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Compliance pathways in the U.S. Phase 2 heavy-duty vehicle efficiency regulation

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1. Introduction

On August 16, 2016, the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Transportation's National Highway Traffic Safety Administration (NHTSA) jointly published the final rulemaking to reduce the fuel consumption and greenhouse gas (GHG) emissions attributable to new heavy-duty vehicles (HDVs) and engines. The new Phase 2 regulations will be implemented from model years 2018 to 2027, building upon the initial Phase 1 standards that cover model years 2014 to 2018.

The structure of the Phase 2 regulation is similar to Phase 1, with regulatory standards for tractors, heavy-duty pickups and vans, vocational vehicles, and the engines used in tractors and vocational vehicles. In addition, the Phase 2 rule incorporates one new major category: trailers. The stringency of the Phase 2 standards varies by vehicle regulatory category. Within each of the four major vehicle and equipment categories covered in the rule, there are further regulatory subcategories based on vehicle features and fuel type (e.g., diesel versus gasoline).

An intrinsic feature of Phase 1 and 2 regulations is that they are performance-based standards. The regulatory fuel consumption and CO_2 targets are technology neutral, and manufacturers may use a variety of individual technology combinations and packages to achieve compliance. Another key aspect of the HDV GHG regulatory program is that manufacturers demonstrate compliance based on sales-weighted averaging. Thus, manufacturers can have a mix of models certified above and below the CO_2 limits as long as their entire fleet of new sales meets the standard, on average. These compliance provisions give manufacturers a large degree of flexibility in achieving compliance using several different approaches, and they can develop products best suited to customer demands and their overall business strategy.

The motivation for this study is to explore some of the technology pathways available to manufacturers in the Phase 2 regulation. The primary objectives of this paper are to develop hypothetical technology packages for certain types of tractor trucks, vocational vehicles, and trailers using distinct technology strategies and then compare the cost-effectiveness of these packages. In their regulatory impact analysis, the EPA and NHTSA developed a hypothetical technology package for achieving the CO_2 targets for each of the regulated engine, vehicle, and trailer subcategories. Because the agencies analyzed only one technology package for each regulated subcategory out of many possible technology combinations, the primary added value of this study is in exploring some of the other technology pathways available to manufacturers and comparing these alternatives in terms of additional capital costs. For the vehicle types included in this analysis, each of the hypothetical technology packages features a particular technology area: aerodynamics, tires, the power train (i.e., engine and transmission), or "other" technologies such as anti-idling devices and speed limiters.

In comparing the costs of the various technology packages for each vehicle or trailer subcategory, this analysis takes the perspective of the regulated entity—that is, the engine, vehicle, or trailer manufacturer. As such, this study

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takes into account only the incremental capital costs associated with the fuel-saving technologies needed for achieving the CO_2 targets and ignores any cost impacts on maintenance or operations. An alternative approach would be to take the perspective of the customer (i.e., fleets of truck owners and/or operators), in which case the maintenance and operations costs would be an important factor.

The balance of this paper is organized as follows:

- Section 2 describes the methods we employed in this analysis to estimate the effectiveness of individual technologies and technology packages as well as their costs.
- Section 3 presents the individual technology CO_2 reduction and cost results.
- Section 4 details the technology packages for each engine-driven vehicle type and provides the package CO_2 reduction and cost results.
- Section 5 covers the technology packages, costs, and results for trailers.
- Section 6 summarizes the analysis and offers some areas for potential future work.

2. Methodology

This study explores the cost-effectiveness of various technology pathways in the Phase 2 HDV GHG regulation. The vehicle and trailer types in this analysis include:

- Tractor Vehicle
  - Class 7 day cab tractor with high roof
  - Class 8 sleeper cab tractor with high roof
- Vocational Vehicle
  - Light heavy-duty (LHD) multipurpose vocational vehicle
  - Medium heavy-duty (MHD) multipurpose vocational vehicle
  - Heavy heavy-duty (HHD) multipurpose vocational vehicle
- Trailer Vehicle
  - Long dry box trailer
  - Short dry box trailer

The following subsection describes how each of the key technology parameters is modeled with a vehicle simulation tool. The technology package descriptions and results for the Class 8 sleeper tractor, medium heavy-duty (MHD) vocational vehicle, and long dry box trailer are included in Sections 3, 4, and 5. The results for the remaining four vehicle and trailer types can be found in the Appendix.

TECHNOLOGY EFFECTIVENESS

In this analysis, we use the Phase 2 Greenhouse gas Emission Model (Phase 2 GEM) to assess the CO_2 reduction effects of individual technologies and combinations of technologies (i.e., technology packages) in each compliance year of the Phase 2 regulation—that is, model years 2021, 2024, and 2027. The GEM simulation tool originally was developed by the EPA as a means for determining compliance with the Phase 1 standards for Class 7 and 8 combination tractors and Class 2B through 8 vocational vehicles. The updated Phase 2 GEM model was revised in several ways as a part of the Phase 2 regulatory development process.[1] These improvements are summarized in the ICCT policy update for the Phase 2 proposal (Lutsey, Sharpe, Muncrief, & Delgado, 2015).

To assess the fuel consumption and CO_2 performance of each vehicle model that is certified, manufacturers are required to enter information into GEM about the vehicle and data on several system components. The GEM data inputs and assumptions used in this analysis for tractor trucks and vocational vehicles are described in Table 1. This table provides information about how each of the key technology areas is modeled in GEM for this analysis. Section 4.1 describes the individual technologies that area selected for each of the technology packages.

In the GEM simulation runs for this analysis, each of the vehicle types is exercised over the same drive cycles and cycle weighting percentages that manufacturers must use for certification in the Phase 2 regulation. The baseline vehicle characteristics, default payloads, and drive cycle weighting factors for each tractor truck and vocational vehicle subcategory are shown in Tables A1 and A2 in the Appendix. Following the completion of the simulations, GEM outputs results in terms of payload-specific fuel consumption (gallons /1,000 ton-miles) and CO_2 emissions (grams CO_2 / ton-mile).

Approximate fuel consumption maps for compliant tractor truck and vocational vehicle engines were developed using engine data available to the ICCT and the authors' best judgment. These engine models are meant to represent typical engines that comply with the engine dynamometer-based standards in model years 2021, 2024, and 2027. The engine models used in this analysis are assumed to have roughly the set of technologies that the EPA and NHTSA project manufacturers will use to achieve the fuel consumption

1 This analysis uses GEM version P2v3.0, the version that was released along with the publication of the final Phase 2 standards.

Table 1. Greenhouse gas Emission Model input data and fuel consumption reduction assumptions for tractor trucks and vocational vehicles in this analysis

Tractor trucks		Vocational vehicles	
Technology	**Inputs for this analysis**	**Technology**	**Inputs for this analysis**
Engine	Representative fuel consumption maps for tractor truck engines that comply with the engine standard in model years 2021, 2024, and 2027	**Engine**	Representative fuel consumption maps for vocational vehicle engines that comply with the engine standard in model years 2021, 2024, and 2027 engines
Transmission	GEM defaults used for manual and automated manual transmissions	**Transmission**[a]	Three transmission-based improvements are used in this analysis. The fuel consumption reduction percentages for each improvement are shown in parentheses and are the midpoint values from the ranges given in Table 2-66 in the RIA. These are post-processing correction factors. 1. Two extra transmission gears (1.2%) 2. Advanced shift strategy (4.5%) 3. Early torque converter lockup (1.5%)
Drive axle configuration	6x2 configuration used in certain packages for the Class 8 sleeper	**Drive axle configuration**	Part-time 6x2 configuration (i.e., axle disconnect) used in certain packages for the HHD vehicle
Drive axle ratio	Default values (Table 2-25 in the RIA)	**Drive axle ratio**	Default values (Tables 2-55, 2-57, and 2-59 in the RIA)
Aerodynamic drag area (C_DA)	The default C_DA value for each aerodynamic bin	Aerodynamic improvements are not explored for vocational vehicles. See Section 4.1 for more information.	
Steer and drive axle tires	Default coefficient of rolling resistance values corresponding to Level 1, 2, and 3 tires (Table 2-25 in the RIA)	**Steer and drive axle tires**	Default coefficient of rolling resistance values corresponding to Level 1v, 2v, 3v, 4v and 5v tires (Tables 2-55, 2-57, and 2-59 in the RIA)
Loaded tire size	Default values (Table 2-25 in the RIA)	**Loaded tire size**	Default values (Tables 2-55, 2-57, and 2-59 in the RIA)
Tire pressure management systems[a]	Default fuel consumption reduction percentages used for automatic tire inflation systems (1.2%)	**Tire pressure management systems**[a]	Default fuel consumption reduction percentages used for tire pressure monitoring systems (0.9%)
Vehicle speed limiter[a]	60 mph limit used in the “Other-Focus” packages (see Table 4)	**Vehicle speed limiter**[a]	60 mph limit used in the “Other-Focus” packages (see Table 4)
Accessory improvements[a]	Default fuel consumption reduction percentages used for air conditioner efficiency improvements (0.5%) and electric accessories (1%)	**Accessory improvements**[a]	Default fuel consumption reduction percentages used for air conditioner efficiency improvements (0.5%) and electric accessories (1%)
Top gear direct drive[a]	Default fuel consumption reduction percentages used for direct drive (2%)	**High efficiency axles**[a]	We used a fuel consumption reduction percentage of 2.5% based on the midpoint of the range of 2% to 3% cited in the RIA (Section 2.9.3.2).
Extended idle reduction[a]	The Phase 2 regulation provides several default fuel consumption reduction percentages for various types of anti-idling technologies. These percentages range from 1% to 6% (Table 2-30 in the RIA)	**Extended idle reduction**	Three anti-idling technologies are used in this analysis. These are yes/no toggle inputs in GEM. 1. Automatic engine shutdown system 2. Neutral idle 3. Start-stop

[a] These technologies are accounted for in GEM by using a post-processing correction factor. As an example of how these technologies are evaluated, say the CO_2 reduction percentage input for Technology A is 2%. At the end of the simulation run, GEM multiplies the CO_2 result by 0.98 (i.e., 1 – 0.02) to account for the impact of Technology A.
Note. RIA refers to the Final Phase 2 Regulatory Impact Analysis (U.S. Environmental Protection Agency and Department of Transportation, 2016)

and CO_2 emission levels prescribed in the regulations.

For trailers, the technology areas investigated in this analysis include aerodynamic improvements, lower rolling resistance tires, and tire inflation systems. The methods by which improvements in these three areas are evaluated are shown in Equation 1 and Table 2. Trailer certification in the Phase 2 regulation is determined using a simplified process. Rather than requiring trailer manufacturers to use GEM, the agencies developed a compliance equation based on regressions from GEM outputs. For the compliance equation below, the input constants for each trailer type are shown in Table 2.

Equation 1:

Certified CO_2 value (grams/ton-mile) =
$$[C_1 + C_2 \times C_{RR} + C_3 \times (\Delta C_D A) + C_4 \times WR] \times C_5$$

where

C_{RR} = tire coefficient of rolling resistance, in kg/ton

$\Delta C_D A$ = change in aerodynamic drag area

WR = weight reduction, in pounds

For all vehicle types as well as trailers, weight reduction is not investigated in this analysis. The primary motivation for excluding this technology area as a means of compliance is that the agencies did not use material substitution or other weight reduction strategies in their projected technology packages that achieve the CO_2 targets. Furthermore, the agencies did not provide cost estimates for the various weight reduction technologies. Because this study is focused on cost-effectiveness, weight reduction technologies are not included.

TECHNOLOGY COSTS

All data for incremental technology costs (in 2013 dollars) are taken directly from Chapter 2 in the Regulatory Impact Analysis (RIA) for the final Phase 2 standards (U.S. Environmental Protection Agency and Department of Transportation, 2016). The detailed cost methodology and results for the vehicle and trailer types analyzed in this study can be found in RIA Sections 2.7 through 2.10.

3. Individual technology efficiency results and costs

Figure 1 summarizes the per-technology results for the Class 8 sleeper cab tractor. The circle data points represent the GEM CO_2 reduction results for each technology, while holding all other technologies at baseline levels. The brown striped columns are the incremental costs of each technology, and the teal columns, representing cost-effectiveness, are derived by dividing the costs by the percent reduction to yield the cost per percent reduction in CO_2 (cost per percent CO_2 reduction = [technology cost] / [percent CO_2 reduction * 100]). From left to right, the technologies are ordered in terms of increasing costs per percent CO_2 reduction. Stated differently, the technologies have decreasing cost-effectiveness in moving from left to right.

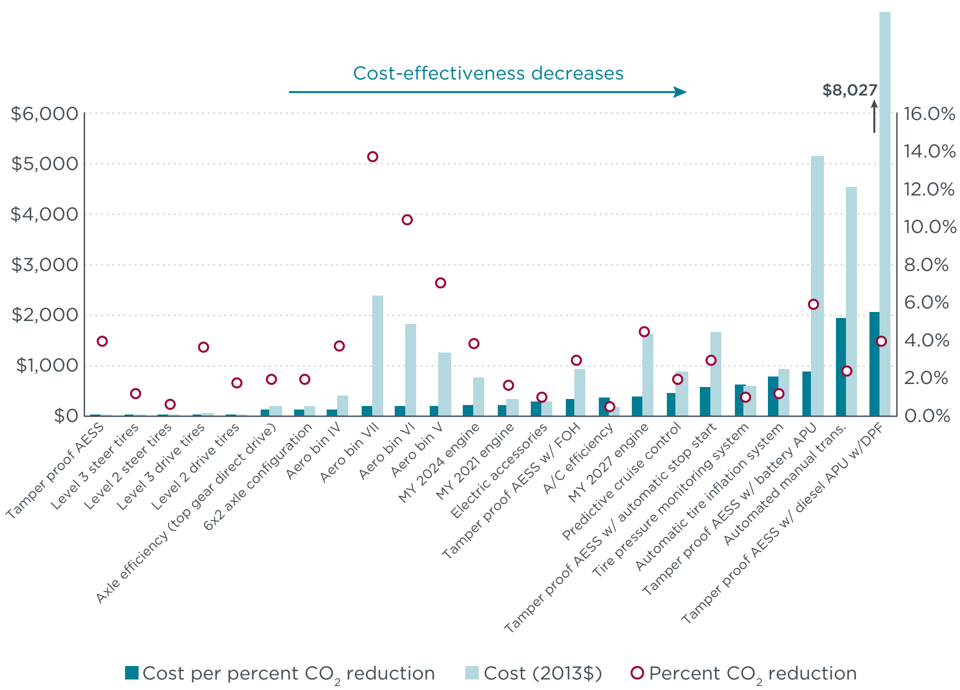

Figure 1. Per-technology CO_2 reductions, costs, and cost per percent CO_2 reduction for Class 8 sleeper cab tractor trucks.

Table 2. Constants for the GEM-based trailer compliance equation

Trailer subcategory	C_1	C_2	C_3	C_4	C_5		
					No tire pressure system	Automatic tire inflation	Tire pressure monitoring system
Long dry van	76.1	1.67	-5.82	-0.00103	1	0.988	0.99
Long refrigerated van	77.4	1.75	-5.78	-0.00103			
Short dry van	117.8	1.78	-9.48	-0.00258			
Short refrigerated van	121.1	1.88	-9.36	-0.00264			

Here are some key points from these results:

- *Tire rolling resistance improvements are by far the most cost-effective technology group*. Costs for Level 2 and 3 low rolling resistance (LRR) steer and drive tires range from roughly $10 to $50 and provide CO_2 reductions between 0.6% and 3.6%. The cost per percent CO_2 reduction values for Level 2 and 3 tires are an order of magnitude less than the aerodynamic bins, which are the next most cost-effective technology group for tractor-trailers. An important caveat is that tires must be replaced at regular intervals. In the rulemaking, the agencies assume a tire replacement interval of 200,000 miles for tractor-trailers and 40,000 miles for all vocational vehicles. So, fleets would incur the additional costs associated with LRR tires at these mileage intervals every time tires need to be replaced. However, even if we multiply the cost-effectiveness of the various level LRR tires by a factor of 10 (i.e., we assume 10 tire replacements for all the tires on the vehicle over its lifetime), the cost per percent reduction values would still be in the range of aerodynamic technologies, which are the next most cost-effective technology area.
- *Aerodynamic improvements yield significant CO_2 reductions at modest costs*. The CO_2 savings from aerodynamic Bins V, VI, and VII are immediately recognizable in Figure 1, as the reductions from these bins are the largest from any individual technology at roughly 7%, 10%, and 14%, respectively. By cutting CO_2 by nearly 4% and with an incremental cost of just over $400, Bin IV is the most attractive aerodynamic level on a cost-effectiveness basis.
- *The three levels of engines have moderate CO_2 benefits and costs*. The model year 2021, 2024, and 2027 engines deliver CO_2 benefits ranging from roughly 1.5% to 4.5% at an additional cost of between approximately $350 and $1,600.
- *Idle reduction technologies vary widely in terms of cost-effectiveness*. At the leftmost side of the figure, the automatic engine shutdown system (AESS) is the most cost-effective technology available for the Class 8 sleeper. Given that AESS requires only simple software modifications in the engine control unit, the costs are very minor (~$30). GEM estimates nearly a 4% decrease in CO_2 from the AESS. Although AESS is extremely cost-effective, without an additional power source, the driver is unable to control the cabin temperature and humidity. As such, AESS is typically paired with an auxiliary power unit (APU) such as a small diesel engine or battery pack so that when the truck's main engine is shut down, the APU is available to power the climate-control system and meet other non-motive energy demands. As shown in the figure, both the battery- and diesel-powered APUs have significant costs: roughly $5,000 for the battery APU and $8,000 for the diesel APU.
- *The automated manual transmission (AMT) ranks worst on cost-effectiveness, but our AMT fuel savings results are conservative*. As a newly added feature in the Phase 2 regulation, manufacturers have the option to evaluate the impacts of deeper engine-transmission integration using a power train test in which the engine and transmission are exercised together on a dynamometer. The default AMT in GEM that we use for this analysis is designed to yield conservative fuel consumption and CO_2 benefits. By erring on the conservative side, the agencies aim to incentivize manufacturers to use the power train test to more accurately access the full benefits of the AMT and deeper integration of the engine and transmission. In an analysis to support the Phase 2 regulatory development process, one of the leading transmission suppliers in the HDV market in North America calculated the percent CO_2 reductions using the default AMT in GEM versus that same engine-transmission combination as evaluated in a power train test. The results from this analysis are summarized in Table 3 (Devito & Dorabantu, 2016). As shown, percent reductions from the default AMT in GEM are roughly a factor of four less than what was determined using a power train test. Acknowledging the conservative nature of the GEM results with regard to the default AMT, we manually adjusted the percent reduction values based on an assessment of the difference between peak engine brake thermal efficiency (BTE) and average BTE over the regulatory cycle. For consistency with previous ICCT research (Delgado, Rodriguez, & Muncrief, 2017), we assumed that the AMT captures one-third of the percent difference between peak and average BTE. This analysis yields approximately 2.5% and 5.5% for the sleeper and day cab tractors, respectively. Particularly for the sleeper tractor, this 2.5% value is more than a factor of three lower than power train test results reported by a transmission manufacturer. The trend toward increased transmission automation in the United

States suggests that this technology is providing attractive return on investment for a large number of trucking fleets. Results from this manufacturer's analysis suggest that our CO_2 reductions related to the AMT are conservative, and a more real-world evaluation likely would yield much better cost-effectiveness results for the AMT and the technology packages that feature power train technologies.

A notable omission from Figure 1 is the vehicle speed limiter. The vehicle speed limiter was not included in this cost-effectiveness ranking because the agencies did not report an incremental cost for this technology in the rulemaking.

Figure 2 shows the per-technology results for the MHD multipurpose vocational vehicle.

- *As with the tractor truck, tires are the most cost-effective technology group*. Lower rolling resistance tires represent a negligible increase in cost (~$10 to $30 per vehicle versus baseline tires) and provide savings between 0.5% and 2%.
- *There is a wide range in cost-effectiveness for the three types of transmission improvements*. By requiring only software updates in the vehicle control system, early torque converter lockup represents a minor cost increase of about $30 and results in CO_2 reductions of slightly over 1%. Advanced shift strategy offers roughly three times the CO_2 savings, but the incremental costs are an order of magnitude higher than early torque converter lockup. Finally, moving from a 6-speed to 8-speed automatic transmission reduces CO_2 by about 1% at a cost of roughly $500.
- *Vocational engine improvements produce CO_2 reductions for approximately half the cost of comparable reductions in tractor trucks*. The cost per percent CO_2 reduction for vocational engines ranges from about $100 to $150, and for tractors the range is roughly $200 to $350.
- *The anti-idling technologies yield the largest individual benefits but differ greatly in costs and cost-effectiveness*. As shown in Table A2 in the Appendix, multipurpose vocational vehicles have a significant idle component (42% weighting factor), and this certainly makes anti-idling devices effective fuel/CO_2 reduction technologies. As with the Class 8 sleeper, AESS is one of the most cost-effective technologies, decreasing CO_2 by about 4% at an additional cost of only $30. At about $25 per percent reduction in CO_2, neutral idle technology is nearly comparable to the cost-effectiveness levels of tire improvements. The start-stop system provides the largest CO_2 savings, but it is by far the most expensive technology at over $900.

Table 3. Manufacturer reported CO_2 reductions due to an automated manual transmission

Vehicle type	Using default automated manual transmission in GEM	Manufacturer data using power train test procedure
Sleeper cab tractor truck	1.9%	8.6%
Day cab tractor truck	1.8%	7.4%
Heavy heavy-duty vocational vehicle (multipurpose)	N/A	11.0%
Medium heavy-duty vocational vehicle (multipurpose)	N/A	8.4%

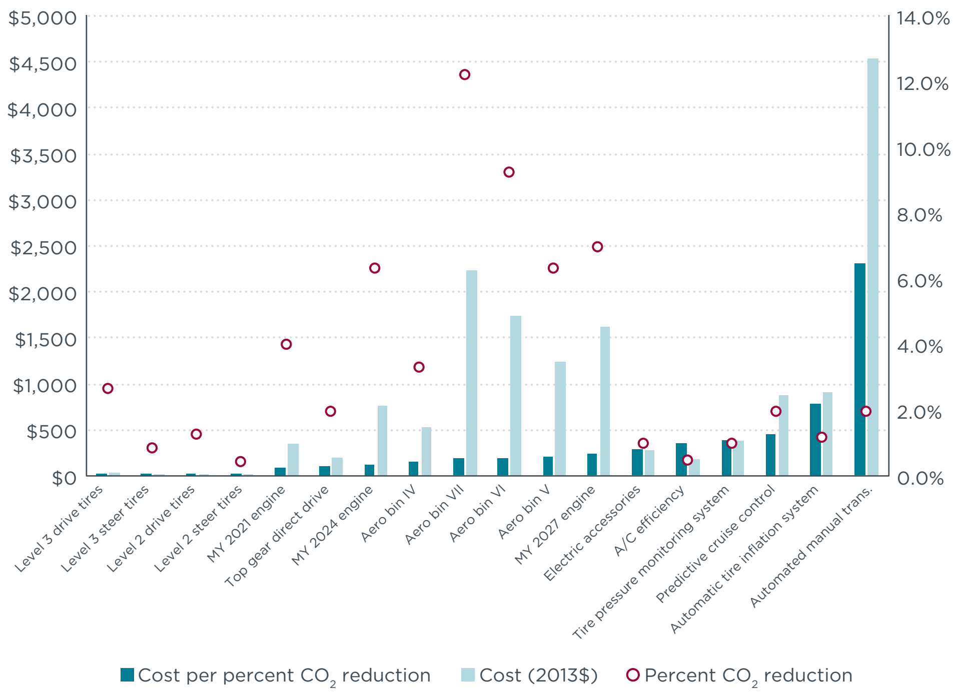

Figure 2. Per-technology CO_2 reductions, costs, and cost per percent CO_2 reduction for medium-duty multipurpose vocational vehicles.

4. Tractor truck and vocational vehicle technology package development and results

4.1 TECHNOLOGY PACKAGE DEVELOPMENT

In developing sets of technology combinations for each vehicle type, the approach was to create distinct packages based on individual technology areas. In each package, a certain technology group is featured in terms of having a high efficiency technology level, while all other technology areas are maintained at or near the baseline level. These packages are described in Table 4.

The packages for tractor trucks and vocational vehicles are similar, with the exception that there is no aerodynamics-focused package for the vocational segment. Although there are opportunities for improving the aerodynamic performance of vocational vehicles, by and large, these types of HDVs tend to operate more frequently in urban drive cycles, where the effectiveness of aerodynamic technologies is more limited. Moreover, the manufacturing process for vocational vehicles is highly fragmented, and the cargo-carrying body is often installed by third-party upfitting companies. As with the Phase 1 regulation, given that chassis manufacturers remain the regulated entity in the vocational segment and these vehicles generally travel at lower average speeds than tractor-trailers, the agencies did not assume aerodynamic technologies in their projected vocational packages that achieve compliance.

After developing the distinct packages each featuring a core technology group, we evaluated each of the packages in 2021, 2024, and 2027 for their fuel consumption and CO_2 performance. Particularly for model years 2024 and 2027, the packages featuring improvements in these core technology areas do not reach the grams CO_2 per ton-mile limit values. In order to do an equitable comparison of the packages on a cost basis, we added technologies to the core packages so that all four packages (three in the case of the vocational vehicles) are below the grams/ton-mile limit values. These packages with additional technologies are the packages that achieve the CO_2 limit values, as shown in the green shaded cells in the “Package result (g/ton-mile)” row in Figures 3, 4, 5, and 8.

Developing the final packages was an iterative process. If a package with only the core technologies failed to reach the CO_2 limit value for a given year, we added a technology with attractive cost-effectiveness values from the per-technology analysis. We incrementally added one technology at a time to the package until the vehicle achieved the grams/ton-mile limit value.

Table 4. Technology package descriptions

Package	Key efficiency measures	Core technologies: Tractor trucks	Core technologies: Vocational vehicles
Aero-Focus	Reduced aerodynamic drag	• MY 2021 → Bin V aerodynamic level • MY 2024 → Bin VI aerodynamic level • MY 2027 → Bin VII aerodynamic level	N/A
Tire-Focus	Reduced tire rolling resistance	• Level 3 tires • Automatic tire inflation system	• Level 5v tires • Tire pressure monitoring system
Power train-Focus	Improved efficiency engine and transmission	• MY 2027 engine in all years • Automated manual transmission	• MY 2027 engine in all years • Two extra transmission gears • Advanced shift strategy • Early torque converter lockup
Other-Focus	Reduced idling; 60 mph maximum speed; reduced accessory loads	• Automatic engine shutoff with battery auxiliary power unit (sleeper only) • 60 mph vehicle speed limiter • Improved accessories • 6x2 axle configuration (sleeper only) • Top gear direct drive	• Automatic engine shutoff • Neutral idle • Start-stop • 60 mph vehicle speed limiter • Improved accessories • 6x2 axle configuration (HHD only) • High-efficiency axles

Note: MY denotes model year.

4.2 TECHNOLOGY PACKAGE RESULTS

For the sake of brevity, the results for the Class 8 tractor truck and MHD multipurpose vocational vehicle are summarized in this section. The summary figures for the remaining three vehicle categories (i.e., the Class 7 tractor truck, HHD vocational, and LHD vocational) are shown in the Appendix.

4.2.1 Class 8 sleeper cab tractor – model year 2021

The technology package results and incremental costs for the Class 8 sleeper tractor truck in model year 2021 are shown in Figure 3. Other-Focus is the only package below the 75.7 grams CO_2/ton-mile limit value without the need for additional technologies. None of the remaining packages can meet the model year 2021 target without the use of additional technologies, as shown in the "Additional" columns in Figure 3. The Aero-Focus and Power train-Focus packages both add Level 3 LRR tires, and Power train-Focus also requires automatic engine shutoff (AESS) to eclipse the 75.7 g/ton-mile mark. Tire-Focus requires the addition of two technologies: AESS and top gear direct drive.

The package cost totals for model year 2021 are shown in the bottom portion of Figure 3. Focusing on the packages that achieve the CO_2 limit value, Tire-Focus and Aero-Focus packages are roughly comparable in terms of incremental costs (~$1,500 to $1,600), but there is a jump of about $4,500 in moving to Power train-Focus and Other-Focus packages. From Figure 1, the AMT (~$4,500) and the battery APU (~$5,100) are the primary factors for the large jump in costs for Power train-Focus and Other-Focus, respectively.

		Aero-Focus		Tire-Focus		Power train-Focus		Other-Focus
		Core	Additional	Core	Additional	Core	Additional	Core
Engine	MY 2021	●		●				●
	MY 2024							
	MY 2027					●		
Transmission	Manual	●		●				●
	Automated manual					●		
Tires	Level 1	●				●		●
	Level 2							
	Level 3		●	●			●	
Aerodynamics	Bin III			●		●		●
	Bin IV							
	Bin V	●						
	Bin VI							
	Bin VII							
Other	Automatic engine shutdown sys. (AESS)				●		●	
	AESS w/ battery APU							●
	60 mph speed limiter							●
	Predictive cruise							
	Improved accessories							●
	Automatic tire inflation			●				
	Top gear direct drive				●			
	6x2 axles							●
	Package result (g/ton-mile)	80.9	74.1	79.1	74.4	82.8	72.8	74.2
	CO_2 limit value (g/ton-mile)	75.7						

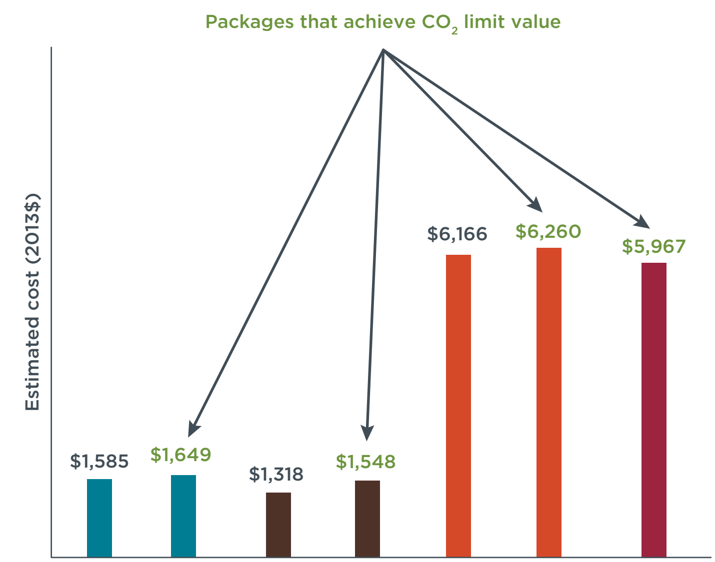

Figure 3. Technology packages and costs for the Class 8 sleeper cab tractor truck in model year 2021.

4.2.2 Class 8 sleeper cab tractor – model year 2024

The Class 8 sleeper technology packages and costs for model year 2024 are shown in Figure 4. The target of 70.7 g/ton-mile is roughly 7% more stringent than in model year 2021 (75.7). As shown in the figure, all four of the packages require additional technologies to achieve the CO_2 target. All three of the non-Tire-Focus packages use improved efficiency tires as additional technologies (Level 3 LRR tires for the Aero-Focus and Power train-Focus packages and Level 2 tires for the Other-Focus package). Both Tire-Focus and Power train-Focus add AESS, top gear direct drive, and 6x2 axles, and Tire-Focus also needs improved accessories to hit the target. In addition to Level 2 LRR tires, Other-Focus also adds predictive cruise.

The cost picture of the four compliant packages is similar to model year 2021, although the cost jump from Tire-Focus and Aero-Focus (~$2,300 to $2,600) to Power train-Focus and Other-Focus (~$6,000 to $6,100) decreases by roughly $1,000.

4.2.3 Class 8 sleeper cab tractor – model year 2027

The Class 8 sleeper technology packages and costs for model year 2027 are shown in Figure 5. With a CO_2 target that is 9% more stringent than in model year 2024, an increasing number of technology additions are required across the four packages. Aero-Focus and Other-Focus required two additional technologies, whereas Tire-Focus and Power train-Focus packages needed five additional technologies to reduce emissions below 64.3 grams/ton-mile. Figure 6 shows an approximate breakdown of the

		Aero-Focus		Tire-Focus		Power train-Focus		Other-Focus	
		Core	Additional	Core	Additional	Core	Additional	Core	Additional
Engine	MY 2021								
	MY 2024	●		●				●	
	MY 2027					●			
Transmission	Manual	●		●				●	
	Automated manual					●			
Tires	Level 1	●				●		●	
	Level 2								●
	Level 3		●	●			●		
Aerodynamics	Bin III			●		●		●	
	Bin IV								
	Bin V								
	Bin VI	●							
	Bin VII								
Other	Automatic engine shutdown sys. (AESS)				●		●		
	AESS w/ battery APU							●	
	60 mph speed limiter							●	
	Predictive cruise								●
	Improved accessories				●			●	
	Automatic tire inflation			●					
	Top gear direct drive				●		●		
	6x2 axles				●		●	●	
	Package result (g/ton-mile)	75.9	69.3	77.0	70.3	82.5	69.7	72.5	67.9
	CO_2 limit value (g/ton-mile)	70.7							

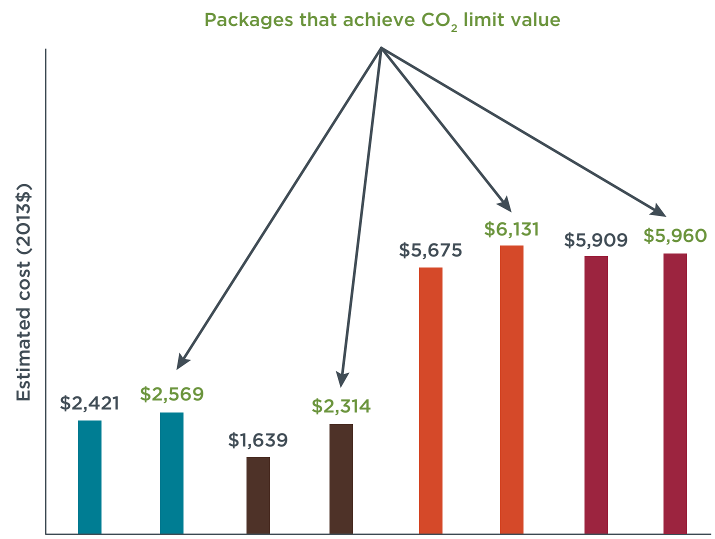

Figure 4. Technology packages and costs for the Class 8 sleeper cab tractor truck in model year 2024.

contribution of each technology to the overall CO_2 reductions in the four compliant packages. As discussed in Section 3, LRR tires are by far the most cost-effective technology area. As such, Level 3 LRR tires are added to all three of the non-Tire-Focus packages (Level 3 tires are already included in the Tire-Focus package) and provide roughly 5 percentage points of the overall 28% required reduction in CO_2. Another highly cost-effective technology that is present on all four of the packages is AESS (Other-Focus has AESS with a battery-powered APU). AESS yields about 4% in savings in the non-Other-Focus packages, and AESS with the battery APU reduces CO_2 by roughly 7%. As intended, aerodynamic improvements play the most significant role in the Aero-Focus package, accounting for roughly half of the total CO_2 reductions. In addition, the compliant Tire-Focus and Power train-Focus packages also use aerodynamics (Bin V), which provide 7%–8% in savings. As expected, transmission and driveline improvements have the most significant impact in the packages based on power train improvements, and reduce CO_2 by about 6%. In the Other-Focus technology package, the 60-mph speed limiter is the most impactful technology area and reduces CO_2 by just over 8%. Across all four compliant packages, engines are responsible for 5%–6% in fuel and CO_2 reductions.

Altogether, the Aero-Focus and Tire-Focus packages are the most cost-effective compliance pathways for the Class 8 sleeper cab tractor truck in the U.S. Phase 2 regulation. As shown in the Figure 7 cost breakdown for each compliant package, the additional costs for compliance of Aero-Focus and Tire-Focus packages is very similar at roughly $3,500–$4,000 in model year 2027. The roughly $3,000

		Aero-Focus		Tire-Focus		Power train-Focus		Other-Focus	
		Core	Additional	Core	Additional	Core	Additional	Core	Additional
Engine	MY 2021								
	MY 2024								
	MY 2027	●		●		●		●	
Transmission	Manual	●		●				●	
	Automated manual					●			
Tires	Level 1	●				●		●	
	Level 2								
	Level 3		●	●			●		●
Aerodynamics	Bin III			●		●		●	
	Bin IV								
	Bin V				●		●		
	Bin VI								
	Bin VII	●							
Other	Automatic engine shutdown sys. (AESS)		●		●		●		
	AESS w/ battery APU							●	
	60 mph speed limiter							●	
	Predictive cruise								●
	Improved accessories				●			●	
	Automatic tire inflation			●					
	Top gear direct drive				●		●		●
	6x2 axles				●		●	●	
	Package result (g/ton-mile)	72.2	63.0	76.0	64.2	81.9	63.9	71.7	61.6
	CO_2 limit value (g/ton-mile)	64.3							

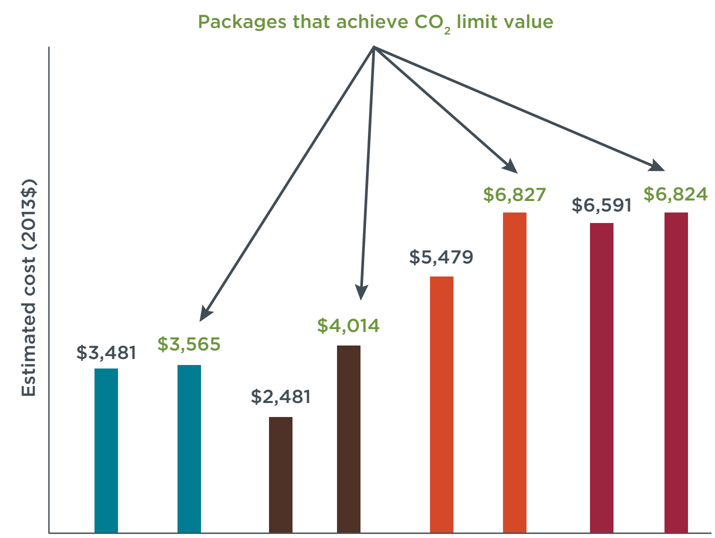

Figure 5. Technology packages and costs for the Class 8 sleeper cab tractor truck in model year 2027.

cost premium for the Power train-Focus and Other-Focus packages is largely due to the AMT (~$4,200) and the battery-powered APU (~$4,500), respectively. As shown in Figure 1, both the AMT and battery-powered APU are two of least cost-effective technologies included in the analysis.

4.2.4 Class 7 sleeper cab tractor

As shown in Figures A1 through A3 in the Appendix, the results for the Class 7 Day cab tractor truck are most different with regard to the costs of the Other-Focus package. Although the estimated costs for the day cab are similar to that of the sleeper truck for the Aero-Focus, Tire-Focus, and Power train-Focus packages, the costs for the Other-Focus package is significantly lower (~$1,900 vs. $6,800). The nearly $5,000 in reduced costs for the day cab truck in this case is due to the lack of the battery-powered APU. In their

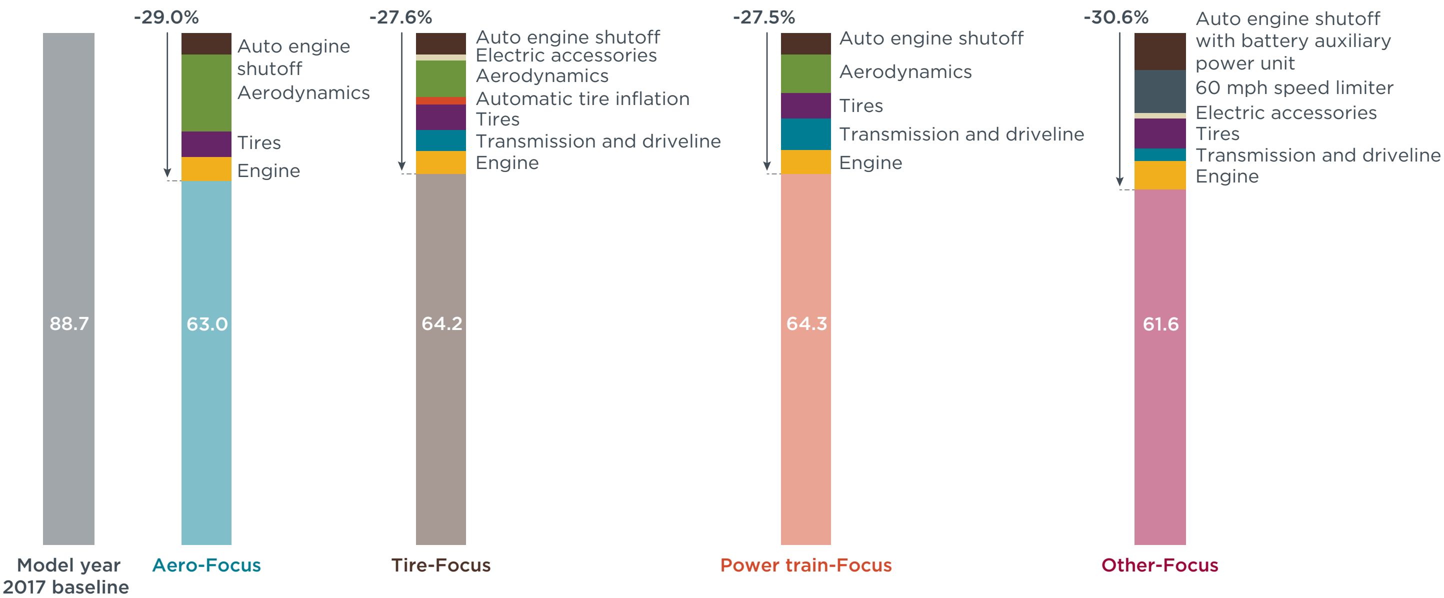

Figure 6. Approximate breakdown of fuel use and CO_2 reductions by technology area for the Class 8 sleeper cab tractor truck in model year 2027.

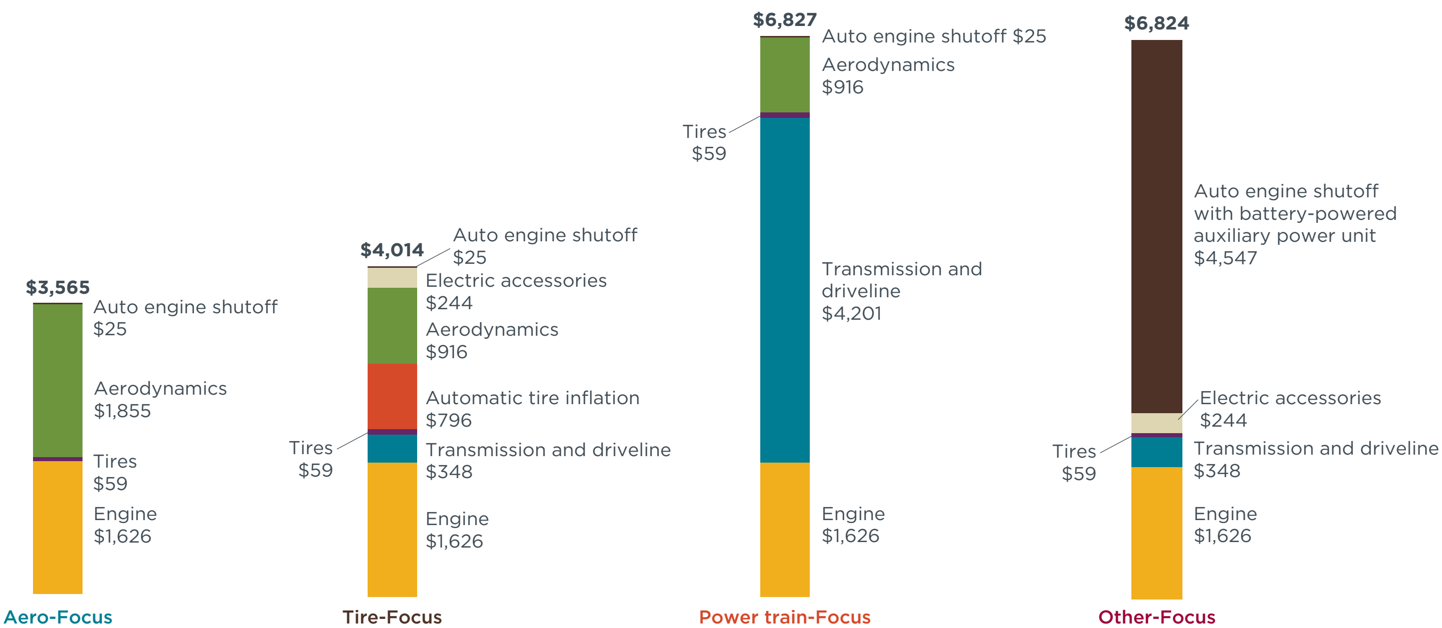

Figure 7. Breakdown of costs by technology area for the Class 8 sleeper cab tractor truck in model year 2027.

assessment of trucking activity patterns, the EPA and NHTSA concluded that typical day cab tractors do not idle for extended periods, and therefore, anti-idling technologies are not assumed to be part of the suite of technologies used for compliance. The technology with the largest contribution to fuel and CO_2 reductions for the Other-Focus package for day cab tractors is the 60-mph speed limiter, which accounts for roughly 40% of the total savings.

4.2.5 Medium heavy-duty multipurpose vocational vehicle

The model year 2027 technology package results and incremental costs for the MHD multipurpose vocational vehicle are shown in Figure 8. The results for model years 2021 and 2024 are shown in Figures A4 and A5 in the Appendix. As shown in Figure 8, Other-Focus is the only package in model year 2027 below the 219.3 grams CO_2/ton-mile limit without the use of additional technologies. Both Tire-Focus and Power train-Focus packages require the addition of AESS and neutral idle as part of the additional technologies needed to achieve the CO_2 target. Figure 9 shows the estimates of each technology area's contribution to overall fuel savings. Idle reduction technology accounts for the largest share of the benefits in all three packages. For the Tire-Focus, Power train-Focus, and Other-Focus packages, anti-idling devices are responsible for 41%, 41%, and 68% of total savings, respectively. Beyond AESS and neutral idle technologies, the Tire-Focus package also includes advanced shift strategy and early torque converter lockup, which account for 18% and 6% of overall CO_2 reductions, respectively. Power train-Focus also incorporates Level 5v tires to reach the required CO_2 level.

The bottom of Figure 8 summarizes the package cost totals for the MHD

		Tire-Focus		Power train-Focus		Other-Focus
		Core	Additional	Core	Additional	Core
Engine	MY 2021					
	MY 2024					
	MY 2027	●		●		●
Transmission	2 extra gears			●		
	Advanced shift strategy		●	●		
	Early torque converter lockup		●	●		
Tires	Level 1v			●		●
	Level 2v					
	Level 3v					
	Level 4v					
	Level 5v	●			●	
Other	Automatic engine shutdown sys. (AESS)		●		●	●
	Neutral idle		●		●	●
	Start-stop					●
	60 mph speed limiter					●
	Improved accessories					●
	Tire pressure monitoring system	●				
	High efficiency axles					●
	Axle disconnect (6x2)					
	Package result (g/ton-mile)	253.5	216.7	241.1	216.0	210.4
	Estimated CO_2 limit value (g/ton-mile)	219.3				

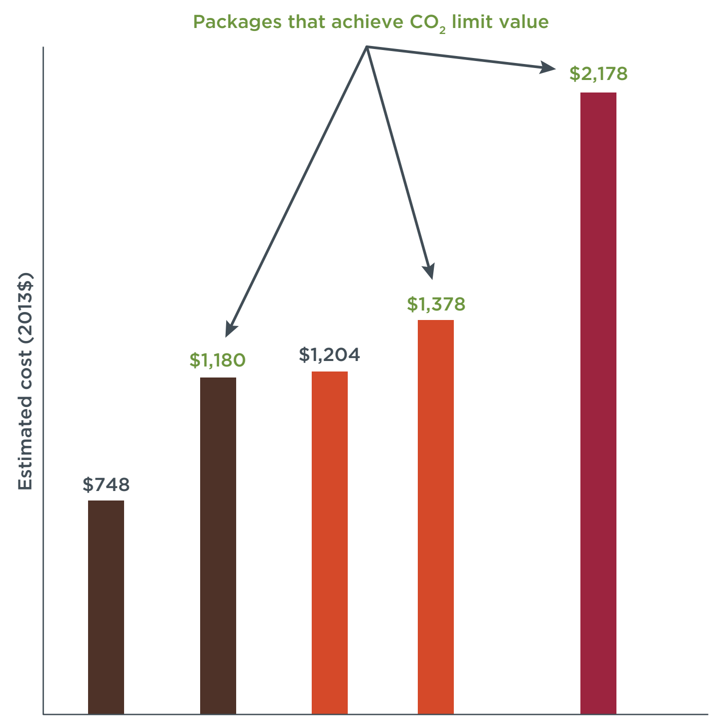

Figure 8. Technology packages and costs for the medium heavy-duty multipurpose vocational vehicle in model year 2027.

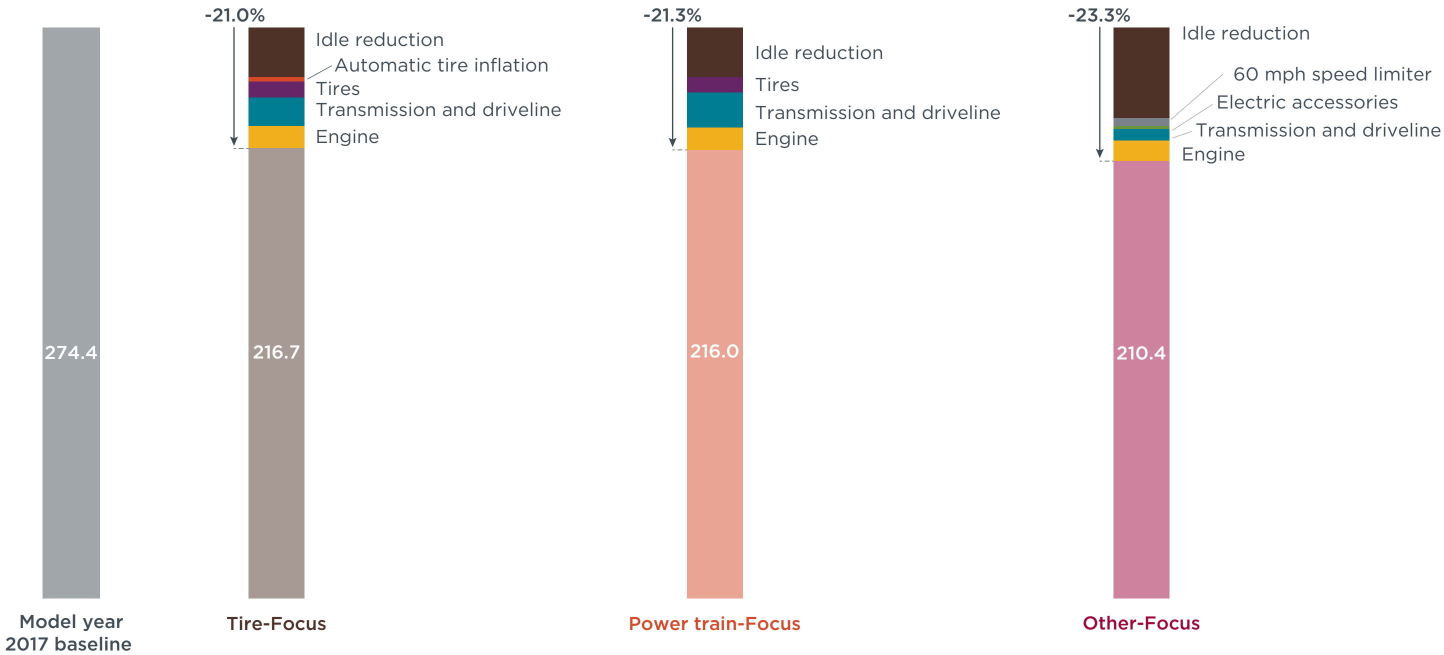

Figure 9. Approximate breakdown of fuel use and CO_2 reductions by technology area for the medium heavy-duty multipurpose vocational vehicle in model year 2027.

multipurpose vehicle in model year 2027, and a cost by technology area breakdown for the three compliant packages is given in Figure 10. Tire-Focus and Power train-Focus are roughly comparable in terms of incremental costs (~$1,200 to $1,400), but Other-Focus represents a cost of approximately $2,200. In the cost breakdown for the MHD vehicle in Figure 10, idle reduction technology (~$900) and electric accessories (~$700) together represent about 75% of the incremental costs of the Other-Focus package.

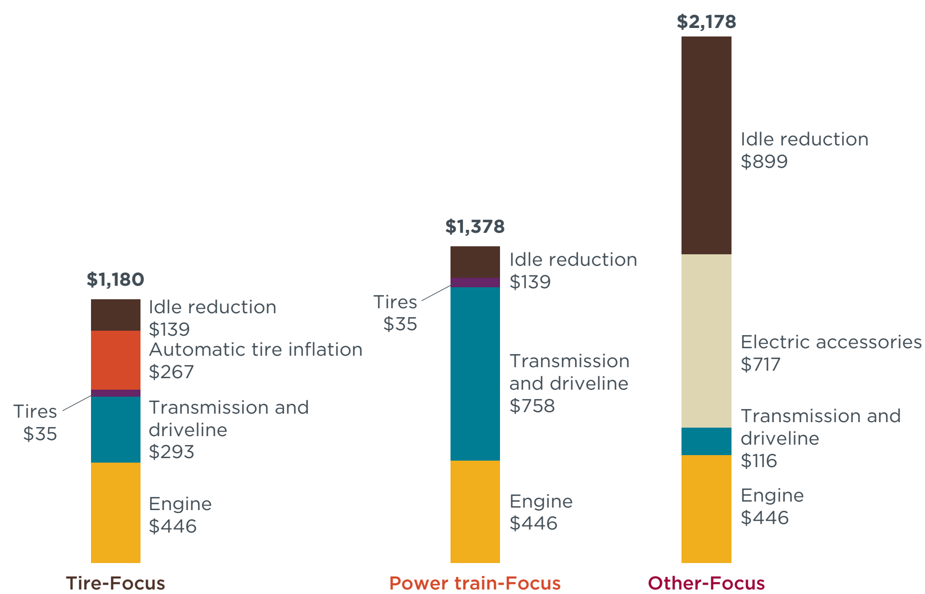

Figure 10. Breakdown of costs by technology area for the Class 8 sleeper cab tractor truck in model year 2027.

4.2.6 Heavy heavy-duty multipurpose vocational vehicle

The model year 2021, 2024, and 2027 results for the HHD multipurpose vehicle are shown in Figures A6, A7, and A8 in the Appendix. Compared to the MHD vehicle results, the rankings of the three packages in each of the three compliance years in terms of total incremental costs are identical for the HHD vehicle: Tire-Focus is the least costly, followed by Power train-Focus and then Other-Focus. However, for the HHD vehicle, Other-Focus represents a more significant jump in cost compared to the Power train-Focus package. The primary reason why Other-Focus is more costly in the HHD case is that the start-stop system for the HHD vehicle is nearly twice as expensive as for the MHD vehicle (roughly $1,400 for the HHD vehicle versus about $800 for the MHD vehicle). As with the MHD vehicle, Other-Focus is the only package that can achieve the CO_2 targets in each of the three compliance years without the use of additional technologies.

4.2.7 Light heavy-duty multipurpose vocational vehicle

The model year 2021, 2024, and 2027 results for the LHD multipurpose vehicle are shown in Figures A9, A10, and A11 in the Appendix. Just as seen with the MHD and HHD vehicles, Tire-Focus is the most cost-effective package, followed by Power train-Focus and then Other-Focus. The differences in costs between the three packages follow a similar trajectory from model year 2021 to 2027 as in the MHD vehicle. Unlike the HHD vehicle, the cost of the start-stop system for the LHD vehicle is very similar to MHD (within roughly 5%), and, as such, the jump in costs for Other-Focus versus the other two packages is very similar for the LHD and MHD vehicles. Finally, as with the MHD and HHD vehicles, Other-Focus is the only package that can achieve the CO_2 targets in each of the three compliance years without the use of additional technologies.

5. Trailer technology package development and results

The Phase 2 regulation includes a new set of regulatory standards to promote the efficiency attributes of commercial trailers. In general, the standards are performance-based for box-shaped or van trailers, allowing manufacturers to increasingly deploy some combination of aerodynamic devices, tire rolling resistance technologies, and automatic inflation systems from 2018 through 2027 to meet the standards. For non-box trailers (e.g., flatbeds, tankers, container chassis, etc.), there are design-based standards that require the deployment of LRR tires and tire inflation systems at certain compliance deadlines. Given the flexible nature of the performance-based standards for box trailers, this study examines various technology packages for long (53 feet or longer) and short (less than 53 feet) box trailers. The results for a long box trailer are presented in this section, and the short box results are shown in the Appendix.

Although the technology packages for the tractor trucks and vocational vehicles focus on an individual technology area, the compliant technology packages for box-type trailers were developed by exploring the unique combinations of aerodynamic and tire improvements needed to achieve the gram per ton-mile targets in model years 2018, 2021, 2024, and 2027. Although weight reduction via material substitution is available to trailer manufacturers as a technology option for achieving compliance, this technology area is not included in the analysis for two reasons. First, the agencies did not explicitly include weight reduction in their projections of technology deployment over time, citing that material substitution is not typically a cost-effective strategy for the majority of trucking fleets. Second, although the agencies provide weight reduction default values for each material (e.g., aluminum, composites) and structural member (e.g., flooring, side panel, cross members) combination, there are no cost estimates provided for these technologies. Because the focus of this study is cost-effectiveness, we did not include weight reduction in any of our trailer technology packages.

Table 5. Minimum technology combinations of aerodynamic and tire technologies that achieve the model year 2018 CO_2 standard for long box trailers

	CO_2 value ($g\ CO_2$/ton-mile)	Incremental cost (2013$)
Package 1: Bin IV aero + Level 3 tires	80.5	$1,011
Package 2: Bin V aero + Level 2 tires	80.3	$1,437
Package 3: Bin III aero + Level 3 tires + ATIS	81.3	$1,470
Package 4: Bin IV aero + Level 2 tires + ATIS	81.1	$1,661

Table 5 shows four unique combinations of aerodynamic bins (as with tractor trucks, trailers are grouped into seven bins by aerodynamic performance), level of tires (based on coefficient of rolling resistance values), and automatic tire inflation systems (ATIS) that can be used to achieve the model year 2018 standard of 81.3 grams CO_2/ton-mile. These combinations are not exhaustive and represent the least-cost pathways to achieving the CO_2 target. The most cost-effective package is Package 1, which employs Level 3 LRR tires and Bin IV aerodynamics, and whose incremental costs are 30% less expensive than the next most cost-effective package, which is Package 2. Packages 3 and 4, which use ATIS, are 45% and 64% more expensive, respectively, than Package 1.

Examining Figure 11, this pattern from model year 2018 repeats itself in model years 2021, 2024, and 2027. In each of the four compliance years, the most cost-effective package maximizes the level of LRR tires (Level 3 or 4) and pairs these LRR tires with the minimum aerodynamic bin needed to achieve the CO_2 target. The exception is model year 2027, in which Level 2 tires are combined with Bin VII aerodynamics. In model year 2027 Level 3 tires plus Bin VI aerodynamics do not hit the target and must also use ATIS, as shown in the second, less cost-effective package ($1,984). Also of note is the fact that the “Bin VII aero + Level

2 tires" package in model year 2024 is $56 less expensive than the "Bin VII aero + Level 2 tires" package in model year 2027. In estimating technology costs of time, the agencies assume that manufacturer learning and economies of scale drive down the incremental costs over time.

As with tractor trucks and vocational vehicles, lowering the rolling resistance of tires is very inexpensive compared to most other technology options, and the compliant packages that tend to be the most cost-effective maximize the use of LRR tires.

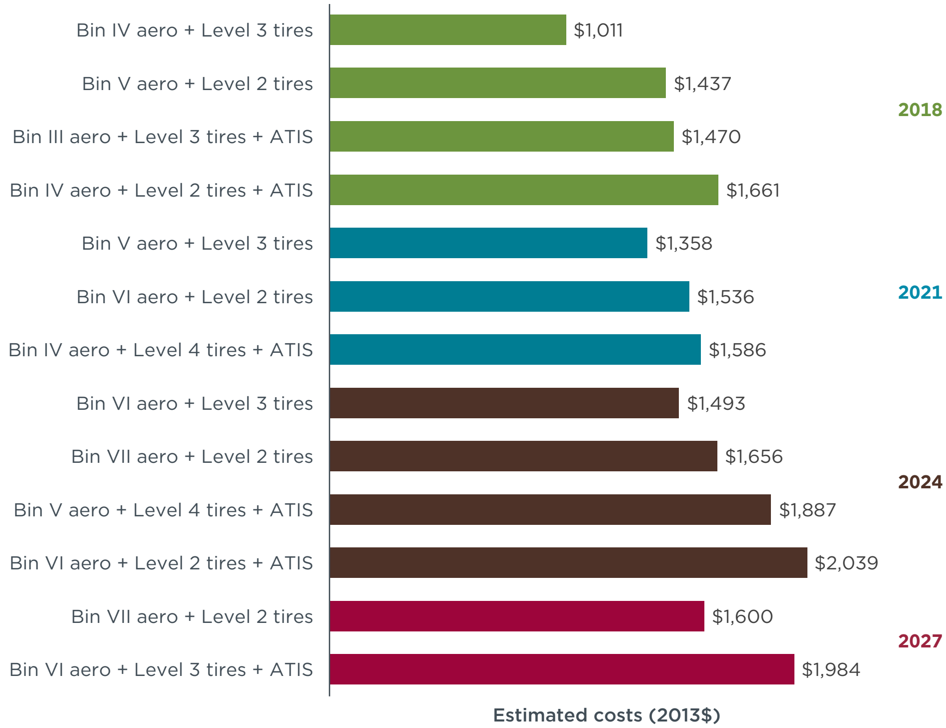

Figure 11. Technology packages and costs for the long box trailer.

6. Discussion and conclusions

This study analyzes the cost-effectiveness of various technology packages for vehicles and trailers that achieve the fuel consumption and CO_2 targets in the Phase 2 U.S. heavy-duty vehicle GHG regulation. A key element of the GHG regulatory program for HDVs in the United States is that manufacturers have the flexibility to employ any number of combinations of various types of technology to demonstrate compliance with the standards. In their regulatory impact assessment, the EPA and NHTSA estimate the deployments of various technologies for each of the regulated vehicle and trailer subcategories. Whereas the agencies use their best judgment to project technology packages out to 2027, manufacturers can use any number of technologies to achieve compliance based on their overall business strategy and customer demands. Given the large degree of autonomy manufacturers have in designing HDVs with different sets of technologies, the added value of this research is in analyzing the range in costs represented by different varieties of technology packages.

In both the Phase 1 and 2 regulations, compliance is demonstrated based on a sales-weighted fleet average, giving OEMs the discretion to sell some models that do not achieve the CO_2 targets, as long as their fleet of new vehicle sales meets the standard, on average. However, in order to have an equitable comparison of the costs of various technology packages, all of the packages developed for this study are at or below the grams CO_2 per ton-mile limit values.

We calculated the per-vehicle fuel consumption and CO_2 impacts from each individual technology and technology package using the Phase 2 Greenhouse gas Emission Model, which is the simulation software that vehicle manufacturers must use to assess vehicle performance. Incremental technology costs for each vehicle and trailer type are taken directly from the agencies' Final Regulatory Impact Analysis.

The cost-effectiveness ranges for the individual technologies after grouping them into five major areas—tires, engines, transmissions, idle reduction, and aerodynamics—are shown in Figure 12. In the figure, the bottom and top of each column represent the lowest and highest cost-effectiveness (i.e., cost per percent CO_2 reduction) value, respectively, for the individual technologies that fall within that technology area. With incremental costs for even the most efficient tires at $50 or less for the entire vehicle, the cost-effectiveness of LRR tires is generally between $10–$20 per percent CO_2 reduction. LRR tires are by far the most cost-effective technology for both tractor trucks and vocational vehicles and also have the smallest degree of variability between the lowest and highest cost-effectiveness values. With regard to tires, one important factor to consider is the fact that this analysis is from the perspective of the manufacturer. As a consequence, we do not take into account all of the incremental costs for LRR tires that are required over the life of the vehicle, as tires are typically replaced at regular intervals. If we were to take the perspective of a trucking fleet, all of the costs associated with tire replacement would negatively affect the individual technology cost-effectiveness of LRR tires as well as the package results—particular the Tire-Focus packages.

Ranging from about $110 to $180 per percent CO_2 reduction, the next most cost-effective technology area is aerodynamics, which was analyzed only for the two tractor trucks. For the vocational vehicles, transmission and driveline technologies rank behind LRR tires as the second most cost-effective technology area. Model year 2021, 2024, and 2027 engines' cost-effectiveness values range from roughly $110 to $140 for the MHD multipurpose vehicle and from $200 to $370 for the Class 8 sleeper truck. For the tractor trucks, the two technology areas with by far the largest disparity between low and high cost-effectiveness values are transmission and driveline improvements and idle reduction technologies. For transmission and driveline technologies, top gear direct drive and 6x2 axles have the lowest costs per percent CO_2 reduction (~$100), and the automated manual transmission has the highest costs per percent reduction (~$1,900). For anti-idling technologies, there are inexpensive, software-only technologies (i.e., automatic engine shutdown systems) at the low end of the range, but systems that use auxiliary power units (e.g., small diesel engine or battery pack) impose much more significant additional costs.

The approach in developing groupings of technologies was to create distinct packages based on individual technology areas. In each package, the core technology group is maximized in terms of having the most efficient technology level, while all other technology areas are maintained at or near the baseline level. Particularly

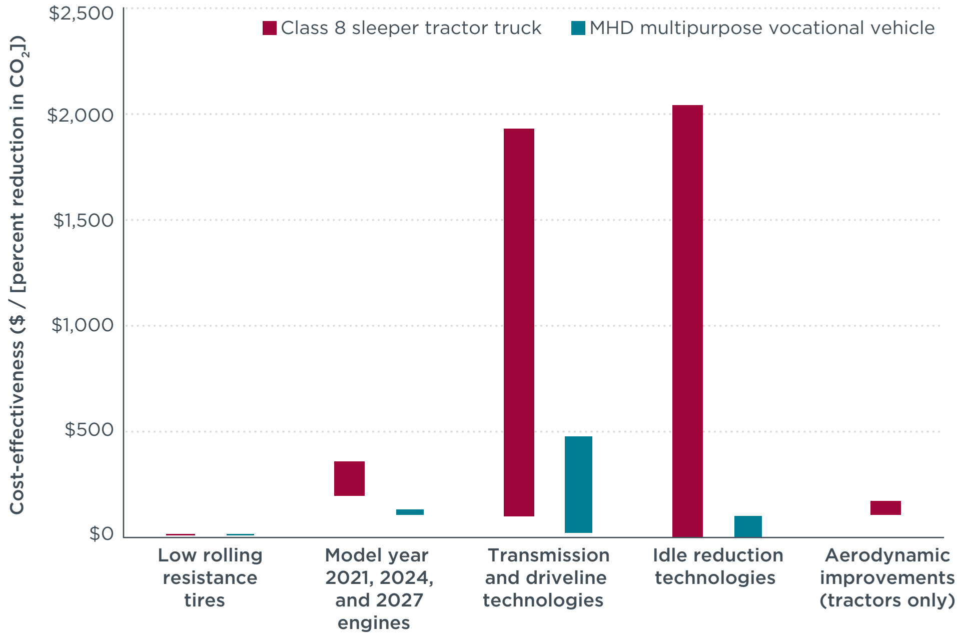

Figure 12. Ranges in cost-effectiveness ($ per percent CO_2 reduction) of individual technologies by major technology area.

Table 6. Cost rankings of the compliant technology packages in 2021, 2024, and 2027. The percentages in rows two through four (three for the MHD vehicle) are the difference in cost versus the low-cost package.

	Class 8 sleeper tractor truck			MHD multipurpose vocational vehicle		
	2021	2024	2027	2021	2024	2027
Best cost-effectiveness	Tire-Focus	Tire-Focus	Tire-Focus	Tire-Focus	Tire-Focus	Tire-Focus
↓	Aero-Focus +7%	Aero-Focus +11%	Aero-Focus +13%	Powertrain-Focus +76%	Powertrain-Focus +45%	Powertrain-Focus +17%
↓	Other-Focus +286%	Other-Focus +158%	Other-Focus +91%	Other-Focus +213%	Other-Focus +149%	Other-Focus +85%
Worst cost-effectiveness	Powertrain-Focus +304%	Powertrain-Focus +165%	Powertrain-Focus +92%			

for model years 2024 and 2027, the core technologies are not sufficient to reach the grams CO_2 per ton-mile limit values. In order to compare the packages equitably on a cost basis, we added technologies to the noncompliant packages so that all four (three in the case of the vocational vehicles) packages are below the grams/ton-mile limit values.

Table 6 shows the ranking of the compliant packages in model years 2021, 2024, and 2027, with decreasing cost-effectiveness moving from top to bottom. The percentages below the package name in rows two through four (three in the case of the MHD vocational vehicle) represent the additional cost compared to the lowest-cost package. With LRR tires performing so well in terms of cost-effectiveness (see Figure 11), it is consistent that Tire-Focus packages are the most cost-effective package in each year for the two tractors and three vocational vehicles. The rankings of the packages are consistent across the compliance years.

For the tractor truck, Aero-Focus packages nearly have cost parity with Tire-Focus packages within 7% to 13%. However, Power train-Focus and Other-Focus cost about four times as much as Tire-Focus in model year 2021, and this decreases to approximately a factor of two by 2027. For the MHD multipurpose vehicle, Tire-Focus is the most cost effective followed by Power train-Focus and then Other-Focus. Although Power train-Focus technologies are nearly twice as expensive as Tire-Focus in 2021, the difference declines to 17% by 2027. In the case of Other-Focus package, the cost disparity with Tire-Focus goes from over a factor of three difference in 2021 to about two by 2027.

The technical analysis for the trailer segment was less rigorous than for the five vehicle types, as we did not perform an individual technology assessment. However, as with tractor trucks and vocational vehicles, lowering the rolling resistance of trailer tires is very inexpensive compared to most other technology options, and the compliant packages that are the most cost-effective are the ones that maximize the use of LRR tires and avoid the use of automatic tire inflation systems.

Although this study is valuable in assessing the comparative costs of various technology pathways for complying with the Phase 2 GHG regulation, there are two key shortcomings. First, we take into account only the technologies for which the agencies provide incremental cost estimates in the Final Regulatory Impact Analysis. As a result, the most significant omissions are weight reduction technologies and advanced transmissions (i.e., automated manual and dual clutch transmissions) for the vocational vehicles.

The second limitation in the study is in estimating the fuel and CO_2 savings associated with the AMT in the tractor segment. The agencies intentionally designed the default AMT in GEM to yield relatively conservative CO_2 reductions (~2%). Acknowledging the conservative nature of the GEM results with regard to the AMT, we manually adjusted the percent reduction values based on an assessment of the difference between peak engine BTE and average BTE. For consistency with previous ICCT research, we assumed that the AMT could capture one-third of the percent difference between peak and average BTE. This analysis yielded approximately 2.5% and 5.5% for the sleeper and day cab tractors, respectively. Particularly for the sleeper tractor, this 2.5% figure is somewhat low compared to values in the literature. The trend toward transmission automation in the United States suggests that this technology is providing attractive return on investment for a large number of trucking fleets.

Future work in this area can extend the per-vehicle fuel and CO_2 assessments to the national fleet level. Moreover, an analysis of payback time for each technology package can complement the incremental cost results.

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Appendix

Table A1. Key baseline vehicle parameters and drive cycle weightings for tractor trucks

	Class 8 high roof sleeper cab	Class 7 high roof day cab
Total weight (lbs.)	70,400	49,998
Payload (lbs.)	38,000	25,000
Drag area (C_DA)	5.90	6.38
Steer tire rolling resistance (C_{RR})	6.54	6.87
Drive tire rolling resistance (C_{RR})	6.92	7.26
Drive cycles and weightings		
CARB HHDDT	0.05	0.19
GEM 55 mph	0.09	0.17
GEM 65 mph	0.86	0.64

Table A2. Key baseline vehicle parameters and drive cycle weightings for multipurpose vocational vehicles

	HHD	MHD	LHD
Total weight (lbs.)	42,000	25,150	16,000
Payload (lbs.)	15,000	11,200	5,700
Drag area (C_DA)	6.9	5.4	3.4
Steer tire rolling resistance (C_{RR})	7.7	7.7	7.7
Drive tire rolling resistance (C_{RR})	7.7	7.7	7.7
Drive cycles and weightings[a]			
Non-Idle Cycle Weighting	**0.58**	**0.58**	**0.58**
CARB HHDDT	0.54	0.54	0.54
GEM 55 mph	0.23	0.29	0.29
GEM 65 mph	0.23	0.17	0.17
Parked Idle	**0.25**	**0.25**	**0.25**
Drive Idle	**0.17**	**0.17**	**0.17**

[a] CARB HHDDT, GEM 55 mph and GEM 65 mph cycles weightings are subsets of the Non-Idle Cycle Weighting. That is, the percentages for Non-Idle Cycle Weighting, Parked Idle, and Drive Idle sum to 1.

		Aero-Focus	Tire-Focus	Power train-Focus	Other-Focus
		Core	Core	Core	Core
Engine	MY 2021	●	●		●
	MY 2024				
	MY 2027			●	
Transmission	Manual	●	●		●
	Automated manual			●	
Tires	Level 1	●		●	●
	Level 2				
	Level 3		●		
Aerodynamics	Bin III		●	●	●
	Bin IV				
	Bin V	●			
	Bin VI				
	Bin VII				
Other	60 mph speed limiter				●
	Predictive cruise				
	Improved accessories				●
	Automatic tire inflation		●		
	Top gear direct drive				
	Package result (g/ton-mile)	109.8	109.1	111.7	108.1
	CO_2 limit value (g/ton-mile)	113.5			

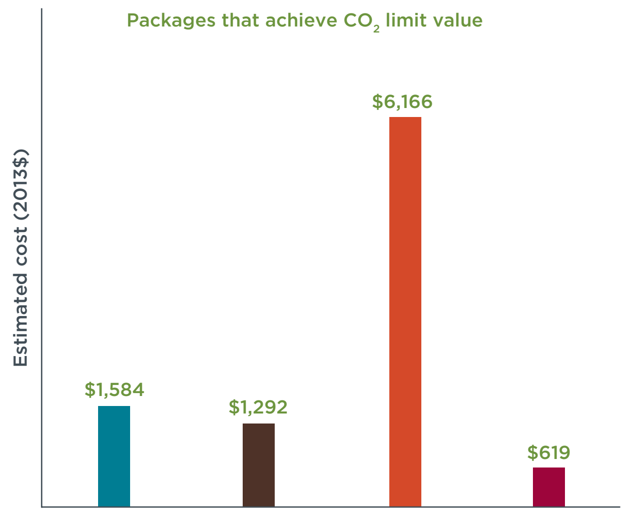

Figure A1. Technology packages and costs for the Class 7 day cab tractor truck in model year 2021.

		Aero-Focus	Tire-Focus	Power train-Focus		Other-Focus	
		Core	Core	Core	Additional	Core	Additional
Engine	MY 2021	●	●			●	
	MY 2024						
	MY 2027			●			
Transmission	Manual	●	●			●	
	Automated manual			●			
Tires	Level 1	●		●		●	
	Level 2						●
	Level 3		●		●		
Aerodynamics	Bin III		●	●		●	
	Bin IV						
	Bin V						
	Bin VI	●					
	Bin VII						
Other	60 mph speed limiter					●	
	Predictive cruise						
	Improved accessories					●	
	Automatic tire inflation		●				
	Top gear direct drive						
	Package result (g/ton-mile)	103.5	106.3	111.5	102.8	107.5	104.5
	CO_2 limit value (g/ton-mile)	106.6					

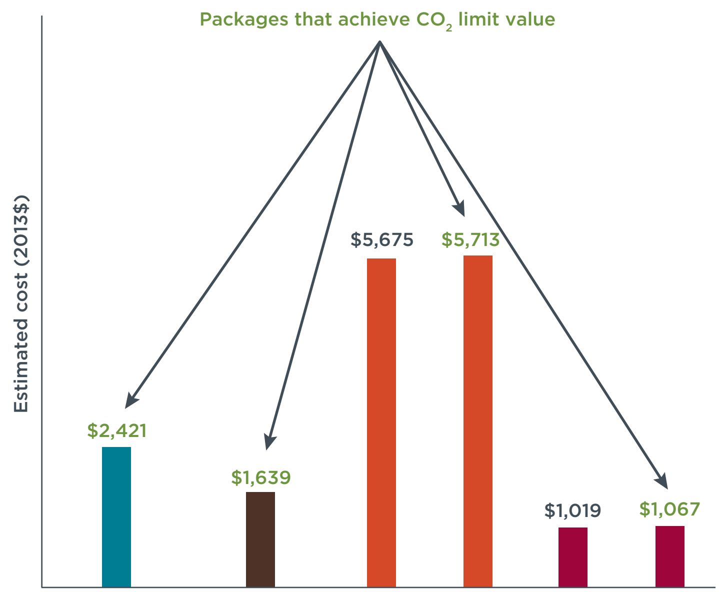

Figure A2. Technology packages and costs for the Class 7 day cab tractor truck in model year 2024.

		Aero-Focus	Tire-Focus		Power train-Focus		Other-Focus	
		Core	Core	Additional	Core	Additional	Core	Additional
Engine	MY 2021							
	MY 2024							
	MY 2027	●	●		●		●	
Transmission	Manual	●	●				●	
	Automated manual				●			
Tires	Level 1	●			●		●	
	Level 2							
	Level 3		●			●		●
Aerodynamics	Bin III		●		●		●	
	Bin IV							
	Bin V			●				
	Bin VI							
	Bin VII	●						
Other	60 mph speed limiter						●	
	Predictive cruise							
	Improved accessories						●	
	Automatic tire inflation		●					
	Top gear direct drive							
	Package result (g/ton-mile)	98.8	105.1	97.8	110.8	99.1	104.6	95.8
	CO_2 limit value (g/ton-mile)	100.0						

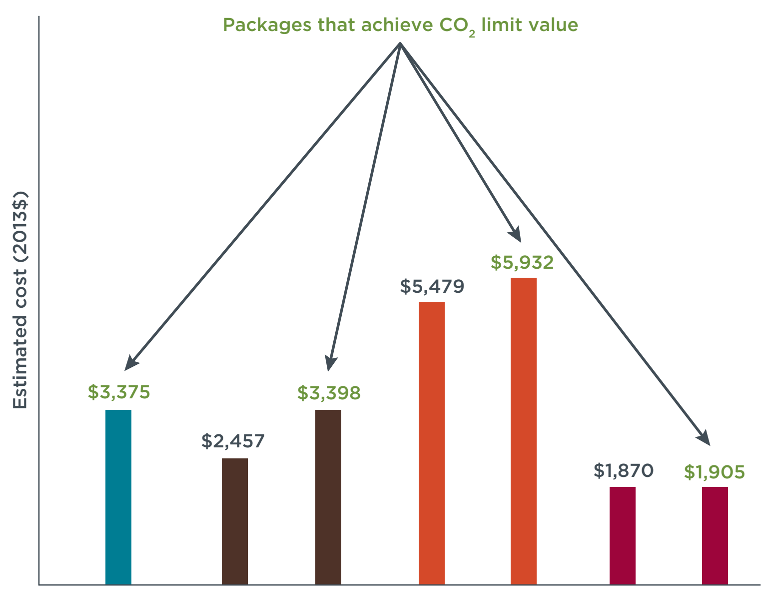

Figure A3. Technology packages and costs for the Class 7 day cab tractor truck in model year 2027.

		Tire-Focus		Power train-Focus	Other-Focus
		Core	Additional	Core	Core
Engine	MY 2021	●			●
	MY 2024				
	MY 2027			●	
Transmission	2 extra gears			●	
	Advanced shift strategy			●	
	Early torque converter lockup			●	
Tires	Level 1v			●	●
	Level 2v				
	Level 3v				
	Level 4v				
	Level 5v	●			
Other	Automatic engine shutdown sys. (AESS)				●
	Neutral idle		●		●
	Start-stop				●
	60 mph speed limiter				●
	Improved accessories				●
	Tire pressure monitoring system	●			
	High efficiency axles				●
	Axle disconnect (6x2)				
	Package result (g/ton-mile)	258.8	245.3	247.0	217.4
	Estimated CO_2 limit value (g/ton-mile)	247.3			

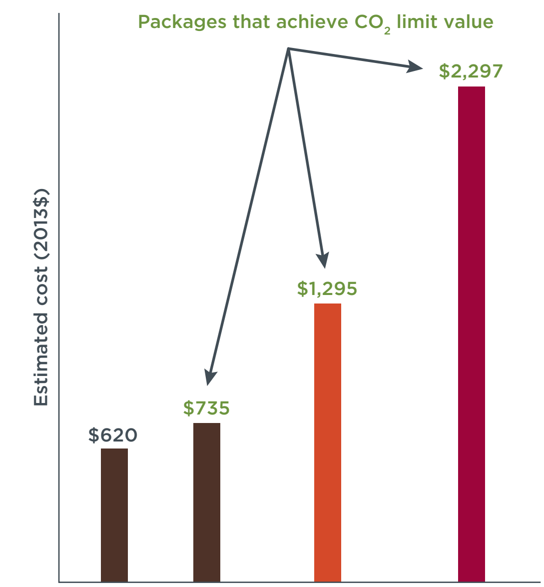

Figure A4. Technology packages and costs for the medium heavy-duty multipurpose vocational vehicle in model year 2021.

		Tire-Focus		Power train-Focus		Other-Focus
		Core	Additional	Core	Additional	Core
Engine	MY 2021					
	MY 2024	●				●
	MY 2027			●		
Transmission	2 extra gears			●		
	Advanced shift strategy			●		
	Early torque converter lockup		●	●		
Tires	Level 1v			●		●
	Level 2v					
	Level 3v					
	Level 4v					
	Level 5v	●			●	
Other	Automatic engine shutdown sys. (AESS)		●		●	●
	Neutral idle		●			●
	Start-stop					●
	60 mph speed limiter					●
	Improved accessories					●
	Tire pressure monitoring system	●				
	High efficiency axles					●
	Axle disconnect (6x2)					
	Package result (g/ton-mile)	254.8	227.5	247.0	228.9	214.1
	Estimated CO_2 limit value (g/ton-mile)	229.6				

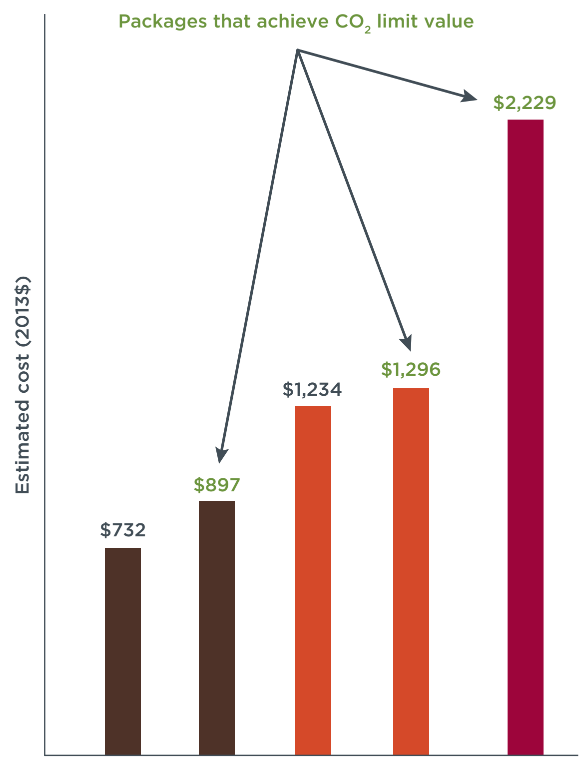

Figure A5. Technology packages and costs for the medium heavy-duty multipurpose vocational vehicle in model year 2024.

		Tire-Focus		Power train-Focus	Other-Focus
		Core	Additional	Core	Core
Engine	MY 2021	●			●
	MY 2024				
	MY 2027			●	
Transmission	2 extra gears			●	
	Advanced shift strategy			●	
	Early torque converter lockup			●	
Tires	Level 1v			●	●
	Level 2v				
	Level 3v				
	Level 4v				
	Level 5v	●			
Other	Automatic engine shutdown sys. (AESS)				●
	Neutral idle		●		●
	Start-stop				●
	60 mph speed limiter				●
	Improved accessories				●
	Tire pressure monitoring system	●			
	High efficiency axles				●
	Axle disconnect (6x2)				●
	Package result (g/ton-mile)	253.6	239.3	241.1	216.9
	Estimated CO_2 limit value (g/ton-mile)	244.6			

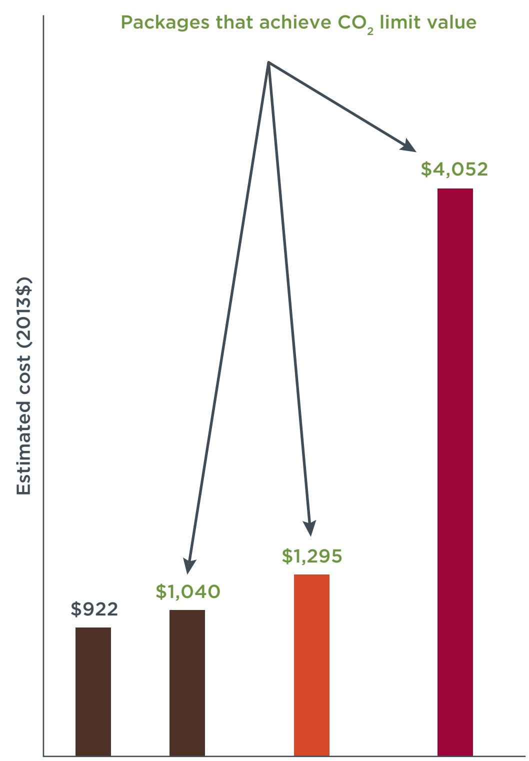

Figure A6. Technology packages and costs for the heavy heavy-duty multipurpose vocational vehicle in model year 2021.

		Tire-Focus		Power train-Focus		Other-Focus
		Core	Additional	Core	Additional	Core
Engine	MY 2021					
	MY 2024	●				●
	MY 2027			●		
Transmission	2 extra gears			●		
	Advanced shift strategy			●		
	Early torque converter lockup			●		
Tires	Level 1v			●		●
	Level 2v					
	Level 3v					
	Level 4v					
	Level 5v	●				
Other	Automatic engine shutdown sys. (AESS)		●		●	●
	Neutral idle		●		●	●
	Start-stop					●
	60 mph speed limiter					●
	Improved accessories					●
	Tire pressure monitoring system	●				
	High efficiency axles					●
	Axle disconnect (6x2)					●
	Package result (g/ton-mile)	248.1	225.3	241.1	218.8	211.8
	Estimated CO_2 limit value (g/ton-mile)	226.8				

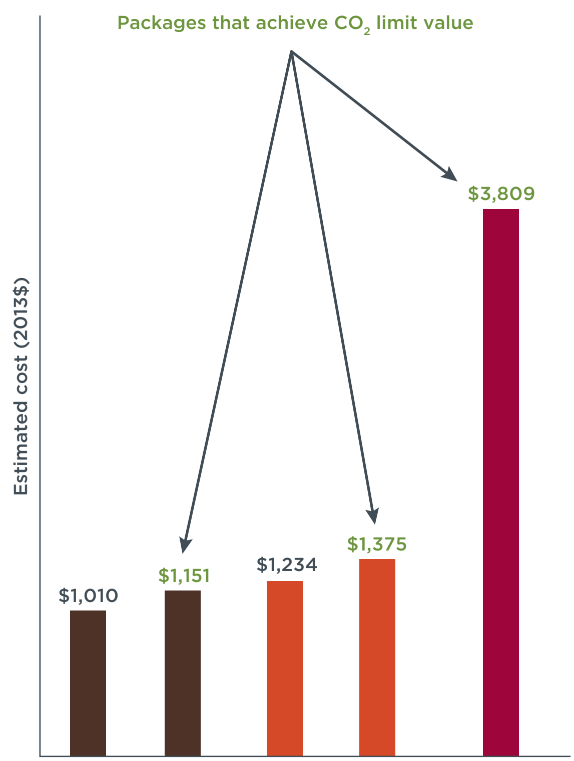

Figure A7. Technology packages and costs for the heavy heavy-duty multipurpose vocational vehicle in model year 2024.

		Tire-Focus		Power train-Focus		Other-Focus
		Core	Additional	Core	Additional	Core
Engine	MY 2021					
	MY 2024					
	MY 2027	●		●		●
Transmission	2 extra gears			●		
	Advanced shift strategy		●	●		
	Early torque converter lockup			●		
Tires	Level 1v			●		●
	Level 2v					
	Level 3v					
	Level 4v					
	Level 5v	●				
Other	Automatic engine shutdown sys. (AESS)		●		●	●
	Neutral idle		●		●	●
	Start-stop					●
	60 mph speed limiter					●
	Improved accessories					●
	Tire pressure monitoring system	●				
	High efficiency axles				●	●
	Axle disconnect (6x2)				●	●
	Package result (g/ton-mile)	246.4	214.2	241.1	212.3	210.4
	Estimated CO_2 limit value (g/ton-mile)	215.6				

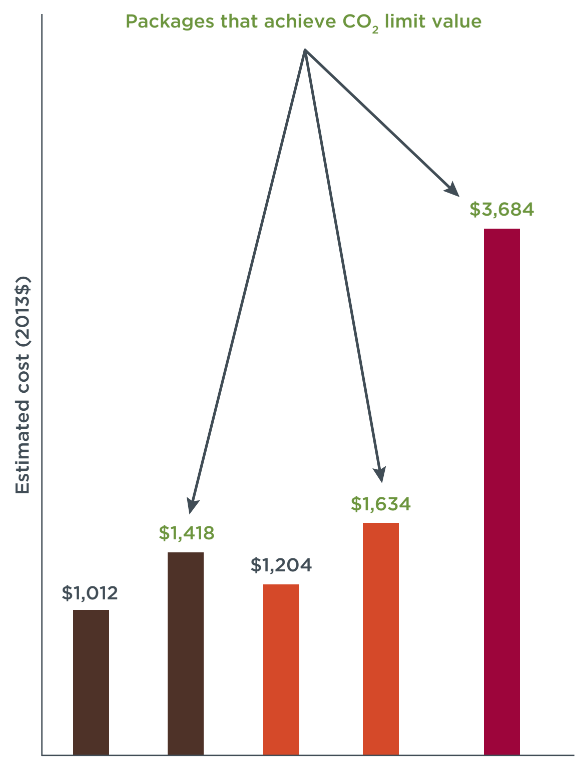

Figure A8. Technology packages and costs for the heavy heavy-duty multipurpose vocational vehicle in model year 2027.

		Tire-Focus		Power train-Focus		Other-Focus
		Core	Additional	Core	Additional	Core
Engine	MY 2021	●				●
	MY 2024					
	MY 2027			●		
Transmission	2 extra gears			●		
	Advanced shift strategy			●		
	Early torque converter lockup			●		
Tires	Level 1v			●		●
	Level 2v					
	Level 3v					
	Level 4v					
	Level 5v	●			●	
Other	Automatic engine shutdown sys. (AESS)		●			●
	Neutral idle		●			●
	Start-stop					●
	60 mph speed limiter					●
	Improved accessories					●
	Tire pressure monitoring system	●				
	High efficiency axles					●
	Axle disconnect (6x2)					●
	Package result (g/ton-mile)	372.2	331.2	354.0	345.1	311.1
	Estimated CO_2 limit value (g/ton-mile)	348.7				

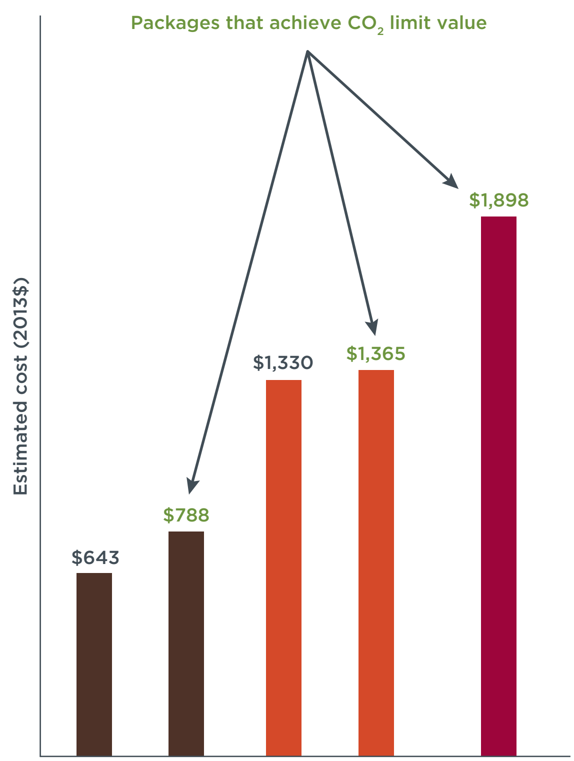

Figure A9. Technology packages and costs for the light heavy-duty multipurpose vocational vehicle in model year 2021.

		Tire-Focus		Power train-Focus		Other-Focus
		Core	Additional	Core	Additional	Core
Engine	MY 2021					
	MY 2024	●				●
	MY 2027			●		
Transmission	2 extra gears			●		
	Advanced shift strategy			●		
	Early torque converter lockup			●		
Tires	Level 1v			●		●
	Level 2v					
	Level 3v					
	Level 4v					
	Level 5v	●				
Other	Automatic engine shutdown sys. (AESS)		●		●	●
	Neutral idle		●		●	●
	Start-stop					●
	60 mph speed limiter					●
	Improved accessories					●
	Tire pressure monitoring system	●				
	High efficiency axles		●			●
	Axle disconnect (6x2)					●
	Package result (g/ton-mile)	366.5	318.5	354.0	314.3	306.4
	Estimated CO_2 limit value (g/ton-mile)	321.6				

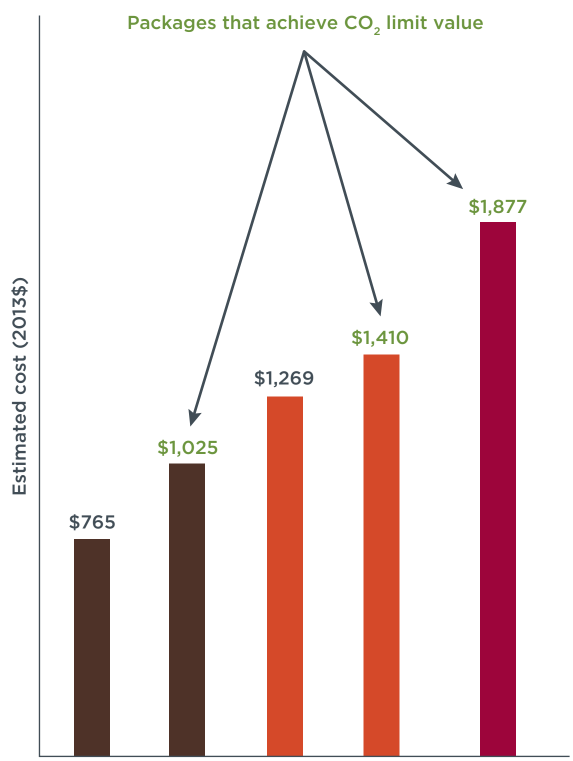

Figure A10. Technology packages and costs for the light heavy-duty multipurpose vocational vehicle in model year 2024.

		Tire-Focus		Power train-Focus		Other-Focus
		Core	Additional	Core	Additional	Core
Engine	MY 2021					
	MY 2024					
	MY 2027	●		●		●
Transmission	2 extra gears			●		
	Advanced shift strategy		●	●		
	Early torque converter lockup		●	●		
Tires	Level 1v			●		●
	Level 2v					
	Level 3v					
	Level 4v					
	Level 5v	●			●	
Other	Automatic engine shutdown sys. (AESS)		●		●	●
	Neutral idle		●		●	●
	Start-stop					●
	60 mph speed limiter					●
	Improved accessories					●
	Tire pressure monitoring system	●				
	High efficiency axles					●
	Axle disconnect (6x2)					●
	Package result (g/ton-mile)	364.6	306.4	354.0	305.5	304.5
	Estimated CO_2 limit value (g/ton-mile)	308.5				

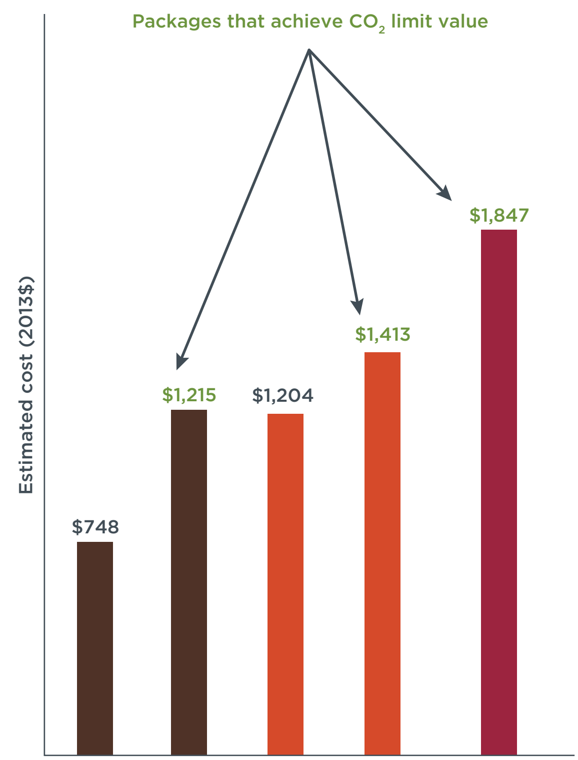

Figure A11. Technology packages and costs for the light heavy-duty multipurpose vocational vehicle in model year 2027.

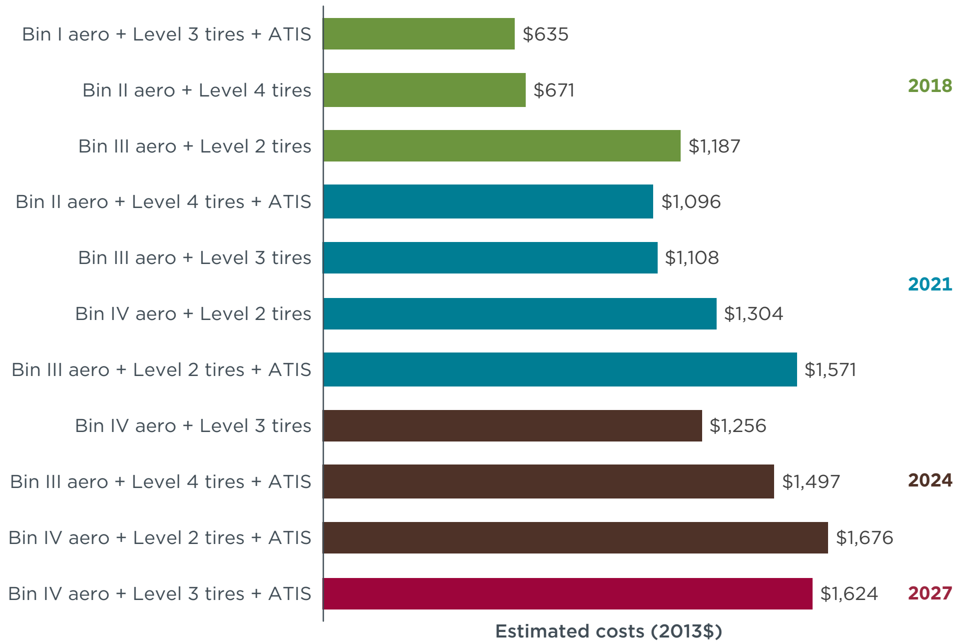

Figure A12. Technology packages and costs for the short box trailer.