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Heavy-Duty Truck Retrofit Technology: Assessment and Regulatory Approach

Final Report

**Report to:
Union of Concerned Scientists
2397 Shattuck Avenue, Ste. 203
Berkeley, CA 94704**

Date: September 12, 2008

**Prepared by:
Raymond Schubert
Matt Kromer
TIAX LLC
20813 Stevens Creek Blvd., Ste. 250
Cupertino, California 95014-2192
Tel: 408-517-1550
Fax: 408-517-1551**

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Executive Summary

This study investigates the financial, emissions-reduction, and petroleum-reduction benefits of heavy-duty vehicle improvements achieved through decreased rolling resistance, aerodynamic modifications, and weight-reducing technologies. Fleet and individual vehicle models were developed to quantify the financial benefits and the potential greenhouse gas (GHG), NO_x, and fuel-consumption reductions from several different retrofit-implementation scenarios.

The results of our analysis suggest there is wide-ranging payoff in implementing a cost-effective retrofit program that focuses on the new and in-use heavy-duty vehicle fleet. Focusing such a program on the highest-consuming portion of the fleet, which includes tractor-trailers and straight trucks greater than 14,000 pounds, has the potential to reduce state heavy-duty fleet GHG emissions by 14.9 to 22.2 million metric tons of carbon dioxide-equivalent between 2010 and 2020, and to reduce fuel use by 1.2 to 1.8 billion gallons, in California alone. This represents a reduction of fuel use and GHG emissions from the heavy-duty truck sector in the year 2020 of 4 to 6 percent compared to business-as-usual projections. Such a program also offers a sizeable potential NO_x co-benefit, reducing 2020 NO_x emissions by 41 to 60 tons a year. Accounting for out-of-state benefits could increase these numbers by nearly a factor of 7.

Introduction

On-road transportation is fundamental to our economic system, but it contributes to three important national concerns: energy security, climate change, and air quality. Energy security has gained popular attention both because of political conditions around the world and rising fuel-pump prices. Greenhouse gas (GHG) emissions from vehicles are increasingly worrisome because their predominant component—carbon dioxide (CO₂), an unavoidable product of combustion—has been linked to global climate change. And tailpipe criteria-pollutant emissions—including oxides of nitrogen (NO_x), particulate matter (PM), carbon monoxide (CO), and reactive organic gases (ROGs)—present direct hazards to humans. Addressing each of these three issues is critical to our economic vitality and environmental health.

California agencies have responded through numerous initiatives over the past decade aimed at the transportation sector. In 2000, the legislature passed and the governor signed AB2076^A, which directed the California Energy Commission and the California Air Resources Board (CARB) to develop and adopt recommendations for a state strategy to reduce petroleum dependence and greenhouse gas emissions. The resulting recommendations were:

- Reduce on-road petroleum consumption to 15 percent below 2003 levels by 2020.
- Double the fuel economy of new cars, light trucks, and SUVs.
- Increase alternative fuel use to 20 percent of on-road fuel consumption by 2020 and 30 percent by 2030.

The legislature also passed AB1493^B in 2002 and AB1007^C in 2005. Pursuant to AB1493, CARB developed a regulation to control GHG emissions from passenger vehicles. Approved in 2005, it requires a 22-percent GHG reduction by 2012 (16.4 million fewer tons) and a 30-percent reduction by 2016 (31.7 million fewer tons) compared to business as usual emissions.

AB1007 required the California Energy Commission to develop and adopt a plan to increase the use of alternative fuels without adversely affecting air quality or water quality or causing negative health effects. GHG and criteria-pollutant emissions from a variety of alternative fuels were evaluated on a full fuel-cycle basis (well to wheels), and the State Alternative Fuels Plan was completed in 2007.

In 2005, the governor’s Executive Order S-3-05 established goals to reduce statewide GHG emissions to the level emitted in 2000 by 2010, to the level emitted in 1990 by 2020, and to 80 percent below the 1990 level by 2050. Finally, AB32^D essentially codified the 2020 goal. From the data of Figure 1, which indicates statewide emissions and the portion of the inventory due to on-road transportation and heavy-duty vehicles, CARB has forecast that 170 million metric tons of GHGs will need to be reduced from projected (business-as-usual) 2020 levels.

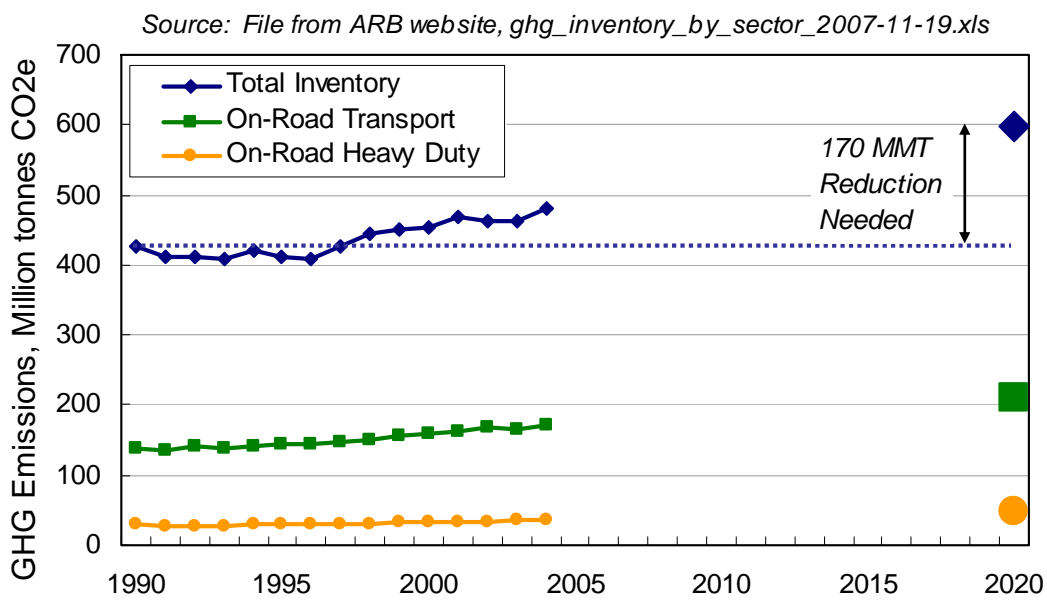


Figure 1: California historic GHG emissions and projected business-as-usual 2020 levels

In addition, AB 32 (passed in 2006), required that CARB identify a list of “discrete early-action greenhouse gas reduction measures.” Once on the list, these measures must be developed into regulatory proposals, adopted by the Board, and made enforceable by January 1, 2010. Nine main early-action items have been identified, four of which directly address the on-road transportation sector:

- Low Carbon Fuel Standard
- Reductions From Mobile Air Conditioning
- Heavy-Duty Measure
- Tire Pressure Program

Executive Order S-01-07 directed CARB to address the first item by establishing the Low Carbon Fuel Standard (LCFS), which requires fuel providers to reduce the carbon intensity of transportation fuels on a full fuel-cycle basis by 10 percent by 2020. The LCFS rulemaking effort

is utilizing the AB1007 full fuel-cycle analysis methodology to estimate GHG emissions of alternative transportation fuels.

Another early-action measure is the proposed Heavy-Duty Vehicle Greenhouse Gas Emission Reduction Measure. Based on the U.S. Environmental Protection Agency's SmartWay Program, this regulation will require the use of technologies that improve the efficiency of heavy-duty tractors and trailers operating in California.

The U.S. heavy-duty vehicle fleet is powered almost entirely by diesel engines. Although favored by fleet operators for heavy-duty applications because of their high torque and relatively good fuel economy, diesel engines emit higher levels of criteria pollution than do comparable gasoline engines. Even with significantly more stringent new-engine emissions standards and in-use vehicle regulations being enacted by California, diesel trucks will be the primary source of NO_x emissions in the state. But preliminary studies have shown that aerodynamic, rolling-resistance, and weight changes to the in-use vehicle fleet could produce NO_x reductions in addition to those being realized through engine and exhaust aftertreatment technologies.

While improved combustion and aftertreatment devices are proven methods of abating critical criteria pollutants, they do not affect CO₂—a natural byproduct of combustion. In fact, the only way to lower CO₂ production without changing the fuel or its composition is simply to burn less fuel. For heavy-duty vehicles, there are three pathways that lead to reduced fuel consumption:

- Reduction in mileage traveled or ton miles
- Improvement in fuel economy
- Electrification

Because the heavy-duty fleet itself is a mature infrastructure, driving fewer miles is not an option that can reasonably be achieved within the next decade. In fact, the greenhouse gas emission levels from diesel trucks are projected to increase 30 percent between 2005 and 2020 due to increases in the miles traveled.^E However, there are a number of technological options that can improve fuel economy. These technologies, both on the market and in development, tend to fall into one of four categories:

- Engine technologies
- Transmission improvements
- Hybridization configurations, including idle-specific subsystems
- Vehicle improvements, including decreased rolling resistance, aerodynamic modifications, and weight reduction.

All of these options are being pursued by engine and truck manufacturers to improve the fuel economy of new trucks entering the market. Generally speaking, for these technologies to be successful the benefits from fuel savings must equal or outweigh the incremental cost of the technology. Meeting and justifying this price point is very difficult when a critical variable in the analysis is the ever-changing price of oil. In addition, purchase decisions by fleet owners tend to evaluate the savings over a relatively short time horizon. As such, the risk-weighted anticipated savings must exceed a steep financial threshold for any technology to find its way onto a heavy-duty vehicle.

This study has chosen to focus on vehicle improvements through decreased rolling resistance, aerodynamic modifications, and weight reduction because they apply both to new vehicles and the in-use vehicle fleet and may be quickly deployed relative to engine, transmission, and hybridization technologies.

Our goals are to: quantify the financial benefits to fleet owners accrued over the life of the vehicle for several different heavy-duty truck retrofit packages; and evaluate the corresponding reductions in GHG emissions, NO_x emissions, and fuel consumption for several different retrofit implementation scenarios. The next section of this report explains our methodology for characterizing the heavy-duty truck fleet, evaluating different GHG retrofit packages, and projecting future fleet-wide benefits of different implementation scenarios. This is followed by a presentation of the results of our analyses, which evaluate both the business case for different retrofit options and the fleet-wide effects of deploying these technologies on new and used vehicles. We weigh the merits of different GHG retrofit packages in emissions, fuel-consumption, and economic terms, and we offer insights on how best to structure a GHG retrofit strategy.

Study Methodology

Task 1. Fleet Characterization by Fuel Use in California

The initial phase of our study focused on characterizing the in-use heavy-duty truck fleet and fuel use in California.

The fleet characterization helped to identify those segments of the fleet on which our analysis would concentrate and to estimate the driving measures—such as annual vehicle miles traveled (VMT), typical duty cycle, and truck lifetime—of the in-use fleet for various truck applications. This data served as the basis for our evaluation of different heavy-duty truck retrofit strategies.

TIAX used the Vehicle Inventory and Use Survey^F (VIUS 2002) from the U.S. Census Bureau to characterize and rank top fuel-consuming applications in California. This survey of commercial truck activity remains the most comprehensive database available for characterizing truck activity trends by body type, vocation, or application. Because the fuel economy and criteria-pollutant emissions improvements of retrofit devices on heavy-duty vehicles (weighing more than 14,000 pounds) were well documented and the vast majority of fuel use (93 percent) in California was diesel, we chose to focus on heavy-duty diesel-fueled vehicles only in the calculations of benefits to the fleet. Thus although gasoline and natural gas heavy-duty vehicles would also have fuel economy benefits from the retrofit devices that were studied—primarily in straight-truck applications—benefits for these vehicles are not presented in this analysis.

The heavy-duty diesel-fueled vehicle fleet was segmented by body type, and the percentage of fuel that each type consumed in the state was identified. The figures were then applied to the future-year fuel consumption estimates from the AB 1007 State Alternative Fuels Plan of the California Energy Commission (CEC).^G These future truck fuel consumption estimates originated from a freight model that used data from a commodity flow survey, a vehicle use survey, and commodity growth forecasts. The commodity flow survey collected information from existing warehouses and reflected the movement of commodities to and from distribution centers in California.^H The vehicle use survey was employed to estimate the average commodity

ton-miles traveled per vehicle. We felt that this top-down segmentation of the fleet would be a reasonable representation of future fuel consumption and would allow the estimation of diesel gallons reduced from the fleet.

During the course of the project we conferred with the California Air Resources Board on its efforts to characterize the medium-sized and heavy-duty fleet in California through a more intensive bottom-up analysis by annual vehicle population and vehicle miles traveled (identified by Department of Motor Vehicles [DMV] and International Registration Plan [IRP] vehicle databases). Based on these discussions, we believe our characterization of the fleet will be reasonably accurate, with a few exceptions. One area of potential disagreement in the methodologies comes from the fact that CEC's ton-miles were truncated to reflect origin-destination distances applying only to in-state California freight movement. Therefore the demand numbers in our forecast do not include any out-of-state demand or any freight traffic within California that does not have either an origin or destination within California. Transit demand also reflects only in-state demand. We believe that a small percentage of the heavy-duty vehicle traffic in goods movement would be discounted and that the overall estimate of gallons reduced may be slightly underestimated because of the additional miles of pass-through traffic.

Truck body types included tractor-trailers, straight or box trucks, dump trucks, flatbed trucks, utility or service trucks, garbage/recycling trucks, cement mixers, and others. While the in-use fleet is not constant over time, we felt that estimates of the fuel consumed by different body-type segments of the fleet could reasonably be considered constant. Some of the retrofit approaches, such as aerodynamic devices, being considered in the study may also be specific to certain body types.

Within the diesel-fueled heavy-duty vehicle fleet, the tractor-trailer body type was by far the highest-ranking fuel consumer—at about 68 percent. The next body types were straight trucks (7.7 percent), trash/recycling (3.9 percent), and flatbed trucks (3.7 percent). All other body types consumed less than 3 percent of the fuel statewide. The complete breakdown by body type is shown in Figure 2.

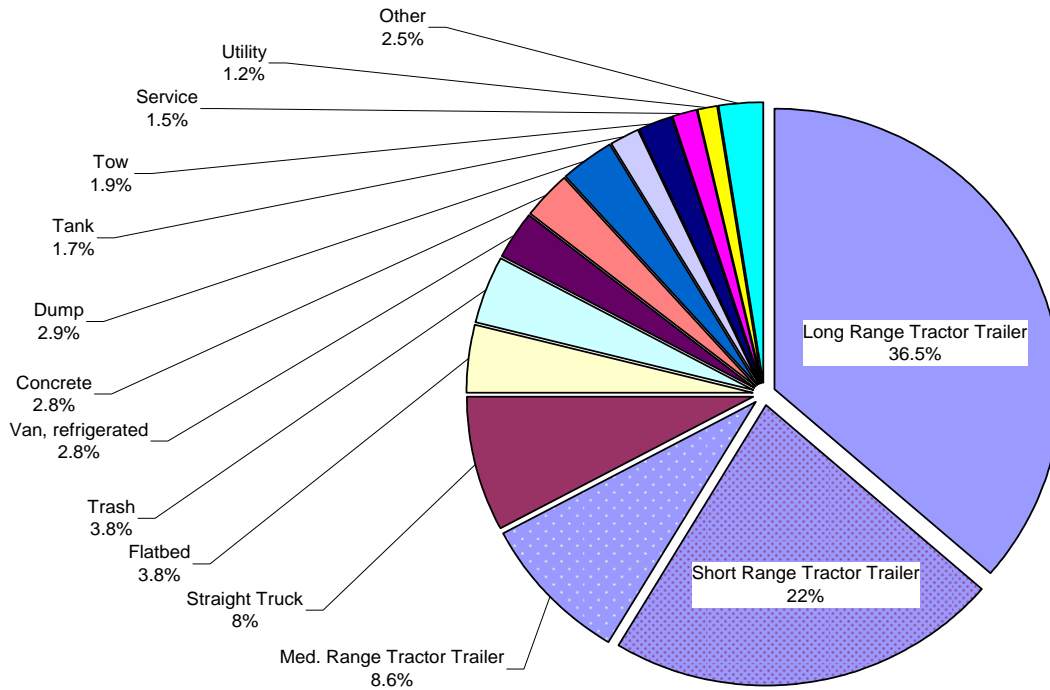


Figure 2: Percentage diesel consumption in California, trucks >14,000 pounds, including out-of-state trucks

Because the tractor-trailer segment accounts for the majority of fuel use, these vehicles served as the focus of our analysis. And because tractor-trailers exhibit different operational profiles (varying duty cycles and annual mileages), we further segmented the tractor-trailer fleet into three subclasses according to the average primary trip length. Short-range regional haul was classified as below 100 miles, medium-range regional haul as 100 to 200 miles, and long-range haul as greater than 200 miles. For each fleet subsegment, we estimated the vehicle population, mileage accrual, and average fuel economy. While this segmentation relied fairly heavily on the surveyed trip length, a factor that some fleets may find it difficult to quantify, we made database checks on factors such as the vehicle miles traveled and fuel economy to ensure that we were getting the segmentation we intended.

In addition to tractor-trailers, we also investigated the benefits of retrofitting straight (or single-body) trucks with GHG-mitigation devices. Straight trucks are estimated to be the second-largest fuel consumer, and they provide a comparison to the cost-effectiveness of the strategies evaluated for the tractor-trailer.

Given that many of the retrofit devices under consideration apply specifically to box trailers and that there may be several trailers for each tractor in use, it was also necessary to separately characterize the trailer fleet. There is little mileage accrual data or age profile data specifically available for that fleet, so VIUS was used to make a best estimate of its size. The VIUS data indicates that approximately 60 percent of the miles traveled by tractor-trailers were completed while pulling a 53-foot box-type trailer (such distances are called “van miles”). This would indicate that aerodynamic trailer retrofit packages would not have an effect on 40 percent of the tractor fleet’s VMT. The 60-percent factor was used for nonexempt tractor-trailers in each sector

(long-, medium-, and short-range). It is estimated that 10 percent of the van miles for tractor-trailers involves trailers with refrigeration units. While some of the retrofit packages may be unavailable for these trailers without further modification, we believe that technologies are under development to address these vehicles; thus an adjustment was not made to account for this difference. Refrigerated straight trucks were not included in the analysis.

In addition, multiple trailers are often staged in warehousing sites so that they can be loaded and unloaded without the tractor present. In such cases, a fleet owner would need to install retrofits on multiple trailers for each tractor. Using Polk survey data¹ on the 150 largest private and for-hire fleets in the United States, we estimated that there are approximately 2.5 trailers for every tractor in use. Cost estimates for the different retrofit packages were made both with a factor of 2.5 trailers per tractor and just one trailer per tractor.

Within the tractor-trailer and straight-truck fleet, VIUS was used to identify segmented population and VMT curves by vehicle age for single-body trucks and short-, medium-, and long-range tractor-trailers. It was estimated that 80 percent of new tractor-trailers are used in the long-haul sector. The remaining 20 percent—regional-haul trucks—were split one-third medium range and two-thirds short range.

Although a small percentage of new tractor-trailers are sold directly into regional service, in general a typical tractor operates for a few years in the long-range fleet and then migrates into the lower-mileage regional segments. A long-range service survivorship curve (which reflects the migration from the long-range to the shorter range fleets) and an overall heavy-duty fleet survivorship curve (which reflects actual scrappage rates) were used to reflect this pattern. The overall heavy-duty fleet curve was derived from data presented in the U.S. Department of Energy's *Transportation Energy Data Book*¹. Because limited data was available on heavy-duty vehicle scrap rates, a single rate was used both for straight trucks and tractor-trailers. For this analysis, it is assumed that long-range service has a median life of eight years, while the median lifetime for all heavy-duty vehicles is 19 years. This difference is another indication that there is often a transition of these trucks from long-haul to regional-haul application during their lifetimes.

We estimated that straight trucks would have duty cycles similar to those of regional-haul applications of the tractor-trailer, although the average annual miles for straight trucks was determined to be quite a bit lower. The figure for a tractor-trailer over a 19-year median life was almost 74,000 miles, compared to approximately 17,800 miles for the straight truck. The tractor-trailer and straight-truck body types, responsible for more than 70 percent of the fuel consumed in California by medium- and heavy-duty vehicles, are the focus of the remainder of the analysis. Key assumptions regarding their operational characteristics are summarized in Table 1.

¹ The scrap curves for 1980-vintage, rather than 1990-vintage, vehicles were used. As discussed in MOVES (EPA's mobile source emissions modeling program) documentation the 1990-vintage projections show dramatically longer lifetimes than those of previous projections and appear to be contradicted by more recent data. Moreover, the later projections were based on a limited data set, as few trucks had yet reached their end of life.

Table 1: Characteristics of in-use tractor-trailer (TT) and straight trucks

Fleet Segment	Avg. VMT ² (new/used)	Median Life (Age)	% of New Sales	Model Year 2008 Fuel Economy (mpg)	% of Box Trailer Miles
Long Range TT	130K/50K	8	80	6.5	60
Medium Range TT	95K/50K	13	13.3	6.3	60
Short Range TT	75K/25K	19	6.7	6.1	60
Straight Truck	31K/5K	19	N/A	11.5	N/A

Task 2. Characterize Technology Options for Each Application

In parallel with our characterization of the heavy-duty fleet, we undertook a survey of available retrofit options both for tractor-trailers and straight trucks. These options were selected on the basis of their demonstrated effectiveness at reducing fuel consumption and the feasibility of installing these devices on a large portion of the in-use fleet. Technologies that were individually characterized included low-rolling-resistance tires, single-wide tires, trailer aerodynamic improvements, cab aerodynamic improvements, and lighter-weight materials.

To the extent possible, the fuel-reduction potentials and costs of different retrofit devices were estimated from a review of published literature^{KLMNOPQRSTUVWXYZ} over duty cycles that reflected typical operation in long-range and regional service. However, fuel efficiency improvement estimates were not available for all devices for each of the duty cycles under evaluation (long-range, medium-range, and short-range/straight truck). Most sources offered estimates for a device deployed on a vehicle operating at a constant speed of 65 miles per hour while a few provided estimates for duty cycles that were not clearly defined.

To fill in these gaps in the fuel-reduction potential estimates, computer simulations were used to develop sensitivity curves that correlated reduced vehicle road load with fuel economy improvement. Curves were generated for each of three different drive cycles—a constant 65 mph cycle, a highway duty cycle typical of long-range trips, and a suburban duty cycle typical of short-range trips—and for three different types of reduction in the vehicle’s road load: reduced coefficient of drag (C_D), reduced rolling resistance (C_{RR}), and reduced weight. The parameters investigated are summarized in Table 2.

Table 2: Modeling parameters

Duty Cycle	Constant 65 mph, SwRI Suburban, SwRI Long Haul
Coefficient of Drag (C_D)	C_D varies from 0.3 to 0.6
Coefficient of Rolling Resistance (C_{RR})	C_{RR} varies from 0.004 to 0.0068
Gross Vehicle Weight (GVW)	GVW varies from 20K lbs to 80K lbs

² The VMT curves assume that mileage declines linearly from the high value (year 0) to the low value (year 16), at which point the annual mileage is assumed to remain constant throughout the remainder of the vehicle’s life.

Simulations were conducted—using AVL Cruise, a vehicle drive-cycle modeling software package—by varying parameters from a baseline vehicle model. The baseline characteristics, summarized in Table 3, reflected typical values for heavy-duty tractor-trailers currently on the road. Individual parameters, such as C_D or C_{RR} , were varied both in isolation (e.g., to see the effect of improving the aerodynamic profile of the baseline vehicle) and in combination (e.g., to see the effect of improving the aerodynamic profile of a vehicle with improved rolling resistance tires). The latter approach was used to estimate the overall impact of combining several technologies into a single package.

Table 3: Baseline vehicle characteristics

Component	Value
Eng/Transmission	13.4 L, 2300 Nm/10-speed trans.
Frontal Area	10.5 m ²
C_D	0.6
C_{RR}	0.0068
GVW	65,000 lbs

L: liter
Nm: Newton-meter

The long-haul and suburban drive cycles that were used for the vehicle simulations are shown in Figure 3 and Figure 4, respectively. The average speed for the long-haul duty cycle is 54 mph; for the suburban duty cycle, it is 31 mph. As shown, a portion of the long-haul duty cycle includes a grade climb.

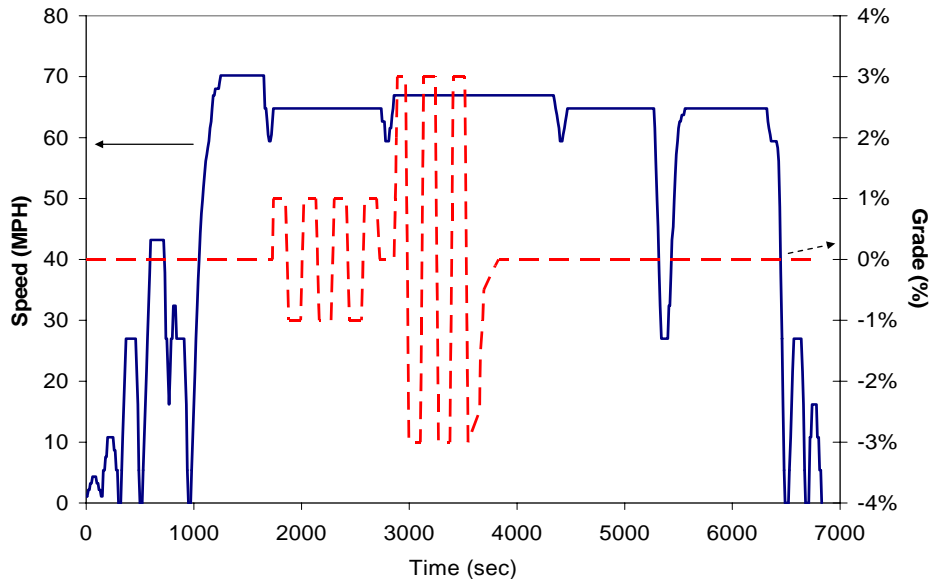


Figure 3: Southwest Research Institute (SwRI) long-haul duty cycle

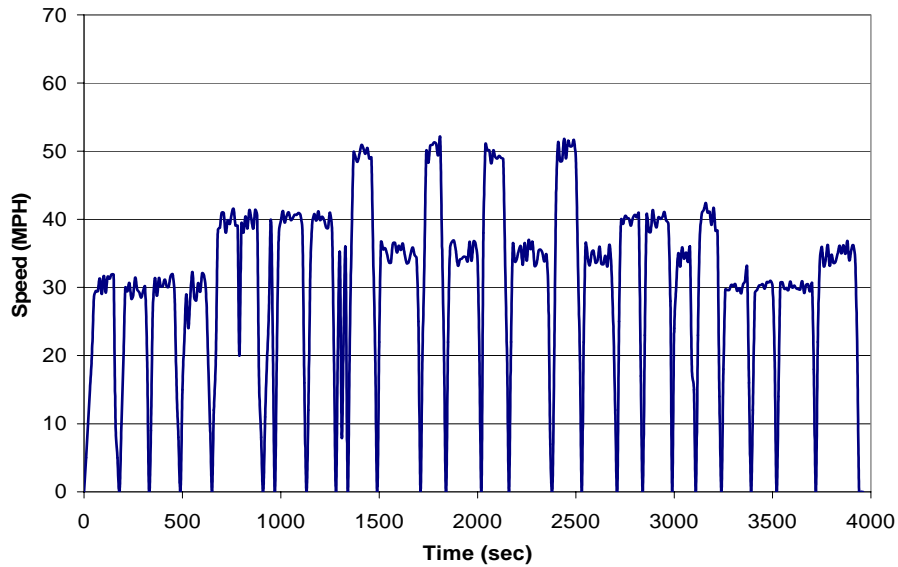


Figure 4: SwRI suburban drive cycle

To estimate the fuel economy improvement for short-range, mid-range, and long-range vehicles, the results from the long-haul and suburban drive cycles were blended to varying degrees to obtain a weighted-average fuel economy improvement. The relative weighting between the long-haul and suburban cycles was obtained by calculating the average vehicle speed needed to achieve the estimated VMT for each of the different duty cycles. These results are summarized in Table 4.

Table 4: Estimated application characteristics for modeling

	Duty Cycles	Avg Speed	Drive time ³	Miles/year
Long Range	100% LH	54 mph	7–8 Hrs/Day	95K–110K
Medium Range	50% LH, 50% Sub	43 mph	6–7 Hrs/Day	65K–75K
Short Range	25% LH, 75% Sub	37 mph	5–7 Hrs/Day	45K–65K

We estimated the NO_x reduction benefits of the various retrofit devices as a function of the device’s fuel economy benefit and the vehicle’s duty cycle. In reality, researchers have found that the relationship between NO_x and fuel consumption is not necessarily linear. They have observed fuel consumption reductions from 3 to 18 percent, with NO_x emissions decreasing from 9 to 45 percent.^x This disparity arises because a number of engine-specific factors—such as engine injection timing, exhaust gas recirculation amount and temperature, and boost level—as well as ambient conditions can all effect NO_x production independent of fuel consumption.

As such, while it is clear that NO_x emissions decrease with reduced fuel consumption, the exact relationship depends on the drive cycle and the engine. To account for this variability we derived a different multiplier, based on the fuel economy benefit of the technology package, to estimate the NO_x benefit. Hence for the long-range duty cycle we assumed a NO_x benefit that was 1.22 times the fuel economy benefit, based on average of published test data. For the short-range duty

³ Assumes 250 work days/yr

cycle we assumed a factor of 0.58 times the fuel economy benefit, based on published data for an urban drive cycle. And for the medium-range duty cycle we assumed a factor of 0.74 times the fuel economy benefit, based on the average of the long- and short-range test data.

We consider these multipliers relatively conservative and believe this to be appropriate, given the facts that: the population of in-use vehicles is expected to employ many of the advanced engine-combustion techniques and aftreatment systems needed to meet 2010 emissions standards; and these vehicles have only limited real-world testing. We then estimated the potential NO_x reductions from the fleet assuming that CARB adopts a regulation requiring heavy-duty trucks to meet 2010 emissions standards by 2020. This regulation is awaiting adoption by the CARB Board. Without this regulation in place, the NO_x reductions from the fleet would be much higher than indicated in this report. Because of the large variation in test results found in literature, we did not attempt to estimate PM reductions.

To evaluate the business case for heavy-duty truck retrofits, six different retrofit packages were considered (summarized in Table 5) for deployment both in new and in-use truck fleets. Package costs were calculated using an average of estimates from a review of published literature (cited above) and include installation labor. Each package was characterized according to its upfront cost, projected fuel savings as a function of age and vocation, and time to payback. Some examples of retrofit technologies are shown in Figure 5.

Table 5: Package summary

Package	Truck Type	Description	Capital Cost	
			2.5 Trailers	1 Trailer
Package A	In-Use TT	- LRR ⁴ tires	\$10,930	\$4,630
	New TT	- Trailer front and side fairings - Aero cab (new trucks only)	\$11,680	\$5,380
Package B	In-Use TT	- LRR or Single-wide tires	\$23,840	\$10,495
	New TT	- Aluminum wheels - Trailer front, side, and rear fairings - Aero cab (new trucks only)	\$24,590	\$11,245
Package C	In-Use TT	- LRR tires	\$2,205	\$1,140
	New TT	- Aero cab (new trucks only)	\$2,955	\$1,890
Package D	In-Use Straight	- LRR tires	N/A	\$1,530
	New Straight	- Front fairings		\$1,530
Package E	In-Use Straight	- LRR tires	N/A	\$3,255
	New Straight	- Aluminum wheels - Front fairings		\$3,255
Package F	In-Use Straight	- LRR tires	N/A	\$525
	New Straight			\$525

⁴ LRR = low rolling resistance

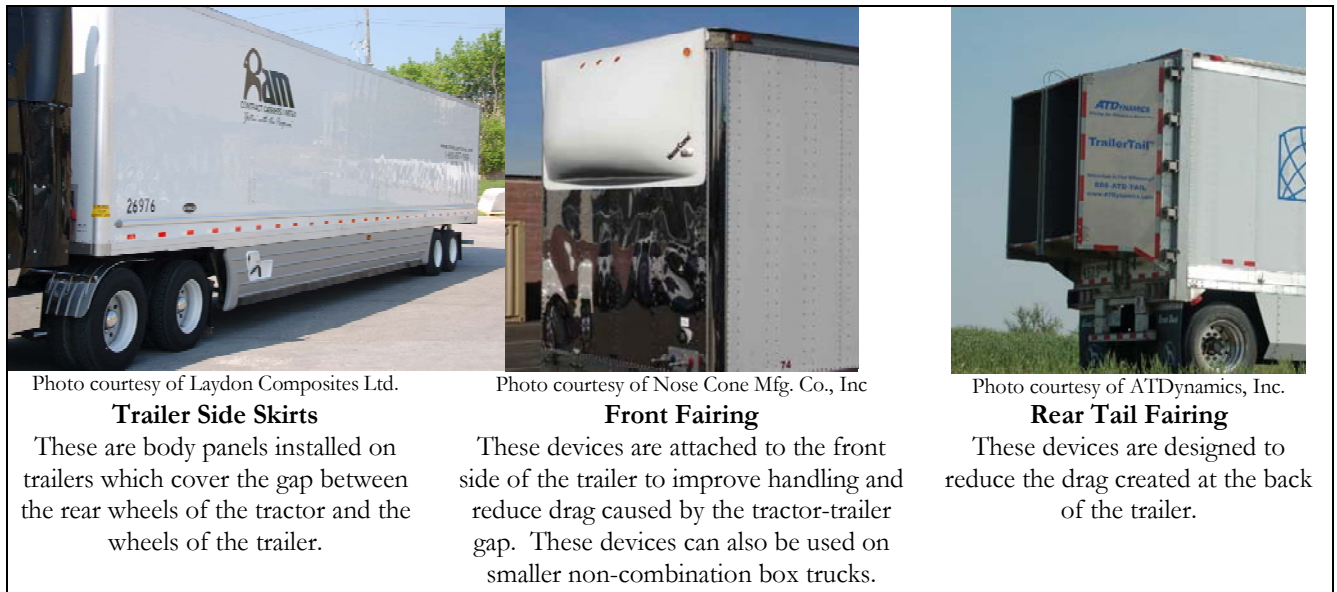


Figure 5: Retrofit technology examples

Packages A, B, and C are variations on retrofit packages intended for use in a tractor-trailer combination truck. Packages D, E, and F are designed for deployment in a straight single-body truck.

- Package A is our baseline GHG retrofit. It features low-rolling-resistance tires and front and side trailer aerodynamic fairings. For new trucks, it includes a fully outfitted aerodynamic tractor with aero bumper, mirrors, cab side extenders, and cab side fairings. It is similar to the EPA “Smartway” package.
- Package B offers the maximum fuel economy benefit, at a reasonable cost, using currently available technologies. It has additional aerodynamic features, including rear trailer-mounted flaps or “boat tails”⁵ and low-rolling-resistance dual or single-wide tires with lightweight aluminum wheels on the trailer and tractor. Ranges of benefits and costs for the tires in the package were used because single-wide tires may not be appropriate to all applications.
- Package C, a subset of package A, is intended for deployment on tractor-trailers that do not typically pull box-type van trailers. It includes the same tires as package A applied both to the tractor and trailer, and those aerodynamic treatments that apply to the tractor. However, it does not include the aerodynamic fairing trailer retrofits.
- Package D is analogous to Package A but intended for straight trucks. It includes a front aerodynamic fairing and low-rolling-resistance tires.
- Package E is analogous to Package B but intended for straight trucks. It has lightweight aluminum wheels in addition to those features included in Package D.
- Package F is analogous to Package C but intended for straight trucks. Like Package C, it aims to offer benefits to those single-body trucks that cannot exploit the full aerodynamic package of a box truck.

In addition, all the new-truck retrofit packages include aerodynamic cab treatments that improve fuel economy by an additional 2 percent for long-range service, 1.3 percent for medium range,

⁵ Manufacturers of rear flaps and boat tails have indicated that devices that accommodate roll-up and swing-out doors, as well as docking logistics at warehouses, will be fully available by 2010.

and 1 percent for short-range. These fuel economy improvements are relative to the performance of an average aerodynamic model tractor. When compared to a classic styled tractor, a full aerodynamic tractor can show much greater improvements, on the order of 15 percent. Examples of both types of tractors are shown in Figure 6.



Figure 6: Aerodynamic and classic cab examples

Table 6: Package performance summary

Package	Description	Body Type	Improvement	
			Fuel Economy	NO _x
A	<ul style="list-style-type: none"> - LRR tires - Trailer front & side fairings - Aero cab (new trucks) 	Long Range TT	10.0%	12.2%
		Medium Range TT	8.1%	7.5%
		Short Range TT	7.1%	4.2%
B	<ul style="list-style-type: none"> - LRR or Single-wide tires - Aluminum wheels - Trailer front, side & rear fairings - Aero cab (new trucks) 	Long Range TT	12.8%	15.6%
		Medium Range TT	11.3%	10.5%
		Short Range TT	10.1%	5.9%
C	<ul style="list-style-type: none"> - LRR tires - Aero cab (new trucks) 	Long Range TT	5.0%	6.1%
		Medium Range TT	4.2%	3.6%
		Short Range TT	3.9%	2.5%
D	<ul style="list-style-type: none"> - LRR tires - Front fairings 	Straight Truck	6.8%	15.6%
E	<ul style="list-style-type: none"> - LRR tires - Aluminum wheels - Front fairings 	Straight Truck	8.1%	15.6%
F	<ul style="list-style-type: none"> - LRR tires 	Straight Truck	1.4%	0.8%

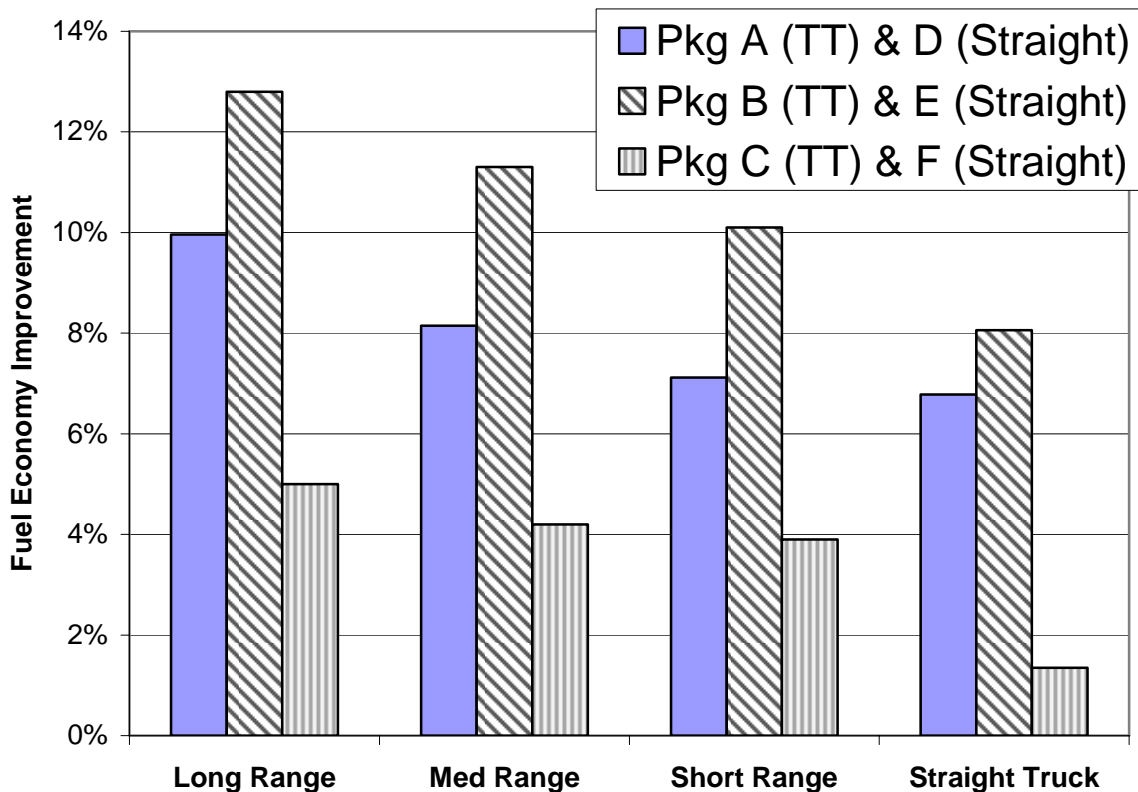


Figure 7: Estimated fuel-economy improvement for new retrofit technology packages, including the improved aerodynamic cab

Table 6 and Figure 7 present the assumptions regarding each package’s fuel economy performance for long, medium, and short range tractor trailers and straight trucks.

Task 3. Estimate the Benefits of Fleet GHG Retrofit Programs

The results of our fleet characterization (Task 1) and evaluation of GHG retrofit devices (Task 2) were used to develop a fleet fuel-consumption model that estimated the benefits of potential in-use truck GHG devices for the targeted vehicle fleets. Estimated GHG benefits were made by first identifying the impact a technology would have on the fuel consumption of the segmented fleet, with the model separately identifying technology-implementation rollouts for in-use vehicles and new vehicles. The fleet-wide effects of implementation of GHG retrofit strategies into these vehicle groups had slight modeling differences.

For the in-use fleet, a proposed phase-in schedule was identified that allowed for compliance with a potential rule over a four-year period. An estimate was also made on the current market penetration of individual technologies in the current fleet; this accounted for the fact that some portion of the population would have realized the economic benefits of the retrofit devices. The market penetration of the packages under consideration was estimated by calculating a weighted average amongst the individual technologies. Next, the percentage of the fleet that fell below a mileage threshold was estimated by sector, using the VMT and population age curves. This threshold is used to represent a potential low mileage vehicle exemption of a retrofit program. As expected, this exemption limit had a large impact on short-range regional haul trucks, as

approximately 62 percent of the short-range fleet miles occur on trucks that travel fewer than 50,000 miles per year. The assumed 60-percent van-miles factor for those devices implemented on nonexempt trailers was only then taken into account. The fleet analysis was based on the mileage accrual of the tractor and assumed that all box-trailer miles used a retrofit box trailer. We also assumed that compliance would be tracked through the tractor VMT and not based on trailer use or mileage.

The percentage of the fleet affected by a strategy was calculated for the calendar years 2007–2020, based on the implementation-rollout schedule and the vehicle population vs. age profile. It was assumed that the age profile (i.e., the fraction of the in-use fleet of a given age) did not change over time. While this assumption could not be accurately applied to individual years, due to buying trends such as emissions-level pre-buy, we felt that this was reasonably accurate for large groups of model year vehicles (i.e., five model years or more)⁶.

Finally, the percentage improvement, with all of these factors taken into account, was multiplied by a fuel economy correction factor to take into account the reality that a given retrofit would offer greater benefit for a vehicle with lower fuel economy (because its baseline fuel consumption was higher). This factor had a small but important effect on the effectiveness of retrofitting older and less fuel-efficient vehicles in the fleet. Based on reported fuel economy by application and model year in the VIUS 2002 database, we estimated an overall fuel economy improvement trend of 0.5 percent per year. Several fuel economy improvement technologies can contribute to this trend, including those pertaining to engine and transmission efficiency, weight reduction, and aerodynamic and rolling resistance.

For implementation of the GHG-reduction packages to new trucks, the fuel economy improvement of 0.5 percent per year was considered to be the baseline case. The percentage improvement of the technology packages was again calculated using a 60 percent/40 percent split for van miles and non-van miles. The implementation schedule assumed 100 percent compliance of new tractors and trailers in a given year. These factors were combined to give a percentage fuel economy improvement, for each body-type sector, and the total gallons reduced from the baseline fuel consumption. The annual fuel consumption projected by the California State Alternative Fuel Plan (AB 1007)^Y served as the business-as-usual case in order to identify the potential overall impact of GHG reduction programs on California's fleet. GHG reductions were calculated on the CO₂-equivalent content of diesel fuel on a full fuel-cycle basis. We used a factor of 90.57g CO₂eq/MJ diesel (16.47 upstream and 74.1 downstream) from the AB 1007 report.

GHG and NO_x emissions and diesel gallon-reduction benefits calculated in-state were then used to estimate out-of-state benefits by means of a VMT or annual-mileage weighting factor. These benefits would be realized if trucks that operated in California were required to employ GHG retrofit strategies that were not removed or taken out of operation when the truck operates out of state. VIUS was used to determine the average annual miles both of California trucks and non-California (but otherwise U.S.-surveyed) trucks and to estimate the percentage of miles that were logged within the state. It was estimated that the California VMT from in-state trucks was

⁶ There is a trend in the light-duty vehicle fleet toward increasing vehicle longevity, and it is likely that such a trend is also present in the heavy-duty sector. However, there is limited data on heavy-duty vehicles that speaks to this point, and over the time horizon under consideration the effect is likely to be marginal.

roughly equal to the California VMT from out-of-state trucks. Out-of-state weighting factors were developed for the four sectors of trucks to identify the differences between short-range, medium-range, and long-range tractor-trailers. Straight trucks were assumed to have a VMT distribution similar to that of a short-range tractor-trailer. Overall, the trucks considered in this analysis had out-of-state miles that were more than nine times the number of in-state miles.

Task 4. Calculate Costs and Savings

Economic viability is essential to any strategy for reducing GHG emissions from heavy-duty trucks. There are, however, a virtually infinite number of circumstances that affect the economic advantages of an individual truck. We therefore chose a manageable number of fleet and truck-owner scenarios and estimated the costs and payback periods for these cases.

For combination trucks, capital costs were calculated for two scenarios—one in which fleet owners deploy and retrofit 2.5 trailers per tractor on average and one in which fleet owners deploy and retrofit only a single trailer per tractor. The single-trailer case reflects the situation for small fleets and single-truck owner-operators who actually may own only one trailer per truck. Moreover, it reflects the possibility that, if trailers become costlier, fleet operators may find it more economical to implement operational efficiencies by using fewer trailers.

Fuel savings were calculated for two different fuel-price scenarios: a low-cost case, in which diesel is priced \$2.56 per gallon; and a high-cost case of \$5.00 per gallon. The lower cost is an average of estimated diesel prices 2008–2020 from the Energy Information Administration's (EIA) Annual Energy Outlook 2008 (reference case scenario),^Z while the high-cost scenario uses the average pump price recorded by EIA in California in July 2008.^{AA}

Capital costs for packages were assumed to occur in the year the retrofit would be installed on the vehicle, while fuel savings costs were conveyed in net present value (NPV) using a 7-percent discount rate. All costs were expressed in constant 2008 dollars.

Results

The benefits of heavy-duty truck retrofits were evaluated first in business terms for fleet owners and then with respect to fleet-wide reductions in greenhouse gas emissions, NO_x emissions, and fuel consumption.

As discussed in the methodology section, our characterization of the heavy-duty fleet suggests that the expected yearly mileage of trucks varies considerably with vehicle age and fleet segment (long-range, medium-range, short-range, straight truck). In addition, older trucks have less time to recoup the initial investment in a retrofit package through reduced fuel consumption.

As such, financial analysis of a retrofit package must carefully weigh how to apply it to the fleet so as to achieve maximum benefit at reasonable cost. For example, an in-use retrofit strategy might be applied to the fleet using an age-based metric (all trucks newer than a given age are affected) or a mileage-based metric (strategy applies to all trucks with average VMT above a certain threshold).

For this analysis, we calculated retrofits' time to payback and NPV as functions of age and fleet segment. Because our model of truck operations has VMT varying with age and fleet segment, as shown in Figure 8, it can be equated to a mileage-based approach.

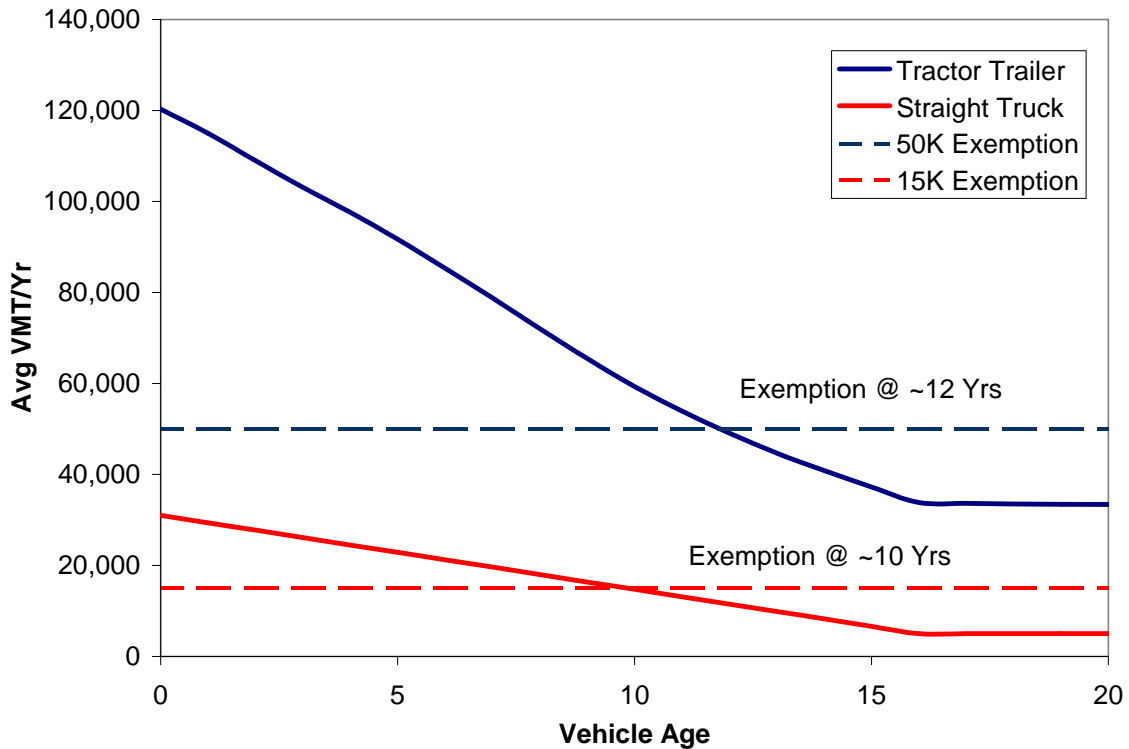


Figure 8: Average VMT for surviving trucks as a function of age

Both the payback and net-savings calculations assume that future savings are discounted at a rate of 7 percent per year. The net-savings calculations for new-truck retrofits are based on the NPV of the estimated fuel savings through the truck's median life minus the capital cost of the technology package. For example, the calculation for a long-range truck assumes that fuel savings are accrued until the truck is nine years old (using an eight-year median life).

As shown in Tables 7 and 8, each of the packages, with the exception of Package B in short-range service and an average (low) fuel price of \$2.56/gallon diesel, offers positive discounted cash flow over the life of the vehicle, and most packages offer payback (calculated in discounted dollars) within a few years. For new vehicles, these results are relatively robust with respect to which assumptions are used (high vs. low fuel price and 1 vs. 2.5 trailers). As expected, package B—which is more expensive, but offers the greatest fuel economy benefit—has the greatest benefit when fuel prices are high and when expected VMT is high (i.e., long- and medium-range service). For straight trucks, Package D appears to be the most cost-effective option.

Table 7: Time to payback and net savings, new tractor-trailer retrofits

Fleet (Med. Life)	Case ⁷	Package A		Package B		Package C	
		Payback	Savings ⁸	Payback	Savings	Payback	Savings
Long (8 yrs)	Low/2.5	35 mths	\$ 15.8	71 mths	\$ 8.3	16 mths	\$ 11.5
	Low/1	16 mths	\$ 22.1	28 mths	\$ 22.5	10 mths	\$ 12.5
	High/2.5	17 mths	\$ 42.2	32 mths	\$ 41.3	8 mths	\$ 25.4
	High/1	8 mths	\$ 48.5	14 mths	\$ 55.5	5 mths	\$ 26.4
Medium (13 yrs)	Low/2.5	54 mths	\$ 10.8	111 mths	\$ 5.8	25 mths	\$ 9.1
	Low/1	24 mths	\$ 17.1	43 mths	\$ 19.2	16 mths	\$ 10.2
	High/2.5	27 mths	\$ 32.4	45 mths	\$ 34.9	12 mths	\$ 20.6
	High/1	13 mths	\$ 38.7	20 mths	\$ 48.2	8 mths	\$ 21.7
Short (19 yrs)	Low/2.5	76 mths	\$ 4.7	X	\$ (0.6)	34 mths	\$ 6.3
	Low/1	33 mths	\$ 11.0	50 mths	\$ 11.9	20 mths	\$ 7.4
	High/2.5	37 mths	\$ 20.2	66 mths	\$ 20.9	17 mths	\$ 15.1
	High/1	17 mths	\$ 26.5	25 mths	\$ 33.4	10 mths	\$ 16.2

Table 8: Time to payback and net savings, new straight-truck retrofits

Fleet (Med. Life)	Case ⁶	Package D		Package E		Package F	
		Payback	Savings	Payback	Savings	Payback	Savings
Straight Trucks (19 yrs)	Low	51 mths	\$ 1.5	144 mths	\$ 0.4	123 mths	\$ 0.1
	High	23 mths	\$ 4.5	47 mths	\$ 3.8	43 mths	\$ 0.7

The results shown in Tables 7 and 8 illustrate the savings for a typical new truck over a median life in a single fleet segment; this data is particularly useful for characterizing vehicles according to average annual VMT. In reality, however, as trucks age they tend to migrate from long-range to short-range operation. In addition, the median total lifetime of an older vehicle (which has already survived for a number of years) is longer than the median lifetime of a new vehicle (which might be scrapped early in its life). For the calculation of an average truck, we assume it transitions from long haul to regional application during year nine.

These factors are reflected in the results shown in Figures 9, 10, 11, and 12. Each figure corresponds to a different retrofit package (A through D, respectively) and shows the expected discounted fuel savings (solid lines) over the life of the vehicle as a function of its age at the time of retrofit, both for the high- and low-fuel-price scenarios. The dashed lines show the initial capital costs of implementing the package in question; for tractor-trailers, these include the 1-

⁷ “Low” or “High” fuel price (\$2.56 vs \$5.00 per gallon)/“1” or “2.5” Trailers per tractor for TT

⁸ NPV expressed in thousands of dollars, includes fuel savings minus package capital cost

and 2.5- trailer per tractor cases. Moving up in vehicle age, the point at which the fuel savings line crosses the capital cost threshold represents the age at which the expected cost savings for a given package becomes negative.

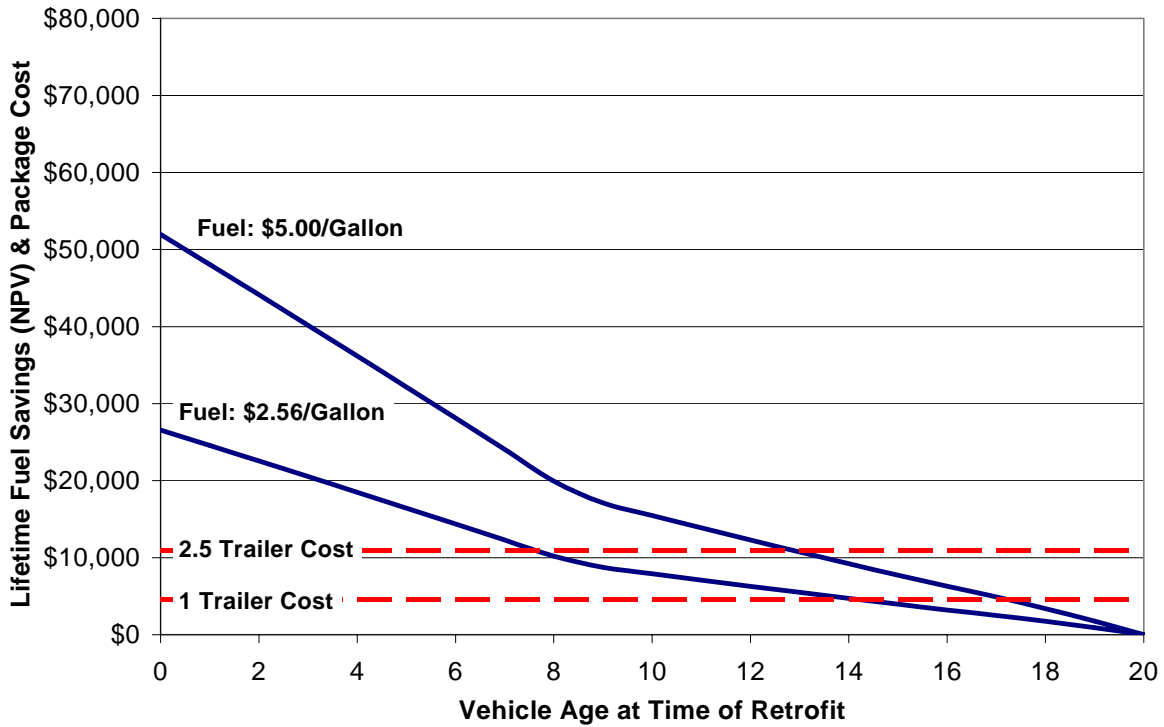


Figure 9: Expected fuel savings as a function of age at retrofit, Package A

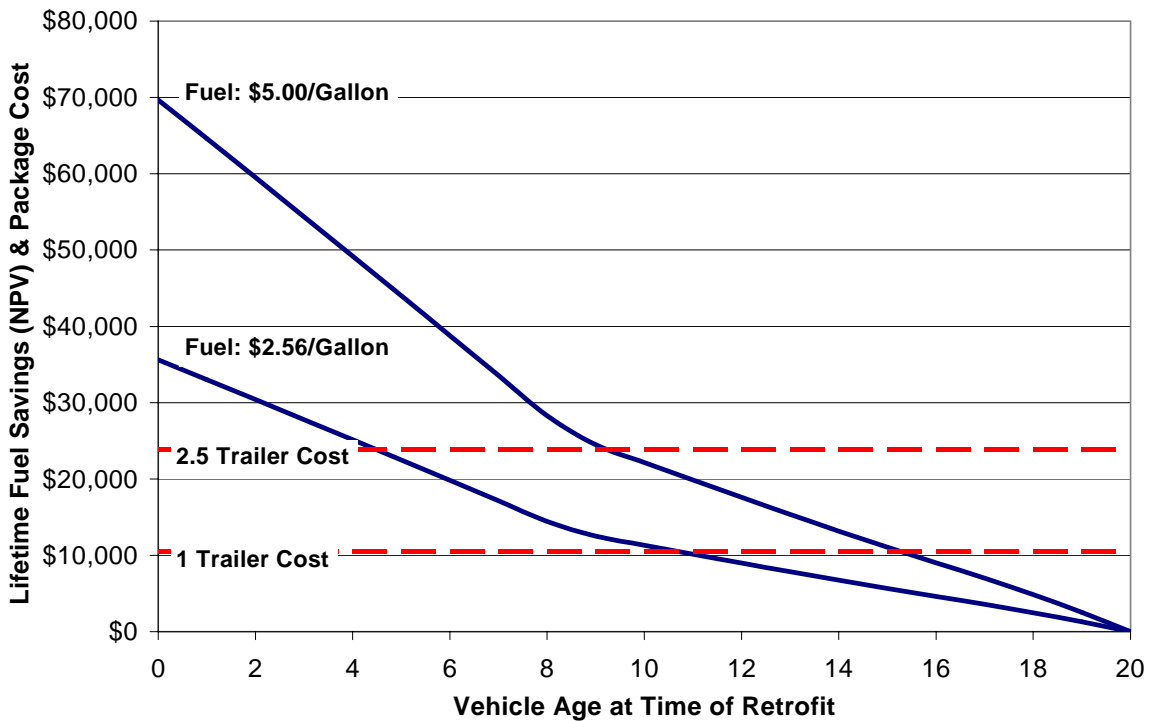


Figure 10: Expected fuel savings as a function of age at retrofit, Package B

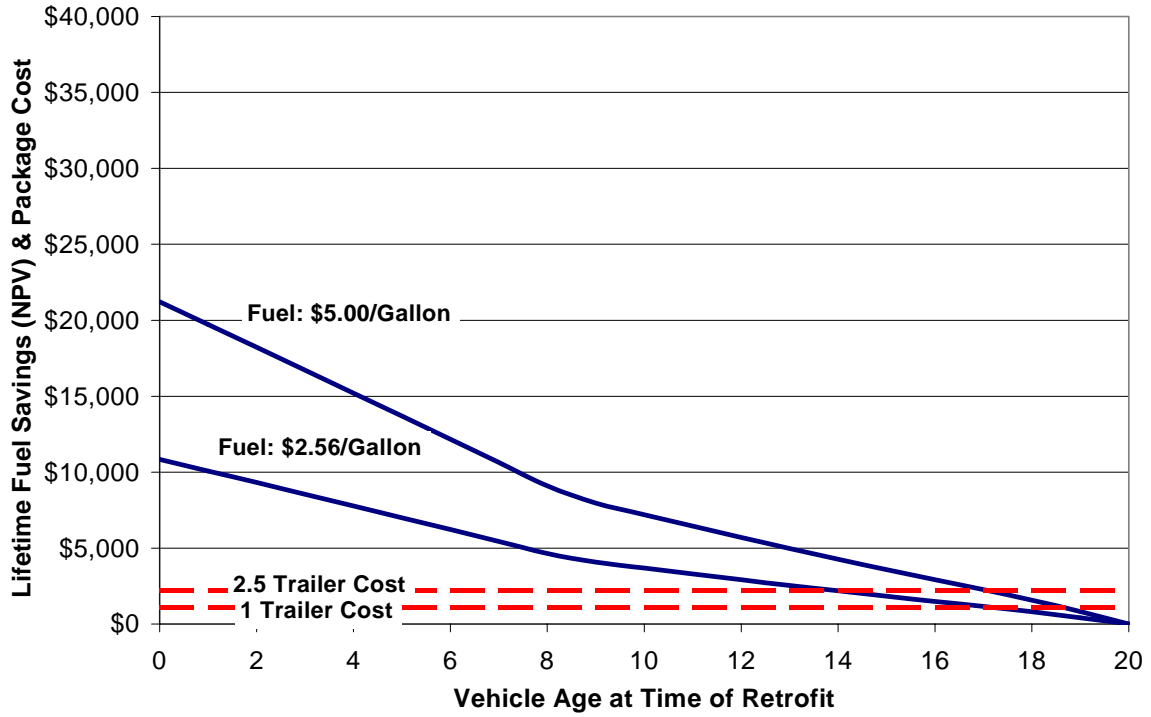


Figure 11: Expected fuel savings as a function of age at retrofit, Package C

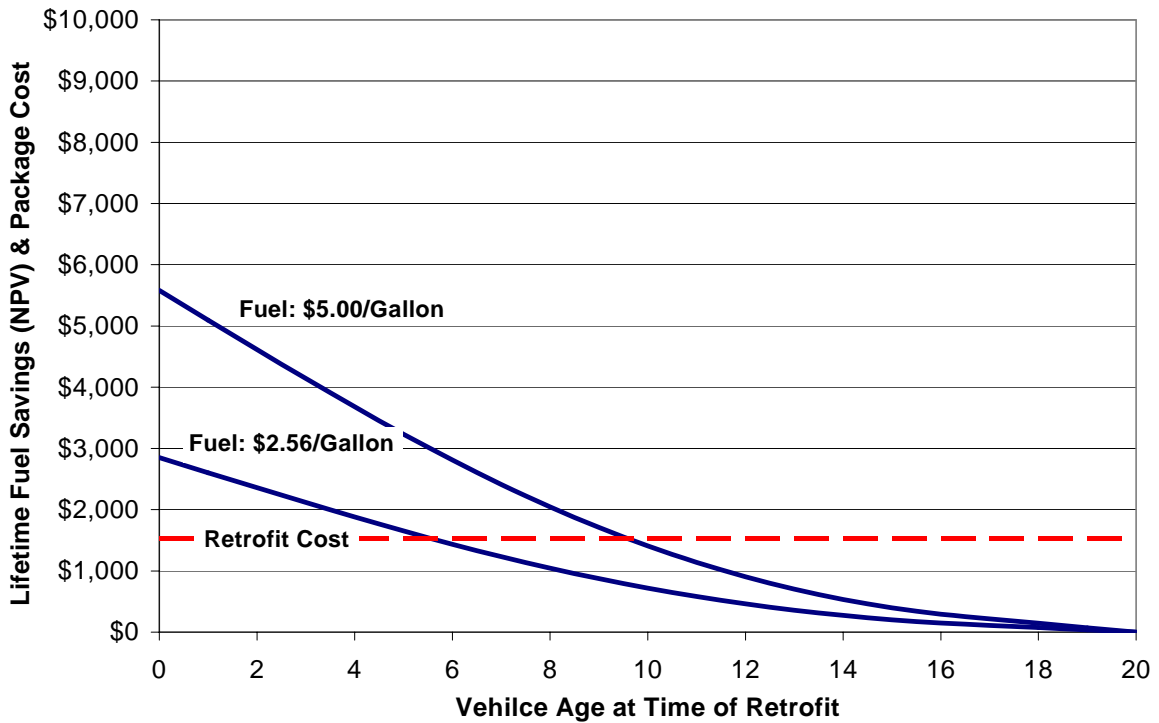


Figure 12: Expected fuel savings as a function of age at retrofit, Package D

The results of these payback calculations support a financial argument for any of the retrofit packages on new vehicles. Even using the most conservative assumptions (fuel price of \$2.56 and 2.5 trailers per tractor), the lifetime fuel savings of each of the packages significantly outweighs the implementation cost for the average truck. On new vehicles, the expected lifetime NPV is highest for Package B, and this finding is robust across the different fuel price and capital cost assumptions.

There is also a significant benefit to implementing retrofits on in-use vehicles that are up to 10 years old. In particular, the financial benefits of Package A (for tractor-trailers) and Package D (for straight trucks) are fairly robust across the different price and capital cost assumptions. Package B is likely to offer benefit on newer-truck retrofits (3–5 years old), particularly if fuel prices remain high. Package C (tires-only) retrofits appear to offer significant benefit, at low cost, throughout the vehicle's life.

The financial argument for retrofitting vehicles older than 10 years is more difficult to make: between the limited mileage and proximity to end-of-life, these vehicles are less likely to yield positive payback. Based on the relationship between vehicle age and mileage that is shown in Figure 8, it appears that a 50,000-annual-VMT exemption fits well with our conclusion that the financial benefits of full retrofits are tenuous for older vehicles. It should be noted, however, that these observations are based on the average truck's VMT at a certain age. Trucks older than 10 years that operate more than the average number of miles may still accrue positive savings through retrofits.

Fleet Implementation Scenarios

Based on our analysis of the different retrofit packages discussed above, several fleet-wide deployment scenarios were characterized according to their potential fuel-savings and emissions benefits. The base-case scenario (Scenario 1) calls for deployment of Package A on all new trucks beginning in 2010 and on all in-use trucks that travel over 50,000 miles per year. The in-use portion of the fleet would have a four-year phase-in period requiring eventual compliance of 100 percent; the new-truck portion of the 2010 fleet would be affected immediately.

Table 9: Summary of fleet scenarios

Scenario	Fleet Segment ⁹	Package	Implementation Scope		
			Age of Truck	Exemption for in-use trucks with VMT	Truck types
1	TT	Pkg A	New & In-Use	<50K Mi/Yr	Box trailer
	Straight	Pkg D		<15K Mi/Yr	Box truck
2	TT	Pkg B	New & In-Use	<50K Mi/Yr	Box trailer
	Straight	Pkg E		<15K Mi/Yr	Box truck
3	TT	Pkg A	New & In-Use	<30K Mi/Yr	Box trailer
	Straight	Pkg D		<15K Mi/Yr	Box truck
4 ¹⁰	TT	Pkg A&C	New & In-Use	<50K Mi/Yr	All Trucks
	Straight	Pkg D&F		<15K Mi/Yr	
5	TT	Pkg A	New	<50K Mi/Yr	Box trailer
	Straight	Pkg D		<15K Mi/Yr	Box truck
6 ¹¹	TT	Pkg B&C	New & In-Use	<50K Mi/Yr	All Trucks
	Straight	Pkg E&F		<15K Mi/Yr	
7	TT	Pkg B&C	New	<50K Mi/Yr	All Trucks
	Straight	Pkg E&F		<15K Mi/Yr	
	TT	Pkg A&C	In-Use	<50K Mi/Yr	
	Straight	Pkg D&F		<15K Mi/Yr	

The additional scenarios, summarized in Table 9, vary Scenario 1 in accordance with the technology packages deployed and the scope of the strategy (i.e., to which segment of the fleet the strategy applies).

⁹ TT = Tractor-Trailer

¹⁰ Package A is applied to all van-type tractor-trailers and Package C is applied to the remainder of the TT fleet. Similarly, Package D is applied to all box-truck straight trucks while Package F is applied to the remainder of the straight truck fleet.

¹¹ Package B is applied to all van-type tractor-trailers and Package C is applied to the remainder of the TT fleet. Similarly, Package E is applied to all box-truck straight trucks while Package F is applied to the remainder of the straight truck fleet.

Table 10: Fleet scenario results (in-state + out-of-state benefits)

Scenario	2020 Fuel Savings (MGal/year)	2020 GHG (MMTons/year)	2020 NO _x (Tons/year)	2010-2020 Fuel Savings (M Gal)	2010-2020 Cum GHG (MMTons)
1	997	12.1	320	8,496	104
2	1,262	15.4	412	10,903	123
3	1,014	12.4	325	8,733	106
4	1,178	14.4	384	10,136	124
5	942	11.5	303	6,595	80
6	1,443	17.6	476	12,543	153
7	1,421	17.3	473	11,824	144

Table 11: Fleet scenario results (in-state benefits only)

Scenario	2020 Fuel Savings (MGal/year)	2020 GHG (MMTons/year)	2020 NO _x (Tons/year)	2010-2020 Fuel Savings (M Gal)	2010-2020 Cum GHG (MMTons)
1	149	1.8	41	1,226	14.9
2	191	2.3	54	1,592	19.4
3	156	1.9	43	1,318	16.1
4	175	2.1	50	1,456	17.7
5	132	1.6	38	870	10.6
6	218	2.7	63	1,823	22.2
7	211	2.6	61	1,688	20.6

Tables 10 and 11 summarize the key results from this scenario analysis, including the estimated GHG, fuel reduction, and NO_x benefits in the year 2020 as well as the cumulative GHG and fuel-savings benefits spanning 2010–2020. Although our discussion of these results focuses on the GHG emissions-reduction benefits of different scenarios, the percent changes in fuel savings are identical to the GHG reductions. And although the NO_x benefits do not scale linearly with the GHG benefits and these gases do not accumulate in the same way as greenhouse gases, a discussion of the NO_x co-benefit would be qualitatively similar. The 149 million gallons of avoided in-state fuel use in Scenario 1 represents a 4-percent reduction in total heavy-duty fuel use and a 7-percent reduction in fuel used by the long-range fleet.

Figure 13 shows a detailed breakdown of the avoided GHG emissions in Scenario 1 for the year 2020. The left-hand bar differentiates these savings according to the fleet subsegment. As shown, the great majority (87 percent) of avoided emissions come from the long-range truck fleet. This outcome reflects several factors: the long-range truck fleet accounts for nearly 50 percent of the California VMT for the vehicles covered in this analysis; this fleet segment is comprised almost entirely of vehicles that travel greater than the 50,000-mile-per-year exemption; and the aerodynamic retrofit packages offer significantly greater benefit over the long-range duty cycle than the other duty cycles we evaluated (Figure 7).

The wedge associated with the short-range fleet is also significant; although these trucks tend to have relatively low VMT, this subsegment of the fleet has the largest truck population. In all, 7 percent of the total reduction comes from the short-range fleet. Although medium-range trucks are assumed to travel a significant number of miles per year and do receive significant fuel-economy benefits from retrofits, they represent a fairly small fraction of the overall fleet. As such, they account for only 3 percent of the overall avoided emissions. The straight-truck fleet accounts for only a small fraction of the total VMT as well, and hence represents a fairly small wedge too—about 3 percent of the total avoided emissions in 2020. However, it should be noted that although the straight-truck and medium-range tractor-trailer fleet contribute only modestly to total GHG reductions, the financial calculations cited in the previous section show that a viable business case may be made for implementing retrofits in both of these fleet subsegments.

As shown, approximately 85 percent of the GHG-reduction benefits and fuel savings occur on miles driven outside the state of California. This is again a reflection of the contribution of the long-range fleet to the overall GHG reductions. Although out-of-state NO_x reductions are of limited benefit to the state of California, both GHG and fuel-consumption reductions are global benefits, with significant value regardless of where they occur.

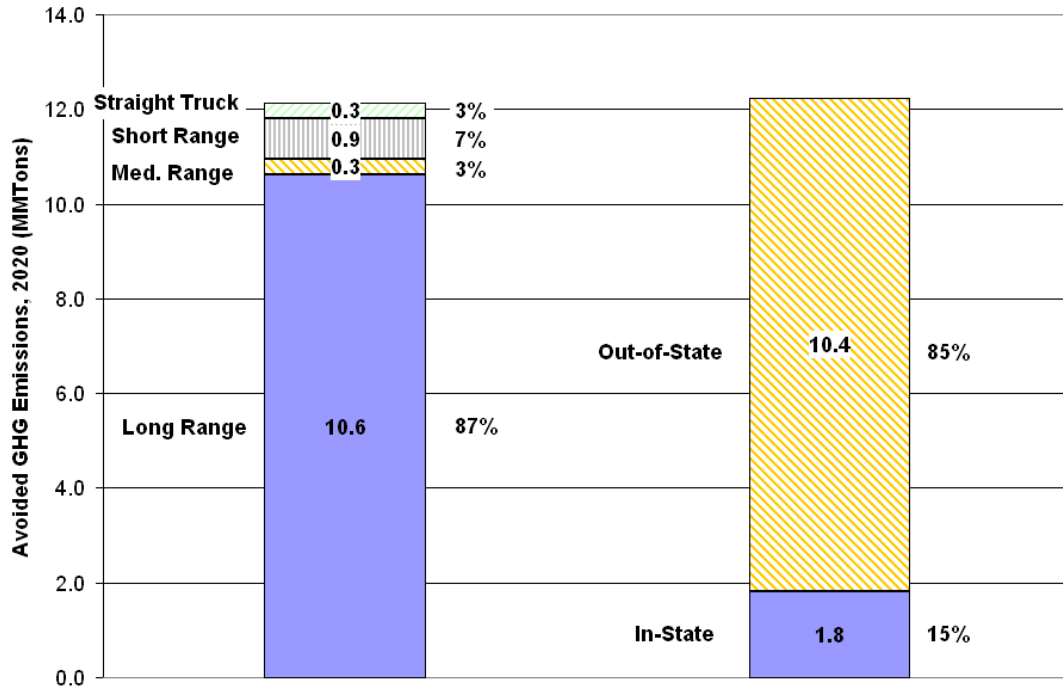


Figure 13: Scenario 1, avoided GHG emissions: By fleet subsegment and miles traveled in-state/out-of-state.

Figures 14 and 15 respectively show avoided GHG emissions in the year 2020 and cumulatively (2010-2020) for each of the implementation scenarios. As shown in Figure 14, Scenario 2 and Scenario 4 both accrue significantly greater benefits than Scenario 1 (base case). Scenario 2 deploys the most fuel-efficient retrofit packages (B and E), which gives it efficiency gains surpassing those of Scenario 1 by 26 percent (year 2020) and 28 percent (cumulative), while reducing fuel use by an additional 42 million gallons in 2020.

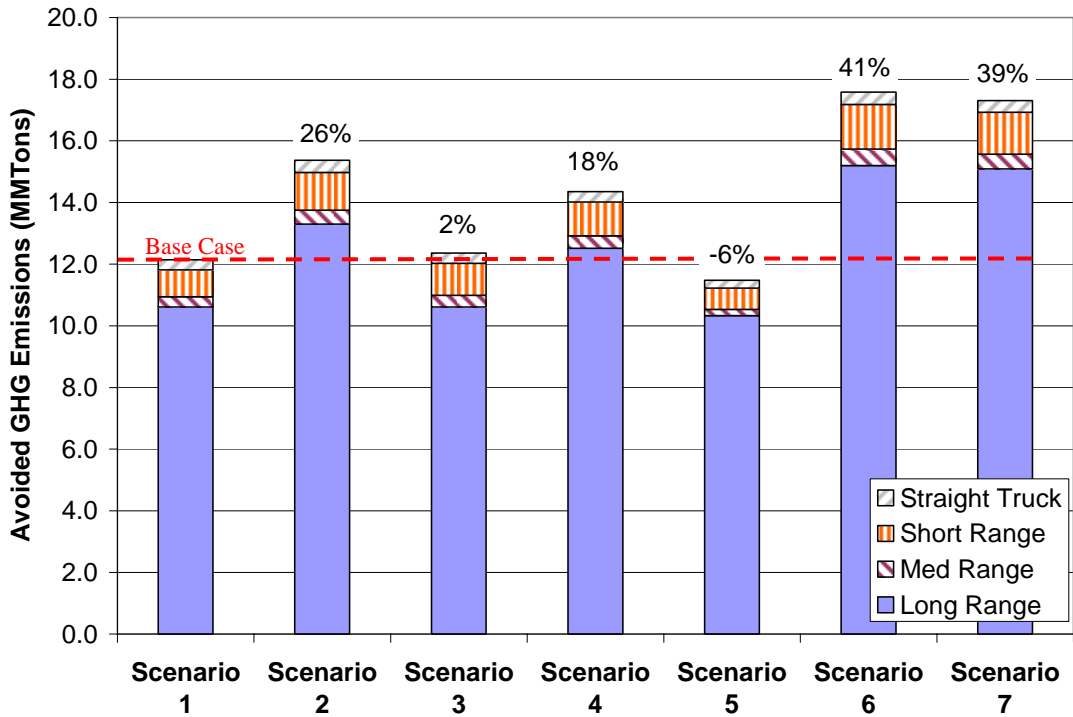


Figure 14: Total (in-state + out-of-state) GHG reduction in year 2020

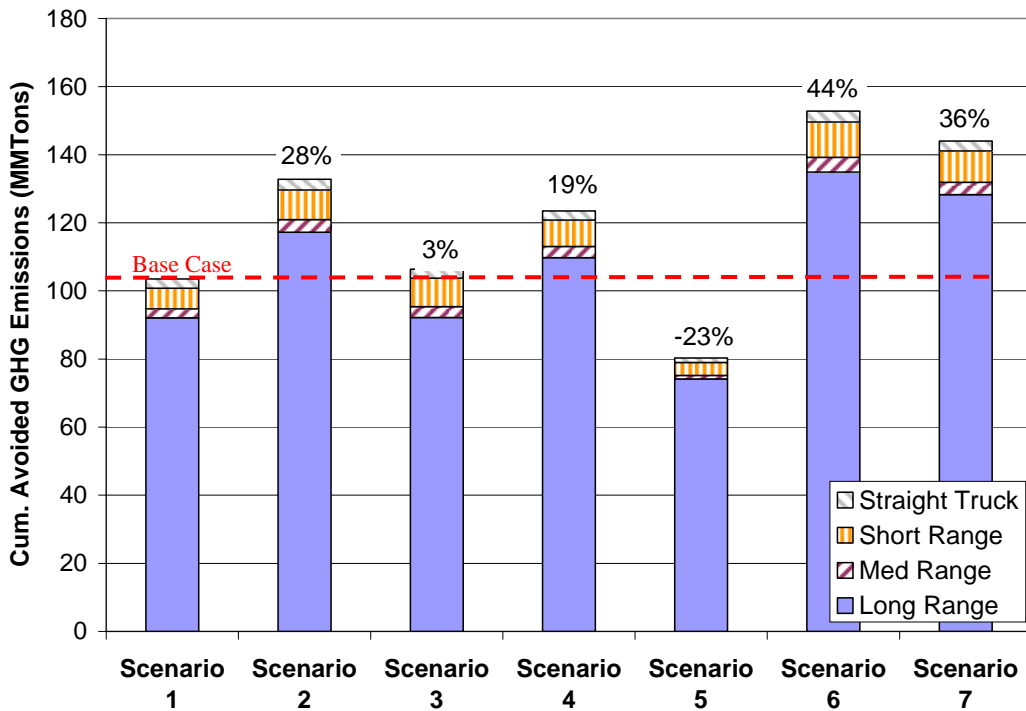


Figure 15: Combined (in-state + out-of-state) 2010-2020 avoided GHG emissions

Scenario 4 offers GHG-reduction benefits of 18 percent (year 2020) and 19 percent (cumulative) beyond Scenario, together with 26 million additional gallons saved in 2020. These benefits are realized by broadening the scope of regulation to include *all* tractor-trailers, not just those box

trailers that can benefit from the full aerodynamic treatments considered in Packages A and B. This wider scope would apply to trucks that capture 40 percent of the total tractor-trailer vehicle miles. Moreover, as noted previously, the financials of this more modest retrofit package are extremely favorable.

Scenario 3, which lowers the mileage exemption of tractor-trailers from 50,000 to 30,000 miles, offers benefits only marginal greater than those of Scenario 1. Because this segment of the fleet accounts for a small portion of the total truck-miles, there is little added benefit to broadening the scope of the strategy in this fashion. In addition, because most of these low-mileage vehicles are older vehicles, the business case for implementing a retrofit package is much more tenuous. For example, the average annual mileage of a tractor-trailer goes below 50,000 miles per year when the truck is about 13 years old (Figure 8). Extending the exemption below this threshold for Package A (Figure 9) has a minor positive present value in the high-fuel-cost/low-package-cost case and a modest *negative* present value in the low-fuel-cost/high-package-cost case.

Given the significant added benefits of Scenarios 2 and 4—as well as their economic appeal—we also considered two hybrid scenarios. The first (Scenario 6) is a “max technology” scenario that combines Scenarios 2 and 4. This broadens the scope of the base case to include all trucks and deploys the more fuel-efficient Package B in the box-truck segment of the fleet, including both new and in-use vehicles. This scenario, also shown in Figure 14 and Figure 15, gives a 44-percent reduction in cumulative GHG emissions (41 percent in year 2020) and a cumulative savings of 12.5 billion gallons of fuel (1.4 billion gallons in year 2020).

The second hybrid scenario (Scenario 7) attempts to capture most of the benefits of Scenario 6 while deploying technologies in the most cost-effective fashion. Although Scenario 6 maximizes the fuel savings and GHG reductions, Package B is significantly more expensive than Package A. Our financial calculations suggest that for new vehicles this higher capital cost is more than offset by the increased fuel savings that accrue over the life of a vehicle outfitted with Package B. On the other hand, for in-use vehicles the financial benefits of Package A appear to be more robust with regard to varying fuel and capital cost assumptions. Hence Scenario 7 assumes that Package B is deployed on new vehicles and Package A is deployed on the in-use fleet.

In addition, as in the case of Scenario 6, Scenario 7 deploys the tires-and-wheels packages of Scenario 4 for non-box trailers and straight trucks. This combination of measures gives a 36-percent reduction in cumulative GHG emissions (39 percent in year 2020) and saves 11.8 billion gallons of fuel (1.4 billion gallons in year 2020). Although yielding total benefits slightly lower than those offered by Scenario 6, Scenario 7 appears to be a more cost-effective option. Note that while there is a difference in the cumulative benefit of Scenario 6 compared to that of Scenario 7, given the rate of fleet turnover, the two scenarios have very similar results in year 2020 and onward.

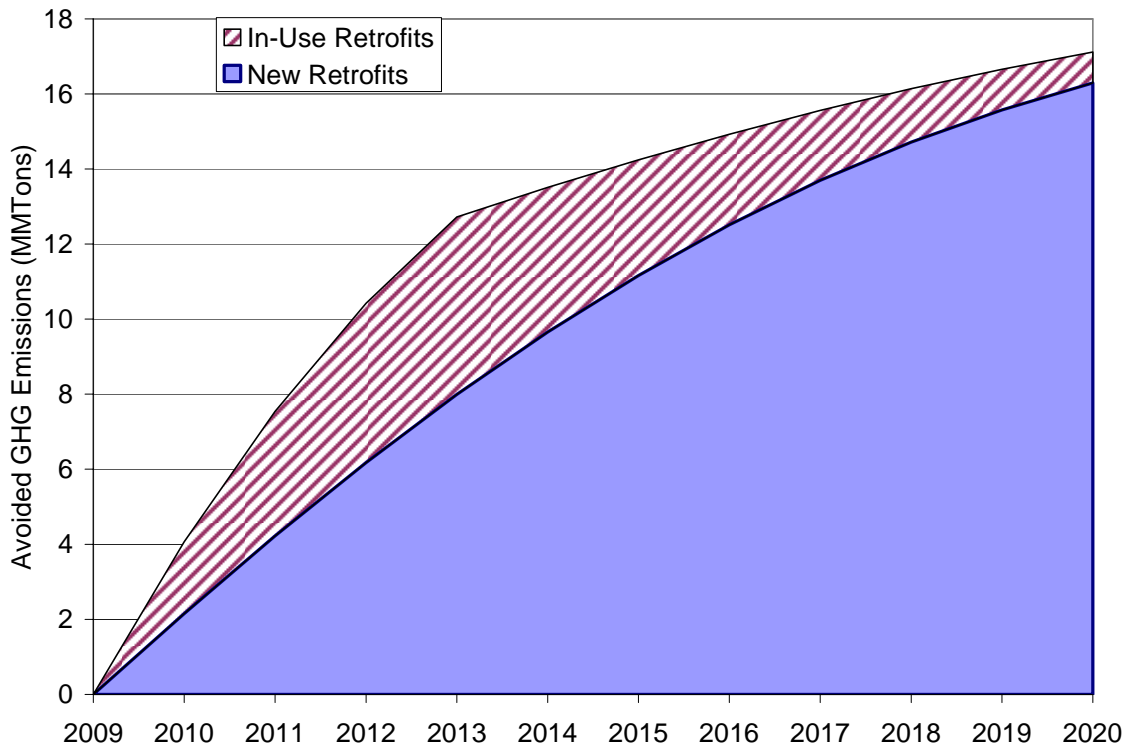


Figure 16: Year-by-year avoided GHG emissions, Scenario 7, 2010-2020

The final portion of our scenario analysis focuses on whether to apply retrofits to new and in-use trucks alike or just new trucks. The results shown in Figure 16 indicate that only 11 percent of the avoided GHG emissions for the year 2020 are due to in-use retrofits. However, when the avoided GHG emissions are examined year by year from 2009 through 2020, or in terms of the cumulative benefit, the in-use retrofit program becomes a much more critical component, accounting for 25 percent of the cumulative GHG reductions. Because in-use retrofits can be applied immediately to a large fraction of the fleet, they provide for much of the total benefit during the early years of retrofit implementation. The estimated benefits of retrofitting in-use trucks are also highly dependent on the assumptions regarding tractor and trailer replacement rates. We believe that the median lifetime assumptions made in this study are conservative and that longer lifetimes on either the tractor or the trailer will extend the impacts of in-use retrofits considerably. A properly implemented control strategy should not, however, encourage the increased use of older and noncompliant tractors or trailers.

Conclusions

Based on the above findings, we can offer several recommendations on how best to craft a heavy-duty retrofit program for the state of California:

Technologies Deployed. An emissions-control strategy based on GHG retrofit devices should deploy a version of our max-technology retrofit package for new vehicles (Package B) and our moderate-technology retrofit package for the in-use fleet (Package A). For newer vehicles, which have many years to recoup the initial capital cost of the more expensive package and which tend to log the highest annual miles, package B offers the greatest long-term financial and environmental benefits. For the in-use segment of the fleet, Package A offers financial benefits that are robust with respect to different fuel-price and capital-cost scenarios for vehicles up to 10–12 years old.

Applicability to Tractor-Trailers and Straight Trucks. Control strategies should focus on tractor-trailers pulling box trailers but also include other tractor-trailers and straight trucks. The greatest opportunity for achieving GHG reductions in the heavy-duty fleet comes from retrofitting tractor-trailers and their box trailers, as this segment accounts for some 60 percent of the truck miles; box trailers are particularly well suited to cost-effective aerodynamic retrofit packages.

Moreover, significant benefits can be realized by deploying a modified tires-only retrofit package (for in-use retrofits) and a tires-plus-improved aerodynamic cab package (for new retrofits) in those tractor-trailers that cannot fully utilize the standard box-trailer retrofit package. Our payback calculations indicate that these packages are cost-effective regardless of vehicle age; deploying them increases the base-case GHG reduction by 18 percent.

The results also indicate that the straight truck fleet accrues modest financial and environmental benefits. Although this subsegment of the fleet accounts for only a few percent of the overall heavy-duty fuel use, several cost-effective packages are quite suitable for it.

Applicability to New and In-Use Vehicles. Ideally, strategies should focus on retrofitting both new and in-use tractors and trailers. In the year 2020 and beyond, the majority of the program's benefits will apply to new vehicles. In addition, new-vehicle retrofits, which may recoup their initial investment over the life of the vehicle, have a greater financial benefit than vehicles that are several years old. However, focusing only on this segment of the fleet would preclude another significant benefit.

Because they can be deployed quickly, in-use truck retrofits offer the greatest opportunity for near-term reductions in GHG and fuel consumption. In addition, in-use retrofits offer financial benefits across a range of capital-cost and fuel-price scenarios for vehicles up to 12 years old. The inclusion both of new and in-use vehicles increases the overall program efficacy (in terms of cumulative avoided GHG emissions during 2010–2020) by nearly 25 percent, compared to a program that focuses only on new vehicles. Lifetimes that are longer than modeled, whether regarding tractor or trailer, would increase the impact of in-use retrofits considerably.

Mileage Exemption. A control strategy focused on those tractor-trailers that travel more than 50,000 miles per year and on straight trucks that travel over 15,000 miles per year maximizes the environmental benefit while reducing financial hardship on fleet operators. Focusing on the higher-mileage fleet subsegments involves those operators who are most likely to recoup their initial investments in retrofit technologies. Our characterization of the heavy-duty fleet indicates that high-mileage vehicles are more likely to achieve positive lifetime cash flow, both because they use more fuel and because they tend to be newer. Expanding the scope below the recommended exemption levels offers only marginal additional benefit (2–3 percent) while obligating operators to make financial investments they are unlikely to recoup.

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Appendix A. Retrofit Devices

Package	Devices	Fuel Economy Improvements			Cost*
		Long-Range Cycle	Medium-Range Cycle	Short-Range Cycle	
Tractor-Trailer					
	Low-Rolling-Resistance Tires or Super Single	3.0% ^A	2.9% ^B	2.9% ^B	\$1,070–\$1,210 ^{**} C,D,E
	Front Fairing & Side Skirts	4.4% ^{F,G,H}	3.3% ^{B,I}	2.6% ^B	\$3,140–\$3,840 ^{I,J}
	Aluminum Wheels	2.0% ^{A,K}	2.0% ^B	2.0% ^B	\$3,200–\$4,600 A,L,M
	Rear Flaps or Boat Tail	5.1% ^{C,F,H,N}	3.5% ^B	2.8% ^B	\$1,690–\$2,240 ^{O,P}
	Improved Aero Cab	2.0% ^C	1.3% ^B	1.0% ^B	\$750 ^D
A	Low-Rolling-Resistance Tires, Front Fairing, Side Skirts, & Aero Cab	10.0% ^{A,B,C,F,G,H,Q,R}	8.1% ^{B,R}	7.1% ^{B,R}	\$4,960–\$5,800 ^{**} C,D,E,I,J
B	Aluminum Wheels, Super Single, Front Fairing, Side Skirt, Rear Flaps, & Aero Cab	12.8% ^{A,B,C,F,G,H,K,N,Q,R}	11.3% ^{B,R}	10.1% ^{B,R}	\$9,850–\$12,640 ^{**} A,C,D,E,I,J,L,M,O,P
C	Low-Rolling-Resistance Tires & Aero Cab	5.0% ^{A,B,C}	4.2% ^B	3.9% ^B	\$1,820–\$1,960 ^{**} C,D,E
Straight Truck					
	Front Fairing	n/a	n/a	4.9% ^I	\$830–\$1,180 ^I
	Aluminum Wheels	n/a	n/a	1.3% ^B	\$1,200 ^M
D	Low-Rolling-Resistance Tires & Front Fairing	n/a	n/a	6.8% ^{B,I}	\$1,355–\$1,705 ^{**} E,I
E	Low-Rolling-Resistance Tires, Aluminum Wheels, & Front Fairing	n/a	n/a	8.1% ^{B,I}	\$3,080–\$3,430 ^{**} E,I,M
F	Low-Rolling-Resistance Tires	n/a	n/a	1.4% ^B	\$525 ^{**} E

* Costs include estimated retail price for the device(s) with tax and labor

** Costs include the estimated lifetime incremental replacement cost

FOOTNOTES FOR TABLE

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