Baseline axle efficiency (93.5%)		20%			$0	$0	$0
Axle efficiency with low friction lubricants (95.4%)	$190	80%			$152	$0	$0
Improved axle efficiency (96%)	$285				$0	$0	$0
Advanced axle efficiency (97%)	$380			100%	$0	$0	$380

Tire rolling resistance	Tech cost Steer	Tech cost Drive	Tech cost Trailer	MY 2027 std. Steer	MY 2027 std. Drive	MY 2027 std. Trailer	MY 2027 low-cost Steer	MY 2027 low-cost Drive	MY 2027 low-cost Trailer	MY 2035 Steer	MY 2035 Drive	MY 2035 Trailer	Pkg MY 2027 std. Steer	Pkg MY 2027 std. Drive	Pkg MY 2027 std. Trailer	Pkg MY 2027 low-cost Steer	Pkg MY 2027 low-cost Drive	Pkg MY 2027 low-cost Trailer	Pkg MY 2035 Steer	Pkg MY 2035 Drive	Pkg MY 2035 Trailer
Baseline	$0	$0	$0	5%	5%								$0	$0	$0	$0	$0	$0	$0	$0	$0
Level 1	$43	$172	$174	10%	10%								($26)	($103)	($17)	($30)	($120)	($17)	($30)	($120)	($17)
Level 2	$49	$198	$201	50%	50%	5%							$15	$59	($171)	($10)	($40)	($181)	($10)	($40)	($181)
Level 3	$56	$223	$227	35%	35%		100%	100%	100%				$20	$78	$0	$56	$223	$227	$0	$0	$0
Level 4	$75	$295	$227			95%							$0	$0	$215	$0	$0	$0	$0	$0	$0
Level 5	$105	$413	$295							100%	100%	100%	$0	$0	$0	$0	$0	$0	$105	$413	$295

	Technology cost (2020$)	Adoption rates: MY 2027 standard	Adoption rates: MY 2027 low-cost compliance	Adoption rates: MY 2035 technology potential	Package costs: MY 2027 standard	Package costs: MY 2027 low-cost compliance	Package costs: MY 2035 technology potential
Aerodynamics							
Bin III	$1,377	20%			($826)	($1,102)	($1,102)
Bin IV	$1,678	30%			$336	($168)	($168)
Bin V	$2,379	50%	100%		$1,189	$2,379	$0
Bin VI	$2,893			100%	$0	$0	$2,893
Bin VII	$3,405					$0	
Idle reduction							
Adjustable automatic engine shutdown system (AESS)	$27	15%	100%		$4	$27	$0
Adjustable AESS + diesel auxiliary power unit (APU)	$7,724	40%		100%	$3,090	$0	$7,724
Adjustable AESS + battery APU	$4,944	15%			$742	$0	$0
Adjustable AESS + automatic stop-start	$1,481	15%			$222	$0	$0
Adjustable AESS + fuel operated heater	$860	15%			$129	$0	$0
Intelligent controls							
Predictive cruise control	$837	40%			$335	$0	$0
Advanced predictive cruise control	$1,675			100%	$0	$0	$1,675
Accessories							
High efficiency or electric A/C	$166	30%		100%	$50	$0	$166
E-accessories (1 kW load reduction)	$133		100%		$0	$133	$0
Advanced e-accessories (2 kW load reduction)	$267	30%		100%	$80	$0	$267
Other technologies							
Tire pressure monitoring system	$554	70%			$388	$0	$0
Automatic tire inflation system	$870	30%	100%	100%	$261	$870	$870
Lightweighting (2,700 lbs)	$5,133			100%	$0	$0	$5,133
Mild hybridization (10-kWh battery)	$14,300			100%	$0	$0	$14,300
TOTAL					**$15,764**	**$4,164**	**$56,735**

Table A4. Class 6–7 multipurpose vocational vehicle technology adoption rates and costs for the Phase 2 model year 2027 standard, the low-cost compliance vehicle in model year 2027, and 2035 technology potential.

	Technology cost (2020$)		Adoption rates: MY 2027 standard		Adoption rates: MY 2027 low-cost compliance		Adoption rates: MY 2035 technology potential		Package costs (2020$): MY 2027 standard		Package costs (2020$): MY 2027 low-cost compliance		Package costs (2020$): MY 2035 technology potential	
Engine														
2027 compliant engine (43% peak BTE)	$495		100%		100%				$495		$495		$0	
Improved engine (44% peak BTE)	$739								$0		$0		$0	
Advanced engine (49% peak BTE)	$3,033						100%		$0		$0		$3,657	
Transmission														
Automatic			100%		100%				$0		$0		$0	
Automated manual							100%		$0		$0		$0	
2 additional gears (8-speed)	$517		20%						$103		$0		$0	
Lock-up in 3rd			50%						$0		$0		$0	
Lock-up in 1st	$29		50%		100%				$14		$29		$0	
Advanced shift strategy	$81		30%		100%		100%		$24		$81		$81	
1% gear efficiency improvement	$297		62%				100%		$184		$0		$297	
Driveline														
4x2 axle configuration			100%		100%		100%		$0		$0		$0	
5.29 drive axle ratio			100%		100%		100%		$0		$0		$0	
Baseline axle efficiency (90.5%)			70%						$0		$0		$0	
Axle efficiency with low friction lubricants (93%)	$129		30%						$39		$0		$0	
Advanced axle efficiency (97%)	$509						100%		$0		$0		$509	
Tire rolling resistance	**Steer**	**Drive**	**Steer**	**Drive**	**Steer**	**Drive**	**Steer**	**Drive**	**Steer**	**Drive**	**Steer**	**Drive**	**Steer**	**Drive**
Level 1v	$43	$88							($43)	($88)	($43)	($88)	($43)	($88)
Level 2v	$43	$88							$0	$0	$0	$0	$0	$0
Level 3v	$50	$101		100%					$0	$101	$0	$0	$0	$0
Level 4v	$57	$113							$0	$0	$0	$0	$0	$0
Level 5v	$57	$113	100%		100%	100%			$57	$0	$57	$113	$0	$0
Level 6v	$75	$150							$0	$0	$0	$0	$0	$0
Level 7v	$105	$210					100%	100%	$0	$0	$0	$0	$105	$210
Aerodynamics														
Skirt	$431						100%		$0		$0		$431	
Nose cone	$500						100%		$0		$0		$500	
Idle reduction														
Neutral idle	$127		60%		100%				$76		$127		$0	
Stop-start	$844		30%				(part of mild hybrid)		$253		$0			
Automatic engine shutdown	$28		70%		100%		100%		$19		$28		$28	
Accessories														
E-accessories (0.4 kW load reduction)	$774		15%						$116		$0		$0	
Advanced e-accessories (0.8 kW load reduction)	$1,549						100%		$0		$0		$1,549	
Other technologies														
Tire pressure monitoring system	$297		80%		100%		100%		$237		$297		$297	
Aluminum wheels (150 lbs)	$652		50%						$326		$0		$0	
Advanced lightweighting (1,250 lbs)	$2,191						100%		$0		$0		$2,191	
Bolt-on mild hybrid	$7,672		6%						$460		$0		$0	
Integrated mild hybrid with stop-start	$8,876		8%				100%		$710		$0		$8,876	
TOTAL									**$3,085**		**$1,095**		**$18,599**	

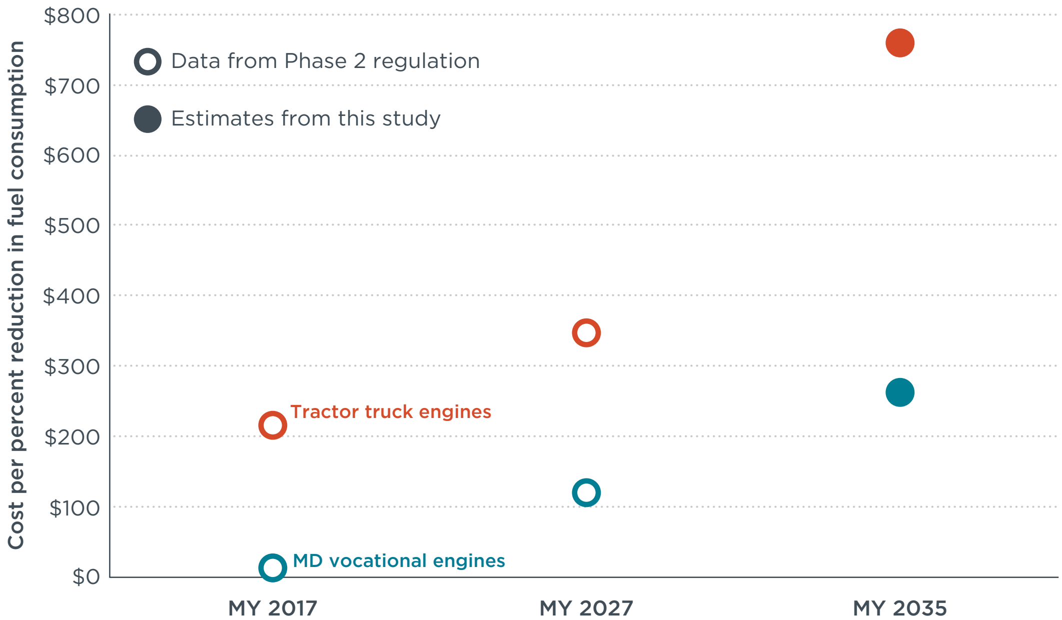

Figure A2. Cost per percent reduction in fuel consumption for heavy-duty tractor truck and medium-duty vocational vehicle engines.

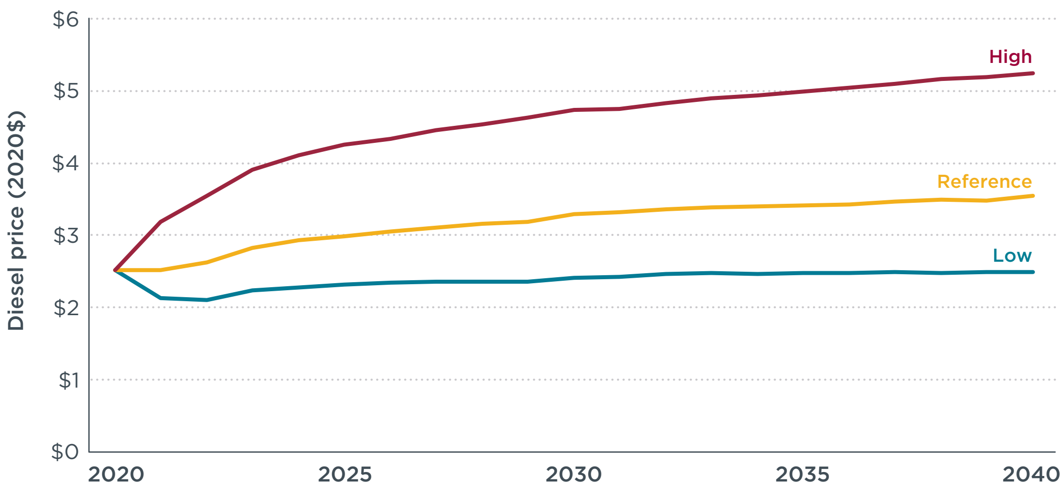

Figure A3. Fuel prices from the Energy Information Administration's 2021 Annual Energy Outlook.

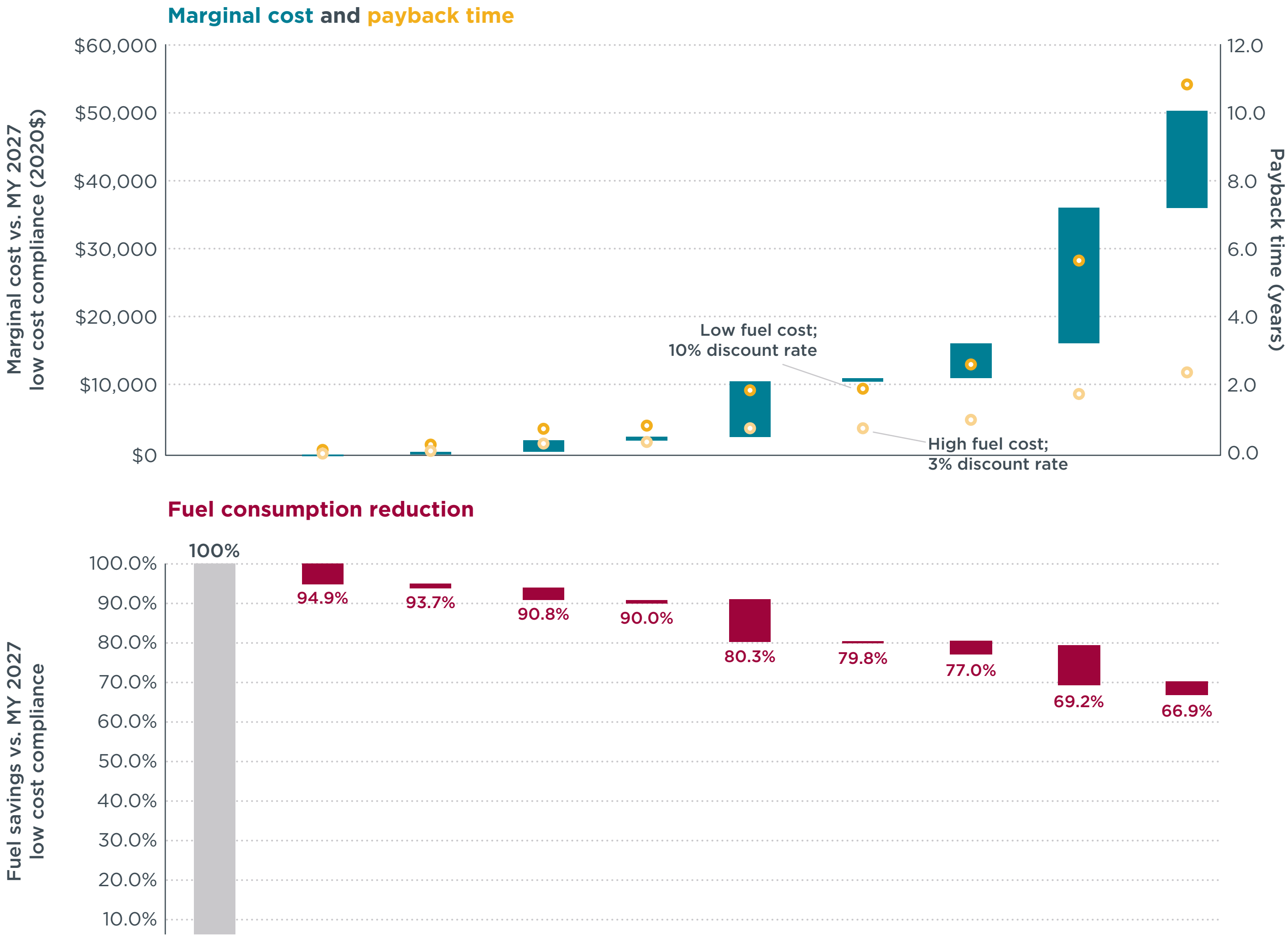

Figure A4. 2035 marginal costs, payback times, and fuel consumption reduction of Class 8 high-roof sleeper cab tractor-trailer technologies compared to the low-cost compliance vehicle in 2027.

Table A5. Class 8 high-roof sleeper cab tractor-trailers technologies and adoption rates projected under the Phase 2 standard compared to the EPA's projected best tractor-trailer in 2027. Technology potential not considered in the Phase 2 rulemaking is highlighted in yellow.

	Phase 2 standard in 2027			Projected best-in-class in 2027		
Engine						
2027 compliant engine (49% peak BTE)	100%					
2027 compliant engine + WHR (50% peak BTE)				X		
Transmission						
Automatic (with neutral idle)	30%					
Automated manual	50%			X		
Dual clutch	10%					
1% gear efficiency improvement	70%					
Top gear direct drive	50%			X		
Transmission-enabled						
2.31 final drive ratio	100%					
2.26 final drive ratio				X		
Idle reduction						
Adjustable AESS	15%					
Adjustable AESS + diesel auxiliary power unit (APU)	40%					
Adjustable AESS + battery APU	15%					
Adjustable AESS + automatic stop-start	15%					
Adjustable AESS + fuel operated heater	15%					
Driveline						
6x2 axle configuration	30%			X		
Baseline axle efficiency (93.5%)	20%					
Axle efficiency with low friction lubricants (95.4%)	80%					
Improved axle efficiency (96%)				X		
Tire rolling resistance	**Steer**	**Drive**	**Trailer**	**Steer**	**Drive**	**Trailer**
Baseline	5%	5%				
Level 1	10%	10%				
Level 2	50%	50%	5%			
Level 3	35%	35%				
Level 4			95%	X	X	X
Model input (C_{rr})	*5.6 kg/t*	*5.8 kg/t*	*4.8 kg/t*	*4.3 kg/t*	*4.5 kg/t*	*4.7 kg/t*
Aerodynamics	**Tractor**	**Trailer**[c]		**Tractor**	**Trailer**	
Bin III	20%					
Bin IV	30%					
Bin V	50%	30%		X	X	
Bin VI		70%				
Model input (C_dA)	*5.3 m²*	*-1.3 m² delta*		*5.0 m²*	*-1.0 m² delta*	
Intelligent controls						
Predictive cruise control	40%			X		
Accessories						
High efficiency or electric A/C	30%			X		
Improved accessories (1 kW load reduction)				X		
Advanced accessories (2 kW load reduction)	30%					
Other technologies						
Tire pressure monitoring system	70%					
Automatic tire inflation system	30%			X		

Table A6. Tractor-trailer technology potential from this study compared to previous ICCT and EPA projections. Values correspond to Figure 7.

	Type	Source	CO_2 emissions (gCO2/ton-mi)	Fuel economy (mpg)	Payload (tons)
Tractor-trailer	Phase 2 tractor-trailer standards	This study, based on EPA rulemaking	57.7	9.3	19
	Best projected in 2027	EPA, 2015	54.5	9.8	19
	Technology potential in 2030[a]	ICCT, 2015	46.8	11.6	18.7
	Two-year payback technology potential in 2035	This study	43.7	12.0	19.5
	Full technology potential in 2035	This study	37.9	13.8	19.4
Tractor only	Phase 2 tractor standard	EPA rulemaking	64.3	8.3	19
	Two-year payback technology potential in 2035	This study	49.7	10.6	19.3
	Full technology potential in 2035	This study	43.6	12.1	19

[a] Modeled in Autonomie over a real-world highway cycle

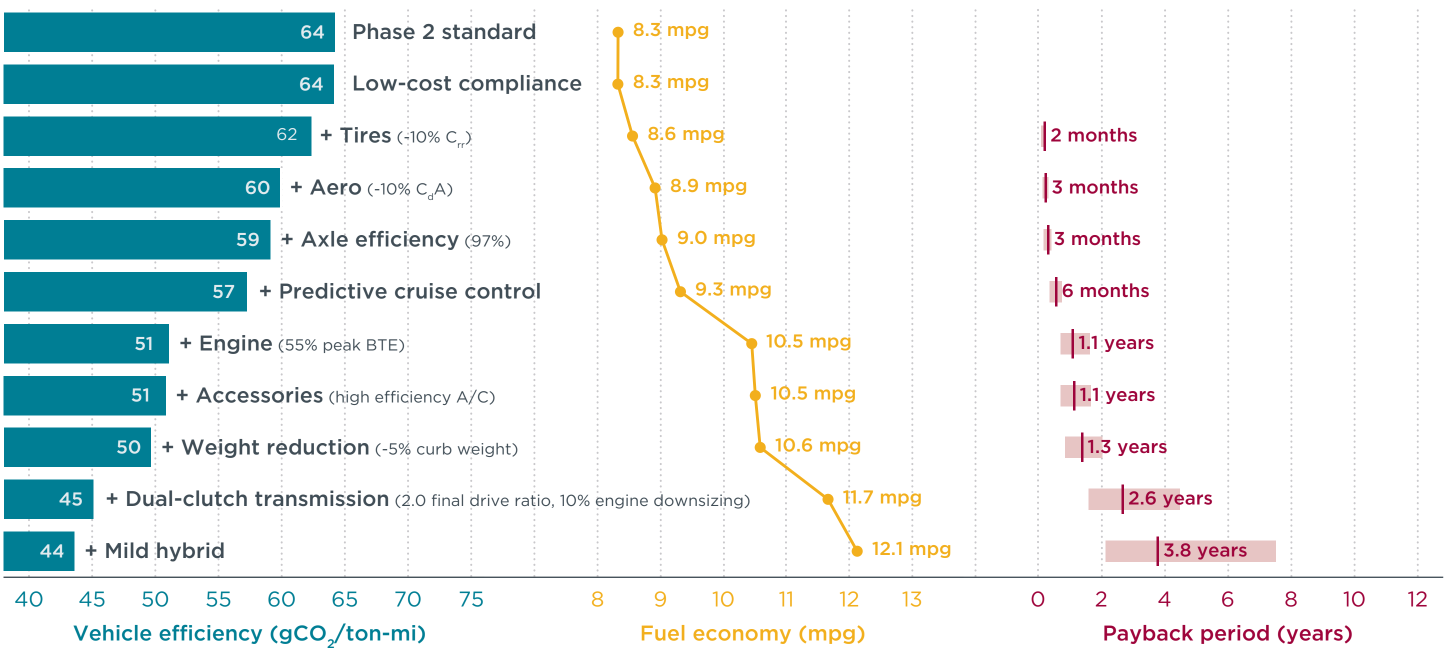

Figure A5. Vehicle efficiency, fuel economy, and payback period for incremental technology improvements from low-cost compliance with the Phase 2 standard for Class 8 high-roof sleeper cab tractors in model year 2027.

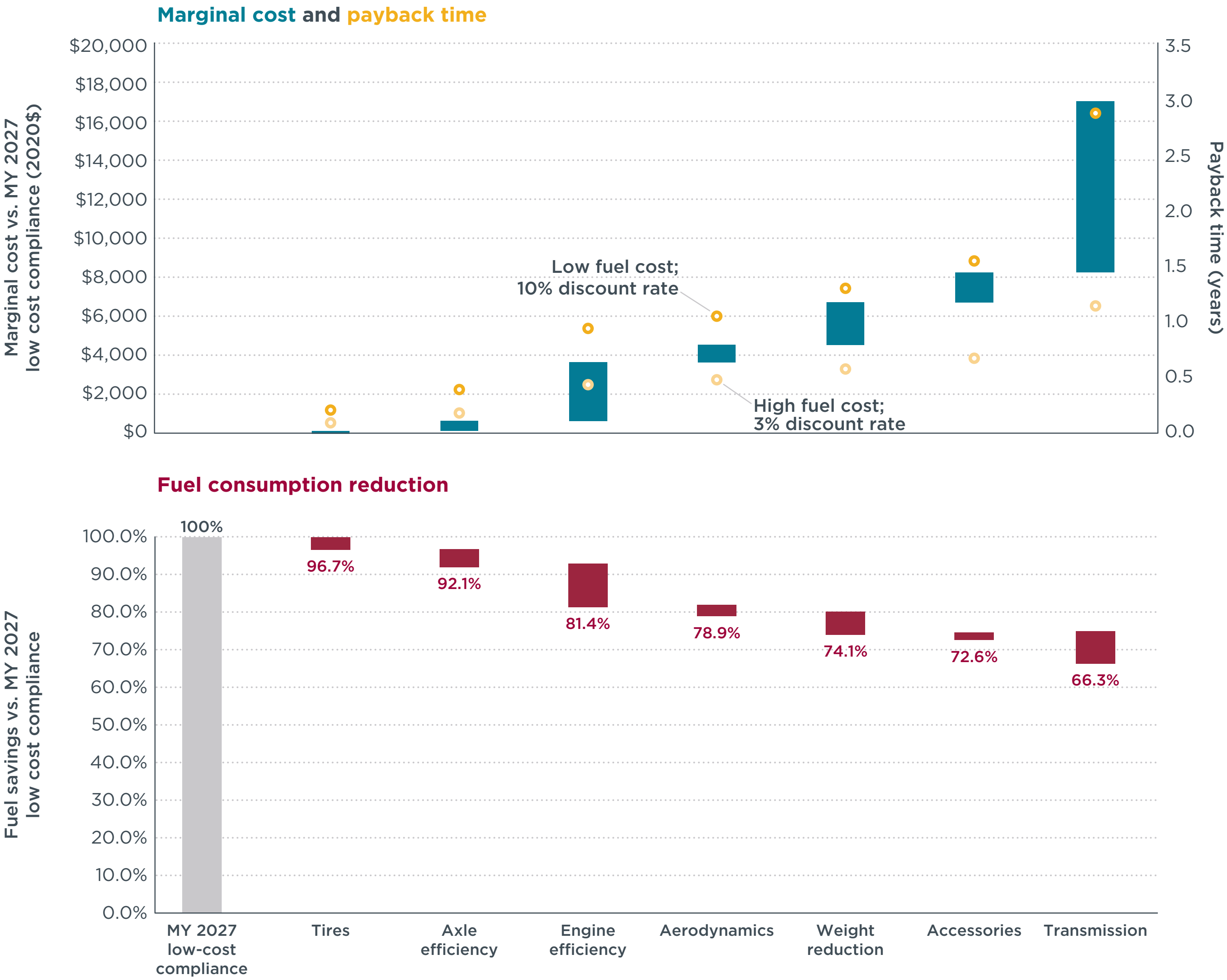

Figure A6. 2035 marginal costs, payback times, and fuel consumption reduction of Class 6–7 multipurpose vocational vehicle technologies compared to the low-cost compliance vehicle in 2027.