STATE OF COLORADO
DEPARTMENT OF PUBLIC HEALTH & ENVIRONMENT

	)	
2022 Colorado Clean Truck Strategy;	)	**Comment Deadline:**
Request for Comments on the Potential	)	**April 4, 2022**
Adoption of California's Advanced Clean	)	
Trucks and Omnibus Low-NO_x Rules	)	

COMMENTS OF THE TRUCK AND ENGINE MANUFACTURERS ASSOCIATION

April 4, 2022

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i) Introduction

The Truck and Engine Manufacturers Association (EMA) appreciates the opportunity to submit comments regarding the Colorado Department of Public Health & Environment's (DPHE's) "2022 Colorado Clean Truck Strategy" (or "Strategy"), which Strategy seeks, among other things, accelerate the deployment of medium-duty (MD) and heavy-duty (HD) zero-emission vehicles (ZEVs) in the State. While EMA supports the DPHE's push toward ZEV trucks, we do not agree that the Strategy's recommendation to adopt California Air Resources Board's (CARB's) Advanced Clean Trucks (ACT) Regulation, as well as CARB's Omnibus Low-NO_x Regulations, is the best pathway to reach that shared objective. Of note, EMA was actively engaged in the rulemaking process for both of those CARB regulations, and actively participated in the public stakeholder process relating to the development of the Strategy at issue.

EMA represents the world's leading manufacturers of MD and HD on-highway trucks and engines. EMA member companies design and manufacture highly-customized vehicles to perform a wide variety of commercial functions, including interstate trucking, regional freight shipping, local parcel pickup and delivery, refuse hauling, and construction – to name a few. EMA member companies are investing billions of dollars to develop MD and HD ZEVs, and fully support expanding the market in Colorado for those zero-emission vehicles. EMA and its members agree that ZEVs are and need to be the future of the commercial trucking industry. However, as detailed below, state-specific opt-ins to programs designed to meet California's unique air quality needs and economic capabilities are not well-suited to the shared goal of accelerating the deployment of ZEV trucks in Colorado and elsewhere across the country. That is especially true in the absence of sufficient state-specific programs to incentivize the purchase of ZEV trucks and to build-out the necessary ZEV-refueling/recharging infrastructure.

ii) CARB's ACT Rule is not well-suited to the accelerated deployment of MD and HD ZEVs in Colorado

One of EMA's principal concerns is that **the structure of CARB's ACT Regulation threatens to hinder, not promote, the emerging market for zero-emission commercial vehicles.** In brief, the ACT Rule amounts to a naked sales mandate that requires manufacturers to sell a prescribed and increasing number of zero-emission medium- and heavy-duty vehicles, without any corresponding ZEV-purchase incentives. Consequently, instead of buying ZEV trucks, fleet customers in Colorado may simply choose to purchase other less expensive truck technologies, or to continue maintaining their existing trucks.

In that regard, MD and HD ZEVs currently have higher purchase prices (2-to-3 times higher than conventionally-fueled trucks), higher life-cycle costs, and lower utility (i.e., less cargo capacity) than conventionally-fueled vehicles. The ACT Rule fails to consider the significant financial incentives needed to make MD and HD ZEVs an attractive investment for a trucking business. Further, the ACT Rule does not address or provide in any way for the electricity charging and hydrogen fueling infrastructures that will be needed at fleet facilities to operate the mandated ZEVs, the build-out of which will be expensive, complicated, and time-consuming. **An effective MD/HD ZEV program needs to include up-front significant and sustained ZEV-purchase incentives, and significant and sustained public investments in ZEV infrastructure build-out** and related costs. The ACT Rule does not address those necessary prerequisites, and so will not result in an effective ZEV program for MD and HD ZEVs.

Colorado's commercial vehicle market includes many distinct segments that each require unique vehicle configurations, and each application has a different level of suitability for HD and MD ZEVs. We estimate that there are at least 70 different market segments for Class 4 through 8 trucks in Colorado, with some applications (*e.g.,* residential parcel delivery) representing reasonable targets for electrification, while others (*e.g.,* plowing snow) are much less suitable. Any analysis of the opportunities for deploying MD and HD ZEVs in Colorado must consider the diverse market segments and include a robust evaluation of each one. Those segments identified as highly suitable may be considered "beachhead" markets, where zero-emission trucks can be deployed first before expanding to other market segments.

As the DPHE staff is well aware, commercial trucks are not just big cars. Unlike the passenger car market where purchasers select from a limited number of vehicle options, commercial fleets provide truck manufacturers with extensive and detailed vehicle specifications so their trucks will meet the particular demands of the fleets' unique operations in the most efficient and cost-effective manner. When a trucking company purchases a commercial vehicle, it is making a significant capital investment in business equipment that it expects to deploy in a manner that will return a profit. Trucks are amortized over longer time periods than cars, and they are assessed, not with regard to subjective criteria such as style and comfort, but solely on the objective basis of performance capability and cost-efficiency. Thus, truck purchasers' decisions turn on detailed up-front assessments of the customized truck's utility for the job at hand, and its purchase price, durability, operating costs, and resale value. In short, a trucking company will only invest in a new commercial vehicle when it will improve the bottom line of its business.

In light of the foregoing, **the zero-emission MD and HD vehicle market in Colorado will require significant up-front incentive funding** until zero-emission trucks become profitable investments for trucking businesses. Incentives must be sufficient to offset all of the ZEV truck initial acquisition and life-cycle costs that will exceed current commercial vehicle costs, including: (i) higher purchase prices, and increased federal and state sales taxes; (ii) operational inefficiencies (*i.e.*, it takes more ZEV trucks to perform the work of conventionally-fueled trucks); (iii) lower residual values; (iv) required investments in new maintenance facilities, training, and parts inventories; and (v) significant investments to install and maintain the necessary charging and refueling infrastructure. Additionally, incentives must be available for an extended period of time so fleets can rely on them in developing and implementing their long-term business plans.

The DPHE also must consider the substantial challenges involved in developing the requisite charging infrastructure to support zero-emission MD and HD battery-electric trucks — something that CARB's ACT Rule failed to do. Charging stations are expensive (costing more than $350,000), and must be located at fleet terminals and other depots where trucks are typically parked, and, as noted, developing that infrastructure will be complicated and time-consuming. Moreover, fleets will need to expand the charging infrastructure over time if they plan to deploy additional battery-electric trucks. Since it may take 24 to 48 months from concept to having a fully functional and grid-integrated charging station in place, **the DPHE should establish a primary near-term objective of providing sufficient public funding to incentivize and assist in the development of a sufficiently widespread charging infrastructure** to enable the deployment of battery-electric commercial vehicles. Additionally, for fleet applications where fuel-cell electric vehicles may be the better option, hydrogen fueling stations will be needed.

The critical need for publicly-funded infrastructure development and public incentive funding as prerequisites to any viable ZEV truck program is widely acknowledged and well understood. For example, the University of California, Davis (UC-Davis) oversees a Sustainable Freight Research Program, which sponsors workshops for the leading policy makers and stakeholders involved in accelerating the deployment of ZEV trucks. The presentations and summaries from the most recent workshop in October of 2021 include the following findings and conclusions:

> ARB [ZEV-truck] regulations will cover OEMs manufacturing and fleet purchases, but there is no requirement for ZEV infrastructure to be in place when ZEV trucks arrive at fleets. **The need to have infrastructure placement lead truck purchases is critical.** This infrastructure includes not only the charging or refueling stations but also the necessary infrastructure to bring power or fuel to those stations.
>
> ZEV pilot programs have found that ZEV infrastructure could take 1 to 2 years or more from the initial request to full implementation. That timeline creates large difficulties for fleets because they may not know enough about their futures vehicle purchases to request infrastructure in time.
>
> A vastly shortened timeline for installation including permitting is necessary for fleets to have confidence that they can order vehicles and know that the infrastructure will be available for charging or refueling when the vehicles are delivered.
>
> The ACT and ACF regulation specify the timing of ZEV OEM truck manufacture and fleet purchase, **but infrastructure must be in place to support the vehicles.** The timing of ZEV manufacture, purchase, and infrastructure must be aligned for a successful rollout.

Infrastructure should be coordinated with vehicle sales and in many cases will need to precede it. Since infrastructure requires longer lead time to install than purchase time for vehicles, government should facilitate bringing fleets and utilities together. Make-ready infrastructure is critical and often expensive, and **incentives must be available for infrastructure.** There could be a focus on long-term contracts to assist with infrastructure goals.

Most other states do not have an ongoing history of ZEV related regulation, and **those states do not have the same level of incentive funding available for vehicles or infrastructure.** States considering ZEV regulation are playing catch up with California and may require more time to become as effective.

It is not clear that incentive funding and infrastructure development can keep up with such rapid growth in sales requirements from many states around the US, and more analysis of sustainable ZEV market expansion rates is warranted.

The foregoing findings and conclusions confirm that the adoption of ZEV-truck sales mandates, without first addressing **and funding** the necessary build-out of the critical infrastructure, is not a pathway to the successful acceleration of ZEV-truck deployment. Unfortunately, that is precisely the path that the DPHE is taking. It is a path that will not lead to a successful outcome.

Stated differently, Colorado is not providing – and may not be capable of providing – the very significant public funding programs that are required **up-front** to ensure the successful deployment of ZEV trucks. By way of comparison, the 2021-2022 budget for the State of California includes more than $4 billion in public funding commitment to build-out the initial ZEV infrastructure and to incentivize the initial purchases of ZEVs, including ZEV trucks. In that regard, California is allocating more than $1.2 billion in 2021-2022 toward the infrastructure needed to enable to increase utilization of MD and HD ZEV-trucks.

DPHE's Strategy includes insufficient funding commitments for commercial ZEV trucks, let alone the tens of billions of dollars required to actually create the infrastructure and incentive programs that are fundamental to the success of any mandates for the sale of ZEV trucks. Without that level of up-front and sustained funding commitments, the Strategy's opt-in recommendations are, in effect, ZEV-deployment policies in name only, but without any real prospect for success.

In sum, the ACT Rule, with its unilateral ZEV sales mandates and nothing more, is not the regulatory platform on which Colorado should build its program to accelerate the deployment of MD and HD ZEVs. Consequently, the DPHE should not recommend opting-in to that Rule at this time.

iii) CARB's Omnibus Rule is cost-prohibitive and infeasible, and should not be finalized as a component of Colorado's ZEV strategy

The DPHE also is recommending an opt-in to CARB's Omnibus Low-NO_x Regulations in tandem with the ACT Rule. Colorado should not opt-in to the Omnibus Regulations for numerous reasons, including the following:

a. The Omnibus Rule was finalized on December 22, 2021. As a result, CARB is only providing, at most, two full years of lead time before the Omnibus low-NO_x standards take effect in model year 2024. That is a clear violation of the federal Clean Air Act's (CAA's) four-year leadtime requirement. (See CAA, section 202(a)(3)(C).) Thus, **the Omnibus Rule is unlawful and ineligible for a preemption waiver,** and cannot be opted-in to in a lawful manner under CAA section 177.

   The net result is that **the DPHE cannot lawfully opt-in to a CARB rule that fails to provide the federally-mandated leadtime.** Indeed, CARB's underlying failure to provide sufficient leadtime for the Omnibus regulations will disqualify CARB from receiving a federal preemption waiver for those regulations. Consequently, the DPHE's current opt-in proposal will be unlawful as well.

b. **The Omnibus Regulations are cost-prohibitive.** Multiple independent studies have been conducted to assess the costs and benefits of the Omnibus Rule. Those five studies, **copies of which are attached**, include: (i) a cost study prepared by ACT Research showing that the resultant cost increase for heavy-duty vehicles will be approximately $58,000 per vehicle (ii) a supplemental study by ACT Research critiquing the Standardized Regulatory Impact Analysis (SRIA) that CARB prepared for the Omnibus Regulations; (iii) a cost study that CARB commissioned the National Renewable Energy Laboratory (NREL) to prepare, which shows that the Omnibus regulations will increase the purchase price of heavy-duty vehicles by up to $47,000 per vehicle (mostly due to the costs ascribed to CARB's extended "useful life" requirements and extended emission warranties); (iv) a recent cost assessment prepared by Ricardo establishing that even if nationwide truck-sales volumes are applied, the Omnibus regulations will increase the cost of heavy-duty trucks by $35,000 per vehicle, again mostly due to the extended FUL and warranty requirements; and (v) an updated report from NERA Economic Consulting showing that the monetized benefits of adopting CARB's Omnibus regulations in Colorado will total no more than approximately $1,300 per vehicle.

c. The conclusion from the relevant independent expert cost and benefit studies is that the costs of adopting the Omnibus regulations in Colorado will exceed their benefits by a factor of as high as 44 ($58,000÷$1,300). Regulations that are cost-prohibitive to such an extreme extent are invalid under Colorado law, and cannot qualify for a federal preemption waiver under the CAA.

d. Currently available market data and pricing information show that the incremental costs associated with CARB's "Step 1" extended emission warranties — which went into effect this year — amount to approximately $2,500 per-vehicle. That is what the extended "Step 1" warranty requirements actually add to the cost of heavy-duty vehicles that are actually being bought and sold in the market today. What this shows, therefore — and, in fact, <u>proves</u> — is that CARB severely underestimated the cost increases due to the Omnibus regulations.

e. The Omnibus low-NO_x emission standards and related requirements also are inherently infeasible, especially since CARB will be providing *just two full-years of leadtime* for the 2024-2026 MY standards and requirements, which, as noted, is a violation of the CAA.

f. CARB failed to demonstrate the technical feasibility of the proposed 2024-2026 MY and 2027 MY and later low-NO_x emission standards and related requirements. The Southwest Research Institute (SwRI) "Stage 3" prototypes that CARB relied on have not demonstrated the feasibility of maintaining compliance with the standards throughout the proposed useful life periods, and no testing has shown that the Stage 3 prototype is capable of meeting EPA's existing GHG standards.

g. The Omnibus Regulations, when coupled with the ACT Rule, will cause fleet operators in Colorado to accelerate their purchases of new HD vehicles before the 2027 MY, and to refrain from purchasing new HD vehicles after the 2027 MY (a "pre-buy/no-buy" response), which will significantly diminish the assumed benefits of opting-in to the CARB Regulations. ACT Research has estimated that the expected pre-buy/no-buy response will impact more than 40% of the new truck market. The DPHE has not conducted any analysis of the magnitude of the pre-buy/no-buy that will occur in Colorado in response to the opt-ins at issue, or how that market response will diminish the presumed benefits from the proposed recommended opt-ins.

h. The Omnibus Regulations likely will compel some HDOH engine and vehicle manufacturers to exit the California market starting in advance of the 2024 MY, which, in turn, would result in a lack of CARB-compliant MD and HD trucks in Colorado, if Colorado opts-in to those CARB regulations.

i. If HDOH diesel trucks are forced out of the California and Colorado markets, or if truck purchasers refrain from buying the much more expensive CARB-compliant trucks (as expected), that will frustrate the implementation of the ACT Rule, since the HD ZEV-sales mandates under that Rule are calculated as a percentage of new in-state HD diesel truck sales, which will be significantly reduced, if not eliminated, due to the Omnibus Regulations. That in turn will delay, not accelerate the deployment of ZEV trucks in Colorado.

For all of the foregoing reasons, the DPHE should not include CARB's Omnibus Regulation as an element of Colorado's Strategy to promote the deployment of MD and HD ZEVs. CARB's Omnibus Regulations will suppress the sales of CARB-compliant conventionally-fueled vehicles, which in turn will reduce, if not vitiate, the efficacy of the ACT Rule, since, as noted, the percentage-sales requirements of that rule are based on the number of sales of conventional trucks. Thus, the net effect of CARB's Rule, if adopted in Colorado, is more likely to frustrate rather than foster Colorado's objective to accelerate ZEV truck sales.[1]

iv) <u>Colorado would be better served by advocating for an effective next-tier nationwide HDOH standards as a "bridge" to ZEVs</u>

While not supportive of the proposed opt-ins, EMA and its members fully recognize that zero-emission vehicles (ZEVs) are key to the future of the commercial trucking industry. Accordingly, as noted previously, EMA member companies are investing billions of dollars to develop and bring to market MD and HD ZEVs. Our efforts alone, however, will not achieve

[1] According to Polk Data Services, average annual heavy-duty truck sales (Class 4-8) in Colorado over the past three years have been only approximately 5,870 units. The market impacts in Colorado of opting-in to CARB's rules, including the expected pre-buy/no-buy impacts, likely would dramatically reduce that already-low annual sales number, and so dramatically reduce, if not eliminate, any postulated benefit of opting-in to CARB's Rules.

success. A broad-based transition of the trucking industry to ZEVs will take a determined and concerted effort by federal and state policymakers, manufacturers, trucking fleets, utilities, and other key stakeholders. During that period of transition, new cost-effective interim standards to reduce NO_x and GHG emissions from conventionally-fueled trucks will be necessary to bridge the gap to the longer-term development and deployment of commercial ZEVs.

More specifically, effective next-tier nationwide emission-reduction regulations for conventionally-fueled trucks will be key to establishing a cost-effective bridge to heavy-duty and medium-duty ZEVs. To that end, the DPHE should work with EMA to advocate for next-tier EPA regulations for HD and MD vehicles and engines that include the following elements:

- Meaningful reductions in the tailpipe NO_x standard.
- New test procedures focused on reducing emissions under lightly-loaded operating conditions typical of urban centers.
- Additional NO_x control under extended idle conditions.
- Next generation "in-use" compliance-assurance protocols to control emissions over a broader range of real-world operating conditions.
- Program elements to ensure compliance over multiple years.
- Continued reduction of GHG emissions.
- Flexible emissions credits to incentivize ZEVs.

While several of CARB's Omnibus program elements are directionally consistent with those EMA envisions for EPA's next-tier nationwide rule, CARB will be implementing those elements with unreasonably short timelines, questionable technical feasibility, unsustainable cost-benefit metrics, and material adverse impacts on new vehicle prices and sales volumes. The overall impacts of CARB's new Omnibus regulations are likely to have extremely negative consequences. In that regard, commercial fleets have not reacted positively in the past to the deployment of major new emissions-control technologies on an accelerated timeline, and, as a result, we fully expect that the significant "pre-buy/no-buy" scenarios that occurred in 2007 with respect to commercial vehicles will be experienced again in California, as well as in any opt-in states.

If the Colorado market does not accept the substantially increased costs associated with the few CARB-compliant products that might be available, fleet operators will accelerate their purchase of new federally-certified vehicles in Colorado, or acquire new trucks in adjacent non-opt-in states, rely more on the used truck market, or simply retain their existing fleet vehicles longer. All of those actions will have a negative impact on air quality and delay progress in the attainment of air quality goals. In addition, to the extent that fleet operators are compelled to acquire new vehicles out-of-state, that would result in a cascading series of negative economic impacts as well. In particular, truck dealerships in Colorado would face significant adverse consequences, and if Colorado-based fleet operators were to choose to relocate out-of-state, significant in-state job losses would result across the wide-ranging trucking sector, including within the goods-movement, warehousing, and truck-servicing and repair sectors.

A far more effective bridge to widespread commercial MD and HD ZEV sales and deployment is through a cost-effective nationwide EPA-implemented lower-NO_x program. Future federally-certified lower-NO_x HD/MD engines and vehicles will ensure that businesses and municipalities in each state have access to the full range of powertrain and vehicle solutions they are accustomed to purchasing today. They will not be forced to pay premium prices for new products, to purchase outside their brand preference, or to seek purchase opportunities in neighboring states. They can maintain profitability without resorting to purchasing used, higher-emitting vehicles, or maintaining their existing fleet longer without the environmental benefits gained from new vehicle purchases.

The significant nationwide NO_x reductions from an EPA lower-NO_x program for commercial vehicles and engines would address any remaining nearer-term air quality attainment issues in Colorado. To the extent that there might be other local needs to reduce emissions from NO_x "hotspots" within the State, those local needs could be best addressed through more specific approaches, such as targeted accelerated fleet turnover programs, utilization of alternative fuels, deployment of zero-emission vehicles and equipment at specific facilities, utilization of the State's purchasing and contracting power to acquire ZEV trucks, and other targeted incentive programs to address environmental justice issues, rather than through the adverse statewide economic and environmental impacts that would result from the adoption of CARB's Omnibus program. Accordingly, Colorado should work for the implementation of EPA's next-tier HD/MD regulations as the best option for achieving the State's air quality goals during the bridge years before significant ZEV-truck market penetration takes hold.

Significant in that regard, on March 28, 2022, EPA published a notice of proposed rulemaking (NPRM) to implement the Agency's "Clean Trucks Plan," which plan includes robust next-tier HD and MD NO_x and PM standards. Just as significant, EPA intends to finalize those low-NO_x (and PM) regulations by the end of this year, with those standards taking effect in 2027. Under the Clean Trucks Plan, EPA's new low-NO_x regulations will be followed by "Phase 3" GHG standards taking effect in 2030, which likely will continue to accelerate the deployment of ZEV trucks on a nationwide basis. While the details of those EPA programs will need to be revised through the pending notice-and-comment process to ensure cost-effective outcomes, the DPHE should align its programs with those inherently more effective nationwide regulations. Thus, and for this additional reason, the pending opt-in rulemaking should, at the very least, be deferred to allow for a thorough assessment of the efficacy of EPA's proposed regulations for HD/MD trucks.

v) <u>The recommended roadmap to a commercial ZEV future</u>

Transitioning the commercial trucking industry to ZEVs demands a strategic and concerted effort by state and federal policymakers, manufacturers, trucking fleets, utilities, and others. More specifically, successfully bridging to a medium- and heavy-duty ZEV future will require the following steps:

<u>Undertake technical and economic research to:</u>

- Determine the level of incentives needed to overcome the financial barriers to purchasing ZEVs and converting commercial fleets to zero emissions.

- Identify the funding and other potential impediments to building out the necessary electric charging/hydrogen fueling infrastructure.
- Assess the optimal commercial vehicle market segments most suitable for the near-term deployment of ZEVs; properly prioritize and allocate resources for early deployment in those market segments; and establish reasonable pathways to the broader adoption of commercial ZEVs.
- Determine the optimal long-term ZEV power source for each commercial vehicle market segment and the corresponding infrastructure needs (*i.e.,* electricity and/or hydrogen), including generation and storage.

Establish practical, implementable, and effective policies to:

- Incentivize trucking fleet transitions to ZEVs.
- Accelerate the turnover/retirement of older, high-emitting commercial vehicles.
- Target the commercial vehicle applications and markets most suitable for near-term transition to ZEVs.
- Fund construction of the unique charging/fueling infrastructure needed for MD and HD ZEVs, including electricity grid modernization and decarbonization.
- Implement new EPA lower-emission standards for conventionally-fueled trucks on a nationwide basis to allow for broad near-term NO_x and GHG reductions and to help manage the longer-term transition (the bridge) to commercial ZEVs.
- Utilize carbon neutral liquid and gaseous fuels for interim GHG reductions.

EPA's Clean Trucks Plan affords the best regulatory opportunity, once revised, for implementing the concerted nationwide strategy to accelerate the deployment of ZEV trucks. The DPHE should work to align with those national strategies.

vi) Conclusion

There is no doubt that ZEVs are the future of the commercial trucking industry, and EMA's suggested roadmap identifies realistic and necessary steps to develop and bring to market medium- and heavy-duty ZEVs. Policymakers and other stakeholders should collaborate on those targeted and holistic strategies to successfully establish the commercial ZEV market. In the meantime, a complementary nationwide EPA bridge program is needed—and is in the works—to reduce NO_x emissions from conventionally-fueled commercial vehicles.

Increasing the market penetration of ZEV trucks requires the iterative and multi-pronged approach spelled out in our roadmap, including, among other things: (i) identifying the trucking fleet applications best-suited to a nearer-term transition to ZEV trucks — the "beachhead" markets; (ii) implementing robust incentive programs to enable the identified beachhead fleets to acquire and maintain ZEV trucks; (iii) researching and building-out the necessary ZEV infrastructure to support the beachhead ZEV fleets; and (iv) coordinating with other agencies, including EPA, to expand the deployment of ZEV trucks across other applications, using sufficient public resources and incentives to expand the necessary ZEV infrastructure and offset the higher total cost of ownership of commercial ZEVs.

CARB's ACT and Omnibus Low-NO_x Rules are not well-suited to implementing the necessary multi-prong approach, or to achieving our common goal for the accelerated deployment of MD and HD ZEV trucks. Rather, those Rules impose both infeasible ZEV-sales mandates on manufacturers (without accounting in any way for the necessary incentives and infrastructure deployment, and without including any corresponding ZEV-purchase strategies), and also establish unreasonably stringent, cost-prohibitive and infeasible NO_x standards. As a result, a ZEV-deployment strategy that is centered around CARB's Rules will more likely frustrate rather than foster the acquisition and use of ZEV trucks in Colorado, will hurt the Colorado's economy, and will impede any envisioned environmental gains (i.e., due to delayed fleet turnover or increased out-of-state truck purchases). The roadmap that EMA has outlined offers a better and more collaborative way forward.

Respectfully Submitted,

TRUCK AND ENGINE
MANUFACTURERS ASSOCIATION

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FINAL DRAFT

COST STUDY:

PROPOSED HEAVY-DUTY ENGINE AND VEHICLE EMISSIONS REGULATIONS

PREPARED FOR:

TRUCK & ENGINE MANUFACTURERS ASSOCIATION

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March 19, 2020

Contents

ACT Research Cost Study of the Proposed Omnibus Low-NO_x Rulemaking

Executive Summary

Based on a survey of the commercial vehicle and engine manufacturing industry completed in Q1, 2020, this study presents ACT Research's best estimates of the sum of the direct and indirect costs of meeting the goals of the California Air Resources Board (CARB) Omnibus Low-NO_x Rulemaking (Omnibus Regulations), as also referenced in the ANPRM for EPA's Cleaner Trucks Initiative (CTI). We present estimates for costs of both a nationwide and a California-only program.

This study's focus is on the costs (including per-vehicle costs) that the truck and engine manufacturing industry likely will incur to comply with the proposed Omnibus Regulations. The study's primary conclusion is that full compliance with the proposed low-NO_x emission standards and other requirements, assuming they track the proposed Omnibus Regulations, will cost the truck and engine manufacturing sector a Net Present Value (NPV) of **$9.1 – $13.0 billion**.

Assuming the proposed Omnibus Regulations are implemented, manufacturers ultimately will recoup most of those costs through higher vehicle prices. It is the trucking industry that will bear most of the increased costs going forward. Longer-term, the trucking industry eventually will be able to pass the higher costs of compliance on to the shipping community, which in turn will pass them on to consumers. However, given the highly competitive nature of the trucking industry, we also detail the costs of the very likely scenario of a substantive equipment "pre-buy/no-buy" to avoid, at least initially, the higher truck and engine costs associated with the proposed Omnibus Regulations. In ACT's modeling, the resulting overcapacitization in the freight hauling industry (due to pre-buys of vehicles) likely will yield aggregate pre-buy impacts between **$6.5 - $8.6 billion** in 2019 dollars, solely as a result of lower freight rates due to overcapacity, and there will be little opportunity to recoup the lost shipping revenues during the periods of overcapacity.

The combined regulatory impact on the manufacturing sector and trucking companies falls between NPVs of $15.6 and $21.6 billion.

Our estimates do not model the increased costs out into perpetuity. Rather, our cost estimates are focused on the two key years when costs are likely to rise significantly: 2027 and 2031. In our analysis, fixed costs were allocated over multi-year product programs. In addition, we have not tried (yet) to estimate the long-run costs to the trucking industry from deploying higher-cost equipment. The costs studied here are solely for the truck and engine manufacturing sector, and just include the pre-buy related effects on trucking. In our judgement, adding the long-run costs on trucking, while likely worth a more thorough analysis, would effectively be double-counting the costs we have estimated for the manufacturers. We include an analysis of the costs for the trucking industry in the Pre-buy/No-buy section, but only to inform our modeling regarding the degree of excess capacity. It should be noted that the increased taxes, insurance costs, financing costs, and emissions fluid costs that trucking companies will face are not included in this aggregate cost estimate of $15.6 to $21.6 billion.

Summary Tables. Tables 1-3 summarize the results of our cost study. Our findings related to the costs associated with the **MY2027** step of the proposed Omnibus Regulations are itemized in *Table 1: Cost Estimates to Meet Proposed MY2027 Vehicle Standards*. In MY2027 at the national level, and using the 3% and 7% discount rates to bracket the ranges, we estimate the proposed emissions requirements would cost the industry $1.8 – $2.4 billion for medium-heavy duty vehicles and engines, and $4.5 – $6.1 billion for heavy-heavy duty vehicles and engines, which **sums to $6.3 billion at a 7% discount rate, and $8.5 billion at a 3% rate**. **On a per-unit basis, the cost of compliance ranges from $17,610 to $23,886 for heavy-heavy-duty (HHD) diesel vehicles, and $11,752 to $15,940 for medium-heavy-duty (MHD) diesel vehicles.** The total cost figures are smaller for a California-only program, but per-unit costs rise sharply because of the relatively small number of units sold in California.

Table 1: Cost Estimates to Meet Proposed MY2027 Vehicle Standards

	National				California			
	MY2027 from MY2018 base				MY2027 from MY2018 base			
Discount Rate	7%	3%	7%	3%	7%	3%	7%	3%
	MDD	MDD	HDD	HDD	MDD	MDD	HDD	HDD
per unit								
Total Direct Costs	$3,688	$5,002	$5,376	$7,292	$9,058	$12,286	$7,738	$10,495
Total Indirect Costs	$8,064	$10,938	$12,234	$16,594	$32,416	$43,968	$39,949	$54,184
Cost Increase per Unit ($)	**$11,752**	**$15,940**	**$17,610**	**$23,886**	**$41,474**	**$56,254**	**$47,686**	**$64,679**
$ in millions								
Total Direct Costs	$562	$762	$1,380	$1,872	$72	$98	$122	$166
Total Indirect Costs	$1,228	$1,666	$3,141	$4,260	$258	$349	$631	$856
Total Cost Increase ($M)	**$1,790**	**$2,428**	**$4,521**	**$6,132**	**$329**	**$447**	**$753**	**$1,021**

Source: ACT Research Co., LLC: Copyright 2020

The cost estimates itemized in *Table 2* summarize the results of our cost study for **MY2031** compliance. Those costs are primarily related to meeting the extended useful life and emission warranty provisions of the proposed Omnibus Regulations. The cost figures amount to additions to the baseline MY2027 costs (in Table 1), and show the incremental cost estimates for MY2031. **For HDD vehicles, our survey indicated an additional $8,352 – $13,194 in costs per truck, depending on the discount rate utilized. For MHD vehicles, the additional costs would range from $3,689 – $5,827 per truck.** Combining the HHD and the MHD diesel model outputs, we estimate a discounted cost that ranges between **$2.7 – $4.4 billion for the MY2031 proposals on a nationwide basis.**

Table 2: Additional Cost Estimates to Meet Proposed MY2031 Vehicle Standards

	National				California			
	MY2031 from MY2027 base				**MY2031 from MY2027 base**			
Discount Rate	7%	3%	7%	3%	7%	3%	7%	3%
	MDD	MDD	HDD	HDD	MDD	MDD	HDD	HDD
per unit								
Total Direct Costs	$0	$0	$157	$248	$0	$0	$150	$238
Total Indirect Costs	$3,689	$5,827	$8,196	$12,946	$9,891	$15,624	$10,068	$15,904
Cost Increase per Unit ($)	**$3,689**	**$5,827**	**$8,352**	**$13,194**	**$9,891**	**$15,624**	**$10,219**	**$16,142**
$ in millions								
Total Direct Costs	$0	$0	$42	$66	$0	$0	$2	$4
Total Indirect Costs	$585	$924	$2,189	$3,458	$55	$86	$152	$240
Total Cost Increase ($M)	**$585**	**$924**	**$2,231**	**$3,525**	**$55**	**$86**	**$154**	**$244**

Table 3 aggregates the cost estimates for the **MY2027 and MY2031** cost models, reflecting our estimates of the combined costs of the proposed Omnibus Regulations. On a nationwide basis, the total combined cost of the Omnibus Regulations for both MHD and HHD vehicles is **$9.1 billion to $13.0 billion**, depending on whether a 7% or 3% discount rate is utilized. **On a per-unit basis, the nationwide cost for HHD vehicles ranges from $25,963 at a 7% discount rate, to $37,079 at the 3% rate. For MHD vehicles, the per-unit costs range from $15,441 to $22,767, respectively.** On a California-only basis, the aggregate total costs range from $1.3 – $1.8 billion, which are much smaller than the nationwide costs, but some expense line-items like R&D were relatively fixed. Therefore, on a per-unit basis, the per-unit cost increases range from $57,905 to $80,821 per HHD vehicle, and from $51,365 to $71,878, per MHD vehicle.

Table 3: Cost Estimates to Meet Proposed Combined MY 2027 and MY2031 Vehicle Standards

	National				California			
	MY2027 + MY2031 from MY2018 base				**MY2027 + MY2031 from MY2018 base**			
Discount Rate	7%	3%	7%	3%	7%	3%	7%	3%
	MDD	MDD	HDD	HDD	MDD	MDD	HDD	HDD
per unit								
Total Direct Costs	$3,688	$5,002	$5,533	$7,540	$9,058	$12,286	$7,888	$10,732
Total Indirect Costs	$11,753	$16,765	$20,430	$29,540	$42,307	$59,591	$50,017	$70,089
Cost Increase per Unit ($)	**$15,441**	**$21,767**	**$25,963**	**$37,079**	**$51,365**	**$71,878**	**$57,905**	**$80,821**
$ in millions								
Total Direct Costs	$562	$762	$1,422	$1,938	$72	$98	$124	$169
Total Indirect Costs	$1,813	$2,590	$5,330	$7,718	$312	$435	$783	$1,096
Total Cost Increase ($M)	**$2,375**	**$3,352**	**$6,752**	**$9,656**	**$384**	**$533**	**$907**	**$1,265**

Methodology

This cost study was performed using federal guidelines that correspond to EPA's Guidelines for Economic Analysis and OMB Circular A-4. The baseline assumptions for our analysis are that:

1) Heavy-duty truck manufacturers would continue to work toward meeting the established GHG-2,
2) but would otherwise not explicitly target
   a. incremental NO_x emissions reductions,
   b. improved low-load SCR performance, or
   c. longer useful lives for aftertreatment systems.

In light of the pending GHG-2 regulations, we used professional judgement to discount some of the cost inputs that we received from manufacturers, if those inputs did not take into account the improved fuel economy and reductions in fuel consumption, which will help to meet the proposed Omnibus Regulations.

We followed the methods specified by the Environmental Protection Agency (EPA) and the Office of Management and Budget (OMB) to conform to the government's Social Cost definition, though we have noted where we otherwise would differ with those methods (i.e., inflation and discount rates). We have also presented below an additional set of values that discount the future costs at the private weighted average cost of capital, which for this industry is quite high. Our "Private Cost" estimates below are only alternative results, not EPA/OMB recommended results, and so are not included in the summary tables above.

ACT Research's cost estimates are based upon industry inputs consisting mainly of confidential business information (CBI), and as a result, specific technology solutions will not be discussed here except to note that those anticipated solutions were not uniform. As explained below, we used conservative analytical judgements where possible. For example, the current regulatory baseline for warranty coverage is 100,000 miles (five years, 3,000 hours). However, our research confirmed that the industry standard for new heavy-duty trucks is a 2-year/250,000-mile warranty that is built into the price. As a result, our study uses 250,000 miles as the baseline, resulting in lower incremental costs than otherwise would have been the case had we used the more common government research practice regarding the existing regulatory baseline.

Discount Rates, Social and Private. Consistent with EPA and OMB guidelines to discount future costs back to their present value at 3% and 7% discount rates in order to determine NPV, we have presented our results discounted at both of those rates. However, considering the significant uncertainty involved in estimating the future costs at issue, we also present the results of our cost estimates discounted using an alternative private cost methodology. The private cost methodology provides for the use of the Weighted Average Cost of Capital (WACC) for the truck and engine manufacturing industry as our discount rate. In calculating the 10% WACC, we used current equity values, as of January 2020, and debt and interest rates from the manufacturers' most recent annual reports.

Accordingly, in addition to utilizing the 3% and 7% social cost discount rates, we also present an alternative cost estimate (in Table 4) using our more conservative 10% WACC discount rate. While this is more conservative than the social cost methodology, we believe it accounts for some of the uncertainty inherent in this study, including: significant uncertainty about the future state of emissions-control technology, and regarding the most likely compliance pathways that manufacturers may follow. For example, we are estimating that manufacturers will need to budget for two replacements to aftertreatment systems in the life of their trucks in order to comply with the extended useful life and warranty provisions of the Omnibus Regulations. However, between now and MY2027, it is possible that durability could be improved to remove some of those costs. It also is possible that replacement aftertreatment systems will not last as long on older engines, which also is reflected in this cost study.

In light of these and other uncertainties, the alternative 10% WACC-based discount rate could be a reasonable way to estimate more conservatively the unknown variables pertaining to the various potential cost inputs and impacts. The larger alternative discounting mechanism that we have used, in essence, could serve fairly well in lieu of a more formal sensitivity analysis at a point in time when specific technology paths are not yet known.

Inflation methodology. We used inputs in 2019 dollars as it was the year our cost survey was initiated, adjusting for the OEMs who responded in 2018 dollars using the BEA's GDP Price Deflator. We thought it would be fair to use a lower inflation rate or perhaps even deflationary figure given the historical experience in this industry, but EPA (through EMA) indicated that the GDP Deflator is the standard. Adhering to EPA's recommended use of the GDP Deflator may inflate the estimated cost of the Omnibus Regulations, leaving room for further study.

Heavy-Heavy Duty Market Sizing. We used 2018 vehicle manufacturer (OEM) market shares as our baseline and assumed those shares as a constant into the future. However, instead of using the 2018 market size and simply rolling it forward, we took into account the fact that 2018 was the fifth-largest year ever for U.S. Class 8 truck production. As it happens, two of the higher production years were 2005 and 2006, with 2006 being the biggest U.S. Class 8 production year ever. Not coincidentally, those two "top-five" years occurred immediately ahead of the expensive EPA07 emissions standards for heavy-duty trucks and engines. We will discuss this "pre-buying" issue later in this report.

To provide a representative baseline, we used a five-year trailing average of U.S. Class 8 truck production (HHD diesel), or 239,000 units, and scaled it up at 1% per-year to account for economic growth, and adjusted for freight productivity. While freight demand grows over time as the population grows, shippers also find ways to improve design and packaging in ways that require fewer truckloads for a given set of goods. As a result, our analysis uses a MY2027 U.S. Class 8 nationwide market size estimate of 257,000 units.

For the California market, based on industry inputs, we used a baseline of just under 7% of nationwide industry sales, and scaled that starting point down by 7.5% in MY2027 to reflect assumed progress toward CARB's target of 15% zero-emission heavy duty tractors by 2030. We therefore estimate that California will represent just over 6% of nationwide HHD sales in MY2027.

For MY2031, we continued to scale nationwide HHD sales up by a 1% cumulative annual growth rate, bringing the nationwide HHD market to 267,000 units. We also continued with the assumption that California would achieve its 2030 target of 15% zero emissions heavy-duty vehicles, taking California down under 6% of nationwide HHD duty diesel truck sales.

Medium-Heavy Duty Market Sizing. For the MHD market, we used a trailing five-year average of U.S. sales of 142,000 units per-year, scaled up at 1% per-year to account for economic growth and adjusted freight productivity, in line with the above discussion regarding the HHD market. That resulted in a nationwide MHD market size of 152,000 units.

For the California market, we used a baseline of just under 7% of nationwide industry sales, also based on industry inputs, and scaled that down by 20% in MY2027 to reflect progress toward CARB's target of 50% zero-emission MHD vehicles by 2030. We estimate that California will represent just over 5% of nationwide MHD sales in MY2027.

For MY2031, we continued to scale nationwide MHD sales up at a 1% cumulative annual growth rate, and we made the assumption that California would achieve its target of 50% zero-emission vehicles, taking California down to 3.5% of nationwide MHD diesel truck sales.

State versus Federal Considerations. Based on this cost study, we conclude that the local benefits of California-only regulations do not justify the very significant costs that would impact trucking-related business on a nationwide basis. Due to the relatively small number of trucks sold in California, the research and development costs of advanced aftertreatment on a per-unit basis could be unacceptably high. Our survey of OEMs showed that only about 7% of heavy-duty trucks are sold in California, significantly less than the State's share of GDP.

Our cost survey also shows that the industry would spend $715 million on research and development for the proposed standards nationally, and $603 million on a California-only standard. The difference between the two totals reflects that fewer models would be offered under a California-only scheme. However, on a per-unit basis, using the market size detailed previously and amortizing the costs over an industry-standard three-year product platform cycle, those R&D costs amount to about $2,800 per-unit at a national level and $38,200 per-unit if the regulations applied only to California.

MY2024 Infeasibility. We are not providing separate estimates for the MY2024-26 elements of the proposed Omnibus Regulations because we did not receive indications that manufacturers can, or will, develop and introduce the technologies that could be used to meet those proposed standards by the 2024MY at reliable product-quality levels. The industry respondents to our survey cited numerous feasibility problems with the MY2024 time horizon. We believe that for some key vehicle categories, the standards proposed under the Omnibus Regulations are technically infeasible within the lead time allowed. Accordingly, we have not fully estimated the costs for the initial phase of the Omnibus Regulations for tractors and vocational vehicles. The lack of sufficient lead times for the development of the required additional technologies would result in significant risks of quality issues later in vehicle life. Simply stated, we could not develop any realistic cost estimates for a near-term regulatory program that manufacturers indicated is essentially unworkable. We believe that the MY2024 proposals would result in a decrease in the in-use reliability and durability of new heavy-duty vehicles, and we cannot accurately quantify the costs that would be associated with such problems. Instead, we merely note that unit costs would likely be greater than the costs we have estimated in this study for a nationwide MY2027 and MY2031 standard.

Heavy-Heavy Duty MY2027 Costs. We estimate in Table 4 that the low-NO_x standards proposed for MY2027, including a carry-forward of the MY2024 proposals, would cost HHD truck manufacturers $6.6 billion on a nationwide level, or $25,825 per-unit, in 2019 dollars. For California, our cost estimate of $1.1 billion for the HHD vehicle sector equates to $69,930 per-unit. That level of price increase would in all likelihood significantly reduce the choices of vehicles available in the California market, and could force some smaller volume manufacturers out of the California market. **On an inflation-adjusted and discounted basis, using the 3% and 7% discount rates recommended in the EPA and OMB guidelines, the net present value of the HHD costs associated with the Omnibus Regulations on a nationwide basis is $17,600 – $23,900 per HHD vehicle, and $4.5 – $6.1 billion for the HHD industry. For California-only, the net present value ranges from $47,700 – $64,700 per HHD vehicle, and $750 million to $1.02 billion for the HHD industry.** Note that in the far-right column of Table 4, we present the cost figures discounted at the 10% WACC, and those costs are considerably lower and could be a better way to account for the uncertainties relating to the possible incorporation of unforeseen technology improvements in the coming years.

Direct Costs. The direct costs included in the foregoing estimates incorporate specific changes to engines, aftertreatment systems and on-board diagnostics. Those costs do not represent any specific technology path, but rather a weighted average of the various manufacturers' inputs.

Those inputs add up to $7,900 per-unit for HHD diesel vehicles nationally, and $11,350 per-unit in California in 2019 dollars. The net present value of those figures is $5,375 – $7,290 nationally, and $7,740 – $10,500 in California, using the 3 and 7% discount rates to bracket the ranges. (See Table 4.)

Indirect Costs. The industry estimated $603 million in R&D costs to meet the MY2027 requirements (including the MY2024 elements) of the Omnibus Regulations in California, and $715 million for a nationwide program. Using inputs from the manufacturers, we amortized the R&D costs over the typical program life in the industry of three to four years.

The other indirect costs were primarily associated with the proposed extended warranty and useful life periods, as well as the related compliance-enforcement programs. The warranty and useful life costs are largely variable, but the compliance programs and R&D requirements are largely fixed. Some manufacturers may plan to find savings by offering fewer vehicle options, but applying those fixed costs to California's 15,800-unit HHD market still results in major per-unit cost increases relative to the 257,000-unit nationwide market.

Table 4: Cost Estimates to Meet Proposed Combined MY2027 Standards for HHD Vehicles

Heavy-heavy Duty Diesel										
Social Cost Methodology	MY2027 - from MY2018 baseline								*Private Cost (not Social)*	
Costs to Develop & Build Ultra-Low-NOx products	2019 dollars		Inflation-adjusted at:		Discounted at:		Discounted at:		Discounted at WACC	
			2%		3%		7%		10%	
	National	California	National	California	National	California	National	California	National	California
Industry Units	256,712	15,789	256,712	15,789	256,712	15,789	256,712	15,789	256,712	15,789
Per unit costs ($)										
Direct manufacturing costs										
Engine	$3,157	$3,811	$3,699	$4,465	$2,920	$3,525	$2,153	$2,599	$1,675	$2,022
Aftertreatment	$4,589	$6,171	$5,376	$7,230	$4,244	$5,708	$3,129	$4,208	$2,434	$3,274
Vehicle + On-Board Diagnostics	$139	$1,365	$162	$1,599	$128	$1,263	$95	$931	$74	$724
Total Direct Costs	**$7,884**	**$11,347**	**$9,237**	**$13,294**	**$7,292**	**$10,495**	**$5,376**	**$7,738**	**$4,183**	**$6,020**
Indirect Costs to Manufacturers										
Research and development costs	$2,786	$38,171	$3,265	$44,723	$2,577	$35,305	$1,900	$26,029	$1,478	$20,251
Warranty on new technology	$2,208	$2,511	$2,587	$2,943	$2,042	$2,323	$1,506	$1,713	$1,171	$1,332
Warranty Step 2	$3,311	$3,757	$3,880	$4,401	$3,063	$3,475	$2,258	$2,562	$1,757	$1,993
Useful Life extension	$9,451	$11,178	$11,074	$13,097	$8,742	$10,339	$6,445	$7,622	$5,014	$5,930
Compliance program costs	$184	$2,966	$215	$3,475	$170	$2,744	$125	$2,023	$97	$1,574
Total Indirect Costs	**$17,940**	**$58,583**	**$21,020**	**$68,639**	**$16,594**	**$54,184**	**$12,234**	**$39,949**	**$9,518**	**$31,081**
Cost Increase per Unit ($)	**$25,825**	**$69,930**	**$30,258**	**$81,934**	**$23,886**	**$64,679**	**$17,610**	**$47,686**	**$13,701**	**$37,101**
EOEM Costs ($M)										
Direct manufacturing costs										
Engine	$810	$60	$949	$70	$750	$56	$553	$41	$430	$32
Aftertreatment	$1,178	$97	$1,380	$114	$1,090	$90	$803	$66	$625	$52
Vehicle + On-Board Diagnostics	$36	$22	$42	$25	$33	$20	$24	$15	$19	$11
Total Direct Costs	**$2,024**	**$179**	**$2,371**	**$210**	**$1,872**	**$166**	**$1,380**	**$122**	**$1,074**	**$95**
Indirect Costs										
Research and development costs	$715	$603	$838	$706	$662	$557	$488	$411	$379	$320
Warranty on new technology	$567	$40	$664	$46	$524	$37	$387	$27	$301	$21
Warranty Step 2	$850	$59	$996	$69	$786	$55	$580	$40	$451	$31
Useful Life extension	$2,426	$176	$2,843	$207	$2,244	$163	$1,654	$120	$1,287	$94
Compliance program costs	$47	$47	$55	$55	$44	$43	$32	$32	$25	$25
Total Indirect Costs	**$4,606**	**$925**	**$5,396**	**$1,084**	**$4,260**	**$856**	**$3,141**	**$631**	**$2,443**	**$491**
Total Cost Increase ($M)	**$6,629**	**$1,104**	**$7,767**	**$1,294**	**$6,132**	**$1,021**	**$4,521**	**$753**	**$3,517**	**$586**

Medium-Heavy Duty MY2027. We estimate (in Table 5) that the low-NO_x standards contemplated for MY2027, including the MY2024 proposals, would cost $2.6 billion on a nationwide basis, or $17,230 per-unit. On a California-only basis, the program would cost $500 million, which equates to $60,820 per-unit. That level of price increase would in all likelihood significantly reduce the choices available in the California truck market, thereby decreasing competition by forcing some low-volume manufacturers out of the market. **The net present value of those figures is $1.8 – $2.4 billion for the MHD industry on a nationwide basis, or $11,750 – $15,940 per-vehicle, using the 3% and 7% discount rates. For California-only, the net present value ranges from $330 – $450 million at the discounted cost rates, which boost the per-unit costs to $41,500 – $56,250.** Those MHD costs are largely similar to the cost estimates for HHD diesel vehicles. While smaller in absolute terms, they represent similar proportional price increases relative to new vehicle prices.

Table 5: Cost Estimates to Meet Proposed Combined MY2027 Standards for MHD Vehicles

Medium-heavy Duty Diesel										
Social Cost Methodology	MY2027 - from MY2018 baseline								*Private Cost (not Social)*	
Costs to Develop & Build Ultra-Low-NOx products	2019 dollars		Inflation-adjusted at:		Discounted at:		Discounted at:		Discounted at WACC	
Phase 1, part 1			2%		3%		7%		10%	
	National	California	National	California	National	California	National	California	National	California
Units	152,340	7,944	152,340	7,944	152,340	7,944	152,340	7,944	152,340	7,944
Per unit costs ($)										
Direct manufacturing costs										
Engine	$1,894	$4,882	$2,220	$5,720	$1,752	$4,516	$1,292	$3,329	$1,005	$2,590
Aftertreatment	$3,186	$7,762	$3,733	$9,094	$2,947	$7,179	$2,173	$5,293	$1,690	$4,118
Vehicle + On-Board Diagnostics	$328	$640	$384	$749	$303	$592	$224	$436	$174	$339
Total Direct Costs	**$5,408**	**$13,283**	**$6,337**	**$15,564**	**$5,002**	**$12,286**	**$3,688**	**$9,058**	**$2,869**	**$7,047**
Indirect Costs										
Research and development costs	$1,575	$30,198	$1,845	$35,382	$1,456	$27,931	$1,074	$20,593	$835	$16,022
Step 2 warranty	$5,588	$8,873	$6,547	$10,396	$5,168	$8,207	$3,810	$6,051	$2,965	$4,707
Useful Life extension	$4,543	$6,157	$5,323	$7,214	$4,202	$5,695	$3,098	$4,199	$2,410	$3,267
Compliance program costs	$120	$2,309	$141	$2,705	$111	$2,135	$82	$1,574	$64	$1,225
Total Indirect Costs	**$11,826**	**$47,537**	**$13,856**	**$55,697**	**$10,938**	**$43,968**	**$8,064**	**$32,416**	**$6,274**	**$25,221**
Total Cost Increase per Unit	**$17,234**	**$60,820**	**$20,192**	**$71,261**	**$15,940**	**$56,254**	**$11,752**	**$41,474**	**$9,143**	**$32,268**
EOEM Costs ($M)										
Direct manufacturing costs										
Engine	$289	$39	$338	$45	$267	$36	$197	$26	$153	$21
Aftertreatment	$485	$62	$569	$72	$449	$57	$331	$42	$258	$33
Vehicle + On-Board Diagnostics	$50	$5	$59	$6	$46	$5	$34	$3	$27	$3
Total Direct Costs	**$824**	**$106**	**$965**	**$124**	**$762**	**$98**	**$562**	**$72**	**$437**	**$56**
Indirect Costs										
Research and development costs	$240	$240	$281	$281	$222	$222	$164	$164	$127	$127
Step 2 warranty	$851	$70	$997	$83	$787	$65	$580	$48	$452	$37
Useful Life warranty	$692	$49	$811	$57	$640	$45	$472	$33	$367	$26
Compliance program costs	$18	$18	$21	$21	$17	$17	$13	$13	$10	$10
Total Indirect Costs	**$1,802**	**$378**	**$2,111**	**$442**	**$1,666**	**$349**	**$1,228**	**$258**	**$956**	**$200**
Total Cost Increase ($M)	**$2,625**	**$483**	**$3,076**	**$566**	**$2,428**	**$447**	**$1,790**	**$329**	**$1,393**	**$256**

Source: ACT Research Co., LLC: Copyright 2020

Heavy-Heavy Duty MY2031. We also estimate (in Table 6) that the additional low-NO_x requirements for MY2031, using the MY2027 proposals as a baseline, would cost HHD truck manufacturers an additional $4.0 billion on a national level, or $14,830 per-unit, in 2019 dollars. For California, our estimate of $275 million in costs equates to $18,150 per-unit. While there may be modest aftertreatment changes associated with the MY2031 step, there are no additional engine or on-board diagnostics requirements. The costs at issue are almost exclusively related to further extensions to the emissions warranty and useful life periods. On an inflation-adjusted and discounted basis, using the 3% and 7% discount rates recommended by EPA and OMB, **the net present value cost ranges from $8,350 – $13,200 per HHD vehicle, for a total of $2.2 – $3.5 billion for the HHD industry at the national level. For California, we estimate the MY2031 proposed requirements would increase the cost of a HHD truck by $10,220 – $16,140**. Note again that in the far-right column, we present the cost figures discounted at the 10% WACC. These costs are considerably lower and, again, could better reflect the uncertainties relating to the possible incorporation of unforeseen technology improvements in the coming years.

Table 6: Cost Estimates to Meet Proposed Combined MY2031 Standards for HHD Vehicles

Heavy-heavy Duty Diesel										
Social Cost Methodology			**MY2031 - from MY2027 baseline**						*Private Cost (not Social)*	
Costs to Develop & Build Ultra-Low-NOx products	2019 dollars		Inflation-adjusted at:		Discounted at:		Discounted at:		Discounted at WACC	
			2%		3%		7%		10%	
	National	California	National	California	National	California	National	California	National	California
Industry Units	267,135	15,098	267,135	15,098	267,135	15,098	267,135	15,098	267,135	15,098
Per unit costs ($)										
Direct manufacturing costs										
Engine	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Aftertreatment	$278	$267	$353	$339	$248	$238	$157	$150	$108	$103
Vehicle + On-Board Diagnostics	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total Direct Costs	**$278**	**$267**	**$353**	**$339**	**$248**	**$238**	**$157**	**$150**	**$108**	**$103**
Indirect Costs to Manufacturers										
Research and development costs	$16	$301	$20	$382	$14	$268	$9	$169	$6	$116
Warranty on new technology	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Warranty Step 2	$4,729	$5,243	$5,997	$6,649	$4,206	$4,663	$2,663	$2,952	$1,827	$2,026
Useful Life extension	$9,810	$12,336	$12,441	$15,645	$8,726	$10,973	$5,524	$6,947	$3,791	$4,767
Compliance program costs	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total Indirect Costs	**$14,554**	**$17,880**	**$18,458**	**$22,676**	**$12,946**	**$15,904**	**$8,196**	**$10,068**	**$5,624**	**$6,909**
Cost Increase per Unit ($)	**$14,833**	**$18,147**	**$18,811**	**$23,014**	**$13,194**	**$16,142**	**$8,352**	**$10,219**	**$5,732**	**$7,013**
EOEM Costs ($M)										
Direct manufacturing costs										
Engine	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Aftertreatment	$74	$4	$94	$5	$66	$4	$42	$2	$29	$2
Vehicle + On-Board Diagnostics	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total Direct Costs	**$74**	**$4**	**$94**	**$5**	**$66**	**$4**	**$42**	**$2**	**$29**	**$2**
Indirect Costs										
Research and development costs	$4	$5	$5	$6	$4	$4	$2	$3	$2	$2
Warranty on new technology	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Warranty Step 2	$1,263	$79	$1,602	$100	$1,124	$70	$711	$45	$488	$31
Useful Life extension	$2,621	$186	$3,323	$236	$2,331	$166	$1,476	$105	$1,013	$72
Compliance program costs	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total Indirect Costs	**$3,888**	**$270**	**$4,931**	**$342**	**$3,458**	**$240**	**$2,189**	**$152**	**$1,502**	**$104**
Total Cost Increase ($M)	**$3,962**	**$274**	**$5,025**	**$347**	**$3,525**	**$244**	**$2,231**	**$154**	**$1,531**	**$106**

Source: ACT Research Co., LLC: Copyright 2020

Medium-Heavy Duty MY2031. We estimate (in Table 7) that the Omnibus Requirements proposed for MY2031 would cost MHD truck and engine makers an additional $1.0 billion on a national level, or $6,550 per-unit. For California, the projected $100 million cost increase equates to $17,560 per-unit. As noted above in the *Market Sizing* section, we assume a smaller diesel-powered market size in California in 2031 due to the implementation of CARB's ZEV rules. **The net present value of these costs (using the 3% and 7% discount rates) is $615 – $935 million for the MHD industry on a nationwide basis, or $3,700 – $5,800 per MHD vehicle, and $60 – $90**

million in California, or $9,900 – $15,600 per vehicle. The costs were largely similar to the estimates calculated for HHD diesel vehicles. While smaller in absolute terms, they represent similar proportional price increases.

Table 7: Cost Estimates to Meet Proposed Combined MY2031 Standards for MHD Vehicles

Medium-heavy Duty Diesel										
Social Cost Methodology			**MY2031 - from MY2027 baseline**						*Private Cost (not Social)*	
Costs to Develop & Build Ultra-Low-NOx products	2019 dollars		Inflation-adjusted at:		Discounted at:		Discounted at:		Discounted at WACC	
Phase 1, part 1			2%		3%		7%		10%	
	National	California	National	California	National	California	National	California	National	California
Units	158,526	5,511	158,526	5,511	158,526	5,511	158,526	5,511	158,526	5,511
Per unit costs ($)										
Direct manufacturing costs										
Engine	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Aftertreatment	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Vehicle + On-Board Diagnostics	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total Direct Costs	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Indirect Costs										
Research and development costs	$158	$4,537	$200	$5,753	$140	$4,035	$89	$2,555	$61	$1,753
Step 2 warranty	$3,219	$7,049	$4,083	$8,940	$2,864	$6,271	$1,813	$3,970	$1,244	$2,724
Useful Life extension	$3,174	$5,978	$4,026	$7,582	$2,823	$5,318	$1,787	$3,366	$1,227	$2,310
Compliance program costs	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total Indirect Costs	**$6,551**	**$17,564**	**$8,308**	**$22,276**	**$5,827**	**$15,624**	**$3,689**	**$9,891**	**$2,532**	**$6,788**
Total Cost Increase per Unit	**$6,551**	**$17,564**	**$8,308**	**$22,276**	**$5,827**	**$15,624**	**$3,689**	**$9,891**	**$2,532**	**$6,788**
EOEM Costs ($M)										
Direct manufacturing costs										
Engine	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Aftertreatment	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Vehicle + On-Board Diagnostics	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total Direct Costs	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Indirect Costs										
Research and development costs	$25	$25	$32	$32	$22	$22	$14	$14	$10	$10
Step 2 warranty	$510	$39	$647	$49	$454	$35	$287	$22	$197	$15
Useful Life warranty	$503	$33	$638	$42	$448	$29	$283	$19	$194	$13
Compliance program costs	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total Indirect Costs	**$1,039**	**$97**	**$1,317**	**$123**	**$924**	**$86**	**$585**	**$55**	**$401**	**$37**
Total Cost Increase ($M)	**$1,039**	**$97**	**$1,317**	**$123**	**$924**	**$86**	**$585**	**$55**	**$401**	**$37**

Source: ACT Research Co., LLC: Copyright 2020

Pre-Buy/No-Buy Analysis

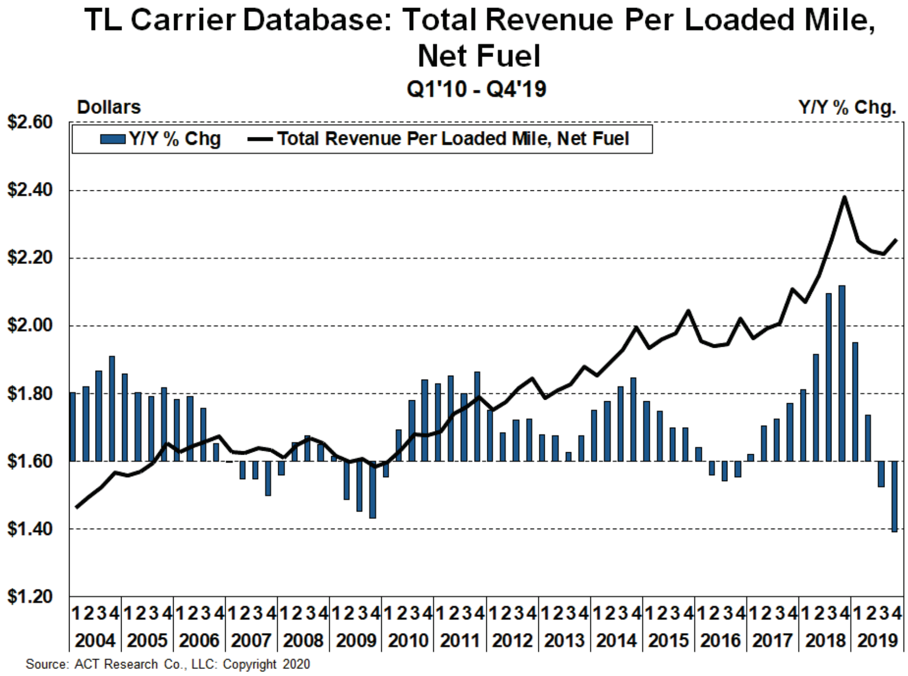
Introduction. A "pre-buy" occurs when industry participants initially reject a regulation-driven change in a product, in this case heavy-duty on-highway commercial vehicles, and instead buy as much of that product as possible in the years before the new regulation takes effect. A "no-buy" occurs in the initial years after the new regulation is implemented, when product demand, while not literally zero, falls sharply. The trucking industry is naturally risk-averse and prone to avoid new regulations that may impact the reliability and operating costs of trucks, since operational reliability is so vital to industry participants' ability to survive in an historically low-margin business.

The base case of our cost study uses a hypothetical market size which takes a trailing five-year average and scales it up by a 1% CAGR. This borrows from the established assumption that freight volume per capita is very stable in the long-run, so freight grows roughly in line with population growth. It also borrows from our view that truck supply and demand always return to equilibrium, notwithstanding intermittent periods of over and under supply relative to freight demand. Based on our cost study, we estimate that HHD truck prices are likely to rise $18k-$24k (14%-18%) in MY2027, and another $8k-$13k (5%-8%) in MY2031. MHD truck prices are likely to rise $12k-$16k in MY2027, and another $4k-$6k in MY2031, with similar percentages, as a result of the proposed Omnibus Regulations.

There is not a great deal of pricing information available in the new MHD and HHD truck markets, though information on freight rates has improved significantly in recent years, so partial equilibrium analysis not very effective for the manufacturing sector, but perhaps better for the trucking industry. And since the costs of the proposed regulations will be passed to the trucking industry, it is those effects which we believe are most important to consider.

Past experience, particularly the pre-buy that occurred in 2005-2006 ahead of EPA07, demonstrates that emissions standards which significantly increase the cost and complexity of HHD tractors are likely to lead to pre-buying of equipment in the years leading up to the regulations, assuming the industry has the financial wherewithal to adjust the timing of capital expenditures. And given the lower tax rates as of 2018, we think the industry is structurally more profitable, or at least it has not been adversely impacted. Therefore, the trucking industry likely will have the ability to pre-buy in advance of the Omnibus Regulations taking effect.

Starting from the experience in 2006-2007, the trend in contract truckload rates, which fell 1.3% in 2007, has risen 3% per-year on average since then. That amounts to a 4%-type opportunity cost for the industry. (See chart below.)



With that opportunity cost in mind, we believe the proposed Omnibus Regulations would precipitate the largest-ever pre-buy for medium-heavy and heavy-heavy duty trucks and tractors. The primary repercussions of a pre-buy would be two years of vehicle underproduction in 2027 and 2028 to counterbalance the likely overproduction in 2025 and 2026. While we can make a case that R&D costs are ultimately recouped over time thanks to higher vehicle prices, not all costs are recoverable. There would be significant costs for the OEMs and their employees in terms of the inefficiencies that come with a rapid ramp-up to meet an artificial demand bubble followed by a demand collapse in the period of capacity rebalancing that leads to layoffs and production cuts.

While the vehicle and engine manufacturers will have to handle major market disruptions relating to nonmarket-driven demand impacts, the HHD market has an additional constituency that likely will be severely impacted by the proposed rule-making. The anticipated pre-buy, like the one that occurred ahead of EPA'07 in 2005–2006, is likely to result in significant and unnecessary capacity additions in the HHD trucking industry. A large portion of those truckers operates on a for-hire basis and is dependent upon market rates to move freight. The lower freight rates which will inevitably result from the regulation-driven overcapacity bubble will have a significant adverse financial impact on the nation's truckers, **with an estimated impact of $6.5 – $8.6 billion at net present value.**

Pre-Buy Model. Using a multi-factor relational model based on a significant history of industry activity before and after the introduction of new emissions regulations, **we estimate (in Table 8) the industry will pre-buy 64,800 (4,200 + 60,600) additional HHD tractors and 25,300 (2,600 + 22,700) MHD vocational trucks in 2025 – 2026 ahead of the MY2027 regulations. This adds up to 90,100 total Class 8 vehicles over the two-year pre-buy. Ahead of the MY2031 standards, we estimate another pre-buy of 35,000 (4,200 + 30,700) HHD tractors and 11,600 (2,300 + 9,200) HHD vocational trucks in 2029 – 2030.** Vocational trucks are similar to MHD vehicles in that they are typically a component of a job (construction/dump/cement) and are not directly subject to market rates, so the modeled freight rate effects exclude vocational trucks. Overcapacity in MHD vocational trucks will primarily impact manufacturers who will have to lay off workers and lower supplier orders. However, in the HHD tractor market, there likely will be very significant price impacts on freight rates.

Table 8: Prebuy Size Estimates in Units and Percent

	MY2027 $ Change Op. Costs	MY2027 % Change Op. Costs	Anticipated Prebuy: 2025	Share of new Market	Anticipated Prebuy: 2026	Share of new Market
US Class 8 Tractor	$ 35,103	18.3%	4,219	2.7%	60,622	39.9%
US Class 8 Vocational	$ 35,190	14.6%	2,620	4.7%	22,667	36.9%
US Total Class 8			6,838	3.2%	83,290	39.0%
Source: ACT Research Co.,LLC: Copyright 2020						

	MY2031 $ Change Op. Costs	MY2031 % Change Op. Costs	Anticipated Prebuy: 2029	Share of new Market	Anticipated Prebuy: 2030	Share of new Market
US Class 8 Tractor	$ 12,491	6%	4,234	2%	26,717	13%
US Class 8 Vocational	$ 14,536	6%	2,344	4%	9,236	14%
US Total Class 8			6,578	3%	35,953	14%
Source: ACT Research Co.,LLC: Copyright 2020						

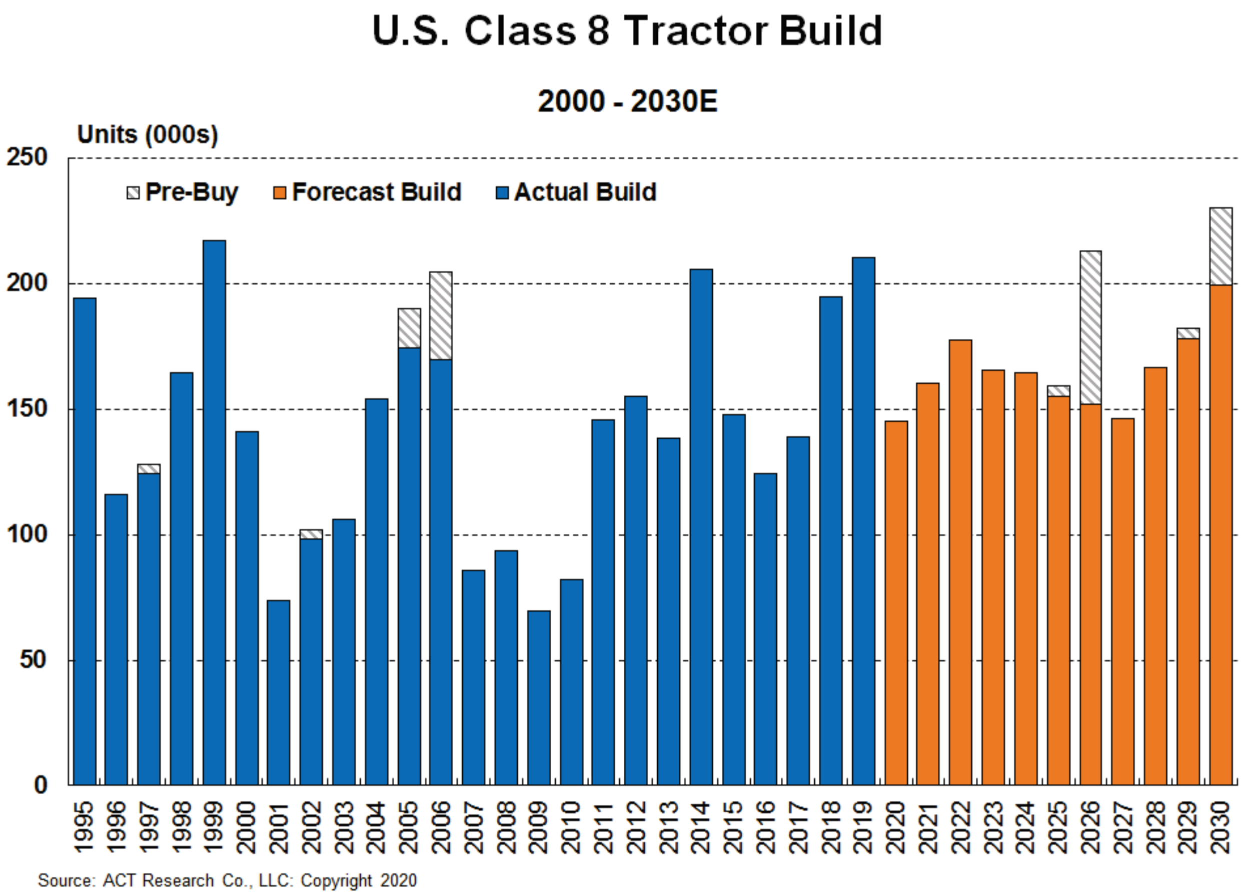
The HHD tractor pre-buy model starts with the base tractor price, adds in the 12% Federal Excise Tax (FET) and an average 8% for State and Local taxes. We then raise the sticker price by the cost of meeting the proposed standards, using $23,885 (18% of base), which we settled on because that cost increase was near the center of the range of the $30,300 per-unit value undiscounted at the 2% inflation rate, and the $17,600 per-unit value using a 7% discount rate. We taxed the $23,885 at the FET + state tax rate, added in three years of insurance at a rate of 5% of the truck cost each year, and added financing costs at an interest rate of 5% for half of the value of the vehicle. This totals about $35,000 of added upfront costs for the HHD vehicle purchaser in MY2027, and another $12,000 in MY2031. (See Table 8.)

Fuel economy considerations all play a role in the model. After considerable discussion, we included the impending fuel economy improvements associated with GHG-2 regulations in MY2027, even though most of those fuel economy improvements will be in effect prior to the Omnibus Regulations. In our cost analysis from the manufacturers' perspective, we did not include costs or benefits for the GHG-2 regulations, except as we understand the state of the market to be in MY2027. To estimate the social cost to the trucking industry, however, our model's purpose is to reflect the conditions impacting the industry in MY2027 and MY2031. We considered both the improvements in fuel efficiency and additional use of diesel emissions fluid (DEF), finding that the 4% improvement in fuel efficiency expected in MY2027 from GHG-2 regulations would more than offset a doubling of the DEF dosing rate. Moving from a 2.5% to a 5% DEF dosing rate on a 90,000 mile per-year truckload application would use 233 additional gallons per-year at a cost of about $665, but the 4% fuel efficiency improvement saves $1,300 per-year at 440 gallons in this application. We are not using those estimates as benefits relating to the Omnibus Regulations, but rather to refine our analysis of the potential magnitude of a pre-buy.

Regarding maintenance costs, some of the technology solutions anticipated for the proposed Omnibus Regulations are targeted towards improving the durability of aftertreatment systems, which could have the effect of lowering maintenance expenses in some instances. However, the overall increase in the complexity of the engine and aftertreatment systems likely will require more frequent maintenance for these trucks through their life-cycles, not less. Given the high degree of uncertainty, however, we have not included explicit estimates of maintenance expenses, except to say that there are positives and negatives from a fleet perspective, and as noted earlier in our report, the higher warranty and useful life costs are included in the estimated sticker price increases.

Tractor Pre-Buy. The sum of the multiple costs result in a "willingness to buy" factor, which is the percentage change in total cost of ownership (TCO) of the vehicle before and after the regulation. At a cost of $35,100 in MY2027, the net TCO impact is 18% of the pre-regulation purchase price. Based on historical pre-buys and assuming reasonable industry profit margins leading into the new regulatory mandates, we estimate that the 18% increase will drive an additional 3% of HHD tractor sales in 2025 (4,200 units), and a 40% pre-buy in 2026 (60,600 units). The $12,500 net TCO increase due to the proposed MY2031 standards, which amounts to an additional 6% price/TCO increase, will drive another 2% of tractor sales in 2028 (4,200 units) and an additional 15% pre-buy in 2029 (30,700 units). (See Table 8.)

Table 9: Retail Sales and Pre-Buy History and Forecast in the U.S. Class 8 Tractor Market



Freight Rate Impact. Adding these 65,000 "pre-bought" tractors into our population models, where we estimate 1.4 million HHD tractors engaged in truckload and/or less-than-truckload freight hauling, amounts to a 4.5% increase in capacity or supply into the industry. Our freight pricing models indicate that the sensitivity of truckload contract pricing is roughly -64% relative to capacity additions when modeled econometrically with demand and regulatory factors included. In other words, a 1% increase in freight-hauling capacity lowers pricing by .64%, so a 4.5% increase in capacity, as expected in this case, would lower truckload pricing by 2.9%.

Trucking Industry Sizing and Earnings Impact. According to the U.S. Census Bureau's Quarterly Services Survey, the U.S. trucking industry is on pace for $195 billion in revenue (NAICS code: 4841, General Freight Trucking) in 2019. Using a trailing 5-year industry growth rate of 3% to extrapolate to 2026, the industry should be generating $240 billion of revenue in 2026. A 2.9% pricing impact on a $240 billion segment of the economy would be a cost to aggregate trucking industry earnings of $6.9 billion on an annual basis, and it would likely last 18-24 months. Thus,

the total impact on the trucking industry would likely be $10.4 – $13.8 billion of lost earnings in 2026 – 2027. This discounts back to $6.5 - $8.6 billion in 2019 dollars at 7%.

We have focused here on the for-hire market reported on by the Census Bureau. Our estimates do not include effects on the private fleet segment of the trucking industry, which makes up just over half of the tractor fleet, but generally hauls freight for a single company. Private fleets are generally a cost center inside companies that ship goods, with few booking revenue for their services. As a result, we did not include that part of the market in estimating financial impacts.

Vocational Pre-buy. The main focus of our analysis (in Table 8) is on the tractor portion of the heavy-duty Class 8 market, since, over the past decade, tractors have represented 75% of the Class 8 vehicles sold in the US, compared to 25% for the Class 8 market's vocational segment. Significantly higher miles traveled per-year for tractors mean shorter lengths of ownership due to reliability/downtime issues as miles accrue. On the vocational side of the market, localized vocational applications (P&D, construction, government) mean fewer miles per-year and longer first-buyer ownership. And, as previously discussed, unlike the tractor market, where every vehicle is a profit center, the vocational truck is often a tool used to facilitate a non-transportation related business. Thus, there is significantly more volatility in US tractor demand from year to year compared to the vocational truck portion of the market.

In that regard, like the MHD market, we do not typically view the vocational portion of the HHD market as a candidate for pre-buying. But in terms of vocational equipment pre-buying ahead of EPA07, ACT's modeling suggests that a prebuy did occur ahead of that regulatory mandate. Vocational buyers and dealers accounted for 30% of the 92,000 units of prebuying that occurred in 2005 and 2006, or 5 percent higher than the segment's long-run market share. We have concluded that the majority of that prebuy resulted from vocational fleet buyers actively working to avoid the EPA07 emissions mandate.

Using our model, the sharp rise in vehicle costs ahead of the MY2027 mandates in this case indicates that vocational truck buyers will pre-buy approximately 26,000 units in 2025 and 2026. (See Table 8.) At $35,200 in MY2027, the net TCO impact is 15% of the pre-regulation purchase price. That includes a $24,000 price increase, plus taxes, insurance, financing and diesel emissions fluid costs. The net result is that we estimate that the increased costs will drive an additional 5% of vocational tractor sales in 2025 (2,600 units) and a 37% pre-buy in 2026 (22,700 units), which totals to a pre-buy of 25,300 units. For the MY2031 mandate step, the model projects another 4% pre-buy in 2029 (2,300 units) with an additional 14% pre-buy in 2030 (9,200 units) due to a $14,500 net TCO increase for the MY2031 proposed standards, which amounts to an additional 6% price/TCO increase. Combined, the MY2031 vocational Class 8 prebuy sums to 11,600 units.

When combined, the projected US Class 8 prebuy for trucks and tractors rises to 90,100 units ahead of the MY2027 regulatory step, with 6,800 units pulled into 2025 and 83,300 units pulled into 2026. The prebuy represents a 3% increase above modeled 2024 demand and a 39% jump above modeled levels in 2025. **For the MY2031 mandate, the model anticipates 6,600 units being pulled into 2029, and an additional pre-buy of 39,900 Class 8 units in 2030.** Prebuying as a percentage of the market is 3% in 2028 and 15% in 2029.

Sensitivity Analysis: Costs Using Pre-buy/No-buy Scenario. The tables below (Tables 10-11) provide a sensitivity analysis from the base case costs of the Omnibus Regulations (see Tables 4-7) which assumed a normalized demand environment. Having established that a normalized demand environment is very unlikely, we show below how the cost estimates change when we envision the significantly depressed post-pre-buy market in MY2027 that we think is more likely. In short, the total costs to the manufacturers fall significantly because most of the costs vary with production levels, but the per-unit costs rise because some of those costs are fixed, mainly R&D and compliance program costs.

For HHD vehicles in MY2027 (see Table 10), these industry Total Cost Increase figures are approximately 52% lower than the National costs presented in the base case discussed earlier in this report, and 53% lower on a California basis. (See Tables 4-7.) That is primarily because of a 38% lower vehicle-build forecast.

However, on a per-unit basis, the MY2027 costs are approximately 3% and 31% higher on a National and California-only basis, respectively. Those percentages are consistent across inflation and discount rates.

Table 10: Cost Estimates Under No-buy MY2027 Scenario for HHD Vehicles

Heavy-heavy Duty Diesel										
Social Cost Methodology	MY2027 - from MY2018 baseline								*Private Cost (not Social)*	
Costs to Develop & Build Ultra-Low-NOx products	2019 dollars		Inflation-adjusted at:		Discounted at:		Discounted at:		Discounted at WACC	
			2%		3%		7%		10%	
	National	California	National	California	National	California	National	California	National	California
Units	175,004	10,763	175,004	10,763	175,004	10,763	175,004	10,763	175,004	10,763
Per unit costs ($)										
Direct manufacturing costs										
Engine	$3,157	$3,833	$3,699	$4,491	$2,920	$3,545	$2,153	$2,614	$1,675	$2,034
Aftertreatment	$4,589	$6,209	$5,376	$7,274	$4,244	$5,742	$3,129	$4,234	$2,434	$3,294
Vehicle + On-Board Diagnostics	$176	$1,990	$206	$2,331	$163	$1,840	$120	$1,357	$93	$1,056
Total Direct Costs	**$7,921**	**$12,031**	**$9,281**	**$14,097**	**$7,327**	**$11,128**	**$5,402**	**$8,204**	**$4,203**	**$6,383**
Indirect Costs to Manufacturers										
Research and development costs	$3,687	$52,808	$4,319	$61,873	$3,410	$48,843	$2,514	$36,011	$1,956	$28,017
Warranty on new technology	$1,844	$2,070	$2,161	$2,426	$1,706	$1,915	$1,258	$1,412	$978	$1,098
Warranty Step 2	$3,311	$3,827	$3,880	$4,484	$3,063	$3,539	$2,258	$2,609	$1,757	$2,030
Useful Life extension	$9,451	$11,283	$11,074	$13,220	$8,742	$10,436	$6,445	$7,694	$5,014	$5,986
Compliance program costs	$261	$4,223	$306	$4,948	$241	$3,906	$178	$2,880	$138	$2,241
Total Indirect Costs	**$18,554**	**$74,212**	**$21,739**	**$86,951**	**$17,161**	**$68,640**	**$12,653**	**$50,606**	**$9,844**	**$39,373**
Cost Increase per Unit ($)	**$26,476**	**$86,243**	**$31,020**	**$101,048**	**$24,488**	**$79,768**	**$18,054**	**$58,811**	**$14,047**	**$45,756**
EOEM Costs ($M)										
Direct manufacturing costs										
Engine	$552	$41	$647	$48	$511	$38	$377	$28	$293	$22
Aftertreatment	$803	$67	$941	$78	$743	$62	$548	$46	$426	$35
Vehicle + On-Board Diagnostics	$31	$21	$36	$25	$28	$20	$21	$15	$16	$11
Total Direct Costs	**$1,386**	**$129**	**$1,624**	**$152**	**$1,282**	**$120**	**$945**	**$88**	**$735**	**$69**
Indirect Costs										
Research and development costs	$645	$568	$756	$666	$597	$526	$440	$388	$342	$302
Warranty on new technology	$323	$22	$378	$26	$299	$21	$220	$15	$171	$12
Warranty Step 2	$579	$41	$679	$48	$536	$38	$395	$28	$307	$22
Useful Life extension	$1,654	$121	$1,938	$142	$1,530	$112	$1,128	$83	$878	$64
Compliance program costs	$46	$45	$53	$53	$42	$42	$31	$31	$24	$24
Total Indirect Costs	**$3,247**	**$799**	**$3,804**	**$936**	**$3,003**	**$739**	**$2,214**	**$545**	**$1,723**	**$424**
Total Cost Increase ($M)	**$4,633**	**$928**	**$5,429**	**$1,088**	**$4,285**	**$859**	**$3,160**	**$633**	**$2,458**	**$492**

Source: ACT Research Co., LLC: Copyright 2020

For MY2031 (see Table 11), and calculated off the MY2027 baseline, the per-unit costs rise 4% and 5%, respectively, for the National and California-only programs under the lower no-buy demand scenario. Those respective percentage increases are closer together because the MY2031 costs are largely variable outside of R&D. On an aggregate basis, the lower vehicle-production assumptions would reduce the total costs of the program by 28% for both a National and a California program, due to the 32% lower vehicle-build forecast.

Table 11: Cost Estimates Under No-buy MY2031 Scenario for HHD Vehicles

Heavy-heavy Duty Diesel										
Social Cost Methodology					MY2031 - from MY2027 baseline				*Private Cost (not Social)*	
Costs to Develop & Build Ultra-Low-NOx products	2019 dollars		Inflation-adjusted at:		Discounted at:		Discounted at:		Discounted at WACC	
			2%		3%		7%		10%	
	National	California	National	California	National	California	National	California	National	California
Units	182,540	10,317	182,540	10,317	182,540	10,317	182,540	10,317	182,540	10,317
Per unit costs ($)										
Direct manufacturing costs										
Engine	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Aftertreatment	$290	$302	$367	$383	$258	$269	$163	$170	$112	$117
Vehicle + On-Board Diagnostics	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total Direct Costs	**$290**	**$302**	**$367**	**$383**	**$258**	**$269**	**$163**	**$170**	**$112**	**$117**
Indirect Costs to Manufacturers										
Research and development costs	$16	$313	$21	$397	$15	$279	$9	$176	$6	$121
Warranty on new technology	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Warranty Step 2	$4,921	$5,512	$6,241	$6,991	$4,377	$4,903	$2,771	$3,104	$1,902	$2,130
Useful Life extension	$10,208	$12,940	$12,946	$16,411	$9,080	$11,510	$5,748	$7,287	$3,945	$5,001
Compliance program costs	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total Indirect Costs	**$15,145**	**$18,765**	**$19,208**	**$23,799**	**$13,472**	**$16,692**	**$8,528**	**$10,567**	**$5,853**	**$7,252**
Cost Increase per Unit ($)	**$15,435**	**$19,068**	**$19,575**	**$24,182**	**$13,730**	**$16,961**	**$8,692**	**$10,737**	**$5,965**	**$7,369**
EOEM Costs ($M)										
Direct manufacturing costs										
Engine	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Aftertreatment	$53	$3	$67	$4	$47	$3	$30	$2	$20	$1
Vehicle + On-Board Diagnostics	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total Direct Costs	**$53**	**$3**	**$67**	**$4**	**$47**	**$3**	**$30**	**$2**	**$20**	**$1**
Indirect Costs										
Research and development costs	$3	$3	$4	$4	$3	$3	$2	$2	$1	$1
Warranty on new technology	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Warranty Step 2	$898	$57	$1,139	$72	$799	$51	$506	$32	$347	$22
Useful Life extension	$1,863	$133	$2,363	$169	$1,657	$119	$1,049	$75	$720	$52
Compliance program costs	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total Indirect Costs	**$2,765**	**$194**	**$3,506**	**$246**	**$2,459**	**$172**	**$1,557**	**$109**	**$1,068**	**$75**
Total Cost Increase ($M)	**$2,817**	**$197**	**$3,573**	**$249**	**$2,506**	**$175**	**$1,587**	**$111**	**$1,089**	**$76**

Source: ACT Research Co., LLC: Copyright 2020

Dealer Pre-buy. While we have discussed truckers as the primary drivers of pre-buying, there is another group that is also likely to contribute to pre-buying activity ahead of the MY2027 standard — truck dealers. Based on the experience ahead of EPA'07, we would expect that U.S. MHD and HHD commercial vehicle dealers would likely increase inventory levels aggressively in advance of the proposed MY2027 regulations. Dealers' ability to add to stock, however, would largely be determined by the availability of manufacturers' production capacity. Dealers' pre-buy decisions would be based on several factors:

First, is the cost of pre- versus post-mandate vehicles. With the sharply higher costs likely for the MY2027 vehicles, having lower priced units in inventory should facilitate dealer sales for several months into the post-mandate period.

Second, given the risks that early post-mandate purchasers might face with respect to the reliability of early post-mandate vehicles, most truckers would prefer to let someone else act as the beta-tester for real-world usage. Dealers carrying pre-mandate inventories could provide their risk-averse customers with a competitive edge early in the post-mandate period.

Looking back to the last major pre-buy in 2006, MHD and HHD vehicle dealers both added to inventories over the course of that year. Based on ACT Research data collection, MHD inventory levels rose from 49,500 units at the end of December 2005, to 70,500 units at the end of 2006. A baseline 6% year to year increase in MHD Classes 5-7 retail sales in the U.S. does not explain the 42% inventory increase across 2006.

Reviewing changes to HHD vehicle inventories ahead of EPA07, from December 2005 to January 2007, U.S. Class 8 inventories rose from 42,200 units to 54,600 units, a 29% increase compared to a 12% increase in U.S. Class 8 retail sales from 2005 to 2006. Arguably the HHD dealer inventory pre-buy should have been larger in 2006, but final demand from trucking companies in the U.S. and Canada pushed the North American Class 8 manufacturing to unprecedented levels. In 2006, total North American Class 8 production rose to 376,000 units, 31,000 units higher than the second-best year ever, 2019.

Thus, we suspect that, as was the case in 2006, it will not be a lack of desire on the part of dealers to add inventory that limits Class 8 inventory-building ahead of the MY2027 regulation. Rather, it will be strong purchasing demand on the part of truck fleet operators that will limit dealers' ability to acquire and maintain those stocks.

Conclusions. The tables set forth below summarize the results of our cost study.

Table 12: Aggregate Costs, Discounted to NPV at 7%

	National			**California**		
Dollars in billions	MY2027	MY2031	Total	MY2027	MY2031	Total
Manufacturing Costs	$6.3	$2.8	$9.1	$1.08	$0.21	$1.29
Pre-buy / No-buy Costs	$7.6	$0.0	$7.6	NA	NA	NA
Grand Totals for HHD and MHD	**$13.9**	**$2.8**	**$16.7**	**$1.08**	**$0.21**	**$1.29**
Dollars per unit						
Medium-heavy duty	$11,752	$3,689	$15,441	$41,474	$9,891	$51,365
Heavy-heavy duty	$17,610	$8,352	$25,963	$47,686	$10,219	$57,905
Grand Totals for HHD and MHD	**$15,429**	**$6,616**	**$22,044**	**$45,607**	**$10,131**	**$55,738**

Our results show that on a nationwide base, using a 7% discount rate, the Omnibus Regulations will yield per-vehicle cost increases for HHD vehicles totaling $26,000 ($17,600 in 2027, and $8,400 in 2031), and per-vehicle cost increases for MHD vehicles totaling $15,400 ($11,800 in 2027, and $3,700 in 2031). The aggregate costs to the industry will be $16.7 billion ($13.9 billion in 2027, and $2.8 billion in 2031). This consists of $9.1 billion of manufacturing costs ($6.3 billion in 2027, and $2.8 billion in 2031) and $7.6 billion of pre-buy/no-buy costs (all focused on 2027) on the trucking industry.

On a California-only basis, our results show, again using a 7% discount rate, that the Omnibus Regulations will yield per-vehicle price increase for HHD vehicles totaling $57,900 ($47,700 in 2027, and $10,200 in 2031), and per-vehicle price increases for MHD vehicles totaling $51,400 ($41,500 in 2027, and $9,900 in 2031). The aggregate cost to the vehicle and engine manufacturing industry will be $1.35 billion ($1.14 billion in 2027, and $0.22 billion in 2031).

All in, the aggregate cost to the vehicle and engine manufacturing industry from the Omnibus Regulations, not including the additional costs to vehicle purchasers and operators would be $9.1 billion, and the lost earnings for the trucking industry would be $7.6 billion, bringing the total cost to $17.1 billion. Those very significant cost impacts call into question whether the Omnibus Regulations could be cost-effective, especially on a nationwide basis.

DRAFT

RESPONSE TO STANDARDIZED REGULATORY IMPACT ANALYSIS FOR PROPOSED CARB HEAVY-DUTY EMISSIONS REGULATIONS

PREPARED FOR:

TRUCK & ENGINE MANUFACTURERS ASSOCIATION

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July 31, 2020

ACT Research Company (ACTR) appreciates the opportunity to submit the following comments in response to the Standardized Regulatory Impact Assessment (SRIA) associated with the *Proposed Heavy-Duty Engine and Vehicle Omnibus Regulation and Associated Amendment* that the California Air Resources Board published on June 23, 2020, which was amended on July 10, 2020.

ACTR is a boutique research firm focused on surface transportation dynamics and commercial vehicle demand. ACTR's customers include leading MD and HD vehicle manufacturers, the commercial vehicle industry's supply base, investors in transportation and machinery companies, transportation companies, and other groups of stakeholders who need to understand the impact of economic activity on trucking industry profitability, and by extension, demand for medium- and heavy-duty on-highway vehicles.

ACTR's decision to provide comments on the CARB SRIA relates to a study the company undertook at the behest of the Engine Manufacturers Association (EMA) in early 2020. The resulting study was an upfront cost and total cost of ownership (TCO) analysis relating to the impact of the California Air Resource Board's (CARB) Omnibus Low-NOx standard proposals and the U.S. Environmental Protection Agency's (EPA) advanced notice of proposed rulemaking (ANPRM) published in the Federal Register on January 21, 2020, entitled "Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine Standards." Given the similarities in the CARB and EPA proposals surrounding NOx and warranty extension, we believe our analysis adds to the discourse surrounding CARB's proposed Regulation.

ACTR has been and will continue to be a supporter of CARB and EPA efforts to improve air quality. We applaud the 99% and 98% reductions in particulates and NOx, respectively, that have occurred over the past quarter-century. And in contrast to the costly final mandates that reduced PM and NOx, the more recent GHG Phase 1 and Phase 2 (to date) regulations have pushed industry stakeholders to deliver tremendous advances in on-highway fuel economy at nominal cost, thereby benefitting both the environment and the buyers of new commercial vehicles.

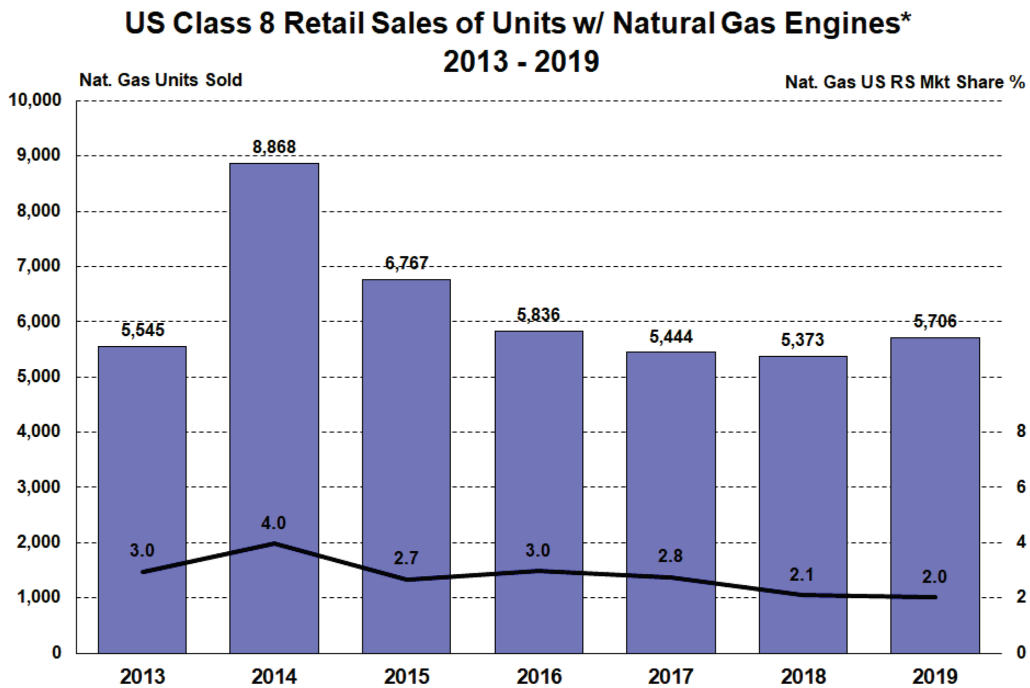
While we at ACTR recognize the need to continue reducing emissions levels from all sources, we also believe that accuracy in accounting is needed for regulators to make the most optimal decisions possible in plotting the way forward on emissions regulations. It is in that spirit that we believe a better accounting needs to be made in regard to CARB's current proposal to improve air quality. Based on our modeled conclusions, it is ACTR's opinion that CARB's accounting for the cost impact of the proposed regulation is incomplete on several fronts, including:

1) Market sizing
2) R&D accounting
3) Useful life accounting for new technologies and downtime impact
4) Warranty accounting

Over the course of this submission, ACTR will lay out where we believe the accounting as presented in the SRIA fails to capture the true costs of CARB's regulatory proposal. If our analysis is correct, the CARB regulation is likely to cause significant market disruptions as trucking companies actively work to minimize their exposure to new vehicles that would leave them at an operating cost disadvantage compared to their competition.

Market Size and Structure. Although we do not have a fully transparent understanding of the sales projections driven by CARB's EMFAC model, we disagree with the use of 2013 as the year from which to draw conclusions about the current and future commercial vehicle market size and structure.

- Based on OEM data, we estimate natural gas vehicles had a Class 8 market share nationally of 3%-4% in 2013-2014, and has since trended down to 2% in the past two years (see chart). Of course, we recognize that California represents an out-sized proportion of natural gas truck sales, but in the SRIA, CARB assumes HD Otto-cycle engines including natural gas were 43.6% of the heavy heavy-duty (Class 8) market in 2013. The market share has fallen considerably in the years since, and a more current weighting of the Class 8 market would increase the diesel units subject to low-NOx standards, which would increase overall costs in the resultant calculations.



* Transit bus data estimated. All other data as reported by OEMs to ACT Research.
Source: ACT Research Co., LLC

- We agree with CARB's earlier sales volume methodology which took into account the smaller market outlook resulting from the implementation of the Advanced Clean Truck (ACT) Regulation. But we disagree with the changes made, as recommended by the California Department of Finance (page IX-7), to adhere to a legal baseline which will not include the mandated zero-emissions vehicles under the ACT Regulation. That may have mixed implications for cost outputs, but suggests per-unit costs are understated. The cost study conducted by ACTR used the smaller market size resulting from the ACT Regulation, which lowered overall costs but raised per-unit costs, though the targets in the ACT Regulation have been raised even further since our study was conducted.

- CARB's SRIA Does not Consider the Likelihood of Pre-buy/No-buy. We agree with the need to include increased DEF consumption costs and financing costs, as CARB did in the SRIA. Costs to truckers were not included in ACTR's manufacturing cost analysis, but were included in our Pre-buy/No-buy analysis. In our view, the largest blind-spot in CARB's SRIA is the failure to consider the industry's anticipated avoidance-response to the prospect of costly and risky new emission-control regulations.

- The higher DEF consumption rate is just one of several additional cost factors that should be considered for the trucking industry, separate from manufacturing costs. Those include the taxes on the higher cost of a truck, which is a 12% Federal Excise Tax plus state taxes, and the costs to insure the more expensive vehicles, typically 5% of the purchase price per year.

- As a result, for every $1 increase in the purchase price of the vehicle, the equipment costs to the operator are likely to rise by $1.40 - $1.75, depending on the assumptions about the operating lifecycle. Hence, we think DEF costs are a very small fraction of the non-manufacturing costs of the Omnibus Low-NOx rulemaking proposal, which would be borne by the trucking industry.
    - In the cost study ACT Research performed for the EMA, we considered how the foregoing costs plus the higher base vehicle prices would impact the trucking industry. Instead of arguing about assumptions, we took a macroeconomic approach.

- We concluded that in this highly fragmented and cyclical industry, which is largely dependent upon market freight rates, a significant pre-buy is likely, with elevated demand for equipment built before the regulations take place. Trucking is a low-margin industry which abhors risk. Considerable historical precedent shows any significant price increase and technological change likely will drive a pre-buy in this industry. This will add excess capacity to the market and drive down freight rates, with a material adverse effect on earnings for the trucking industry. We have expertise in those freight rate sensitivities through *Freight Forecast* service, and we estimate the subsequent decline in truckload rates would cost the industry between $6.5 billion and $8.6 billion in the 2027-2028 timeframe. Further, the combination of the effects of the pre-buy and the cost of lower freight rates would materially reduce the industry's ability and willingness to purchase new vehicles after regulations take effect, thereby delaying the benefits of the regulation. The significant pre-buy/no-buy impacts are missing from the CARB SRIA.

R&D. CARB's SRIA assigns minimal Research and Development (R&D) costs to the implementation of its proposals, ranging from $78-$85 per unit for Medium Heavy-Duty (MHD) vehicles to $354-$356 per unit for Heavy Heavy-Duty (HHD) vehicles (ISOR page IX-10). The underlying sales figures from CARB's EMFAC model are not clear, and the total R&D costs are not broken out in CARB's aggregate table IX-32.

- The Original Equipment Manufacturer (OEM) study conducted by ACT Research yielded an estimate of $603 million of R&D costs to meet the HHD MY2027 standards proposed for California, only modestly less than the $715 million estimated for a full nationwide program. While the core processes are unchanged regardless of whether it is a California-only or national standard, the OEMs intend to reduce the offerings available in California to achieve those modest savings.

- Based on OEM feedback that these costs would be amortized over three- to four-year product cycles, that translates to about $38,000 per unit for the HHD market beginning in MY2027. CARB's SRIA does not explain how it arrived at its significantly lower R&D figure, though we acknowledge there is significant managerial accounting discretion to extend the amortization period and lower the per unit costs. Extending the regulations to a natiowide basis reduces those per-unit costs to just under $2,800 per unit in our model, even keeping with the OEMs' three- to four-year amortization periods, which highlights the benefit of harmonized national standards over regional ones.

<u>Useful Life.</u> Producing aftertreatment systems to meet tighter standards, increasing the Useful Life (UL) of those systems, and providing a warranty on those systems are three of the distinct challenges presented by the proposed Omnibus Low-NOx regulations. CARB's assertion that increased UL is included in the Technology Costs is not realistic because, for example, Cylinder Deactivation technology is not currently commercially viable and likely will require at least one full replacement in order to meet the UL proposal.

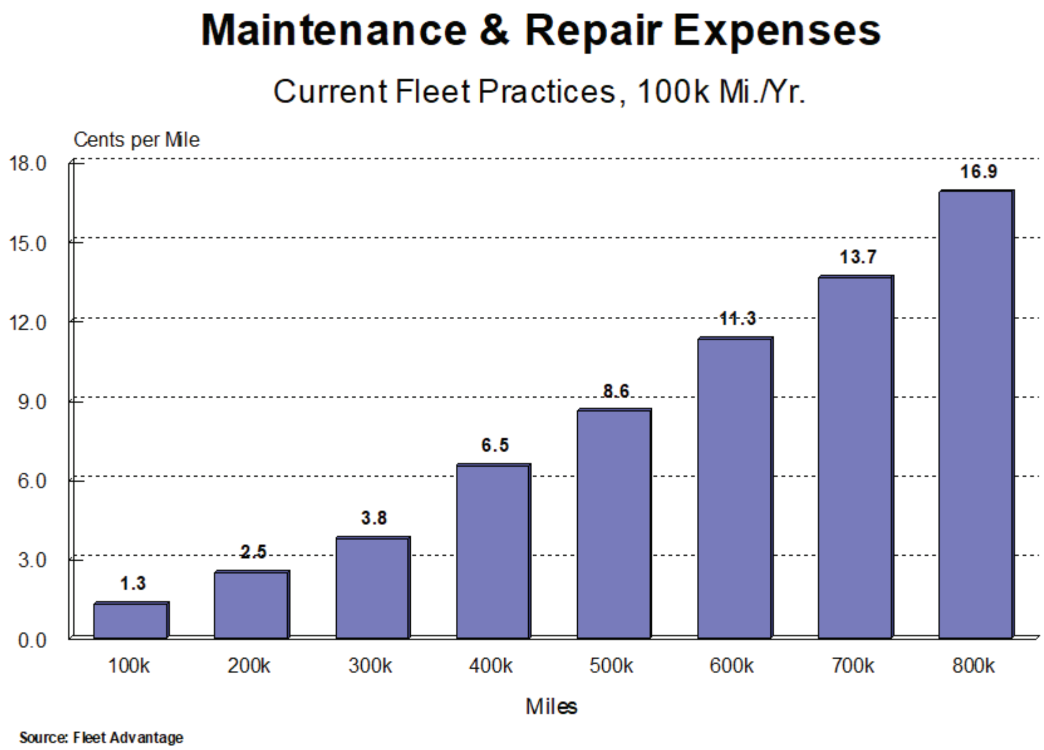
- The OEM survey conducted by ACT Research, which accounted for all major manufacturers, yielded an estimate of $176 million of indirect costs to meet the MY2027 UL provisions in the CARB regulatory proposal for Heavy Heavy-Duty (HHD) vehicles, which added $11,178 of cost per vehicle under our market sizing parameters. It also yielded a similar result for MY2031, with smaller cost figures for medium-duty vehicles. Those costs are missing from the CARB SRIA.

<u>Warranty.</u> In assigning $930 of incremental repair costs for HHD vehicles in order to extend warranties from 350,000 miles to 600,000 miles in MY2031, where no warranty data exists, CARB's warranty analysis (SRIA, page IX-19 to IX-25) materially contradicts the results of both the ACT Research and the NREL cost analyses that was added to the SRIA on July 10, 2020. The $159 estimate for incremental repair costs beginning MY2027 for HHD vehicles also is deeply flawed, again considering the unproven nature of the new technologies expected to be employed, particularly cylinder deactivation.

- The feedback from manufacturers used as input for both the ACT Research and NREL studies is that the extended warranty provisions would effectively require the manufacturers to account for almost a full aftertreatment system replacement for every vehicle, or about $8,000 per HHD unit. NREL's average cost scenario for 12-13L engines included a $23,424 per unit incremental warranty cost, but this appears to include the extended useful life provisions as well, which we detailed separately.

- We do not agree with CARB's linear extrapolation of warranty costs into the extended warranty periods based on MY2013 data.
    - Those data represent significantly lower-cost MY2013 emissions systems, not the more costly systems envisioned in the regulation. Thus, we believe that methodology fails to account for the warranty cost on the added components.
    - We also believe CARB's assumption (page IX-22) "that components would continue to fail at the same rate for the duration of the lengthened warranty period" is flawed. Based on feedback from manufacturers during our survey, our experience analyzing the trucking industry, and the *Fleet Advantage* study charted below, it appears to us to be common knowledge that maintenance costs increase significantly over time. In addition, the

Southwest Research Institute (SwRI) Low-NOx Stage 3 testing program only tested the prototype engine system up to 435,000 miles (page III-7). Thus, CARB's SRIA does not include accurate UL or warranty costs.



- CARB's warranty mileage baseline is not realistics, in our view, and ignores the costs incurred by the trucking industry for extended warranties above the regulatory baseline. CARB's methodology understates warranty costs for California, and would understate warranty costs even more on a national basis where the baseline is below CARB's Step 1 baseline.
  - For MY2027, CARB assumed 40% of HHD trucks would be purchased with 500,000-mile warranties, reducing the distance to the extended 600,000-mile warranty proposal. That ignores the considerable costs some fleets pay for extended warranties and overstates current industry practice. Our research suggests that extended warranties are typically for 400,000 miles, and that the take-rate is likely less than 40%.
  - In reality, the industry-standard base warranty is 250,000 miles, and the EPA regulatory baseline is 100,000 miles. Because those are significantly lower than the 350,000-mile CARB Step 1 baseline, which will be in effect as of 2022, that is materia differencel when considering extending those provisions to the national level. Incremental warranty costs per unit on a national basis from the proposed regulations would be significantly higher than the estimates in CARB's SRIA.
  - Based on CARB's assumption (however questionable) that it can calculate warranty costs linearly, and our view that the incremental warranty costs should be based on the 350,000-mile Step 1 baseline, CARB should be accruing for an incremental 250,000 miles of warranty coverage, not 190,000 miles in its analysis (adding the 40% at 500,000 miles raises the baseline to 410,000 miles). Thus, CARB's analysis misses about 24% of the increase in regulatory warranty costs.

Technology path. The direct engine and aftertreatment component cost output of $11,347 from the ACTR Study, which combined MY2024 and MY2027, was well above the comparable figure from CARB's SRIA of $6,429 ($1,611 in MY2024 and $4,818 in MY2027). The main source of difference is that the manufacturers surveyed by ACT Research did not all choose the same technology path, and so did not all choose the path laid out in CARB's proposal, since CARB's proposals are supposed to be technology neutral, with no picking of winners or losers, an estimate that considers more than one technology path is preferable in our view.

Other. We do not purport to be experts in the management of large manufacturing companies, as our expertise is primarily in data analysis and forecasting for the transportation and commercial vehicle industries. However, we question CARB's assumptions throughout the SRIA cost analysis that the important work of compliance with these emissions regulations would be relegated to a single junior engineer earning just $70 per hour. Including internal management oversight, which seems important from our perspective, would add further incremental compliance costs. In addition, we took particular exception to the doubts CARB cast on the NREL study (page IX-73) by questioning its quality because of a small sample size. CARB knows well the number of major truck OEMs, and while the same could be said of our study, it covered every OEM of consequence. Moreover, the results of the ACTR study fell very close to the NREL study, both in stark constrast to the CARB SRIA.

To conclude, ACTR's analysis suggests that, in 2019 dollars, the new purchase price of an HHD vehicle will rise by $69,930 in MY2027 from the current baseline in a California-only scenario, which would fall to $25,825 on a nationwide basis. CARB's SRIA does not add up the estimated costs to present them on a per-unit basis in total, which seems very pertinent in our view. Nonetheless, adding up the costs in CARB's SRIA, we reach roughly $10,000 per unit for MY2027, though this is not clear given the lack of transparency on market sizing (note: we combined the MY2024 proposals into our MY2027, as the MY2024 timeframe was deemed infeasible from a planning and testing perspective). CARB's numbers do not account for the higher total-cost-of-ownership burden that will be borne by the trucking industry (on ACTR CA-only estimates, $8,392 from 12% FET, $5,070 from 7.25% state taxes, etc.), and eventually, consumers.nor does it realistically reflect the likely pre-buy/no-buy, R&D, UL and warranty cost impacts of the proposed regulations. If we are even "ballpark" correct in our cost assessment, the cost increases at issue have the potential to meaningfully move the trucking industry away from vehicles that meet CARB's proposed mandates, thereby reducing the regulations' benefit for several years, especially if the regulations requiring significantly more expensive trucks align with the peak of an economic cycle. If that happens, we can expect an even larger prebuy ahead of the mandate, and an extended post-mandate delay, which would invalidate much of CARB's cost analysis and delay the anticipated benefits.

On-Road Heavy-Duty Low-NOx Technology Cost Study

Lauren A. Lynch, Chad A. Hunter, Bradley T. Zigler, Matthew J. Thornton, and Evan P. Reznicek

National Renewable Energy Laboratory

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List of Acronyms

ASC	ammonia slip catalyst
CARB	California Air Resources Board
DEF	diesel exhaust fluid
DOC	diesel oxidation catalyst
DPF	diesel particulate filter
EGR	exhaust gas recirculation
EMFAC	EMission FACtor model
EPA	U.S. Environmental Protection Agency
FTP	Federal Test Procedure
FUL	full useful life
g/bhp-hr	grams per brake horsepower-hour
GHG	greenhouse gas
GVWR	gross vehicle weight rating
HD	heavy-duty
HDO	heavy-duty Otto-cycle
HHDD	heavy heavy-duty diesel
hp	horsepower
LHDD	light heavy-duty diesel
LLC	low-load certification
LO-SCR	light-off selective catalytic reduction
MECA	Manufacturers of Emission Controls Association
MHDD	medium heavy-duty diesel
MY	model year

NH_3	ammonia
NO_x	oxides of nitrogen
NREL	National Renewable Energy Laboratory
OBD	on-board diagnostics
OEM	original equipment manufacturer
OOS	out of state
PM	particulate matter
PNA	passive NO_x absorber
R&D	research and development
SCAB	South Coast Air Basin
SCR	selective catalytic reduction
SCRF	selective catalytic reduction on filter
SERA	Scenario Evaluation and Regionalization Analysis
SET-RMC	Supplemental Emission Test with Ramped Mode Cycles
SI	spark ignition
SwRI	Southwest Research Institute
TWC	three-way catalyst

Executive Summary

The National Renewable Energy Laboratory (NREL) conducted a cost analysis for emission control technologies under contract to the California Air Resources Board (CARB). CARB sought incremental cost analysis for emission control technologies for on-road heavy-duty (HD) engines used in vehicles greater than 14,000 pounds (lb) gross vehicle weight rating (GVWR) to achieve oxides of nitrogen (NO_x) emissions rates significantly lower than those required by current emissions standards (CARB 2017). This low-NO_x emission technology cost analysis comprised two main tasks:

- Task 1: An incremental cost analysis for engine and exhaust aftertreatment systems
- Task 2: An engine and exhaust aftertreatment life-cycle cost analysis incorporating incremental upfront costs and operating costs.

The incremental cost analysis included a review of current and under-development engine and exhaust aftertreatment technologies that could achieve 0.02 grams per brake horsepower-hour (g/bhp-hr) NO_x on certification test cycles, including a proposed updated certification test cycle that includes additional low-load operating conditions. Diesel, natural gas, and gasoline HD engine applications were studied. Three diesel technology package combinations of engine and exhaust aftertreatment options were selected based on research in progress at Southwest Research Institute (SwRI), also funded by CARB. The three diesel technology packages were intended to bracket potential cost ranges across two engine displacement levels: ~6–7 liters (L) and ~12–13 L. Representative technology packages for HD natural gas (12 L) and gasoline (6 L) engines were also defined, each with a single displacement level providing a tie point to similar diesel options.

Diesel engines were the primary consideration, as they comprise the majority of HD engines. In addition to studying three diesel technology packages across two engine displacement levels, incremental cost bracketing also included model year (MY) 2023 versus 2027 introduction, U.S. versus California-only implementation, and current full useful life (FUL) versus extended FUL and warranty. Direct and indirect incremental costs were broken down to as discrete a level as possible while maintaining data confidentiality. The calculation of incremental costs was limited by a small number of respondents.

The surveyed original equipment manufacturers (OEMs), Tier 1 suppliers, and trade organizations such as the Manufacturers of Emission Controls Association (MECA) responded with incremental cost, not validation that 0.02 g/bhp-hr emissions levels or specific technology packages are feasible. Engine OEM participation was crucial, as only they could provide estimates for indirect costs that represented a significant portion of the total cost. Incremental costs are largely driven by indirect costs associated with engineering research and development costs and warranty costs. The indirect costs are highly dependent on production volumes over which to amortize research and development costs. Indirect costs due to warranty are high, reflecting high uncertainty with new technology and the introduction timeframes. The incremental costs were not adjusted to reflect a retail markup due to the complexity with which pricing decisions are made.

The average incremental cost for the 6–7-L diesel engines for MY 2023 with current FUL ranged from $3,685 to $5,344, but the absolute low and high bounds were between ~$2,000 and over

$9,000. Extending FUL and warranty moved the average incremental costs to a range of $15,370 to $16,245, with tighter low and high bounds (constrained in part by the limited number of responses). The average incremental cost for the 12–13-L diesel engines for MY 2023 with current FUL ranged from $5,340 to $6,063, but the absolute low and high bounds were between ~$3,000 and over $10,000. Extending FUL and warranty moved the average incremental costs to a range of $28,868 to $47,042, with much wider low and high bounds (driven in part by the limited number of responses). The natural gas 12-L engine application was unable to be studied in detail, but OEM feedback indicated the anticipated incremental cost for natural gas engines and aftertreatment technology is within 10% of the low-cost diesel technology package incremental cost for equivalent displacement, possibly due to requiring a moving average window method to assess emission compliance. The gasoline engine 6-L application was also unable to be studied in detail due to lack of OEM feedback, but comparatively low incremental costs were estimated.

A life-cycle cost analysis was completed to understand the full costs to the owner of the vehicles with a 0.02 g/bhp-hr NO_x technology package outside of the direct upfront vehicle cost increase. The life-cycle cost analysis sought to incorporate costs associated with the following elements: initial incremental purchase cost, fuel consumption changes (changes in fuel economy), diesel exhaust fluid (DEF) consumption changes, and the maximum FUL of the aftertreatment package (major overhaul intervals). Thus, the life-cycle costs depend on the vehicle type (mileage), region, fuel, engine displacement, maximum useful life, fuel economy change, DEF consumption change, and discount rate.

Three scenarios were defined to evaluate the bounds of the life-cycle costs across all parameters evaluated. For the three scenarios evaluated (Low-Cost, Mid-Cost, High-Cost), the life-cycle costs were evaluated for each EMission FACtor (EMFAC) model vehicle type (CARB 2018b), aggregated to a representative average and calculated across the vehicle fleet for the MY 2027 vehicles. The analysis showed that EMFAC vehicles can have significantly different life-cycle costs and that the spread depends on the scenario evaluated: approximately a $4,000 spread across vehicle types in the Low-Cost scenario, while the High-Cost scenario had nearly a $40,000 difference. This large spread was found to be due to the number of aftertreatment package replacements needed throughout the vehicle lifetime. The aggregated, representative average life-cycle costs for the Mid-Cost scenario were estimated to be $12,700 for the 6-L diesel engine, $13,200 for the 12-L diesel engine, $4,800 for the 12-L natural gas engine, and $800 for the 6-L gasoline engine. The total life-cycle costs to California vehicle owners for the MY 2027 vehicles were estimated to range between $92 million and $1.2 billion, depending on the scenario (Low-Cost or High-Cost) realized.

The sensitivity analysis indicated that the manufacturing volume may be the most important parameter impacting the life-cycle cost; however, limited data were received from the external stakeholders surveyed. The next most important parameter was the assumption of extended FUL and extended warranty, as the increase in aftertreatment lifetime may not exceed the vehicle's travel requirement, which results in larger replacement costs over the vehicle's life. However, one may expect that the higher upfront purchase incurred by the vehicle owner should effectively be offset by the repair savings over the lifetime of the vehicle. Next, the aftertreatment cost bound (low/high error bars on the incremental cost data), fuel economy improvement, and discount rate were found to have a moderate impact on the life-cycle cost. Lastly, the region and DEF consumption change were found to have minimal influence on the life-cycle cost.

The results of this cost analysis reflect the specific technology and aftertreatment FUL assumptions on which the study was based. In particular, the incremental cost of moving from a 0.2g/bhp-hr to 0.02 g/bhp-hr standard is expected to be non-linear due to diminishing returns on technology performance. Extrapolating the results beyond this specific study and outside of these specific assumptions is not recommended and should only be done with careful attention to the scope and limits of this study.

Table of Contents

List of Figures

List of Tables

Abstract

The National Renewable Energy Laboratory (NREL) conducted a cost analysis for emission control technologies under contract to the California Air Resources Board (CARB). CARB sought incremental cost analysis for emission control technologies for on-road heavy-duty (HD) engines used in vehicles greater than 14,000 pounds (lb) gross vehicle weight rating (GVWR) to achieve oxides of nitrogen (NO_x) emissions rates significantly lower than those required by current emissions standards. Specifically, incremental costs (without any retail price markup) were estimated for representative diesel, natural gas, and gasoline engine and emission aftertreatment systems that were selected to represent potential technology packages that could achieve 0.02 grams per brake horsepower-hour (g/bhp-hr) NO_x on certification test cycles, including a proposed updated certification test cycle that includes additional low-load operating conditions. NREL surveyed stakeholders including industry association groups, Tier 1 suppliers, and engine original equipment manufacturers (OEMs) to estimate incremental direct and indirect costs. Incremental costs were considered for current engine full useful life (FUL) definitions, as well as with proposed increased FUL and warranty periods. The incremental costs were subsequently incorporated in life-cycle cost analyses examining the incremental engine and aftertreatment costs along with life-cycle costs over the various engine FUL scenarios. Life-cycle costs analysis included the incremental upfront cost, fuel consumption changes (changes in fuel economy), diesel exhaust fluid (DEF) consumption changes, and the maximum FUL of the aftertreatment package (major overhaul intervals).

Project Background and Objective

Current emission standards for heavy-duty diesel engines, established by the United States Environmental Protection Agency (EPA) for 2010, specify a limit of 0.20 grams per brake horsepower-hour (g/bhp-hr) NO_x. This standard represents a 90% reduction from the previous benchmark of 2.0 g/bhp-hr and applies to both heavy-duty diesel engines and heavy-duty Otto-cycle engines used in vehicles greater than 14,000-lb GVWR.

Diesel-engine manufacturers utilize a variety of technologies in order to meet these standards, primarily among them being selective catalytic reduction (SCR). Natural-gas engine manufacturers use SCR for lean-burn engines and three-way catalysts (TWCs) for stoichiometric engines. Both of these methods reduce NO_x emissions by removing them from the engine-out exhaust prior to exiting the tailpipe. These manufacturers have used lessons learned from other applications such as stationary-source and light-duty vehicles to meet current NO_x emission requirements, and as these technologies mature there are opportunities to reduce emissions even further.

The California Air Resources Board (CARB), together with the Southwest Research Institute (SwRI), is currently funding several research programs to investigate the feasibility of achieving NO_x emissions less than the 2010 limit of 0.20 g/bhp-hr. The first ("Stage 1") project is a $1.6 million research contract between CARB and SwRI to evaluate improved engine emission control calibration, enhanced aftertreatment technologies and configurations, improved aftertreatment thermal management, urea dosing strategies, and engine management practices for two heavy-duty engines: one natural-gas engine with a TWC and one diesel engine with a diesel particulate filter (DPF) and SCR. The target emission rate for this project, which was finalized in December 2016, is 0.02 g/bhp-hr NO_x.

CARB is also contracting a $1.05 million "Stage 2" project with SwRI to further optimize the diesel engine aftertreatment system for low engine-load duty cycles typical of city driving. Stage 2 objectives are to develop a supplemental low-load certification test cycle that will, along with the Federal Test Procedure (FTP), ensure NO_x control under nearly all driving conditions and evaluate metrics for in-use testing under low-load operations. The "Stage 3" project, currently in the planning stage, will complement the Stage 1 and Stage 2 efforts with testing on an additional engine that is representative of likely future engine configurations.

Alongside current emission standards, CARB and EPA both require that heavy-duty engines meet these standards throughout their entire useful life. The useful life period is defined according to a vehicle's GVWR, and for heavy-duty engines ranges from 110,000–435,000 miles. The useful life period for Otto-cycle and light heavy-duty diesel engines (14,001–19,500-lb GVWR) is 110,000 miles/10 years; for medium heavy-duty diesel engines (19,501–33,000-lb GVWR) 185,000 miles/10 years; and for heavy heavy-duty diesel engines (greater than 33,000-lb GVWR) 435,000 miles/10 years, or 22,000 hours.

Well-maintained on-road diesel engines can operate significantly beyond their currently defined useful life periods (e.g., many heavy-duty diesel engines currently operate upwards of 800,000 miles to over a million miles), and CARB is taking this reality into consideration as it evaluates the consequences of lowering its NO_x emission targets. Engine durability becomes a critical factor with longer useful life definitions, particularly in preventing “upstream” engine component failures that can damage “downstream” emission control system components and cause excess emissions of criteria pollutants such as particulate matter (PM) and NO_x. Therefore, manufacturers will need to improve the durability of their engines and emission control systems by developing higher-quality parts and assembly methods and replacement of components and/or subsystems.

CARB is expected to propose new standards to be implemented by 2024, which will set even lower NO_x emission standards and add new certification test cycles to ensure emission control at low-load operations. Adding this new test cycle to the certification requirement is expected to drive further improvements to aftertreatment hardware and engine control and calibration.

With these new emission standards of approximately 0.02 g/bhp-hr NO_x in mind, it is important to examine the direct and indirect costs of implementing new technologies, both the incremental costs to original equipment manufacturers and the costs of using the technology packages throughout the engines’ useful life. These costs can be divided by category, including the specific technologies for achieving the NO_x standard, the costs to increase durability (extended useful life), and the costs of the on-board diagnostics (OBD) hardware and calibration works impacted by the changes. This cost analysis will use specific emission control and engine technologies identified by SwRI in Stages 1 and 2, along with testing that is representative of likely future engine configurations.

Project Summary

This project was defined by two tasks—Task 1: Engine Incremental Cost Analysis and Task 2: Engine Life-Cycle Costs. For Task 1, NREL reviewed current technologies and technology packages that are being examined as part of the SwRI projects, Stages 2 and 3, as provided by CARB. NREL identified and reviewed likely emission control and engine technologies to meet 0.02 g/bhp-hr NO_x requirements with CARB staff based on Stage 2 and 3 efforts from SwRI testing of potential future engine configurations. These technologies were then defined as the potential technologies and the starting point of developing a low-NO_x technology incremental cost analysis from 2018 baseline costs.

NREL then evaluated these potential technologies and technology packages for engine plus aftertreatment incremental cost analysis via a series of surveys sent to Tier 1 suppliers, trade organizations, and engine OEMs. The surveys defined the potential technologies broken into engine components, emission control components, subsystems, and indirect costs. The combination of incremental costs (over the 2018 baseline) associated with developing and integrating the specified lower NO_x emission control technologies into the engines, the costs of increasing the durability of these engines and their emission control systems, and the costs of directly impacted OBD hardware and calibration works of these specified technology packages were then examined to understand the total incremental cost implications to Tier 1 suppliers and engine OEMs of the potential technologies.

The evaluation of costs was dependent on cooperation from Tier 1 suppliers, trade organizations and engine OEMs, as well as the availability of direct and indirect cost information for engine and emission control technologies. NREL utilized existing relationships with industry partners in order to perform a thorough cost assessment but could not guarantee full cooperation or sharing of confidential cost information from Tier 1 suppliers, trade organizations, and engine OEMs.

After accounting for the initial incremental cost implications to Tier 1 suppliers (both collectively through the Manufacturers of Emission Controls Association [MECA] and individually) and engine OEMs, NREL conducted a life-cycle cost analysis as Task 2 to examine the costs of using the specified technology packages during the engines' certification full useful life (FUL). NREL utilized a range of FUL values for each heavy-duty vehicle category, Classes 4 through 8. The current FUL mileage—for heavy-duty engines of 110,000 miles up to 435,000 miles, depending on a vehicle's GVWR; 110,000 miles/10 years for heavy-duty Otto-cycle (HDO) and light heavy-duty diesel (LHDD) engines (14,001–19,500-lb GVWR); 185,000 miles/10 years for medium heavy-duty diesel (MHDD) engines (19,501–33,000-lb GVWR); and 435,000 miles/10 years or 22,000 hours for heavy heavy-duty diesel (HHDD) engines (greater than 33,000-lb GVWR)—was defined as the low-end value of the range for each specific vehicle class. For the high-end value of the range, NREL utilized input from CARB for proposed extended FUL targets as the upper-bound levels for each specific vehicle class: 250,000 miles/15 years for HDO engines (14,001–19,500-lb GVWR), 550,000 miles/15 years for LHDD engines (14,001–19,500-lb GVWR) and MHDD engines (14,001–19,500-lb GVWR), and 1,000,000 miles/15 years for HHDD engines (greater than 33,000-lb GVWR). Additionally, per CARB's guidance, the high-end value with extended FUL also includes the provision that warranty periods will increase to 80% of the extended FUL, both in mileage and time, except for heavy-duty Otto-cycle, which was specified as 220,000 miles/12 years. The current FUL defining the lower bound and the extended FUL defining the upper bound are summarized in Table 1.

Table 1. Current and Proposed Extended Full Useful Life and Warranty for Engine Life-Cycle Cost Analysis

	LHDD	MHDD	HHDD	Natural Gas – Otto	Heavy-Duty – Otto
GVWR (lb)	14,001–19,500	19,501–33,000	>33,000	>33,000	14,000
Current full useful life	110,000 miles/10 years	185,000 miles/10 years	435,000 miles/10 years, 22,000 hours	435,000 miles/10 years, 22,000 hours	110,000 miles/15 years
Proposed extended full useful life	550,000 miles/15 years	550,000 miles/15 years	1,000,000 miles/15 years	1,000,000 miles/15 years	250,000 miles/15 years
Proposed warranty period with extended full useful life	440,000 miles/12 years	440,000 miles/12 years	800,000 miles/12 years	800,000 miles/12 years	220,000 miles/12 years

After accounting for the initial incremental costs of the technologies, as determined in Task 1, the life-cycle cost assessment of Task 2 then took into account the aftertreatment technologies' effects on fuel consumption, DEF consumption, major overhaul intervals (full useful life estimates), manufacturing volume, and financial discount rates. The life-cycle cost modeled for each vehicle is specific to the EMission FACtor (EMFAC) model's vehicle definition of vehicle miles traveled, which depends on the specific region, vocation, model year, fuel type, and age.

For the life-cycle cost analysis in Task 2, the aftertreatment full useful life mileage was used to set the equipment overhaul schedule. For all scenarios in the life-cycle cost analysis, the incremental cost associated with the aftertreatment package was assumed to be incurred after the truck mileage exceeded the stated maximum FUL. This assumption is expected to be conservative, as not all aftertreatment packages will fail immediately after they exceed their stated maximum FUL and statistical analysis of failure rates combined with data on aftertreatment technology operating and maintenance costs were not available. To understand the impact of this assumption on the life-cycle cost, a sensitivity analysis was completed assuming the aftertreatment package would not need to be replaced over the vehicle's lifetime, as that provides the lower bound on the life-cycle cost.

1. Task 1: Engine Incremental Cost Analysis

1.1 Representative Engine Platform Approach

The engine and aftertreatment incremental cost analysis began with a review of 54 model year (MY) 2018 medium- and heavy-duty engine family CARB certification summaries, covering Class 4–8 vehicle applications. The review provided background on the fuels used, range of engine displacements for each service class (i.e., LHDD, MHDD, HHDD, HDO), current technologies utilized, and certification levels versus Federal Test Procedure (FTP) and heavy-duty Supplemental Emissions Test with Ramped Mode Cycles (SET-RMC) standards for NO_x. Because the majority of Class 4–8 engines are diesel fueled, incremental costs for diesel engines was the primary focus of the study. Natural gas and gasoline were also studied, but liquified petroleum gas/propane was not. A limited number of engine platforms were initially selected to represent the Class 4–8 vehicle population, based on engine displacement. This down-selection was necessary to come up with a reasonable number of representative engine platforms to use for the incremental cost analysis that could subsequently be used in the Task 2 life-cycle cost analysis over large vehicle populations, while keeping manageable the burden of calculating incremental cost for surveys conducted with Tier 1 suppliers, trade organizations, and engine OEMs. The initial engine platforms included: 6-L LHDD, 9-L MHDD, 12-L HHDD, 15-L HHDD, 12-L natural gas, and 6-L HDO (gasoline). Initial reviews with industry provided feedback that this number of engine platforms was still too large, and the diesel engine platforms could be consolidated and referenced to approximate horsepower levels. As a result, the diesel engine platforms were reduced to ~6–7 L with ~300 horsepower (hp) and ~12–13 L with ~475 hp. This reduction would still provide incremental costs with appropriate discrete levels. The in-between calculation for a 9-L engine was agreed to not be worth the additional burden for industry survey responses. The elimination of the 15-L engine was agreed to be covered by increased power density from ~12–13-L engines with future trends.

Current technologies were reviewed to benchmark the baseline for the 0.02 g/bhp-hr NO_x incremental cost. The industry surveys were designed to collect direct and indirect cost information for engine and aftertreatment subsystems from a 2018 baseline, with a 0.20 g/bhp-hr standard, as well as multiple technology packages assumed to meet a potential future 0.02 g/bhp-hr NO_x standard under a proposed new low-load certification (LLC), in addition to FTP and SET-RMC. The incremental costs would form the basis of Task 1. While the surveys were designed to allow industry respondents to start with their own 2018 baseline and did not explicitly define a common set of identical technologies, the CARB certification review showed most diesel engines in the 6–7-L and 12–13-L ranges were common in having direct diesel injection, cooled exhaust gas recirculation (EGR), turbocharging, a diesel oxidation catalyst (DOC), a diesel particulate filter (DPF), and selective catalytic reduction (SCR) using DEF. The technology packages supporting 0.02 g/bhp-hr NO_x selected for incremental cost study are described in more detail below.

A single natural-gas engine platform was selected at 12 L to align with the ~12–13-L diesel platform. The CARB certification review showed a number of natural-gas engines (in various displacements, meeting MHDD and HHDD requirements) sharing the same technologies: stoichiometric Otto-cycle operation, spark ignition (SI), throttle body fuel injection, turbocharging, cooled EGR, and a three-way catalyst (TWC).

A single gasoline-fueled HDO platform was selected at 6 L to align with the ~6–7-L diesel platform. The CARB certification review showed HDO gasoline is approaching 0.02 g/bhp-hr NO_x on the current certification cycles using stoichiometric, SI, naturally aspirated, EGR technologies with a TWC technology package.

Utilizing the results and recommendations from Stage 2 and 3 efforts from SwRI testing of potential future diesel-engine configurations, NREL identified three diesel technology packages to evaluate the total incremental cost implications for an MY 2023 release nationwide. These identified diesel technology packages were intended to represent potential low-, average-, and high-cost options to meet a 0.02 g/bhp-hr NO_x standard and were meant to provide a broader assessment of potential incremental costs than a single option. As previously referenced, no natural-gas technology package was surveyed for incremental costs related to 0.02 g/bhp-hr NO_x, and the HDO gasoline technology package only included TWC and calibration upgrades. The resulting engine platforms defined for the incremental cost study are summarized in Table 2.

Table 2. Engine Platform Analysis for Incremental Cost Analysis

	LHDD	HHDD	Natural Gas – HHDD standard	Gasoline – HDO
Engines	~6–7 L ~300 hp	~12–13 L ~475 hp	12 L	6 L
Current full useful life	110,000 miles/10 years	435,000 miles/10 years, 22,000 hours	435,000 miles/10 years, 22,000 hours	110,000 miles/10 years
Low-Cost Tech.	$$$	$$$	Not applicable	Not applicable
Avg.-Cost Tech.	$$$	$$$	Not applicable	$$$
High-Cost Tech.	$$$	$$$	Not applicable	Not applicable

NREL then directly surveyed heavy-duty engine OEMs, Tier 1 suppliers, emission control technology manufacturers, and industry trade organizations to obtain the most accurate and current cost information for the identified likely technology packages to meet 0.02 g/bhp-hr NO_x requirements and the cost implications for using these specific technologies. The cost survey included a definition of the potential technologies as engine components, emission control components, subsystems and strategies, and indirect costs broken into categories of research and development (R&D) costs, certification costs, and warranty costs. The combination of costs associated with developing and integrating the specified lower NO_x emission control technologies into the engines, the costs of increasing the durability of these engines and their emission control systems, and the costs of impacted OBD hardware and calibration of these specified technology package were then examined to understand the total incremental cost implications to Tier 1 suppliers and engine OEMs of the potential technologies in two different surveys. Any incremental costs associated with future OBD requirements unrelated to meeting 0.02 g/bhp-hr NO_x were excluded from this study. Similarly, incremental costs related to future greenhouse gas (GHG) or fuel efficiency requirements and not specifically to meeting 0.02 g/bhp-hr NO_x were also excluded.

The first survey assumed that the 0.02 g/bhp-hr NO_x regulation beginning MY 2023 included current FTP and SET-RMC steady-state test cycles, as well as a proposed new LLC for medium- and heavy-duty engine system certification. While not finalized and currently the topic of ongoing research, the new LLC engine cycle was assumed to last approximately 90 minutes, including a combination of motoring, sustained low load, and high-power transients. This first survey considered FUL hours/miles to remain the same as the current regulation. The survey was designed to allow industry respondents to start with their own 2018 baseline and did not explicitly define a common set of identical technologies. As a reference point, NREL provided internally generated estimates (from research, literature review, and engineering judgement) for the 2018 current technology costs (Posada, Chambliss, and Blumberg 2016; Posada Sanchez, Bandivadekar, and German 2012; Ou et al. 2019). Direct costs for both a 2018 baseline and 0.02 g/bhp-hr technology packages were surveyed on discrete engine and aftertreatment subsystem levels, along with indirect costs. The level of discrete subsystems was kept as small as possible to provide insight for where the costs accumulate while also being kept large enough to prevent identification of proprietary or confidential cost information from an individual respondent. Furthermore, only incremental costs are reported in this report and preliminary reviews with CARB to prevent identifying proprietary or confidential 2018 baseline costs. The survey requested future costs be calculated in 2018 dollars. The first survey asked for production volumes to be identified and to provide guidance on cost impacts for 0.02 g/bhp-hr incremental costs if regulation were to include all of the United States or California only.

The second survey was a follow-up survey sent to those Tier 1 suppliers, trade organization, and engine OEMs that responded to the first survey. The technology packages remained the same as the first survey, but instead assumed 0.02 g/bhp-hr NO_x regulation beginning MY 2027 and again included current FTP and SET-RMC steady-state test cycles, as well as a new LLC. This second survey also considered extended useful life hours/miles as proposed by CARB in Table 1. The second survey asked for costing information to consider 0.02 g/bhp-hr regulation if only California were included, representing lower production volumes than a scenario where all of the U.S. were included.

NREL then aggregated all of the data from the cost survey responses and the initial estimates derived by NREL from research, literature review, and engineering judgement. The incremental costs were not adjusted to reflect a retail markup due to the complexity with which pricing decisions are made. In responding to NREL's surveys, trade organizations, Tier 1 suppliers, and OEMs did provide feedback that they did not agree or conclude that these technologies would be feasible for meeting the 0.02 g/bhp-hr NO_x requirements by MY 2023. Their valuable input was strictly a costing exercise and not a technology feasibility assessment. The diesel incremental cost information resulted in a range of costs due to the format of the provided data from the responses received. This range consisted of a low, average, and high estimate for engine technology costs, aftertreatment technology costs, OBD-related direct costs, and indirect costs. The survey results for the diesel engine and aftertreatment technology packages were then defined as three total incremental costs of low, average, and high estimates based on the identified potential technology packages to achieve 0.02 g/bhp-hr NO_x requirements.

Fewer responses were received for the natural gas (HHDD standard) engine platform, preventing NREL from sufficiently aggregating incremental cost information to protect proprietary information. Therefore, NREL reported the total integrated incremental cost as an order of magnitude in comparison to the diesel engine with similar displacement results; the subsystem-level engine, aftertreatment, and OBD system direct costs as well as the indirect costs were not broken out or reported.

Similarly, few responses were received for the gasoline HDO engine platform. Some aggregation was possible for direct costs, but only NREL estimates were available for indirect costs. As a result, only total integrated incremental costs are reported.

1.2 Identifying Potential Diesel Technologies to Achieve 0.02 g/bhp-hr NO_x

CARB is currently funding several research programs with SwRI to investigate the feasibility of achieving 0.02 g/bhp-hr NO_x emissions with a diesel engine and is in the Stage 3 process of testing specific emission control and diesel engine technologies. Based on SwRI's research and results from Stages 1 and 2 (Sharp et al., "Thermal Management," 2017; Sharp et al., "Comparison of Advanced," 2017; Sharp et al., "NO_x Management," 2017), NREL identified different engine and emission control technologies that showed potential capabilities of achieving 0.02 g/bhp-hr NO_x emissions during current FTP and SET-RMC steady-state test cycles, as well as a proposed new LLC cycle by MY 2023. These diesel engine and emission control technologies were grouped into three different diesel technology packages to represent a range of potential low-, average-, and high-costing diesel technology package solutions.

The potential low-cost diesel technology package consisted of an EPA 2017 certification-compliant engine with a variable-geometry turbo charger, no turbo compounding, and a combined engine thermal management strategy of EGR cooler bypass, charge air cooler bypass, and a turbine bypass. In addition to the engine system, the emission control technologies included two points of DEF dosing and DEF mixers, one light-off SCR (LO-SCR), one DOC, one DPF, two SCRs, and one ammonia slip catalyst (ASC). The aftertreatment system also contained a NO_x sensor upstream of the first DEF dosing system and mixer, a temperature sensor upstream of the LO-SCR, a second temperature sensor downstream of the LO-SCR, a second NO_x sensor downstream LO-SCR and upstream of the DOC, a third temperature sensor downstream of the LO-SCR and upstream of the DOC, a fourth temperature sensor downstream of the DOC and upstream of the DPF, a fifth temperature sensor downstream of the DPF and upstream of the first second DEF dosing system and mixer, an ammonia (NH_3) sensor downstream the first SCR and upstream the second SCR, a sixth temperature sensor downstream of the ASC, and a third NO_x sensor downstream of the ASC. An example of the aftertreatment technology system with sensors is illustrated in Figure 1.

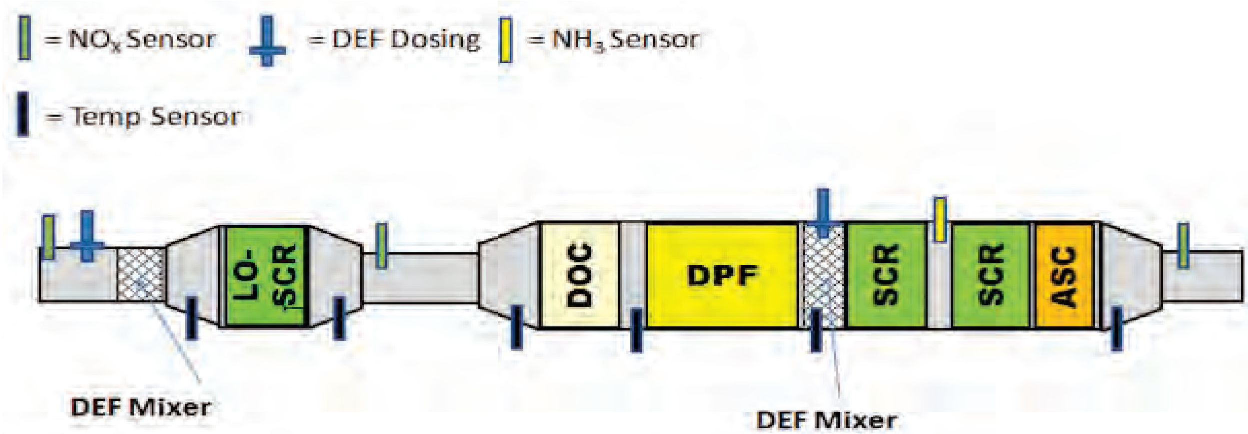

Figure 1. Schematic of proposed low- and average-cost diesel aftertreatment technology
Figure from SwRI

The potential average-cost diesel technology package consisted of an EPA 2017 certification-compliant engine with a variable-geometry turbo charger, no turbo compounding, and an engine thermal management strategy and technology for cylinder deactivation. In addition to the engine system, the emission control technologies again included the same aftertreatment system as the low-cost diesel technology package with two points of DEF dosing and DEF mixers, one LO-SCR, one DOC, one DPF, two SCRs, and one ASC, as shown in Figure 1. The aftertreatment system also contained a NO_x sensor upstream of the first DEF dosing system and mixer, a temperature sensor upstream of the LO-SCR, a second temperature sensor downstream of the LO-SCR, a second NO_x sensor downstream LO-SCR and upstream of the DOC, a third temperature sensor downstream of the LO-SCR and upstream of the DOC, a fourth temperature sensor downstream of the DOC and upstream of the DPF, a fifth temperature sensor downstream of the DPF and upstream of the first second DEF dosing system and mixer, an NH_3 sensor downstream of the first SCR and upstream of the second SCR, a sixth temperature sensor downstream of the ASC, and a third NO_x sensor downstream of the ASC.

The proposed high-cost diesel technology package consisted of an EPA 2017 certification-compliant engine with a variable-geometry turbo charger, no turbo compounding, and a combined engine thermal management strategy of EGR cooler bypass, charge air cooler bypass, and a turbine bypass. In addition to the engine system, the emission control technologies included a passive NO_x absorber (PNA), one DOC, one DEF doser and DEF mixer, one selective catalytic reduction on filter (SCRF), one SCR, and one ASC. The aftertreatment system also contained a NO_x sensor upstream of the PNA, a second NO_x sensor downstream of the PNA, an NH_3 sensor downstream of the SCRF and upstream of the SCR, and a third NO_x sensor downstream of the ASC. An example of the aftertreatment technology is illustrated in Figure 2.

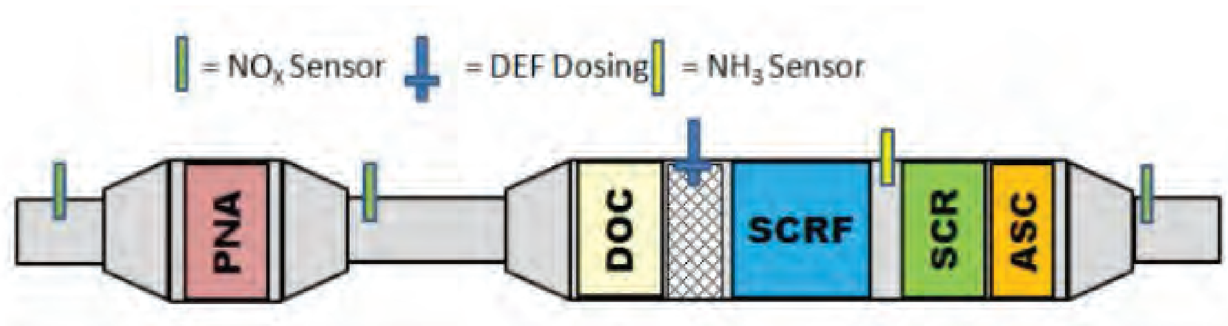

Figure 2. Schematic of proposed high-cost diesel aftertreatment technology

Figure from SwRI

Note that the proposed technology packages that were initially designed to represent low-, average-, and high-cost combinations. It was assumed that the PNA, as a very new technology, would drive incremental costs to be higher than other packages. Likewise, cylinder deactivation was assumed to have a higher incremental cost than cooler bypasses for charge air, EGR, and turbine given the same aftertreatment package. However, once incremental cost information became available, the relative incremental costs did not necessarily turn out in that order. Nevertheless, to maintain consistency in the study, the proposed technology packages continued to be referred by their initial naming convention.

1.3 Identifying Potential Gasoline and Natural Gas Technologies to Achieve 0.02 g/bhp-hr NO_x

The single natural-gas 12-L engine platform was selected to align with the ~12–13-L diesel platform. The CARB certification review showed a number of natural-gas engines (in various displacements, meeting MHDD and HHDD requirements) sharing the same technologies: stoichiometric Otto-cycle operation, SI, throttle body fuel injection, turbocharging, cooled EGR, and a TWC. Notably, most of the natural-gas engines already meet CARB's optional low-NO_x standard at 0.02 g/bhp-hr under the current certification cycles. Because the proposed LLC certification was assessed to be less challenging for a stoichiometric SI engine than a diesel engine, it was assumed that the current 2018 "baseline" technology package would already meet the new 0.02 g/bhp-hr NO_x requirement. Incremental cost for 0.02 g/bhp-hr NO_x was therefore not calculated, but cost increases related to extending FUL were considered. As noted later in this report, industry feedback identified this assumption as incorrect.

The single gasoline-fueled HDO platform was selected at 6 L to align with the ~6–7-L diesel platform. The CARB certification review showed HDO gasoline is approaching 0.02 g/bhp-hr NO_x on the current certification cycles, and similar technology (stoichiometric, SI, naturally aspirated, EGR technologies with a TWC) with liquified petroleum gas fuel has recently been certified at 0.05 g/bhp-hr and 0.02 g/bhp-hr under CARB's optional low-NO_x standards. The base engine was assumed to need no significant upgrades for the 0.02 g/bhp-hr standard with proposed LLC certification cost study, but TWC direct cost upgrades and indirect costs for engineering, certification, and warranty were surveyed, as well as extended FUL impacts. Vehicle packaging impacts were noted to also potentially be required to enable close coupling of the TWCs.

1.4 NREL Survey of Potential Technologies to Achieve 0.02 g/bhp-hr NO_x

NREL created a cost survey with a baseline price of an MY 2018 system representing an EPA 2018 certification-compliant engine and aftertreatment system in 2018 dollars and asked trade organizations, Tier 1 suppliers, and engine OEMs to provide incremental cost estimates in comparison to the above-defined technologies with the potential to achieve 0.02 g/bhp-hr NO_x requirements. The cost survey was reviewed with CARB and EPA staff and approved by CARB before submitting for requested responses. The survey consisted of two technology packages for diesel engine and aftertreatment systems, one technology package for natural-gas engines and aftertreatment, and one technology package for gasoline engines and aftertreatment systems. To simplify the survey for stakeholder input and avoid asking for input on three separate combinations of engine and aftertreatment technology packages, the two unique diesel engine technology packages (charge air, EGR, and turbine cooler bypass vs. cylinder deactivation) were surveyed with the two unique aftertreatment technology packages (Figure 1 and Figure 2). From these incremental cost inputs, NREL could construct the proposed low-, average-, and high-cost combined engine and aftertreatment technology packages.

The first survey assumed that the 0.02 g/bhp-hr NO_x regulation beginning MY 2023 included current FTP and SET-RMC steady-state test cycles, as well as a new LLC cycle. While not finalized and currently the topic of ongoing research, the LLC was assumed as a new engine certification cycle lasting approximately 90 minutes and included a combination of motoring, sustained low load, and high-power transients. This first survey also considered FUL hours/miles to remain the same as the current regulation. NREL also prefaced the likely follow-up survey seeking additional guidance on how increasing FUL hour/mile requirements may further affect the provided costs.

The second survey was a follow-up survey sent to the same Tier 1 suppliers, trade organizations, and engine OEMs that responded to the first survey. The technology packages remained the same and instead assumed 0.02 g/bhp-hr NO_x regulation beginning MY 2027 and again included current FTP and SET-RMC steady-state test cycles, as well as a proposed new LLC cycle. Again, while not finalized and currently the topic of ongoing research, the LLC was assumed as a new engine certification cycle lasting approximately 90 minutes and included a combination of motoring, sustained low load, and high-power transients. This second survey considered extended FUL hours/miles as proposed by CARB's Stage 2 definitions defined in Table 1. Additionally, per CARB's guidance, the extended FUL also included the assumption that warranty periods will increase to 80% of the extended FUL, both in mileage and time, except for heavy-duty Otto cycle, which was specified as 220,000 miles/12 years.

1.4.1 Definition of Baseline Costs of Current Technologies With 2018 EPA Certification

As a starting point for the incremental cost definition of potential technologies to meet 0.02 g/bhp-hr NO_x requirements, NREL estimated the direct manufacturing costs and indirect costs for an EPA 2018-certified engine and aftertreatment system production costs of current technology to meet 0.20 g/bhp-hr NO_x in 2018 dollars for the U.S. market based on literature reviews and engineering judgement (Posada, Chambliss, and Blumberg, 2016; Posada Sanchez, Bandivadekar, and German 2012; Ou 2019). These estimates were defined for two diesel platforms, 6–7 L and 12–13 L, based on the majority of current market offerings. NREL then estimated the incremental cost of MY 2023 technologies to meet a 0.02 g/bhp-hr NO_x requirement based on literature review, engineering judgement, and feedback from SwRI to provide a baseline estimate of the incremental costs for the two potential diesel technology packages for each of the two engine platforms. The NREL estimates for EPA 2018-certified (0.20 g/bhp-hr NO_x) engine and aftertreatment direct and indirect costs, as well as NREL estimates for incremental direct and indirect costs for MY 2023 0.02 g/bhp-hr NO_x were generated as starting points for stakeholders to consider in the survey. NREL requested survey responses to utilize the baseline estimates, if accurate, or to correct NREL's incremental cost estimates as necessary. Only incremental costs are revealed in this report.

The baseline technology packages for the diesel engine and aftertreatment technology consisted of an EPA 2018-certified engine, a DOC, a DPF, a DEF dosing system and mixer (with a single doser), am SCR with ASC, one NO_x sensor, three NH_3 sensors, and four temperature sensors. These components were the same for the two platforms of 6–7 L and 12–13 L. The baseline costs and resulting incremental costs were scaled accordingly. The baseline technology package for the gasoline HDO engine platform consisted of stoichiometric, SI, naturally aspirated, EGR technologies with a TWC. The baseline technology package for the natural-gas system consisted of stoichiometric Otto-cycle operation, SI, throttle body fuel injection, turbocharging, cooled EGR, and a TWC.

1.4.2 NREL Initial Incremental Cost Estimates

NREL’s initial estimated incremental costs of the potential diesel technology package likely to be the lowest incremental cost to meet 0.02 g/bhp-hr NO_x for the 6–7-L platform are depicted in Table 3. This technology package consisted of an EPA 2017 certification-compliant engine with a variable-geometry turbo charger, no turbo compounding, and a combined engine thermal management strategy of EGR cooler bypass, charge air cooler bypass, and a turbine bypass. In addition to the engine system, the emission control technologies included two points of DEF dosing and DEF mixers, one LO-SCR, one DOC, one DPF, two SCRs, and one ASC. In the following tables, note that negative incremental costs mean the cost for that component/subsystem reduce from the 2018 baseline.

Table 3. NREL Estimates of Potential Low-Cost Diesel Technology Package 6–7 L

Cost Component	Incremental Cost Estimate
EGR Cooler Bypass	$330
Charge Air Cooler Bypass	$200
Turbine Bypass	$220
Total Engine Technology Incremental Cost	**$750**
LO-SCR	$530
DOC	($15)
DPF	($45)
SCR+ASC and DEF Dosing System	$751
OBD Sensors and Controllers (NO_x, NH_3, and Temp Sensors)	($66)
Total Aftertreatment Technology Incremental Cost	**$1,155**
R&D Engineering Incremental Cost	$100
Certification Incremental Costs	$0
Warranty Incremental Costs	$0
Total Indirect Incremental Costs to Manufacturer	**$100**
Total Incremental Cost Comparison	**$2,005**

NREL's initial estimated incremental costs of the potential diesel technology package, likely to be the lowest incremental cost to meet 0.02 g/bhp-hr NO_x for the 12–13-L platform, are depicted in Table 4.

Table 4. NREL Estimates of Potential Low-Cost Diesel Technology Package 12–13 L

Cost Component	Incremental Cost Estimate
EGR Cooler Bypass	$330
Charge Air Cooler Bypass	$200
Turbine Bypass	$220
Total Engine Technology Incremental Cost	**$750**
LO-SCR	$750
DOC	$504
DPF	($98)
SCR+ASC and DEF Dosing System	$1,277
OBD Sensors and Controllers (NO_x, NH_3, and Temp Sensors)	($66)
Total Aftertreatment Technology Incremental Cost	**$2,367**
R&D Engineering Incremental Cost	$100
Certification Incremental Costs	$0
Warranty Incremental Costs	$0
Total Indirect Incremental Costs to Manufacturer	**$100**
Total Incremental Cost Comparison	**$3,217**

NREL's initial estimated incremental costs of the potential diesel technology package, likely to be an average of incremental cost to meet 0.02 g/bhp-hr NO_x for the 6–7-L platform, are depicted in Table 5. The potential average-cost diesel technology package consisted of an EPA 2017 certification-compliant engine with a variable-geometry turbo charger, no turbo compounding, and an engine thermal management strategy and technology for cylinder deactivation. In addition to the engine system, the emission control technologies again included the same aftertreatment system as the low-cost diesel technology package with two points of DEF dosing and DEF mixers, one LO-SCR, one DOC, one DPF, two SCRs, and one ASC.

Table 5. NREL Estimate of Potential Average-Cost Diesel Technology Package 6–7 L

Cost Component	Incremental Cost Estimate
Cylinder Deactivation	$1,050
Total Engine Technology Incremental Cost	**$1,050**
LO-SCR	$530
DOC	($15)
DPF	($45)
SCR+ASC and DEF Dosing System	$751
OBD Sensors and Controllers (NO_x, NH_3, and Temp Sensors)	($66)
Total Aftertreatment Technology Incremental Cost	**$1,155**
R&D Engineering Incremental Cost	$100
Certification Incremental Costs	$0
Warranty Incremental Costs	$0
Total Indirect Incremental Costs to Manufacturer	**$100**
Total Incremental Cost Comparison	**$2,305**

NREL's initial estimated incremental costs of the potential diesel technology package, likely to be the average incremental cost to meet 0.02 g/bhp-hr NO_x for the 12–13-L platform, are depicted in Table 6.

Table 6. NREL Estimates of Potential Average-Cost Diesel Technology Package 12–13 L

Cost Component	Incremental Cost Estimate
Cylinder Deactivation	$1,050
Total Engine Technology Incremental Cost	**$1,050**
LO-SCR	$750
DOC	$504
DPF	$98
SCR+ASC and DEF Dosing System	$1,277
OBD Sensors and Controllers (NO_x, NH_3, and Temp Sensors)	($66)
Total Aftertreatment Technology Incremental Cost	**$2,563**
R&D Engineering Incremental Cost	$100
Certification Incremental Costs	$0
Warranty Incremental Costs	$0
Total Indirect Incremental Costs to Manufacturer	**$100**
Total Incremental Cost Comparison	**$3,713**

NREL's initial estimated incremental costs of the potential diesel technology package, likely to be the highest incremental cost to meet 0.02 g/bhp-hr NO_x for the 6–7-L platform, are depicted in Table 7. The potential high-cost diesel technology package consisted of an EPA 2017 certification-compliant engine with a variable-geometry turbo charger, no turbo compounding, and a combined engine thermal management strategy of EGR cooler bypass, charge air cooler bypass, and a turbine bypass. In addition to the engine system, the emission control technologies included a PNA, one DOC, one DEF doser and DEF mixer, one SCRF, one SCR, and one ASC.

Table 7. NREL Estimates of Potential High-Cost Diesel Technology Package 6–7 L

Cost Component	Incremental Cost Estimate
EGR Cooler Bypass	$330
Charge Air Cooler Bypass	$200
Turbine Bypass	$220
Total Engine Technology Incremental Cost	**$750**
PNA	$730
DOC	($15)
DPF (2018 baseline system only)	($759)
SCRF	$714
SCR+ASC and DEF Dosing System	$74
OBD Sensors and Controllers (NO_x, NH_3, and Temp Sensors)	$314
Total Aftertreatment Technology Incremental Cost	**$1,058**
R&D Engineering Incremental Cost	$0
Certification Incremental Costs	$0
Warranty Incremental Costs	$0
Total Indirect Incremental Costs to Manufacturer	**$0**
Total Incremental Cost Comparison	**$1,808**

NREL's initial estimated incremental costs of the potential diesel technology package, likely to be the highest incremental cost to meet 0.02 g/bhp-hr NO_x for the 12–13-L platform, are depicted in Table 8.

Table 8. NREL Estimates of Potential High-Cost Diesel Technology Package 12–13 L

Cost Component	Incremental Cost Estimate
EGR Cooler Bypass	$330
Charge Air Cooler Bypass	$200
Turbine Bypass	$220
Total Engine Technology Incremental Cost	**$750**
PNA	$1,256
DOC	$4
DPF (2018 baseline system only)	($1,398)
SCRF	$1,300
SCR+ASC and DEF Dosing System	$227
OBD Sensors and Controllers (NO_x, NH_3, and Temp Sensors)	$314
Total Aftertreatment Technology Incremental Cost	**$1,703**
R&D Engineering Incremental Cost	$0
Certification Incremental Costs	$0
Warranty Incremental Costs	$0
Total Indirect Incremental Costs to Manufacturer	**$0**
Total Incremental Cost Comparison	**$2,453**

1.4.3 First Survey Responses for Incremental Costs of Potential Diesel Technologies

NREL received a total of five survey responses from a mix of advanced engine technology and emission control technology trade organizations, Tier 1 suppliers, and engine OEMs. As referenced in the Acknowledgements, MECA responded to the survey in a single, aggregated response (to protect confidential cost information). NREL does not know how many MECA member companies are included in that aggregated response.

As a reminder, the first survey specified:

- 0.02 g/bhp-hr NO_x on FTP, RMC-SET, in addition to the new proposed LLC
- MY 2023 introduction
- Current FUL
- Current warranty offered by the OEMs (whatever that may be)
- Production volumes for all of the United States, with guidance for changes for California-only adoption.

NREL received feedback for U.S. volumes, with very little information regarding impacts for California-only adoption. As NREL was unable to aggregate California-only adoption incremental costs, only incremental costs for U.S. volumes are reported.

After receiving the responses to the first survey request, NREL aggregated the incremental cost data into a range of low, average, and high responses for the potential low-cost diesel technology package, as summarized below for 6–7 L in Table 9 and 12–13 L in Table 10. Note that these low, average, and high incremental cost responses are not to be confused with the proposed low-, average-, and high-cost technology packages. Also, note that the low, average, and high responses for each component/subsystem (row) were calculated so that the total low, average, and high incremental cost may not directly reflect any single survey response.

Table 9. Survey Responses for Potential Low-Cost Diesel Technology Package 6–7 L

6–7 L	Low	Avg.	High
EGR Cooler Bypass	$170	$243	$330
Charge Air Cooler Bypass	$128	$167	$200
Turbine Bypass	$170	$207	$230
Total Engine Technology Incremental Cost	**$468**	**$617**	**$760**
LO-SCR	$401	$944	$2,200
DOC	($15)	$10	$30
DPF	($45)	($17)	$0
SCR+ASC and DEF Dosing System	$300	$621	$823
OBD Sensors and Controllers (NO_x, NH_3, and Temp Sensors)	$141	$333	$800
Other	$50	$175	$300
Total Aftertreatment Technology Incremental Cost	**$832**	**$2,066**	**$4,153**
R&D Engineering Incremental Cost	$70	$85	$100
Certification Incremental Costs	$0	$25	$50
Warranty Incremental Costs	$750	$1,875	$3,000
Total Indirect Incremental Costs to Manufacturer	**$820**	**$1,985**	**$3,150**
Total Incremental Cost Comparison	**$2,120**	**$4,668**	**$8,063**

Table 10. Survey Responses for Potential Low-Cost Diesel Technology Package 12–13 L

12–13 L	Low	Avg.	High
EGR Cooler Bypass	$170	$302	$408
Charge Air Cooler Bypass	$128	$185	$240
Turbine Bypass	$170	$215	$240
Total Engine Technology Incremental Cost	**$468**	**$702**	**$888**
LO-SCR	$574	$1,120	$2,450
DOC	$0	$89	$250
DPF	($98)	($44)	$0
SCR+ASC and DEF Dosing System	$500	$784	$1,100
OBD Sensors and Controllers (NO_x, NH_3, and Temp Sensors)	$158	$330	$600
Other	$50	$150	$300
Total Aftertreatment Technology Incremental Cost	**$1,184**	**$2,429**	**$4,700**
R&D Engineering Incremental Cost	$110	$354	$503
Certification Incremental Costs	$0	$21	$50
Warranty Incremental Costs	$1,500	$1,833	$2,500
Total Indirect Incremental Costs to Manufacturer	**$1,610**	**$2,208**	**$3,053**
Total Incremental Cost Comparison	**$3,262**	**$5,339**	**$8,641**

After receiving the responses to the first survey request, NREL aggregated the incremental cost data into a range of low, average, and high estimates for the potential average-cost diesel technology package, as summarized for 6–7 L in Table 11 and 12–13 L in Table 12.

Table 11. Survey Responses for Potential Average-Cost Diesel Technology Package 6–7 L

6–7 L	Low	Avg.	High
Cylinder Deactivation	$480	$790	$1,140
Other	$150	$505	$860
Total Engine Technology Incremental Cost	**$630**	**$1,295**	**$2,000**
LO-SCR	$401	$944	$2,200
DOC	($15)	$10	$30
DPF	($45)	($17)	$0
SCR+ASC and DEF Dosing System	$300	$621	$823
OBD Sensors and Controllers (NO_x, NH_3, and Temp Sensors)	$141	$333	$800
Other	$50	$175	$300
Total Aftertreatment Technology Incremental Cost	**$832**	**$2,064**	**$4,153**
R&D Engineering Incremental Cost	$70	$85	$100
Certification Incremental Costs	$0	$25	$50
Warranty Incremental Costs	$750	$1,875	$3,000
Total Indirect Incremental Costs to Manufacturer	**$820**	**$1,985**	**$3,150**
Total Incremental Cost Comparison	**$2,282**	**$5,344**	**$9,303**

Table 12. Survey Responses for Potential Average-Cost Diesel Technology Package 12–13 L

12–13 L	Low	Avg.	High
Cylinder Deactivation	$561	$952	$1,550
Other	$150	$625	$1,100
Total Engine Technology Cost	**$711**	**$1,577**	**$2,650**
LO-SCR	$574	$1,120	$2,450
DOC	$0	$89	$250
DPF	($98)	($44)	$0
SCR+ASC and DEF Dosing System	$500	$784	$1,100
OBD Sensors and Controllers (NO_x, NH_3, and Temp Sensors)	$158	$330	$600
Other	$50	$150	$300
Total Aftertreatment Technology Incremental Cost	**$1,184**	**$2,429**	**$4,700**
R&D Engineering Incremental Cost	$110	$354	$503
Certification Incremental Costs	$0	$21	$50
Warranty Incremental Costs	$1,500	$1,833	$2,500
Total Indirect Incremental Costs to Manufacturer	**$1,610**	**$2,209**	**$3,053**
Total Incremental Cost Comparison	**$3,505**	**$6,214**	**$10,403**

After receiving the responses to the first survey request, NREL aggregated the incremental cost data into a range of low, average, and high estimates for the potential high-cost diesel technology package, as summarized for 6–7 L in Table 13 and 12–13 L in Table 14.

Table 13. Survey Responses for Potential High-Cost Diesel Technology Package 6–7 L

6–7 L	Low	Avg.	High
EGR Cooler Bypass	$170	$243	$330
Charge Air Cooler Bypass	$128	$167	$200
Turbine Bypass	$170	$207	$230
Total Engine Technology Incremental Cost	**$468**	**$617**	**$760**
PNA	$701	$883	$1,000
DOC	($15)	($12)	($9)
DPF (2018 baseline system only)	($759)	($549)	($377)
SCRF	$500	$559	$677
SCR+ASC and DEF Dosing System	$584	$722	$793
OBD Sensors and Controllers (NO_x, NH_3, and Temp Sensors)	$141	$214	$313
Other	$50	$50	$50
Total Aftertreatment Technology Incremental Cost	**$1,202**	**$1,868**	**$2,447**
R&D Engineering Incremental Cost	$400	$400	$400
Certification Incremental Costs	$50	$50	$50
Warranty Incremental Costs	$750	$750	$750
Total Indirect Incremental Costs to Manufacturer	**$1,200**	**$1,200**	**$1,200**
Total Incremental Cost Comparison	**$2,870**	**$3,685**	**$4,407**

Table 14. Survey Responses for Potential High-Cost Diesel Technology Package 12–13 L

12–13 L	Low	Avg.	High
EGR Cooler Bypass	$170	$302	$408
Charge Air Cooler Bypass	$128	$185	$240
Turbine Bypass	$170	$215	$240
Total Engine Technology Incremental Cost	**$468**	**$702**	**$888**
PNA	$1,147	$2,270	$3,880
DOC	$0	$11	$22
DPF (2018 baseline system only)	($881)	($673)	($560)
SCRF	$800	$930	$1,162
SCR+ASC and DEF Dosing System	($209)	$387	$723
OBD Sensors and Controllers (NO_x, NH_3, and Temp Sensors)	$158	$254	$330
Other	$50	$75	$100
Total Aftertreatment Technology Incremental Cost	**$1,065**	**$3,253**	**$5,657**
R&D Engineering Incremental Cost	$350	$427	$503
Certification Incremental Costs	$13	$32	$50
Warranty Incremental Costs	$1,500	$1,650	$1,800
Total Indirect Incremental Costs to Manufacturer	**$1,863**	**$2,108**	**$2,353**
Total Incremental Cost Comparison	**$3,396**	**$6,063**	**$8,898**

1.4.4 Incremental Costs of Potential Technologies with Extended FUL and Warranty, and California-Only Volumes

After receiving the responses to the first survey request, NREL aggregated the incremental cost data into a range of low, average, and high estimates, as summarized previously. NREL then followed up with an additional survey to identify incremental costs from the MY 2018 baseline, but also to add extended FUL and warranty per Table 1. Lower production volumes representing California only (instead of all of the United States) were also incorporated. The survey assumed implementation for MY 2027 (instead of MY 2023, as in the first survey), as additional time would be necessary to engineer for extended FUL and warranty. Table 15 through Table 20 summarize these additional survey responses.

Table 15. Survey Responses for Potential Low-Cost Diesel Technology Package 6–7 L with Extended FUL, Extended Warranty, and California-Only Volumes

6–7 L	Low	Avg.	High
EGR Cooler Bypass	$289	$390	$490
Charge Air Cooler Bypass	$191	$225	$259
Turbine Bypass	$255	$296	$345
Total Engine Technology Incremental Cost	**$735**	**$911**	**$1,094**
LO-SCR	$513	$1135	$2,200
DOC	$0	$99	$171
DPF	$0	$95	$164
SCR+ASC and DEF Dosing System	$300	$1161	$1829
OBD Sensors and Controllers (NO_x, NH_3, and Temp Sensors)	$738	$845	$997
Other	$300	$300	$300
Total Aftertreatment Technology Incremental Cost	**$1,851**	**$3,635**	**$5,661**
R&D Engineering Incremental Cost	$70	$70	$70
Certification Incremental Costs	$0	$0	$0
Warranty Incremental Costs	$10,800	$10,800	$10,800
Total Indirect Incremental Costs to Manufacturer	**$10,870**	**$10,870**	**$10,870**
Total Incremental Cost Comparison	**$13,456**	**$15,416**	**$17,625**

Table 16. Survey Responses for Potential Low-Cost Diesel Technology Package 12–13 L with Extended FUL, Extended Warranty, and CA Volumes

12–13 L	Low	Avg.	High
EGR Cooler Bypass	$289	$390	$490
Charge Air Cooler Bypass	$191	$246	$288
Turbine Bypass	$255	$296	$345
Total Engine Technology Incremental Cost	**$735**	**$932**	**$1,123**
LO-SCR	$736	$1,330	$2,450
DOC	$0	$144	$330
DPF	$0	$83	$191
SCR+ASC and DEF Dosing System	$500	$1,240	$1,892
OBD Sensors and Controllers (NO_x, NH_3, and Temp Sensors)	$476	$765	$997
Other	$300	$950	$1,600
Total Aftertreatment Technology Incremental Cost	**$2,012**	**$4,512**	**$7,460**
R&D Engineering Incremental Cost	$110	$357	$603
Certification Incremental Costs	$0	$7	$13
Warranty Incremental Costs	$7,840	$23,061	$38,282
Total Indirect Incremental Costs to Manufacturer	**$7,950**	**$23,424**	**$38,898**
Total Incremental Cost Comparison	**$10,697**	**$28,868**	**$47,481**

Table 17. Survey Responses for Potential Average-Cost Diesel Technology Package 6–7 L with Extended FUL, Extended Warranty, and California-Only Volumes

6–7 L	Low	Avg.	High
Cylinder Deactivation	$638	$880	$1,140
Other	$860	$860	$860
Total Engine Technology Incremental Cost	**$1,498**	**$1,740**	**$2,000**
LO-SCR	$513	$1,135	$2,200
DOC	$0	$99	$171
DPF	$0	$95	$164
SCR+ASC and DEF Dosing System	$300	$1,161	$1,829
OBD Sensors and Controllers (NO_x, NH_3, and Temp Sensors)	$738	$845	$997
Other	$300	$300	$300
Total Aftertreatment Technology Incremental Cost	**$1,851**	**$3,635**	**$5,661**
R&D Engineering Incremental Cost	$70	$70	$70
Certification Incremental Costs	$0	$0	$0
Warranty Incremental Costs	$10,800	$10,800	$10,800
Total Indirect Incremental Costs to Manufacturer	**$10,870**	**$10,870**	**$10,870**
Total Incremental Cost Comparison	**$14,219**	**$16,245**	**$18,531**

Table 18. Survey Responses for Potential Average-Cost Diesel Technology Package 12–13 L with Extended FUL, Extended Warranty, and California-Only Volumes

12–13 L	Low	Avg.	High
Cylinder Deactivation	$724	$1,176	$1,860
Other	$1,100	$1,100	$1,100
Total Engine Technology Cost	**$1,824**	**$2,276**	**$2,960**
LO-SCR	$736	$1,330	$2,450
DOC	$0	$144	$330
DPF	$0	$83	$191
SCR+ASC and DEF Dosing System	$500	$1,240	$1,892
OBD Sensors and Controllers (NO_x, NH_3, and Temp Sensors)	$476	$765	$997
Other	$300	$950	$1,600
Total Aftertreatment Technology Incremental Cost	**$2,012**	**$4,512**	**$7,460**
R&D Engineering Incremental Cost	$110	$357	$603
Certification Incremental Costs	$0	$7	$13
Warranty Incremental Costs	$7,840	$23,061	$38,282
Total Indirect Incremental Costs to Manufacturer	**$7,950**	**$23,424**	**$38,898**
Total Incremental Cost Comparison	**$11,786**	**$30,212**	**$49,318**

Table 19. Survey Responses for Potential High-Cost Diesel Technology Package 6–7 L with Extended FUL, Extended Warranty, and California-Only Volumes

6–7 L	Low	Avg.	High
EGR Cooler Bypass	$289	$340	$391
Charge Air Cooler Bypass	$191	$225	$259
Turbine Bypass	$255	$296	$345
Total Engine Technology Incremental Cost	**$735**	**$865**	**$995**
PNA	$924	$1,097	$1,250
DOC	$101	$119	$136
DPF (2018 baseline system only)	($511)	($444)	($377)
SCRF	$679	$799	$919
SCR+ASC and DEF Dosing System	$1,374	$1,616	$1,858
OBD Sensors and Controllers (NO_x, NH_3, and Temp Sensors)	$738	$868	$997
Other	$0	$0	$0
Total Aftertreatment Technology Incremental Cost	**$3,305**	**$4,044**	**$4,783**
R&D Engineering Incremental Cost	$xx	$xx	$xx
Certification Incremental Costs	$xx	$xx	$xx
Warranty Incremental Costs	$xx	$xx	$xx
Total Indirect Incremental Costs to Manufacturer	**$xx**	**$xx**	**$xx**
Total Incremental Cost Comparison	**$xx**	**$xx**	**$xx**

Note for Table 19 that insufficient responses were received for this technology package with respect to indirect costs to allow sufficient aggregation. Therefore, indirect and total incremental costs were not calculated.

Table 20. Survey Responses for Potential High-Cost Diesel Technology Package 12–13 L with Extended FUL, Extended Warranty, and California-Only Volumes

12–13 L	Low	Avg.	High
EGR Cooler Bypass	$289	$390	$490
Charge Air Cooler Bypass	$191	$246	$288
Turbine Bypass	$255	$296	$345
Total Engine Technology Incremental Cost	**$735**	**$932**	**$1,123**
PNA	$1,592	$2,801	$4,656
DOC	$0	$153	$263
DPF (2018 baseline system only)	($881)	($698)	($560)
SCRF	$960	$1,220	$1,553
SCR+ASC and DEF Dosing System	($209)	$1,077	$1,977
OBD Sensors and Controllers (NO_x, NH_3, and Temp Sensors)	$426	$720	$997
Other	$1,600	$1,600	$1,600
Total Aftertreatment Technology Incremental Cost	**$3,488**	**$6,873**	**$10,486**
R&D Engineering Incremental Cost	$603	$603	$603
Certification Incremental Costs	$13	$13	$13
Warranty Incremental Costs	$38,621	$38,621	$38,621
Total Indirect Incremental Costs to Manufacturer	**$39,237**	**$39,237**	**$39,273**
Total Incremental Cost Comparison	**$43,460**	**$47,042**	**$50,846**

It should be noted that the total indirect incremental cost estimates by manufacturers, and the total incremental costs in Table 15 to Table 20, are dominated by the warranty incremental costs. In some cases, the high estimate of incremental warranty costs is over $38,000. As discussed in Section 1.4.5, the warranty incremental costs were based on a very small sample size, and may be biased high due to the OEMs' uncertainty regarding covering warranty for unfamiliar technology needed to meet a 0.02 g/bhp-hr NOx standard at the same time with much longer FULs than current FULs.

1.4.5 Incremental Cost Survey Response Observations

The following general observations can be made regarding the incremental costs reported in Table 3 through Table 20.

- The initial NREL estimates for total incremental costs were fairly close to the lower end of survey responses for the first survey (MY 2023, U.S. volume, current FUL).
- Indirect costs are a significant portion of the total cost.

- Total costs are not necessarily tied to engine displacement/power but are heavily dependent on indirect costs. Production volumes of various engine displacements have more of an impact than engine "size" on indirect cost, and therefore total incremental cost.

- High engineering, certification, and warranty costs spread over relatively small volumes are the drivers of indirect costs. Survey respondents did not share amortization strategies or exact volumes, so those effects are unknown.

- Only OEMs responded with indirect costs, as Tier 1 and MECA responses included only direct costs. Due to the limited number of OEM responses, the indirect costs may have a high level of variation and may not necessarily represent indirect costs for all OEMs.

- The second survey (MY 2027, California-only volume, extended FUL and warranty) was intended to present "worst case" in many parameters, and the survey results reflect that.

- The second survey results report very high incremental indirect costs, especially for warranty. The OEMs did not break that warranty down into how much was attributed to extended FUL versus the extension of the warranty period. Feedback from OEMs indicated high levels of uncertainty in projected warranty costs for this scenario.

- The second survey results assumed CA-only volumes, but OEMs were free to interpret that assumption on their own. OEMs did not report how these CA-only volumes differed from U.S. volumes in the first survey. They did not explicitly state different assumptions regarding market share or changes in CA-only volume due to potential increased pre-purchases ahead of new emissions regulations or potential reduced purchases due to new emissions regulations.

- Some apparent anomalies in the survey responses may be attributed to the limited number of responses. As noted above, not all respondents reported incremental cost estimates for all proposed technology combinations. The aggregated data reported is the best NREL has available that still protects individual confidential costing information.

1.4.6 Incremental Costs for Natural Gas and Gasoline Technology Packages

As previously referenced, few responses were received for the natural gas (HHDD standard) engine platform, preventing NREL from sufficiently aggregating incremental cost information to protect proprietary information. The study assumption that natural-gas engine technology meeting CARB's current optional low-NO_x certification at 0.02 g/bhp-hr would require no significant upgrades to meet a proposed 0.02 g/bhp-hr standard with a new LLC was flawed, based on industry feedback. The feedback focused on changes needed to meet the new LLC cycle and the potential that a moving average window method for emission compliance may be necessary. Based on NREL's analysis and research from literature review, trade organization feedback, and OEM feedback, the anticipated incremental cost of both indirect and direct incremental costs for natural-gas engines and aftertreatment technology to meet an MY 2023 target of 0.02 g/bhp-hr utilizing the moving average window method to assess emission compliance is within 10% of the low-cost diesel technology package for equivalent displacement. A round number estimate total of $3,000 incremental cost was subsequently used for the Task 2: Engine Life-Cycle Costs study.

Similarly, few responses were received for the gasoline HDO engine platform. Some aggregation was possible for direct costs, but only NREL estimates were available for indirect costs. As a result, only total integrated (including direct and indirect) incremental costs ranging from $353 to $468 for MY 2023 were calculated with current FUL.

1.5 Low-, Average-, and High-Cost Estimates

Because NREL received a range of values in response to both surveys, the diesel incremental cost analysis results in nine different points of costs, with low-, average-, and high-cost responses to each of the potential low-, average-, and high-cost diesel technology packages.

1.5.1 Low-, Average-, and High-Cost Estimates for MY 2023 with Current FUL and Warranty

These different points of cost defining the range of data received in response to the first survey for MY 2023 and current full useful life as defined in Table 1 are depicted by error bars within the summary graphs in Figure 3 and Figure 4. The incremental cost variance within any one package is larger than the differences between the engine and aftertreatment packages. In addition, the range of costs seem to have a greater impact on the larger displacement platforms, resulting in a large variance within the individual technology packages.

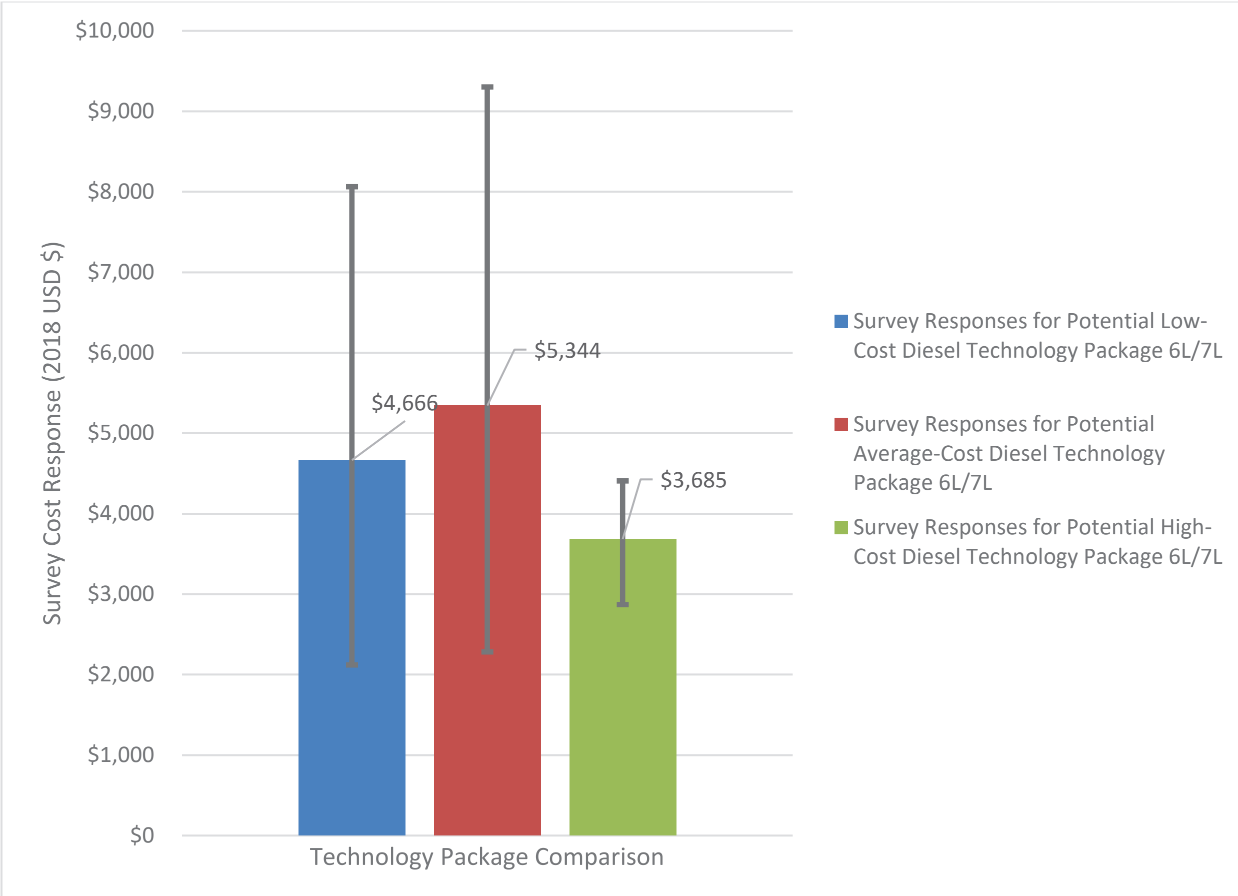

Figure 3. Summary of 6–7-L potential technology packages for MY 2023 with current FUL

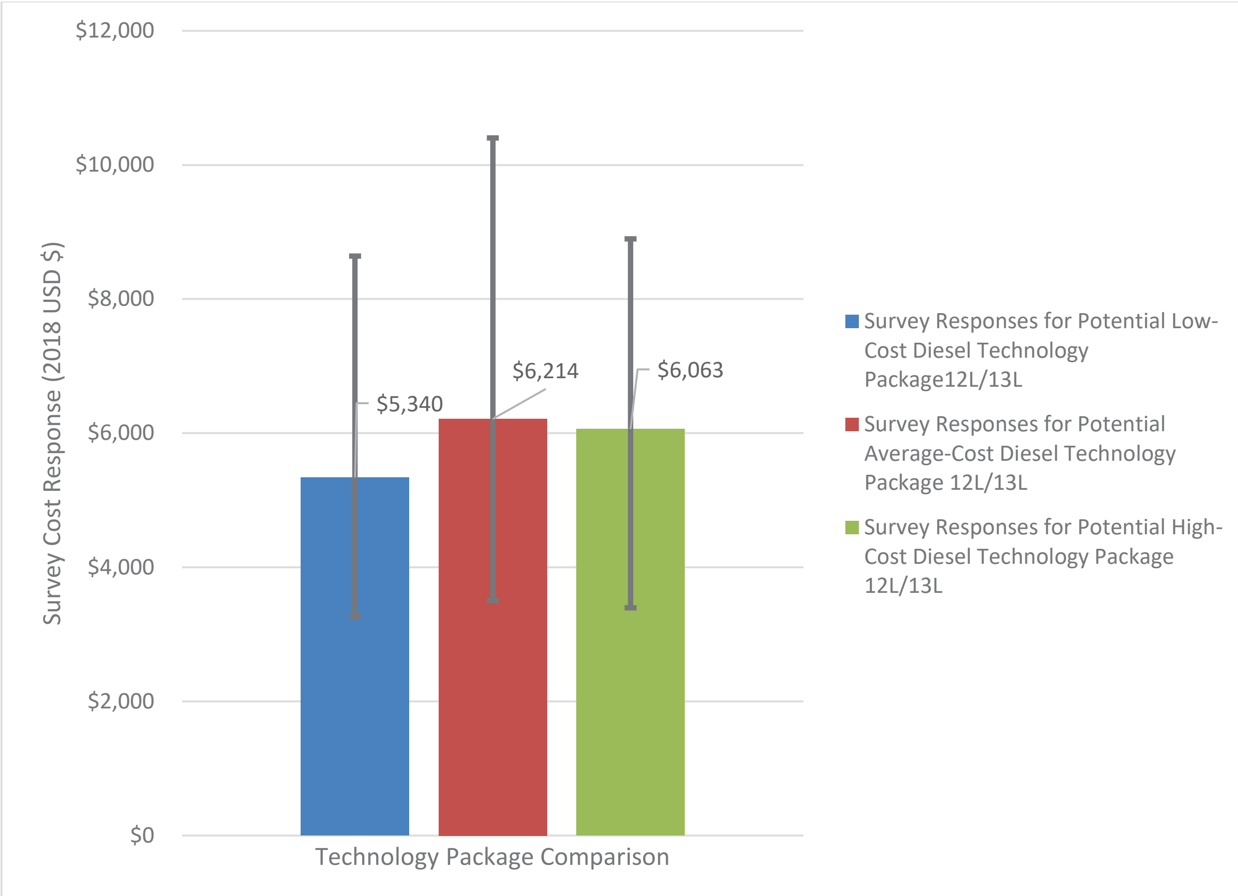

Figure 4. Summary of 12–13-L potential technology packages for MY 2023 with current FUL

1.5.2 Low-, Average-, and High-Cost Estimates for MY 2027 with Extended Warranty and Extended Useful Life

The range of incremental costs received in response to the second survey for MY 2027 with extended useful life and warranty as defined in Table 1 are depicted by error bars within the summary graphs in Figure 5 and Figure 6. NREL did not receive enough responses for the third technology package of the potential high-cost diesel technology to aggregate and therefore did not include the estimates received in order to protect the source of the data.

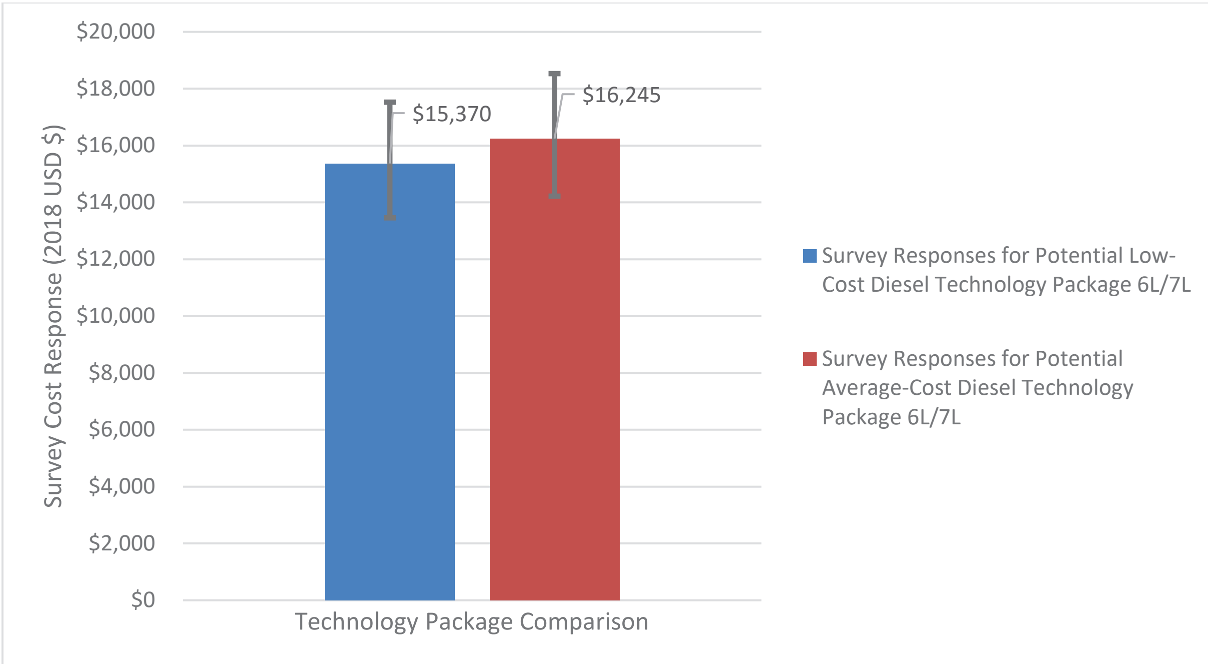

Figure 5. Summary of 6–7-L potential technology packages for MY 2027 with extended FUL and warranty

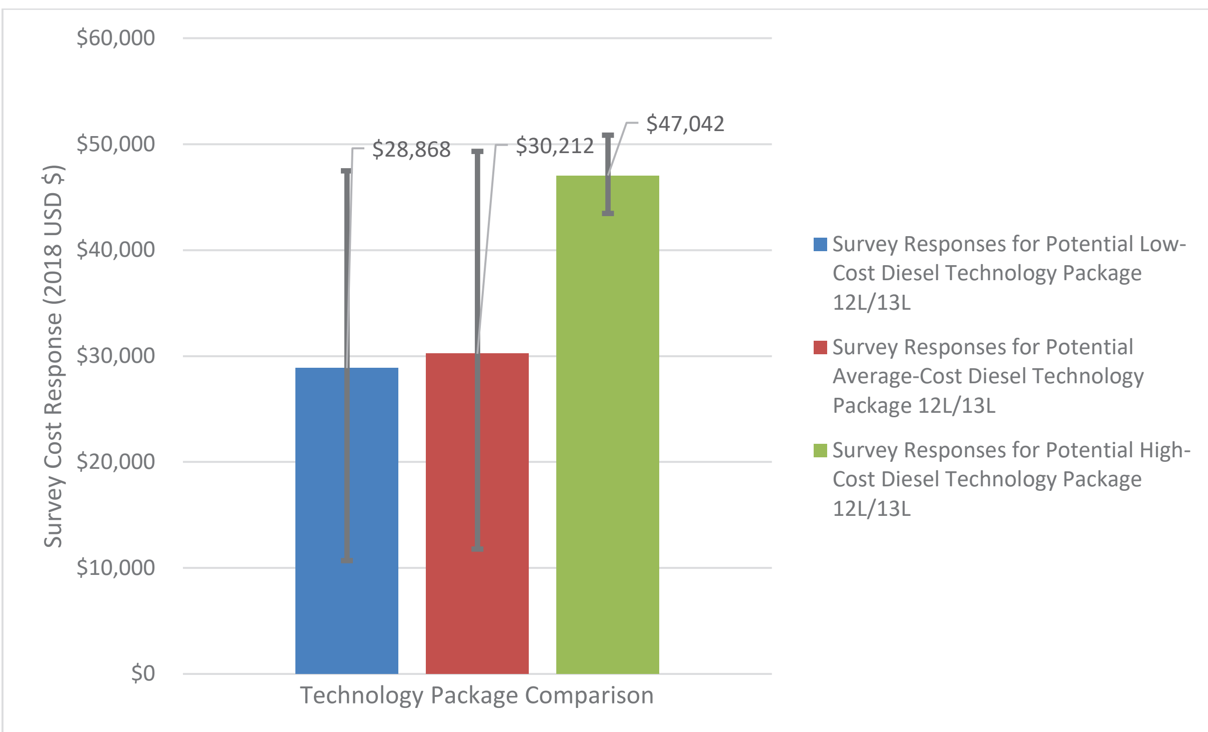

Figure 6. Summary of 12–13-L potential technology packages for MY 2027 with extended FUL and warranty

1.6 Summary of Incremental Cost Analysis

NREL received a total of five survey responses from a mix of advanced engine technology and emission control technology trade organizations, Tier 1 suppliers, and engine OEMs. Data were aggregated with the incremental cost estimates NREL derived from literature review and engineering judgments. The survey responses included incremental cost estimates in a range of values, creating variance for each potential low-, average-, and high-cost technology package. The wide variance in the SCR+ASC and DEF dosing system costs drive most of the variance within the total aftertreatment costs. The cost variance is also much greater in larger displacements due to the high costs of the aftertreatment components and the variance within each of those. Indirect costs are a significant portion of the combined hardware costs of the engine and aftertreatment. Lastly, the incremental costs were not adjusted to reflect a retail markup due to the complexity with which pricing decisions are made.

2 Task 2: Engine Life-Cycle Costs

This section details a life-cycle cost analysis completed to understand the true costs to the owner of a vehicle with a 0.02 g/bhp-hr NO_x aftertreatment package outside of the direct upfront vehicle cost increase. The life-cycle cost analysis sought to incorporate costs associated with the following elements:

- Initial purchase cost
- Fuel consumption changes (changes in fuel economy)
- DEF consumption
- Maximum useful life of the aftertreatment package (major overhaul intervals)
- Other operating and maintenance costs.

To complete the life-cycle cost analysis, two main tasks were completed: assessing the maximum useful life for the aftertreatment packages and computing the life-cycle costs. Section 2.1 reviews the maximum useful life analysis in detail, Section 2.2 reviews the life-cycle cost approach, Section 2.3 outlines the scenarios evaluated in this study, and Section 2.4 summarizes the results of the life-cycle cost analysis.

2.1 Maximum Full Useful Life Analysis

The maximum useful life for the aftertreatment system determines the mileage at which costs to the owner may be incurred if the system begins to fail. For all scenarios in the life-cycle cost analysis, the incremental cost associated with the aftertreatment package was assumed to be incurred after the truck mileage exceeded the stated maximum useful life. This assumption is expected to be conservative as not all aftertreatment packages will fail immediately after they exceed their stated maximum useful life. Statistical analysis of failure rates combined with data on aftertreatment technology operating and maintenance costs could give a more accurate depiction of life-cycle costs. However, such data are not currently available.

The extended maximum useful life option was evaluated by considering the tradeoff between increased upfront costs due to improved durability needed for the extended maximum useful life[1] and the decrease in owner-related replacement costs at the end of the maximum useful life.

The maximum useful life depends on both the displacement of the vehicle and the fuel type. The extended maximum useful life values were defined based on the CARB proposal in January 2019 and previously shown in Table 1.

2.2 Approach

This analysis leverages the high-fidelity vehicle stock model within NREL's Scenario Evaluation and Regionalization Analysis (SERA) model. The SERA stock model tracks vehicle miles traveled, fuel consumption, and ownership costs throughout each vehicle's lifetime and is resolved temporally and spatially with high fidelity. The SERA model was complemented by

[1] It is important to note that the data received from the cost survey (Section 1.3) combined both an extended useful life and an extended warranty. Thus, the cost data used for the extended useful life scenarios couples both the extended useful life and extended warranty information together.

additional data sets to effectively map the vehicles to the aftertreatment packages evaluated in this study.

The following sections provide a brief overview of the SERA stock model, the data sources used in this study, model validation, scenario design, and the life-cycle cost results.

2.2.1 Scenario Evaluation and Regionalization Analysis (SERA) Model

The SERA model's stock module capability provides a flexible framework for tracking vehicles over their life. The SERA's stock model has been used for a variety of U.S. Department of Energy and California Energy Commission projects and, in particular, is described in detail in Bush et al. (2019). The general data flow for the SERA stock model is shown in Figure 7, which shows how data for regional sales (total vehicles sold), market shares (disaggregation of vehicle sales by vehicle type), vehicle survival (salvage rate data), annual travel (vehicle-miles traveled), fuel consumption data (fuel economy and fuel types), and emission rate data are combined to track vehicle population, travel, and resulting energy consumption and emissions.

For this analysis, the SERA model was expanded to track vehicle life-cycle costs over the vehicle's lifetime. The model was updated to account for vehicle costs that could be incurred when purchasing a vehicle or driving the vehicle, as the model already has those data within it.

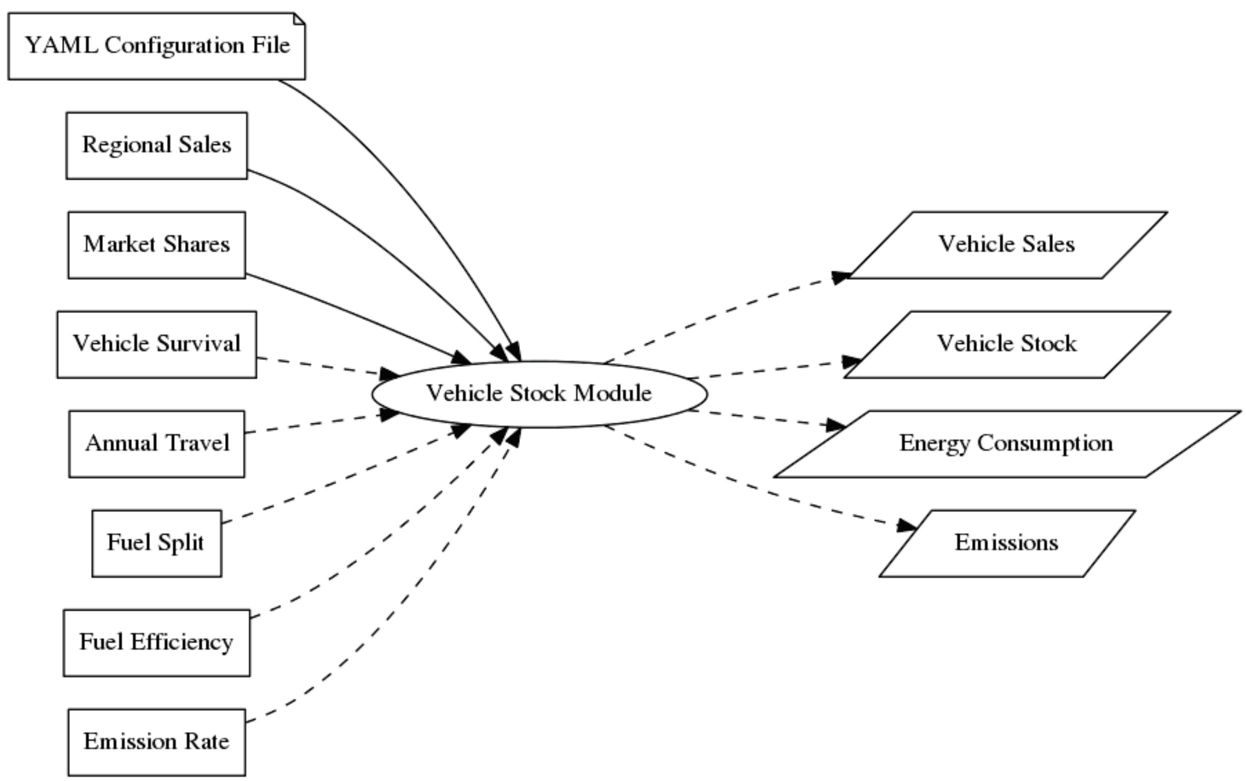

Figure 7. The general SERA stock model data flow

2.2.2 Data Sources

The SERA model provides the analytic framework for a detailed stock model but is complemented by additional data sets to complete the life-cycle analysis required in this study. The data sources used in this analysis are summarized in Table 21.

Table 21. Data Sources Used in Life-Cycle Cost Analysis

Data Source	Description	How it was used
EMFAC/CA Vision 2.1	The EMFAC emissions model is used by CARB to assess emissions from on-road vehicles (cars, trucks, and buses). The CA Vision 2.1 model (2017) is a scenario-planning model and provides the detailed stock data required for the SERA model. It should be noted that the CA Vision model is based on the EMFAC 2014 results.	The CA Vision 2.1 model data was used as the base stock model to create within SERA (e.g., vehicle sales, survival, vehicle miles traveled, and fuel economy were matched between SERA and the CA Vision 2.1 model). Thus, the SERA stock model vehicles, population, total mileage, and fuel consumption match the EMFAC and CA Vision 2.1 models.
IHS Markit (Polk) Department of Motor Vehicles Registration Data	The IHS Markit (formerly known as Polk) Department of Motor Vehicles registration database (2013) provides data across the United States on the quantity and types of trucks registered in each zip code.	The IHS Markit data were used to disaggregate EMFAC vehicles by their engine displacement to compute fleet-wide costs. For example, the T6 Instate Small truck comprises GVWR classes 4–7, which correspond to multiple engine displacements. The IHS Markit data were used to determine the fraction of T6 Instate Small trucks within each engine displacement class.
Task 1 Cost Data	The Task 1 survey cost data includes the incremental cost for three different aftertreatment packages, two engine displacements, three different fuel types, different maximum useful life estimates, different manufacturing volumes, and different model years.	The Task 1 data were incorporated into the SERA model as upfront costs to the vehicle owner mapped to the appropriate vehicle (model year, engine displacement, fuel type). The incremental upfront cost was also assumed to be incurred after the maximum useful life of the aftertreatment package was surpassed in most scenarios.
California Energy Commission Fuel Prices	California Energy Commission's forecast of fuel prices (2017)	Scenario analysis was used to evaluate a 1.25% improvement in fuel economy. The marginal improvement in fuel economy results in fuel cost savings during the vehicle's life. Preliminary data from SwRI indicates an improvement of 0%–4%, depending on the engine cycle, with 1.25% as a good central estimate per SwRI feedback. No reductions in fuel economy were evaluated as the vehicles must still meet the existing GHG standards regulated by CARB.
Diesel Exhaust Fluid Price	A constant $6/gal DEF cost was assumed based on NREL's Co-Optima analysis	Scenario analysis as completed to determine the life-cycle cost of increased DEF consumption.

As seen in Table 21, there are several data sources that combine within the SERA model to evaluate the life-cycle cost of the low-NO_x fuel standard. Visually, these data sources are combined as seen in Figure 8.

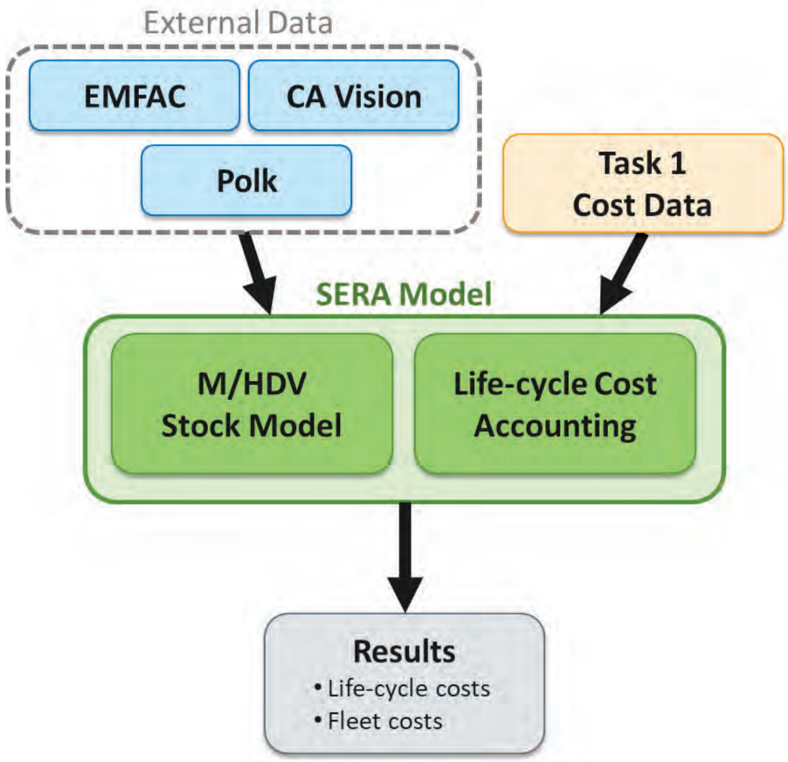

Figure 8. Data flow and analysis using the SERA model for life-cycle cost analysis

Due to the EMFAC and CA Vision 2.1 model spatial and temporal fidelity, each vehicle is defined by a specific region, vocation, model year, fuel type, and age. These vehicles are then further disaggregated by engine displacement using the IHS Markit (formerly Polk) Department of Motor Vehicles registration data. Thus, the life-cycle costs for each vehicle are a function of all of these parameters, and there is a distribution of life-cycle costs across the California fleet due to different vehicle types and travel profiles. For example, the life-cycle costs for a Class 8 long haul tractor will be very different than a Class 6 parcel delivery truck due to the different aftertreatment package costs (which vary by displacement), in addition to the different marginal fuel cost reductions, because they have very different travel requirements profiles and fuel economies.

The distribution in life-cycle costs will be analyzed across the California fleet vehicle types, engine technologies, displacements, and regions using multiple analytic methods, including scenario analysis and sensitivity analysis.

2.2.3 SERA Model Validation

The SERA model was validated against the CA Vision 2.1 model to ensure the starting point for the life-cycle cost analysis was accurate. Figure 9 summarizes the results of the model validation, which show very close agreement between the SERA model and the CA Vision model for predicting stock through 2050. Additionally, validating the model by region, Figure 9 shows there is a less than 1.2% error in predicting the California vehicle population through 2050 for each region.

This model validation indicates that the SERA model matches the CA Vision 2.1 model closely through 2050. For this analysis, the life-cycle cost analysis is focused on model years 2023 and 2027, so this validation signifies that those vehicle sales and survival (lifetimes) will be accurately accounted for in the life-cycle analysis. Additionally, the vehicle travel and fuel consumption data influence the life-cycle costs for each vehicle, and this validation indicates that those costs will be accurately accounted for.

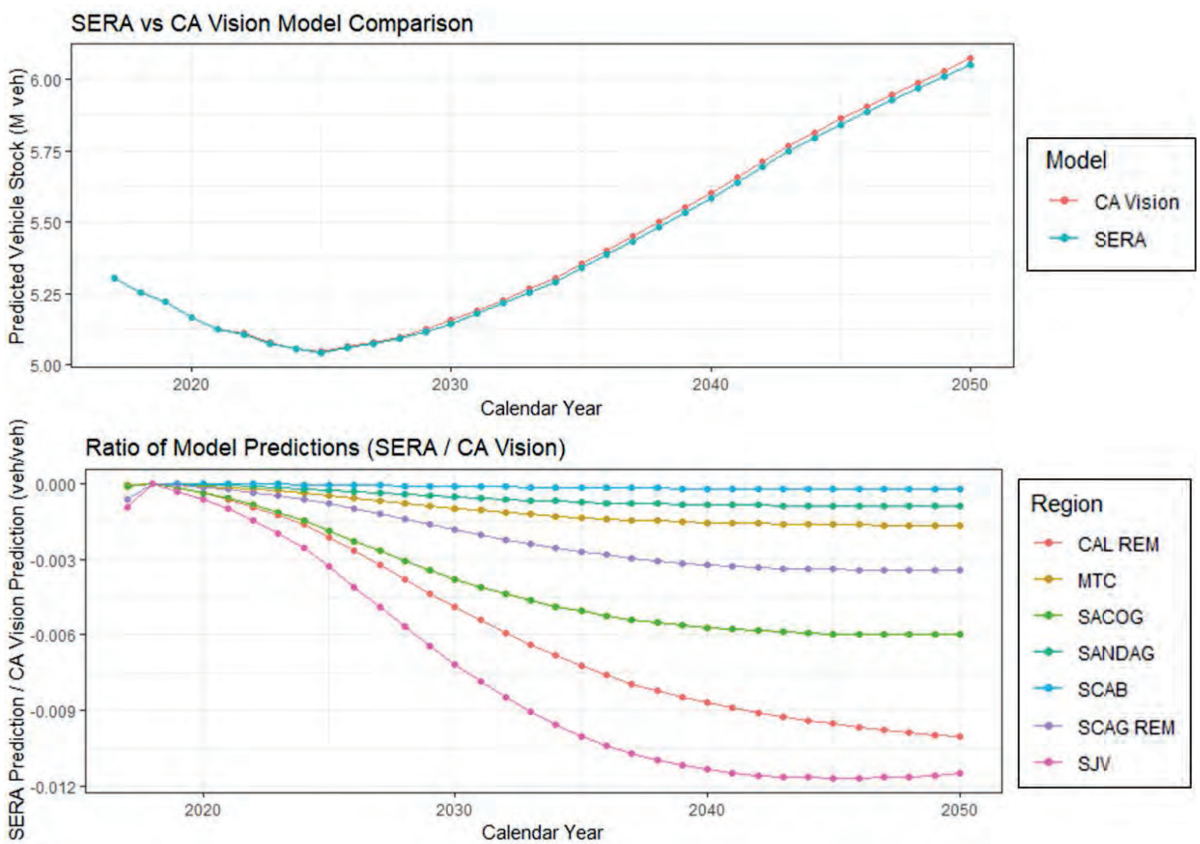

Figure 9. SERA model validation against the CA Vision 2.1 model

2.2.4 Manufacturing Volume Analysis

Manufacturing volume influences the upfront cost of aftertreatment systems, as large manufacturing volumes allow the firm to spread capital and fixed operating costs over more units sold, reducing the per-unit cost. As discussed in the Task 1 section of this report, most data collected from OEMs are for a national manufacturing volume. One OEM provided cost estimates for the 12–13-L diesel engine for a California-only manufacturing volume basis. These data were included in the sensitivity analysis to show its potential importance but not in the scenario analysis given the limited data set.

2.3 Parameters Investigated

The realized life-cycle cost to the vehicle owner depends on a variety of parameters that need to be evaluated. Some of the key parameters assessed in this study include:

- Aftertreatment design cost basis (Task 1)

- Extended maximum useful life
- Manufacturing volume
- Engine displacement
- Vehicle type, region, model year
- Fuel economy impact
- DEF consumption impact.

These parameters and their analysis bounds are summarized in Table 22. Each parameter was varied independently of others to understand the life-cycle cost sensitivity to that parameter.

Table 22. Life-Cycle Cost Parameters Investigated in this Study

Parameter	Description
Adoption Rate	1) 100% compliance by 2023 (Current useful life, only) 2) 100% by 2027 (Extended full useful life, only)
Max Useful Life	1) (Min) Current useful life 2) (Max) Extended useful life 3–5) 25%/50%/75% of min/max spread
Cost Basis	1–3) Low/Avg/High cost basis from Task 1
Other	Will be needed to investigate life-cycle costs differences due to: 1) Varying aftertreatment packages (displacement) 2) Vehicle types (EMFAC definition) 3) Region (Seven CA Vision 2.1 Model Regions) 4) Model year (2023, 2027) 5) Fuel economy impacts (e.g., no change, 1.25% improvement) 6) DEF consumption changes (e.g., 0%, 2.5%, 5% change) 7) Discount rates (3%, 7%) 8) Manufacturing volume (U.S. vs. California-only)

Due to the large number of parameters, each with its own uncertainty around it, the results look at a scenario analysis (varying multiple parameters at one time) and a sensitivity analysis (varying one parameter at a time).

Adoption rate was originally intended to be a parameter of investigation. However, data were only available for current useful life with 100% compliance by 2023 and extended useful life with 100% compliance by 2027. No data were available to determine learning curves or how costs might change depending on the adoption deadline. For this reason, it was assumed that the current full useful life costs for 2023 adoption would hold for 2027 adoption as well. This allows side-by-side comparison of current and extended full useful life life-cycle costs.

2.3.1 Scenario Analysis

Due to the large number of parameters that could influence the life-cycle cost of each vehicle, a scenario analysis approach was taken. Three scenarios were defined to understand the bounds on the life-cycle costs: low-cost scenario, mid-cost scenario, and high-cost scenario. These scenarios were defined to bound the life-cycle cost as well as provide a scenario evaluating a mid-cost life-cycle analysis; however, they do not represent the most likely scenarios that could be realized.

The three scenarios are defined in Table 23 and outline the parameter assumptions used for each scenario. The scenarios were defined to look at the bounds of the life-cycle cost analysis, while the sensitivity analysis was completed to understand the critical parameters driving the life-cycle cost of the aftertreatment system. Because California manufacturing volume data were available from only one OEM for only one engine displacement, all scenarios consider U.S. manufacturing volumes.

Additionally, the upfront cost (Task 1 data) was based only on the average-cost technology package and used the low/average/high error bar bounds. This technology package was selected because the error bar bounds of the average-cost technology package effectively span the full spectrum of potential costs (as seen in Section 1.4). Additionally, the low-cost technology package and high-cost technology package may not actually represent the lowest-cost or highest-cost packages, as found from the survey data in Task 1.

Table 23. Scenario Definitions for Bounding Analysis

Parameter	Low-Cost Scenario	Mid-Cost Scenario	High-Cost Scenario
Upfront Cost	Low	Mid	High
Manufacturing Scale	U.S.	U.S.	U.S.
Useful Life	Current Full Useful Life	Current Full Useful Life	Extended Full Useful Life
Fuel Economy Change	1.25% improvement	No change	No change
DEF Consumption Impact	No change	2.5% increase	5% increase
Discount Rate	7%	7%	3%

In addition to the above parameters, the life-cycle cost also depends on the model year of the vehicle (compliance rate), the engine displacement, the fuel type (diesel, gasoline, natural gas), the vehicle's vocation (defined by EMFAC, which affects the vehicle miles traveled over its lifetime), as well as the region the vehicle is operating in (vehicle miles traveled varies slightly by region within the EMFAC model). Thus, to explore the life-cycle costs across this parameter space, three primary metrics were evaluated for each scenario:

1. Life-cycle costs for each vehicle/displacement/fuel/vocation/region combination
2. A vehicle sales weighted-average life-cycle cost across all vehicle/displacement/fuel/vocation/region combinations
3. A life-cycle cost across the full California fleet.

First, the life-cycle cost was calculated for each vehicle, engine displacement, fuel technology, EMFAC vocation, and region within each of low-cost, mid-cost, and high-cost scenarios. This provides vehicle-specific data and can be used to demonstrate the potential life-cycle costs that could be realized for each vehicle owner.

Second, a sales-weighted average life-cycle cost was determined based on the CA Vision 2.1 predicted sales for the model year 2027. This average metric weights the regions and vocations more heavily if there are more vehicles sold in that aftertreatment definition. For example, assume there are only two vehicles in California and each has a different life-cycle cost and are sold in different proportions, as seen in Table 24.

Table 24. Example Vehicle Sales Weighted Average

Vehicle/Vocation	Example Life-Cycle Cost	Example Sales (vehicles)
T7 Tractor	$1,000	100
T7 Single	$2,000	50

One estimate of representative life-cycle costs for vehicles in California may be a simple average of the two life-cycle costs ($1,500). However, a more accurate and representative life-cycle cost would be a vehicle sales weighted average that accounts for the relative proportion of vehicles within each vocation ($1,333).[2] This approach was used to estimate a single life-cycle cost across all vehicles in California, which would represent an approximate cost for all vehicle owners in the state.

To complete the sales-weighted average, the EMFAC vehicles must be disaggregated into specific vocation, fuel, and engine displacement categories. IHS Markit (formerly Polk) Department of Motor Vehicles registration data were used to disaggregate the EMFAC vehicles into the appropriate vocation, fuel, and engine displacement categories. A summary of the breakdown can be found in Appendix B, while the full data file is provided as an attachment to the report.

In addition to the vehicle-specific life-cycle costs discussed previously, the life-cycle costs of all vehicles sold across California in 2027 were assessed for each scenario. This metric accounts for the relative proportion of vehicle types sold in California and the total cost California fleet owners would be expected to bear for each scenario. This calculation also accounts for the fact that not all vehicles survive the full expected lifetime (e.g., some Class 8 tractors will last only three years while others will last seven). These survival data are important, as vehicles may be retired before they travel more than the aftertreatment package's maximum useful life and thus would not incur those future replacement costs.

2.3.2 Sensitivity Analysis

To better understand the relative importance of each parameter affecting the life-cycle cost of the aftertreatment package, a sensitivity analysis was completed. A sensitivity analysis varies one single parameter and then shows the impact of that parameter on the life-cycle cost of the vehicle. For this analysis, the mid-cost scenario was used as the starting point for the sensitivity analysis, and the variation in each parameter either increases or decreases the life-cycle cost. By varying each parameter independently, one can determine which parameters are the key cost drivers for the life-cycle cost.

[2] Calculated as: $1,000 * (100/(100 + 50)) + $2,000 * (50/(100 + 50)) = $1,333/vehicle

2.4 Results

The results are presented in three sections: a case study to demonstrate life-cycle cost methodologies, scenario analysis results, and a sensitivity analysis.

The case study section illustrates the calculation methodologies that are described above and ultimately used in both the scenario and sensitivity analyses. The case study looks at the calculation methods and assumptions through the lens of two specific vehicles of interest to CARB: the T7 Tractor (heavy heavy-duty tractor truck) and the T6 OOS small (medium heavy-duty out-of-state truck with GVWR ≤ 26,000 lb) (CARB 2018b). The case-study graphics aim to systematically depict some of the key calculation assumptions, limitations, and findings in an easier-to-understand format than when aggregated across all the California vehicles, vocations, displacements, regions, and scenario descriptions. Additional, single-vehicle results for EMFAC vehicles of specific interest to CARB can be found in Appendix A.

The Scenario Analysis and Sensitivity Analysis sections then summarize the core findings of the study, as discussed in Section 2.3.

2.4.1 Case Study: T7 Tractor and T6 OOS Small Vehicle Life-Cycle Costs

The life-cycle cost analysis methodologies are most easily understood through a specific example. Figure 10 shows the present value annual costs[3] for a T7 Tractor (Class 8 line-haul) equipped with a 12–13-L diesel engine for two aftertreatment scenarios: (1) current FUL and (2) extended FUL. Life-cycle costs include the incremental replacement costs after full useful life is achieved (vehicle costs) and potential fuel economy improvements associated with the aftertreatment technology discounted back to present value (fuel costs). For the T7 Tractor 12–13-L engine, the current full useful life is 435,000 miles. If designed for this lifespan, the aftertreatment technology would require two replacements. Extending the aftertreatment's full useful life to 1,000,000 miles significantly increases the upfront cost of the aftertreatment technology but eliminates the need for replacements through 2050, as seen in Figure 10.

[3] The present value annual costs for future years are determined using the discount rate (7% for Figure 10). All values are reported in 2018 dollars, consistent with the Task 1 data, and the first year for discounting is assumed to be in 2027. Using this convention, the incremental vehicle costs (i.e., those due directly to the aftertreatment package) incurred in year 2027 exactly match the Task 1 incremental cost data, while future years are lower due to discounting.

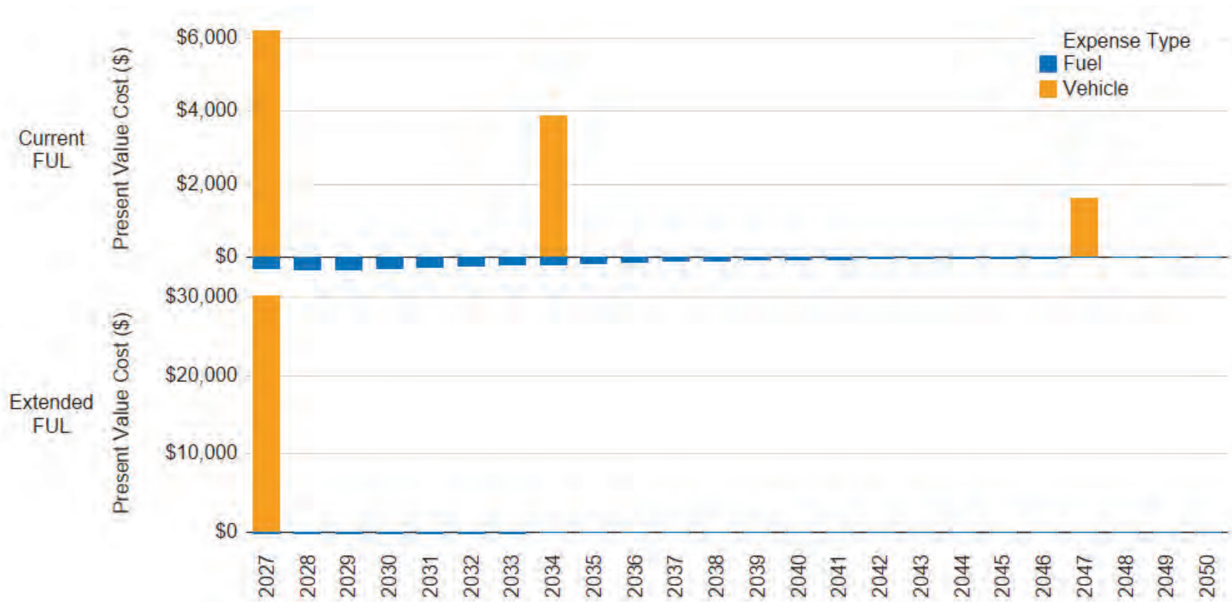

Figure 10. Annual present value cost for a T7 Tractor 12-L diesel engine designed for current full useful life (435,000 miles; top) and extended full useful life (1,000,000 miles; bottom) for MY 2027 in the South Coast Air Basin with a 2.5% increase in DEF consumption, a discount rate of 7%, and national manufacturing volumes

Figure 11 shows annual costs for a T6 OOS small truck with a 6–7-L diesel engine. For the current full useful life design scenario of 110,000 miles, the aftertreatment technology must be replaced three times through 2050. Designing the aftertreatment technology for an extended full useful life of 550,000 miles results in no aftertreatment replacements through 2050.

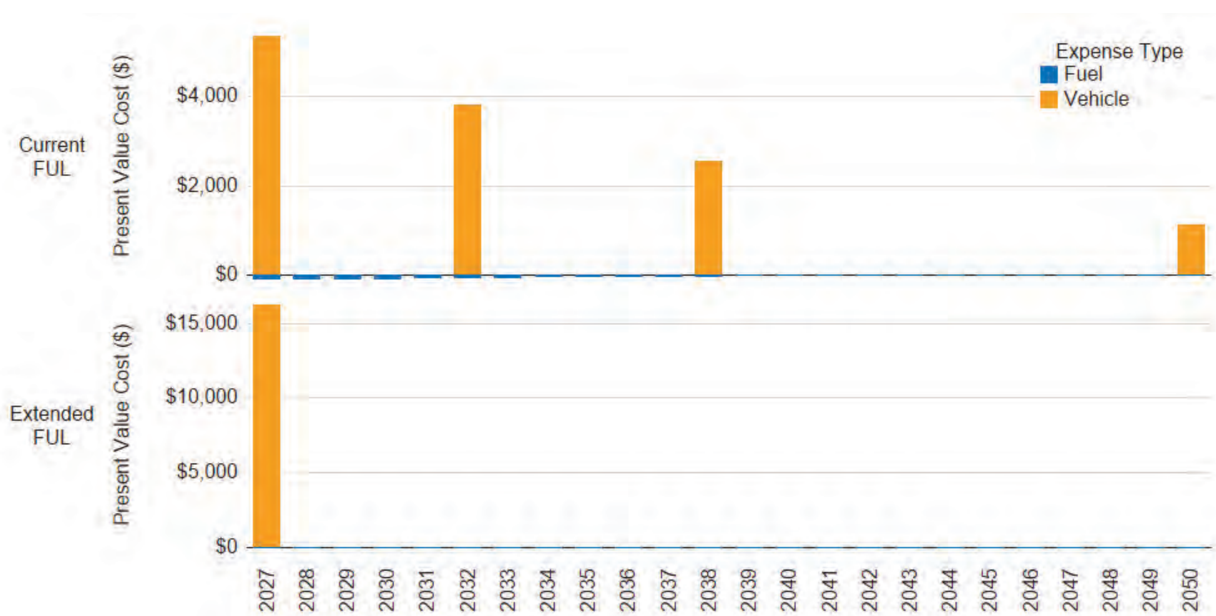

Figure 11. Annual present value cost for a T6 OOS small 6–7-L diesel engine designed for current full useful life (110,000 miles; top) and extended full useful life (550,000 miles; bottom) for MY 2027 in the South Coast Air Basin with a 2.5% increase in DEF consumption, a discount rate of 7%, and national manufacturing volumes

The previous two plots assume that replacement costs are incurred to the owner immediately upon termination of full useful life. In practice, full useful life might be extended by routine maintenance.[4] As a result, Figure 10 and Figure 11 likely represent the upper bound on actual life-cycle costs. Statistical analysis of failure rates combined with data on aftertreatment technology operating and maintenance costs could give a more accurate depiction of life-cycle costs. However, such data were not available for these potential future systems.

To explore the full useful life replacement assumption, the life-cycle costs of a vehicle can be compared assuming either no replacements are completed after vehicle mileage exceeds the aftertreatment's maximum useful life or that replacements are completed. The lower bound on life-cycle costs is set by the condition in which no replacements or maintenance are performed on the aftertreatment package regardless of vehicle mileage. This is unlikely for the current full useful life design but could be realistic for an extended full useful life scenario in which the full useful life of the aftertreatment technology is met near the end of life of the entire truck.

Figure 12 shows total present value cost for the T7 Tractor and T6 OOS small diesel engines as a function of the aftertreatment package's maximum useful life. The orange markers represent the upper-cost bound that assumes the aftertreatment package will be replaced after the vehicle mileage exceeds the maximum useful life. The blue markers reflect the lower-cost bound of no aftertreatment package replacements over the vehicle lifetime. This analysis assumes linear increments in aftertreatment cost as the designed full useful life increases from current to extended. The actual total present value cost lies somewhere between these two bounds, which are typically less than ~$5,000–$7,000 but depend on the vehicle being evaluated. As the aftertreatment package maximum useful life increases, the spread between the two conditions (orange and blue markers) typically decreases as the number of replacements decreases to zero over the lifetime of the vehicle.

Interestingly, for the T7 Tractor, designing for 75% of extended FUL is slightly more expensive than designing for 100% of extended FUL, as the one replacement that would be necessary in 2047 costs more than the incremental step in upfront cost associated with a 25% longer FUL. However, it is unlikely that the truck owner will replace the entire aftertreatment system that close to the end of life, indicating that the true cost is likely lower than the value estimated here.

[4] It should be noted that rather than incurring the replacement cost at the end of the full useful life, one could amortize those costs throughout each year of the vehicle's operation. This would effectively add incremental routine maintenance for each year and the cost would be mathematically equivalent to the end-of-full-useful-life assumption calculated here. The true incremental lifetime repair cost depends on the expected failure rates for these new aftertreatment packages which were not obtained within this study.

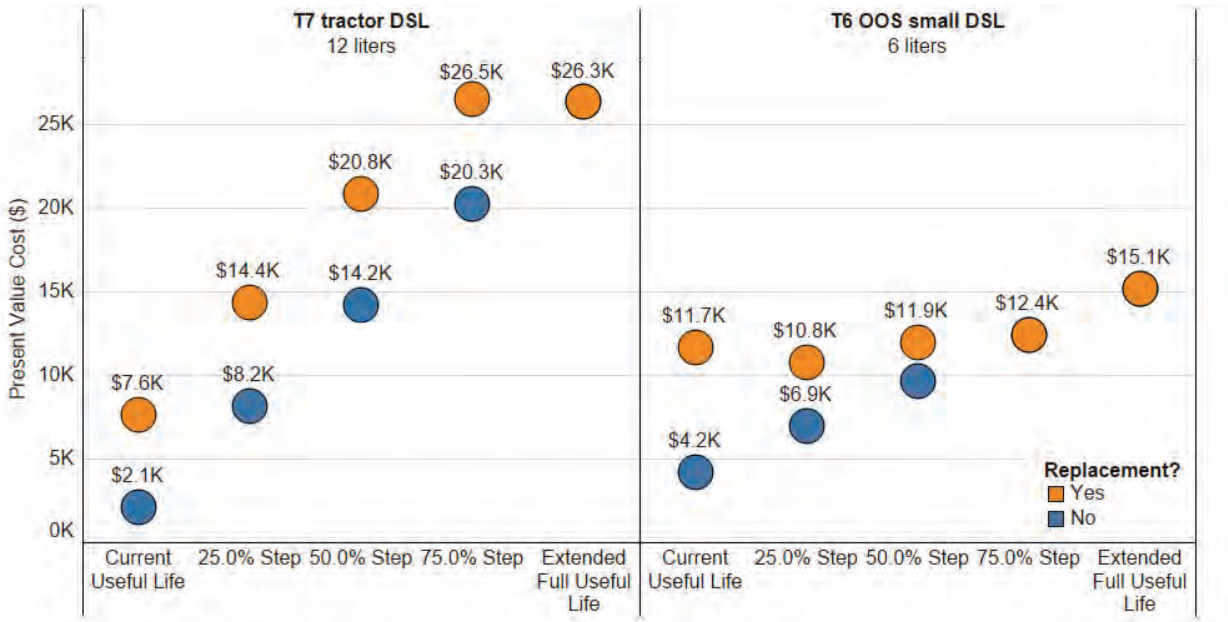

Figure 12. Total present value cost for the T7 Tractor and T6 OOS small vehicles with diesel engine aftertreatment technology as a function of incremental steps between current FUL and extended FUL for two scenarios: replacements at end of FUL (orange) and no replacements (blue)

Because aftertreatment package repair costs are either paid by the vehicle owner or the vehicle manufacturer through the warranty (if applicable), one may expect the higher upfront cost incurred to the vehicle owner for an aftertreatment package with extended full useful life and extended warranty to be offset by the aftertreatment repair cost savings over the life of the vehicle. CARB staff made this assumption when estimating costs for CARB's 2018 Step 1 warranty rulemaking, and CARB's Initial Statement of Reasons (staff report) for this rulemaking (CARB 2018a) assumes that the cost of the warranty packages is equivalent to the lifetime repair savings that the vehicle owner would realize.

The incremental upfront purchase cost that one could estimate based on the survey responses for extended FUL and warranty, and CA-only volumes, as described in Section 1.4.4, would be significantly higher than the repair cost savings that vehicle owners would realize. However, as described more fully in Section 1.4.5, the total incremental costs are dominated by the warranty incremental costs which were based on an extremely small sample size, which may be biased high because of the OEMs' uncertainty regarding covering warranty for unfamiliar technology and much longer useful lives than today's useful lives. These warranty costs may be interpreted to represent "worst case" due to these uncertainties.

While NREL does not know the method used by each OEM to determine their incremental warranty cost estimates and it is beyond the scope of this study to evaluate them in detail, a few additional potential reasons for the vehicle owner upfront costs (driven by the high warranty costs) being higher than the lifetime marginal repair savings could include:

- **Failure uncertainty** – Because the OEMs will not perfectly estimate the probability of failure for their aftertreatment packages, they may charge more than needed initially to ensure they have enough capital to cover any future liabilities. This would be an amount in excess of what the vehicle owners would actually incur but would be expected to decrease over time as the failure rates on new technologies become known with more certainty.

- **Cost of capital** – The OEMs have higher costs of capital than individual vehicle owners. Thus, their cost to reserve funding to cover future warranty liabilities would be more than what a vehicle owner would realize in lifetime repair costs on average.
- **Soft costs** – The OEMs may have embedded additional "soft" costs into the cost estimate for the extended full useful life and extended warranty to account for costs associated with warranty administration (tracking warranty data, contacting vehicle owners, processing payments), legal liability (increased legal staffing in the event of fraud), and potentially others.
- **Customer relationships** – Some manufacturers may reduce the price of the aftertreatment package with extended warranty for some customers with long-standing relationships or high volumes of purchases. These discounts may need to be offset with the "typical" aftertreatment cost, which may be reflected in the values reported from NREL's survey

The previous plots assumed medium-cost aftertreatment technologies, U.S. manufacturing volumes, up to a 1.25% improvement in fuel economy, a 2.5% increase in DEF consumption, and vehicle sales/operation in the South Coast Air Basin region. The next series of plots illustrates some sensitivity of present value cost to some of these assumptions.

Figure 13 shows present value cost of the T7 Tractor and T6 OOS small diesel trucks for the three aftertreatment cost scenarios presented in Task 1 for current full useful life. This graphic suggests that for a T7 Tractor with a 12–13-L diesel engine with current FUL, the present value cost could be ~42% lower or ~65% higher than the average, depending on which aftertreatment technology cost is realized. For the T6 OOS small truck with a 6–7-L diesel engine, the cost could potentially be 57% lower or 74% higher.

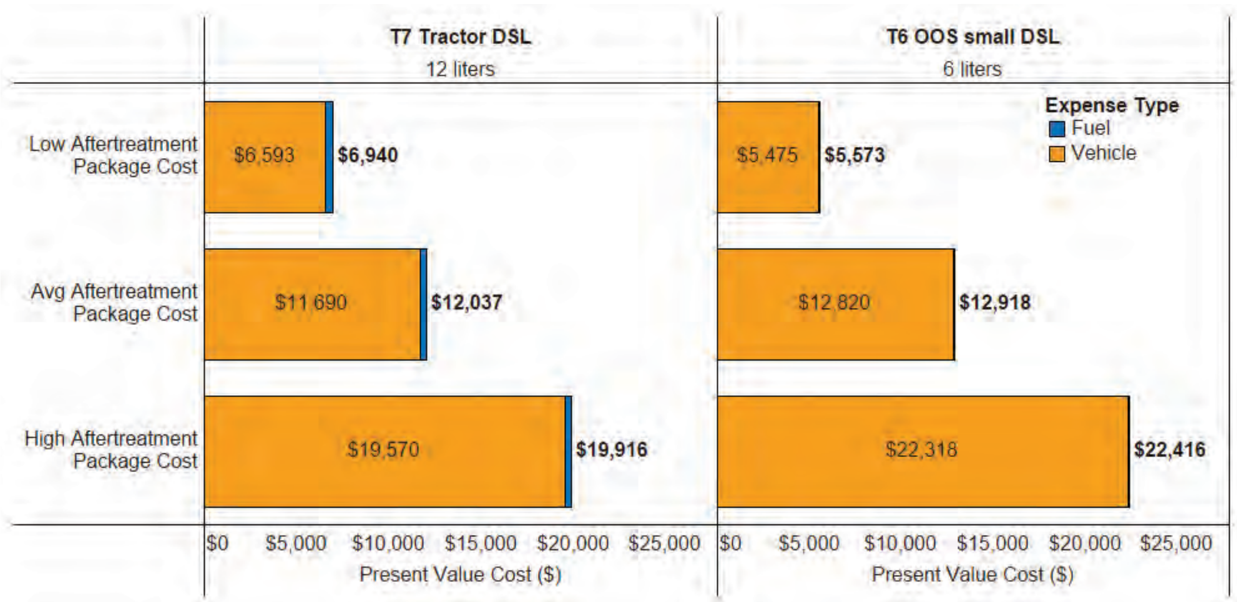

Figure 13. Present value cost for different Class 6 and Class 8 diesel engine aftertreatment technologies with current full useful life

Figure 14 shows present value cost for different aftertreatment technologies with extended full useful life. For this condition, the T6 OOS small truck with a 6–7-L diesel engine could have a life-cycle cost 12% lower or higher. For the T7 Tractor with a 12–13-L diesel engine, the range in present value cost spans 60% lower or 63% higher, about the average aftertreatment cost technology present value.

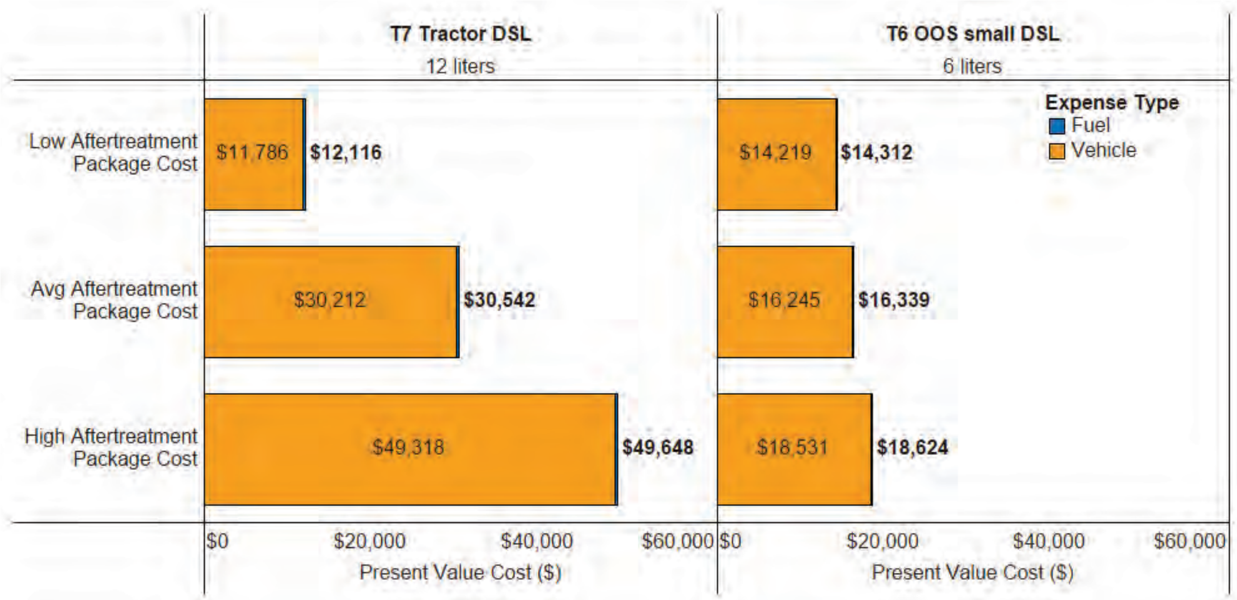

Figure 14. Present value cost for different Class 6 and Class 8 diesel engine aftertreatment technologies with extended full useful life

Figure 15 shows the present value cost for the T7 Tractor with a 12–13-L diesel engine aftertreatment technology manufactured at California and national volumes for current full useful life. No OEM data were available for California manufacturing volumes for extended full useful life. However, this figure suggests that reducing manufacturing volumes to California scales could increase the present value cost by a factor of approximately four to five.

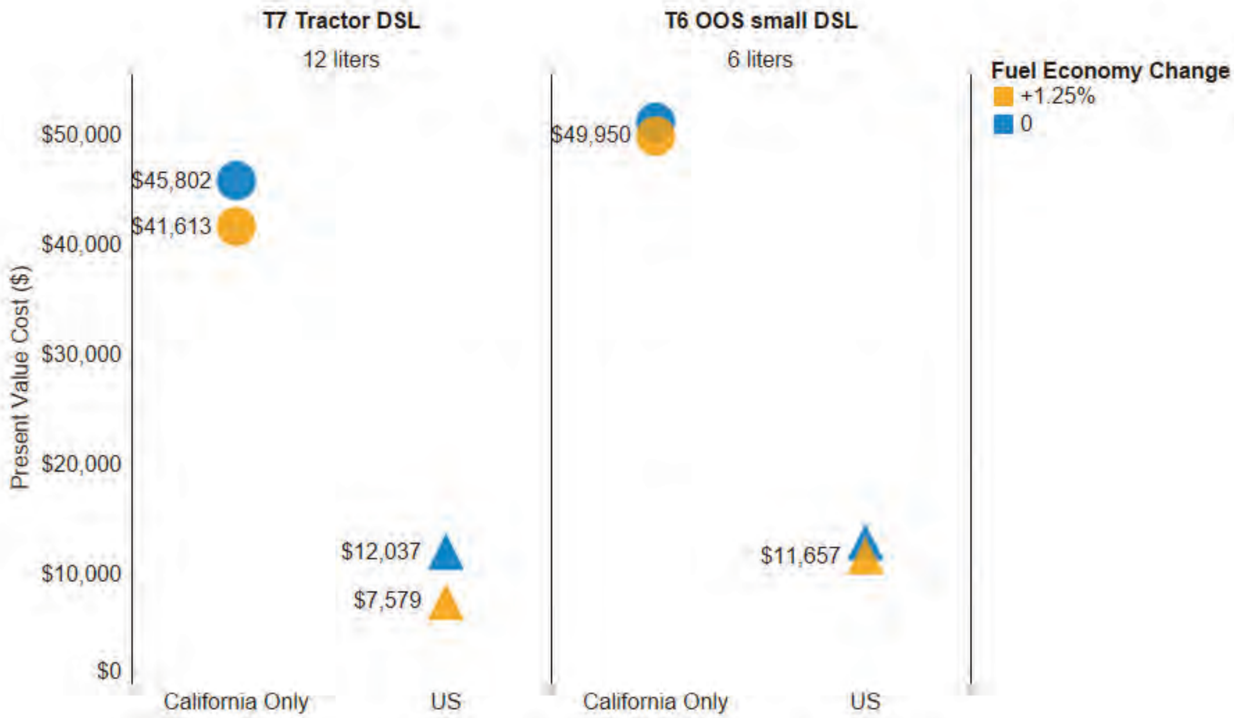

Figure 15. Present value cost for the T7 Tractor and T6 OOS small trucks with diesel engines designed for current full useful life at both California and national manufacturing volumes

Figure 16 and Figure 17 show present value cost for the T7 Tractor and T6 OOS small trucks with diesel engine aftertreatment technologies as a function of the CA Vision model-defined region for current and extended full useful life, respectively. In both cases, regional life-cycle differences are very small—generally less than ~$100. While vehicle miles traveled is dependent on the region the truck operates in, these differences are small across regions. This leads to the conclusion that regional differences in life-cycle costs are not an important factor in the life-cycle cost assessment.

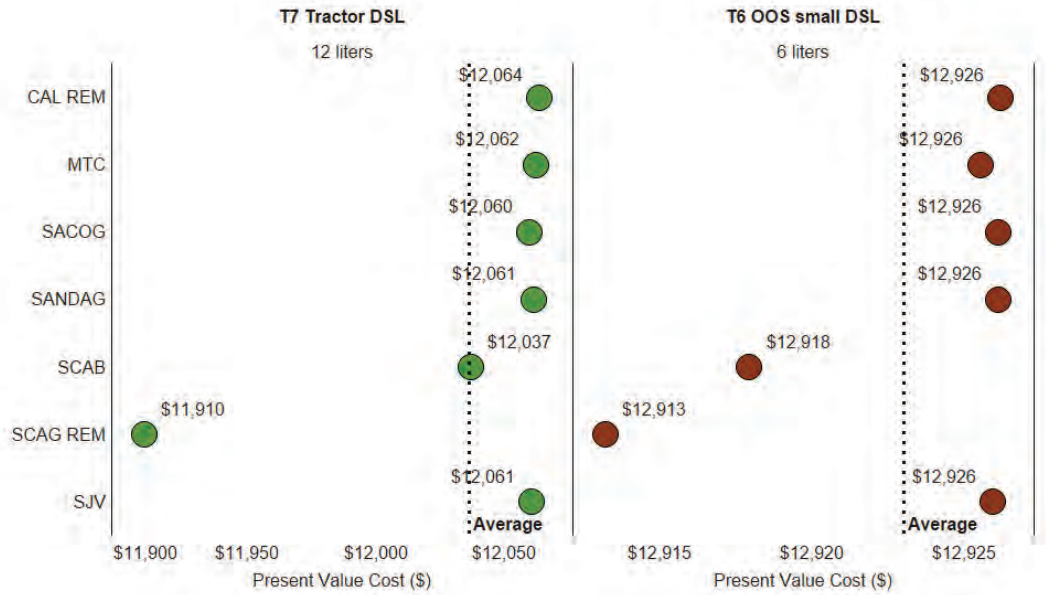

Figure 16. Present value cost for the T7 Tractor and T7 OOS small trucks with diesel engine aftertreatment technologies designed for current FUL as a function of region

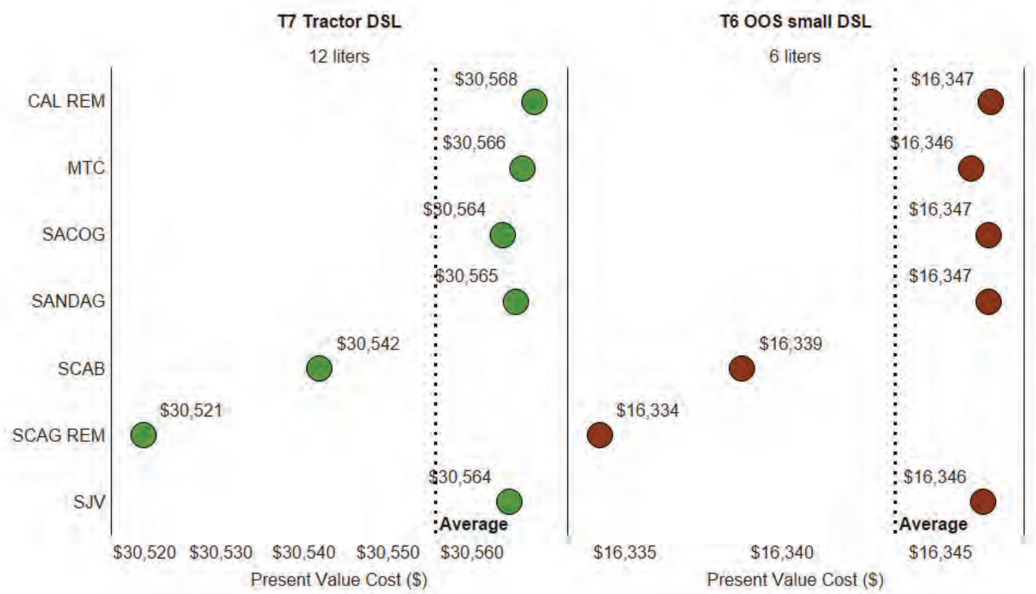

Figure 17. Present value cost for the T7 Tractor and T7 OOS small trucks with diesel engine aftertreatment technologies designed for extended FUL and warranty as a function of region

2.4.2 Scenario Analysis Results

This section presents results from a cost analysis of the three different cost scenarios depicted in Table 23. The scenario analysis results are summarized for the three different metrics discussed in Section 2.3.1:

1. Life-cycle costs for each vehicle/displacement/fuel/vocation/region combination

2. A vehicle sales weighted-average life-cycle cost across all vehicle/displacement/fuel/vocation/region combinations
3. A life-cycle cost across the full California fleet.

2.4.2.1 Vehicle-Specific Life-Cycle Costs

The life-cycle cost was calculated for each EMFAC vehicle, engine displacement, fuel technology, EMFAC vocation, and region within each of the low-, mid-, and high-cost scenarios. This provides vehicle-specific data and can be used to demonstrate the potential life-cycle costs that could be realized for each vehicle owner.

For the low-cost scenario (defined in section 2.3.1), the resulting distribution of vehicle life-cycle costs are shown in Figure 18 for each fuel and engine displacement evaluated in this study. Each EMFAC vehicle is plotted within a density plot that shows the relative proportion of vehicle types that have the associated life-cycle cost. It should be noted that this plot does not account for the projected vehicle sales and how those may differ across vehicle types (e.g., the density shown does not reflect the number of vehicles in California that will have that cost, but rather the number of EMFAC vehicle types that have that cost).

Figure 18. Present value life-cycle cost for all EMFAC vehicles in the low-cost scenario, segmented by fuel type and engine displacement (DSL = diesel, GAS = gasoline)

As seen in Figure 18, some life-cycle costs in the low-cost scenario are negative, indicating the fuel economy benefit outweighs the marginal cost of the aftertreatment package. Additionally, the spread in life-cycle costs is around ~$4,000 for both diesel engine displacements and is primarily due to the different vehicle-miles-traveled profiles across the EMFAC vehicle types. Life-cycle costs for natural gas are not shown, as there was only a single-point estimate of $3,000 for the incremental aftertreatment cost rather than low/high bounds, so natural gas was only evaluated for the mid-cost scenario.

Figure 19 shows the present value life-cycle costs for the mid-cost scenario for all three fuel types. As seen in Figure 19, there could be a significant potential spread in life-cycle costs within a single fuel type and engine displacement category. This is primarily due to the different mileage requirements for certain vehicles combined with the aftertreatment maximum useful life assumption. For the diesel engines, the potential spread in life-cycle costs could be ~$12,000 depending on which EMFAC vehicle type is evaluated. The spread is significantly lower for gasoline and natural-gas engines because there are very few vehicle types defined in EMFAC that use these fuels.

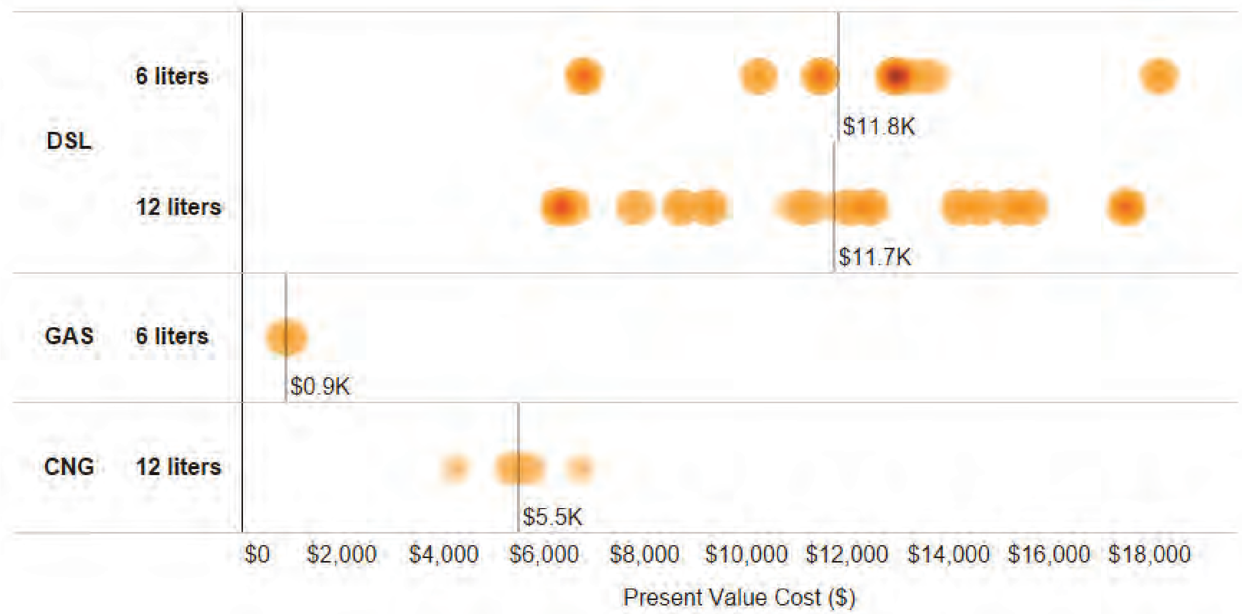

Figure 19. Present value life-cycle cost for all EMFAC vehicles in the mid-cost scenario, segmented by fuel type and engine displacement (DSL = diesel, GAS = gasoline, CNG = compressed natural gas)

The present value life-cycle costs for the high-cost scenario for diesel are shown in Figure 20. Only diesel is shown because this scenario uses the extended useful life cost data, which are not available for gasoline or natural gas. As seen in Figure 20, the life-cycle costs for a vehicle with a 6-L diesel engine in this scenario ranges from ~$18,000 to nearly $30,000. The life-cycle cost for a vehicle with a 12-L diesel engine ranges from ~$50,000 to $88,000 under this high-cost scenario. As seen previously, these higher costs are due to the high incremental cost of the aftertreatment package with both an extended maximum useful life and warranty combined with the assumption that they are replaced after the vehicle mileage exceeds the maximum useful life. The clear definition of two groups of costs in both the 6-L and 12-L engine displacements seen in Figure 20 shows that if the aftertreatment package does not need to be replaced, the life-cycle cost will be on the lower end of each range. However, if the aftertreatment package is replaced (for vehicles that travel more than the extended useful life), the life-cycle cost increases significantly to the upper end of the range.

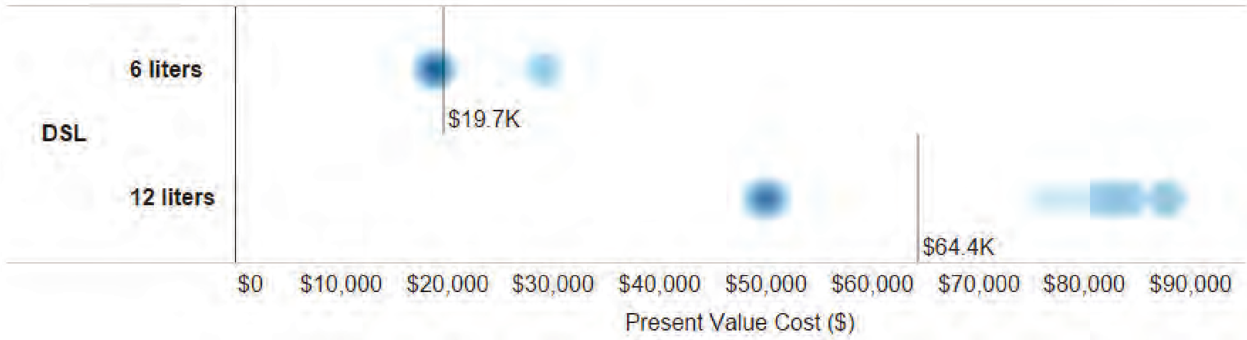

Figure 20. Present value life-cycle cost for all EMFAC vehicles in the high-cost scenario, segmented by fuel type and engine displacement (DSL = diesel)

2.4.2.2 Vehicle Sales Weighted Average Costs

As seen in Section 2.4.2.1, each EMFAC vehicle has a unique life-cycle cost. To combine these into a single, typical life-cycle cost to evaluate, a vehicle sales weighted average can be completed. Figure 21 shows the vehicle sales weighted-average results for the 6–7-L and 12–13-L engine aftertreatment technologies. The analysis shows a significant spread in potential cost between the three 12–13-L engine cases, ranging from roughly $1,500 all the way up to $71,400.[5] Most of this spread is associated with the difference between current and extended full useful life as discussed in Section 2.4.2.1. These sensitivities are discussed in the following section.

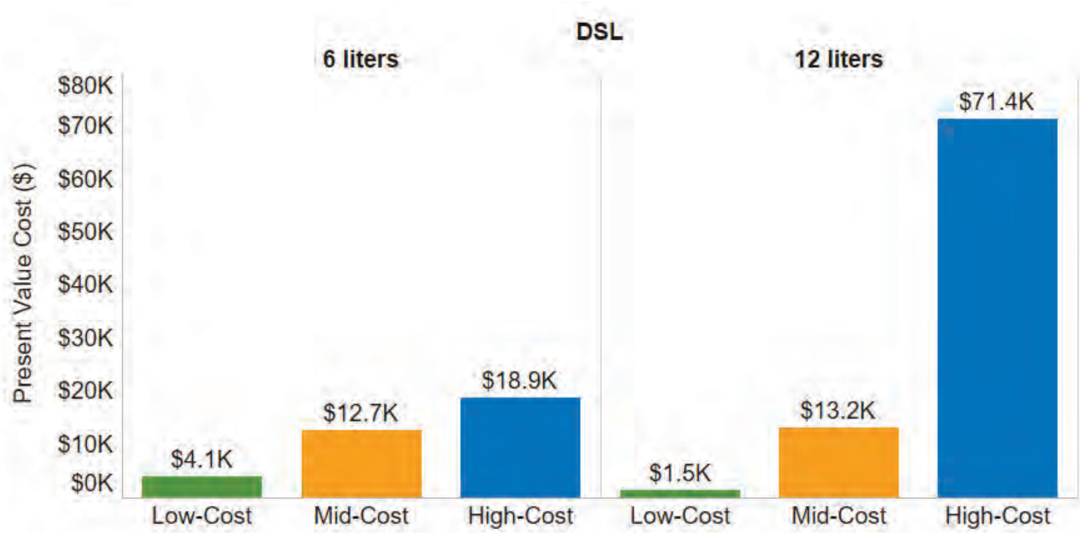

Figure 21. EMFAC vehicle sales-weighted average present value cost for 6-L and 12-L diesel engine technologies under the three cost scenarios described in Table 23

Figure 22 shows the scenario analysis for a 12-L compressed natural-gas engine and a 6-L gasoline engine. The compressed natural-gas costs are based on NREL estimates and do not reflect actual OEM data (only a single-point incremental cost of $3,000 for the aftertreatment

[5] These vehicle sales weighted averages are different than the average values shown in the figures in Section 2.4.2.1 because those averages are simple averages across EMFAC vehicle types without regard to how many of those vehicle types are actually sold in California.

package). The gasoline engine data are based on a small number of OEM estimates with limited spread in upfront cost. As a result, the differences between cases are small. Interestingly, for the low-cost scenario of the gasoline engine, the fuel economy benefits effectively cancel out the incremental aftertreatment package costs, resulting in a near-zero life-cycle cost.

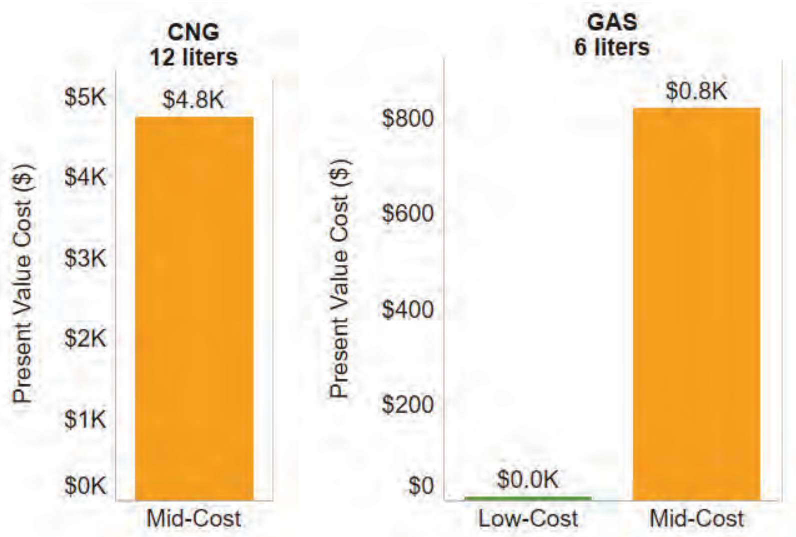

Figure 22. Scenario analysis for a 12-liter compressed natural-gas and 6-liter gasoline engine

2.4.2.3 California Fleet Life-Cycle Costs

The life-cycle cost across the full California fleet was evaluated to better understand what the total cost to all vehicle owners in California would be. As described in Section 2.3.1, this fleet calculation accounts for vehicle attrition over time because not all vehicles in the fleet will last through 2050.

Figure 23 shows the total California fleet costs for MY 2027 for each scenario evaluated in this study. The fleet costs aggregate all fuel types and engine displacements into a single cost metric. As seen in Figure 23, the total fleet life-cycle cost for the MY 2027 vehicles could range from $92 million to $1.2 billion depending on the scenario. As seen before, the large spread in costs across scenarios is primarily due to the higher incremental costs for the aftertreatment extended useful life and extended warranty, which are used in the high-cost scenario.

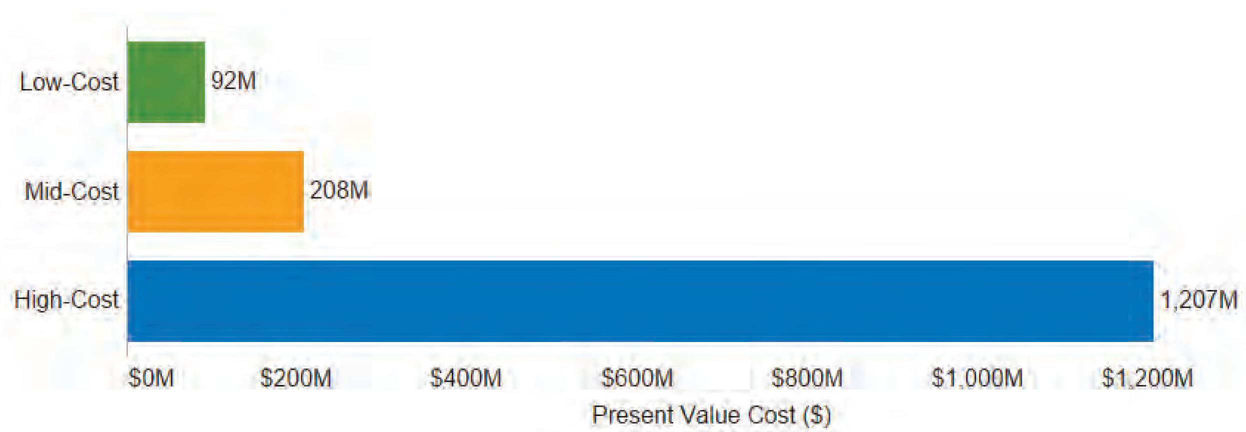

Figure 23. Total California fleet life-cycle cost for the MY 2027 vehicles for each scenario analyzed

2.4.3 Sensitivity Analysis Results

To better understand how each particular parameter assessed in this study impacts the vehicle's incremental life-cycle cost, a sensitivity analysis was completed. The vehicle sales weighted average for the mid-cost scenario (see Section 2.4.2.2 for details) was used as the starting (central) point for the sensitivity analysis.

Figure 24 shows the sensitivity analysis results for the diesel 6–7-L and 12–13-L engines. The sensitivity results are relative to the vehicle sales weighted-average costs of $12,700 and $13,200 for the 6–7-L and 12–13-L engines, respectively. For the 12-L engine, the most influential parameter is manufacturing volume, but this is based on a very limited feedback in the cost survey (Section 1.3.2) and thus was not used outside of this sensitivity analysis. Extended full useful life is the next most significant parameter, which also includes the cost associated with the extended warranty. Figure 24 shows the impact of the extended useful life along with 25% increments between the current useful life and extended useful life (linear interpolation of costs from the two data points). Each step helps illustrate how the cost increases as the full useful life increases up to the extended full useful life mileage.

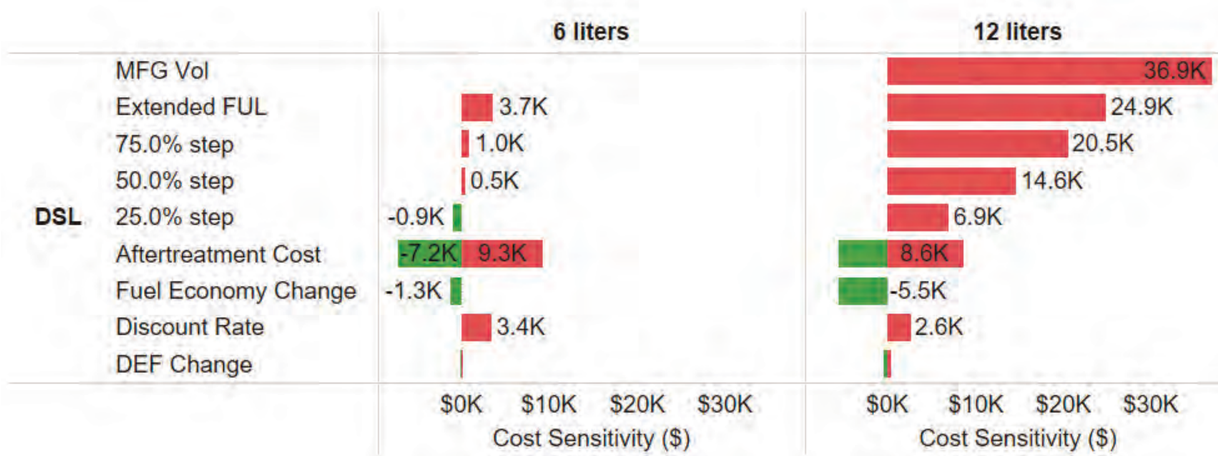

Figure 24. Sensitivity diagram for the diesel 6–7-L and 12–13-L engines relative to the mid-cost scenario

The influence of the incremental aftertreatment technology cost (Task 1 data) is relatively small compared to the aforementioned factors and has the potential to be nearly offset by fuel economy improvements. Discount rate and DEF consumption have minimal influences on the life-cycle cost. For the 6–7-L diesel engine, the aftertreatment cost (incremental cost data from Task 1) was the most influential sensitivity parameter for which data were available. Manufacturing volume may be more significant, as seen in the 12–13-L engine case, but no data were available for California-only manufacturing volume costs for the 6–7 L.

Because no cost data were available for the effect of manufacturing volume or extended useful life, the sensitivity plots for gasoline and natural gas engines have fewer parameters. Figure 25 shows the sensitivity analysis results for gasoline engines. As seen in Figure 25, the gasoline engine life-cycle cost is impacted most by the fuel economy change and incremental aftertreatment cost parameters. This indicates that if the fuel economy benefit is realized, it will likely fully offset the incremental aftertreatment costs.

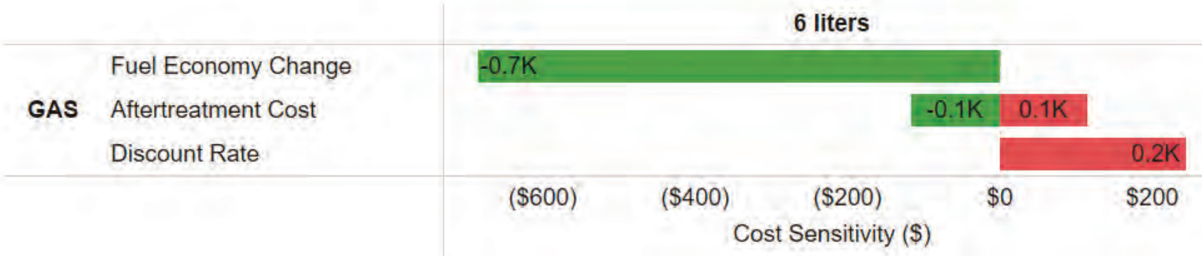

Figure 25. Sensitivity diagram for the gasoline 6-L engine relative to the mid-cost scenario

Figure 26 shows the sensitivity analysis results for the natural-gas engine. Fuel economy impacts and discount rate are approximately equal in magnitude but opposite in the direction of their influence.

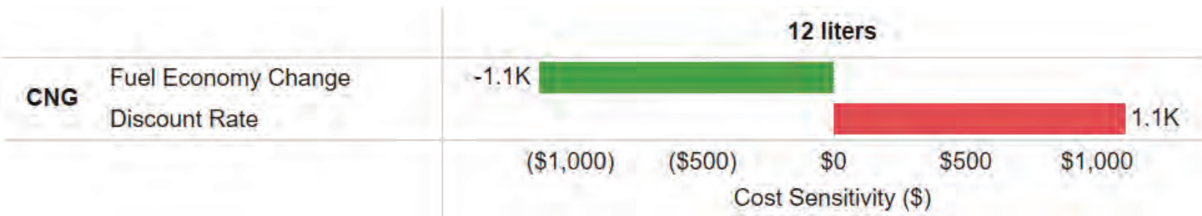

Figure 26. Sensitivity diagram for the natural-gas 12-L engine relative to the mid-cost scenario

2.5 Life-Cycle Cost Analysis Summary and Conclusions

The life-cycle cost analysis seeks to incorporate all direct and indirect incremental costs associated with the different engine aftertreatment technologies over the life of the vehicle. Three scenarios were defined and evaluated to estimate the life-cycle cost across vehicles in California under different conditions.

The scenario results suggest that the life-cycle cost incurred to each vehicle owner depends significantly on the vehicle type and scenario evaluated. Within a given scenario, the spread in life-cycle costs incurred ranges from $4,000 in the low-cost scenario up to nearly $40,000 in the high-cost scenario. Drilling down to the specific EMFAC vehicle definitions (e.g., T7 Tractor), the incremental replacement costs and potential cost savings associated with improved engine fuel economy are two dominant parameters. Because each vehicle has a different mileage profile over its lifetime, the replacement costs and fuel economy savings can vary substantially between vehicles. For example, extending the aftertreatment package's full useful life from current mileages to proposed mileages has the potential to significantly reduce, if not eliminate, the need for aftertreatment technology replacements through 2050 for some vehicles, but not others. Additionally, this extension results in little, if any, reduction in present value cost for the 6–7-L diesel engines and increases present value cost substantially for the 12–13-L diesel engines.

The scenario results also showed that the total California fleet life-cycle costs for the MY 2027 vehicles could be between $92 million and $1.2 billion depending on the scenario realized. Again, the largest factor differentiating scenarios was whether the current or extended full useful life costs were used.

Next, the vehicle sales weighted-average costs provide an approximate, representative per-vehicle life-cycle cost for each scenario. For the mid-cost scenario, the life-cycle cost could be $12,700 and $13,200 for the diesel 6–7-L and 12–13-L engines, respectively. For the mid-cost scenario, the natural gas life-cycle cost is estimated to be $4,800 while the gasoline engine life-cycle cost is $800.

Lastly, the life-cycle cost results suggest that regional impacts across California are minimal, while manufacturing volume could have a significant impact on present value cost. Very little data were available for California-only manufacturing volumes, but the data available suggest the costs could be 4–5 times more than if a national manufacturing volume was realized.

3 Conclusions

The incremental cost analysis was constructed to bracket a range of potential incremental costs associated with achieving 0.02 g/bhp-hr NO_x emissions over certification cycles, including a new proposed LLC. Diesel engines were the primary consideration, as they comprise the majority of HD engines. Incremental cost bracketing included three diesel engine and aftertreatment technology packages, two diesel engine displacements, MY 2023 versus 2027 introduction, U.S. versus California-only implementation, and current FUL versus extended FUL and warranty. Direct and indirect incremental costs were broken down to as discrete a level as possible while maintaining data confidentiality. The calculation of incremental costs was limited by the small number of respondents. Engine OEM participation was crucial, as only they could provide estimates for indirect costs, which represented a significant portion of the total cost.

The average incremental cost for the 6–7-L diesel engines for MY 2023 with current FUL ranged from $3,685 to $5,344, but the absolute low and high bounds were between ~$2,000 and over $9,000. Extending FUL and warranty moved the average incremental costs to a range of $15,370 to $16,245, with tighter low and high bounds (constrained in part by the limited number of responses). The average incremental cost for the 12–13-L diesel engines for MY 2023 with current FUL ranged from $5,340 to $6,063, but the absolute low and high bounds were between ~$3,000 and over $10,000. Extending FUL and warranty moved the average incremental costs to a range of $28,868 to $47,042, with much wider low and high bounds (driven in part by the limited number of responses). The natural gas 12-L engine application was unable to be studied in detail, but OEM feedback anticipated that the incremental cost for natural-gas engines and aftertreatment technology is within 10% of the low-cost diesel technology package for equivalent displacement, specifically due to possibly requiring a moving average window method to assess emission compliance. The gasoline engine 6-L application was also unable to be studied in detail, but comparatively low incremental costs were estimated.

Incremental costs are largely driven by indirect costs associated with engineering research and development costs, plus warranty. Those indirect costs, in turn, are driven by production volumes and amortization.

The life-cycle cost analysis incorporates all direct and indirect incremental costs associated with the different engine aftertreatment technologies over the life of the vehicle. The life-cycle costs depend on the vehicle type (mileage), region, fuel, engine displacement, maximum useful life, fuel economy change, diesel exhaust fluid consumption change, and discount rate. The primary drivers of life-cycle cost were the incremental aftertreatment replacement costs and fuel economy benefits.

For the three scenarios evaluated (low-cost, mid-cost, high-cost), the life-cycle costs were evaluated for each EMFAC vehicle type, aggregated to a representative average, and also calculated across the vehicle fleet for the model year 2027 vehicles. The analysis showed that EMFAC vehicles can have significantly different life-cycle costs, and that spread depends on the scenario evaluated: approximately a $4,000 spread across vehicle types in the low-cost scenario, while the high-cost scenario had nearly a $40,000 difference. This large spread was found to be due to the number of aftertreatment package replacements needed throughout the vehicle lifetime. The aggregated, representative average life-cycle costs for the mid-cost scenario were estimated to be $12,700 for the 6–7-L diesel engine, $13,200 for the 12–13-L diesel engine, $4,800 for the 12-L natural-gas engine, and $800 for the 6-L gasoline engine. The total life-cycle cost to California vehicle owners for the model year 2027 vehicles was estimated to range between $92 million and $1.2 billion depending on the scenario (low-cost or high-cost) realized.

The sensitivity analysis indicated that the manufacturing volume may be the most important parameter impacting the life-cycle cost; however, limited data were received from the external stakeholders surveyed. The next most important parameter was the assumption of extended useful life and extended warranty, as the increase in aftertreatment lifetime may not exceed the vehicle's travel requirement, which results in larger replacement costs over the vehicle's life. The aftertreatment cost bound (low/high error bars on the incremental cost data), fuel economy improvement, and discount rate were found to have a moderate impact on the life-cycle cost. Lastly, the region and DEF consumption change were found to have minimal influence on the life-cycle cost.

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Appendix A. Selected Results for Specific EMFAC Vehicles of Interest to CARB

In addition to the life-cycle costs presented in this report, the California Air Resources Board (CARB) indicated a specific interest in the following EMission FACtor (EMFAC) vehicles (CARB 2018b):

Table A1. EMFAC Vehicles of Interest to CARB

EMFAC Vehicle	EMFAC Description (GVWR = Gross Vehicle Weight Rating)
T7 Tractor	Heavy Heavy-Duty Diesel Tractor Truck
T7 Single	Heavy Heavy-Duty Diesel Single Unit Truck
T7 POLA	Heavy Heavy-Duty Diesel Drayage Truck near South Coast
T6 OOS Heavy	Medium Heavy-Duty Diesel Out-of-State (OOS) Truck with GVWR > 26,000 lb
T6 OOS Small	Medium Heavy-Duty Diesel Out-of-State Truck with GVWR ≤ 26,000 lb

Per the CA Vision 2.1 model, the vehicle-miles-traveled profiles for these vehicles with a model year (MY) of 2027 in the South Coast Air Basin (SCAB) region are shown in Figure A1.

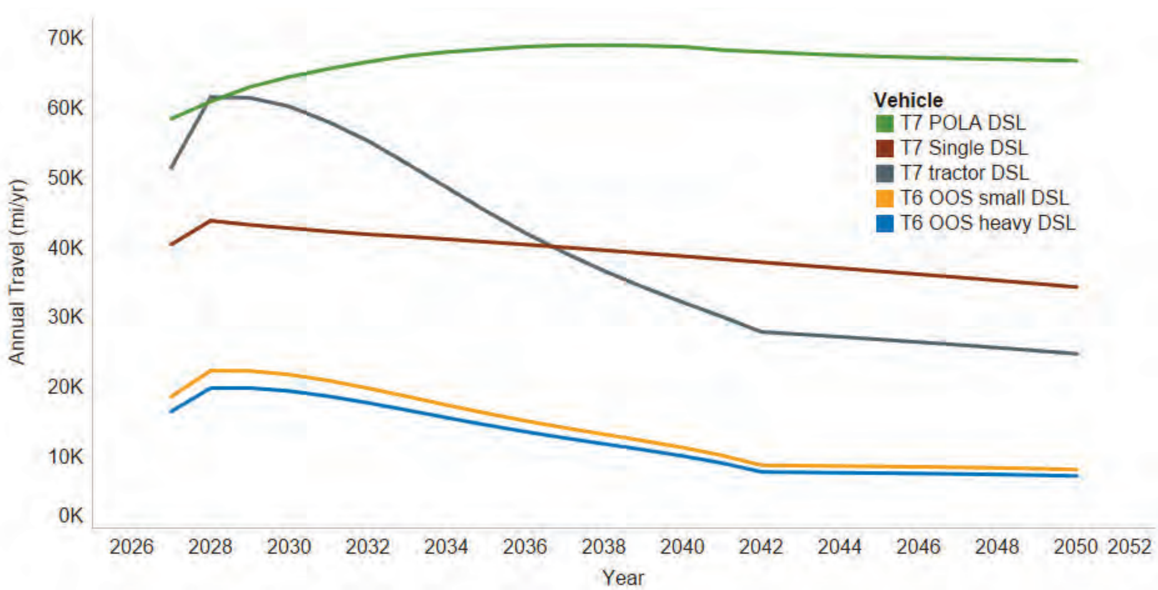


Figure A1. Selected EMFAC vehicle miles traveled for MY 2027 in the SCAB region

For these vehicles, the life-cycle costs for each scenario evaluated (low-cost, mid-cost, and high-cost) are shown in the following figures. Figure A2 shows the life-cycle costs for the low-cost scenario, Figure A3 shows the results for the mid-cost scenario, and Figure A4 shows the results for the high-cost scenario. These results are aggregated for each vehicle, which accounts for the costs incurred from the aftertreatment package as well as any potential fuel economy benefit associated with the scenario.

Of note, the individual vehicle life-cycle cost results are very close to the representative life-cycle costs estimated using the vehicle sales weighted average shown in Figure 21 in Section 2.4.2.2.

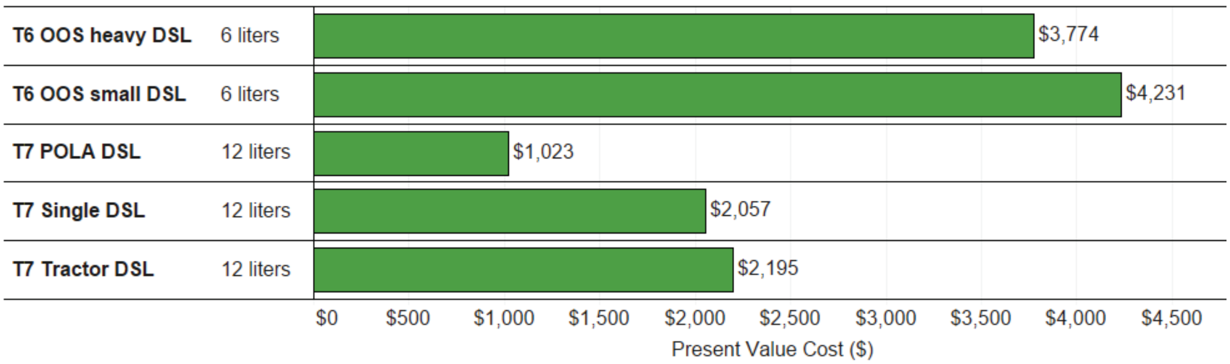


Figure A2. Present value life-cycle cost for selected EMFAC vehicles (MY 2027 in the SCAB region) for the low-cost scenario

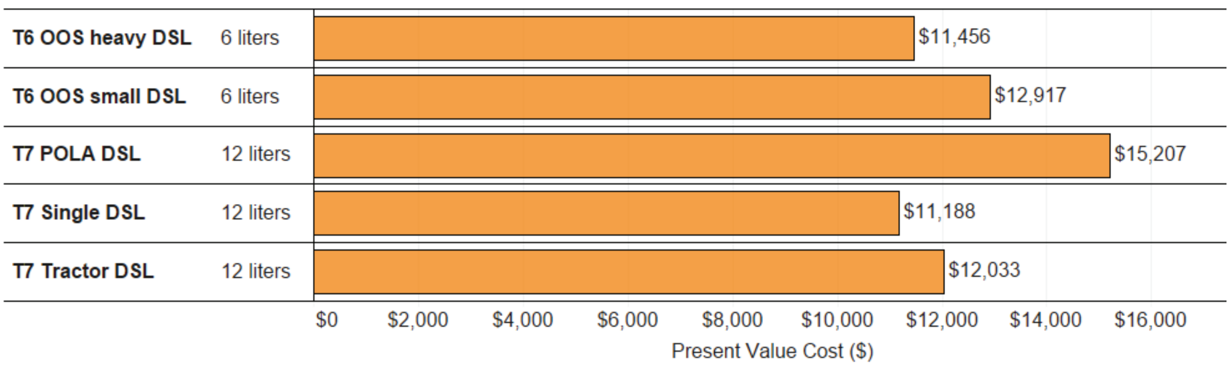


Figure A3. Present value life-cycle cost for selected EMFAC vehicles (MY 2027 in the SCAB region) for the mid-cost scenario

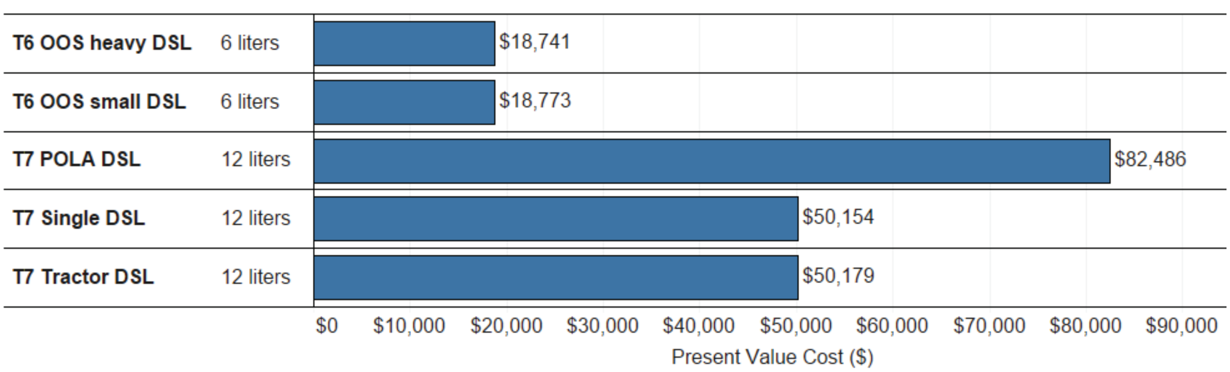


Figure A4. Present value life-cycle cost for selected EMFAC vehicles (MY 2027 in the SCAB region) for the high-cost scenario

Appendix B. EMFAC Vehicle Disaggregation

The EMFAC vehicles needed to be broken down into the appropriate fuel and engine displacement categories. The IHS Markit (formerly Polk) Department of Motor Vehicles registration database was used to disaggregate the EMFAC vehicles. The same disaggregation was used for each CA Vision region and the first few results are summarized in Table B1, while the full table is provided in a separate file.

Table B1. EMFAC Vehicle Disaggregation Results

EMFAC 2011 Vehicle	Displacement (L)	GVWR Class	Fraction (veh/veh)
MH	12	7	0.6008
MH	15	7	0.3992
T6 Ag	6	4	0.3302
T6 Ag	9	4	0.0063
T6 Ag	6	5	0.1554
T6 Ag	9	5	0.0095
T6 Ag	6	6	0.1936
T6 Ag	9	6	0.0995
T6 Ag	6	7	0.0975
T6 Ag	9	7	0.1081
T6 CAIRP heavy	6	7	0.4743
T6 CAIRP heavy	9	7	0.5257
T6 CAIRP small	6	4	0.4156
T6 CAIRP small	9	4	0.0079
T6 CAIRP small	6	5	0.1956
T6 CAIRP small	9	5	0.0119
T6 CAIRP small	6	6	0.2437
T6 CAIRP small	9	6	0.1253
T6 instate construction heavy	6	7	0.4743
T6 instate construction heavy	9	7	0.5257
T6 instate construction small	6	4	0.4156
T6 instate construction small	9	4	0.0079
T6 instate construction small	6	5	0.1956

EMFAC 2011 Vehicle	Displacement (L)	GVWR Class	Fraction (veh/veh)
T6 instate construction small	9	5	0.0119
T6 instate construction small	6	6	0.2437
T6 instate construction small	9	6	0.1253
T6 instate heavy	6	7	0.4743
T6 instate heavy	9	7	0.5257
T6 instate small	6	4	0.4156
T6 instate small	9	4	0.0079
T6 instate small	6	5	0.1956
T6 instate small	9	5	0.0119
T6 instate small	6	6	0.2437
T6 instate small	9	6	0.1253

Cost Impact Stud
EPA HDOH Emis

Final report

October 15, 2021

C022563-003

Contents

Ricardo's cost impact study provides the incremental cost fo comply with potential next-tier EPA HDOH emission regulatio

Summary

- Ricardo performed a cost impact study for assessing the impact of potential nex emission regulations for three engine platforms – HHDDE (heavy heavy-duty die diesel engines), and LHD Gas (light heavy-duty gasoline engines)
- Study investigated costs directly associated with cost drivers like technical soluti laboratory investments, and in-use compliance
- Ricardo's proven methodology for technology cost assessment was used for this
  - Developed scenarios defining potential next-tier EPA emission regulations
  - Engine and truck manufacturing OEMs were then requested to share incremental cost information ba
  - Responses from OEMs were analyzed and validated using Ricardo's experience with engine and afte industry experts, public reports, and desk research

- Based on extensive experience conducting similar studies regarding regulation-driven costs, Ricardo is confident in the methodology and accuracy of the incremental costs we have projected

Incremental cost analysis for potenti		
Platforms	Scenario 1: 90% NOx reduction, ~50% Extended UL and CARB "Step 1" Warranty	
	MY 2027	MY 2031
HHDDE	$5,882	$18,007
MHDDE	$4,255	$7,323
LHD Gasoline	$2,274	$2,475

Ricardo performed a technology cost impact study based on for the EPA Clean Truck Initiative on HHDDE, MHDDE, and LH

Methodology

1. Created 3 scenarios with varying assumptions for NOx reduction stringency, useful life and extended warranty requirements for HHDDE, MHDDE and LHD gasoline platforms

2. Requested information(RFI's) related to incremental costs for various cost elements from 9 different engine and vehicle manufacturers – Stellantis, Ford, GM, Cummins, Navistar, Daimler, Volvo and Paccar

3. Conducted industry expert interviews and desk research for consolidating best practices, cost drivers and opinions related to viability of NOx reduction technologies, costs and costing methodologies

4. RFI analysis, validation through discussions with OEMs and other research inputs

5. Results for incremental cost analysis, Purchase price impact and Pre-buy impact

Nine engine and truck manufacturing OEMs participated in th study for NOx reduction regulations

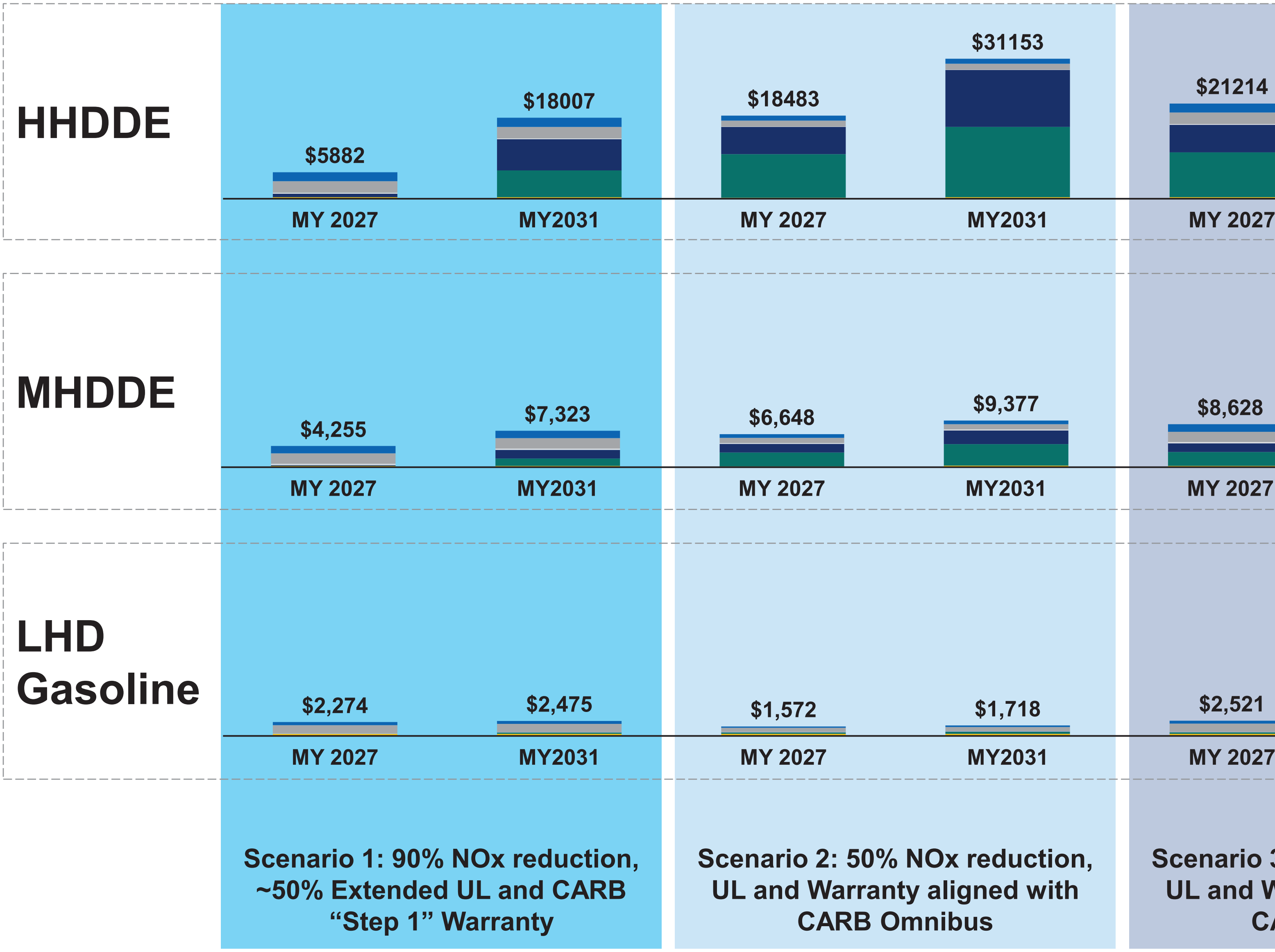
OEM participants

Contents

Incremental cost analysis for potential EPA next-tier HDOH en
MHDDE and LHD Gasoline platforms under 3 different scenar

HHDDE Class 8 > 33k lbs. 12-13L	**NOx Stringency:** 0.02g/bhp-hr. **Useful life:** MY27 - No change; MY31 - 11yr/650k mi **Warranty:** MY27 - No change; MY31 - 5yr/350k mi	**NOx Stringency:** 0.1g/bhp-hr. **Useful life:** MY27 - 11yr/600k mi; MY31 – 12yr/800k mi **Warranty:** MY27 - 7yr/450k mi; MY31 – 10yr/600k mi	**NOx Strin** **Useful life** MY31 – 12y **Warranty:** MY31 – 10y
MHDDE Class 6-7 > 19,501-33k lbs. 7-9L	**NOx Stringency:** 0.02g/bhp-hr. **Useful life:** MY27 - No change; MY31 - 11yr/270k mi **Warranty:** MY27 - No change; MY31 - 5yr/150k mi	**NOx Stringency:** 0.1g/bhp-hr. **Useful life:** MY27 - 11yr/270k mi; MY31 - 12yr/350k mi **Warranty:** MY27 - 7yr/220k mi; MY31 - 10yr/280k mi	**NOx Strin** **Useful life** MY31 - 12yr **Warranty:** MY31 - 10yr
LHD Gasoline > 14,000 lbs. 6-8L	**NOx Stringency:** 0.02g/bhp-hr. **Useful life:** MY27 - No change; MY31 - 12yr/155k mi **Warranty:** MY27 - No change; MY31 - 5yr/75k mi	**NOx Stringency:** 0.1g/bhp-hr. **Useful life:** MY27 - 12yr/155k mi; MY31 - 15yr/200k mi **Warranty:** MY27 - 7yr/110k mi; MY31 - 10yr/160k mi	**NOx Strin** **Useful life** MY31 - 15yr **Warranty:** MY31 - 10yr
	Scenario 1: 90% NOx reduction, ~50% Extended UL and CARB "Step 1" Warranty	**Scenario 2: 50% NOx reduction, UL and Warranty aligned with CARB Omnibus**	**Scenario 3** **UL and W** **CA**

HD diesel platforms will experience significant cost increase p extended UL and warranty; LHD gasoline costs predominately



Contents

Assumptions used for defining 3 scenarios for heavy heavy d platform

Assumptions for HHDDE

Assumptions	Scenario 1: 90% NOx reduction, ~50% Extended UL and CARB "Step 1" Warranty			Scenario 2: 50% NOx reducti Warranty aligned with CARE		
	MY 2027	MY 2031		MY 2027		MY
Engine and vehicle class	12-13L diesel engines; class 8 vehicles; >33k lbs. vehicle weight					
NOx stringency	@ 435k mi	@ 435k mi	435k - 650k mi	@ 435k mi	435k - 600k mi	@ 435k mi
FTP(Federal Test Procedure) (g/bhp-hr.) NOx	0.020	0.020	0.040	0.100	0.130	0.100
RMC-SET(Ramped Modal Cycle) (g/bhp-hr.) NOx	0.020	0.020	0.040	0.100	0.130	0.100
LLC(Low Load Cycle) (g/bhp-hr.) NOx	0.050	0.050	0.100	0.250	0.320	0.250
Idling (g/hr.) NOx	5	5	5	15	15	15
HDIUT(Heavy-Duty In-Use Test)	Method: 3-Bin Moving average window with cold start; Threshold: 1.5x Standards			Method: 3-Bin Moving average win start; Threshold: 1.5x Standards		
Useful life	No change from current (10yr/435k mi)	10yr/650k mi		11yr/600k mi		12yr/800k
Extended warranty	No change from current (5yr/100k mi)	5yr/350k mi		7yr/450k mi		10yr/600k

90% NOx reduction, 10yr/650k mi UL, and 5yr/350k mi extende to an incremental cost of $18.1k p.u. for HHDDEs

Scenario 1: HHDDE Incremental cost per vehicle

HHDDE: Incremental costs per vehicle: – Class 8 > 33,000 lbs. – 12-13L platform	Tech costs in 2021 $		Inflation adjusted @ 2%	
	MY 2027	MY 2031	MY 2027	MY 2031
Total incremental cost per vehicle *(relative to MY21 baseline costs)*	**$5,882**	**$18,007**	**$6,624**	**$21,951**
Direct costs	**$4,765**	**$4,765**	**$5,366**	**$5,809**
1 Engine technology	$1,989	$1,989	$2,240	$2,424
2 Aftertreatment technology	$2,588	$2,588	$2,915	$3,155
3 Vehicle side changes	$188	$188	$212	$229
Indirect costs	**$1,116**	**$13,242**	**$1,257**	**$16,142**
4 Extended useful life	$774	$6,937	$872	$8,457
5 Extended warranty of ERC	$0	$5,962	$0	$7,268
6 Research and development	$260	$260	$293	$317
7 On-board diagnostics	$41	$41	$46	$50
8 Laboratory & equipment	$36	$36	$40	$44
9 In-Use Testing	$5	$5	$6	$7

50% NOx reduction along with CARB Omnibus UL (12yr/800k (10yr/600k mi) will lead to an incremental cost of $31k p.u. for

Scenario 2: HHDDE Incremental cost per vehicle

HHDDE: Incremental costs per vehicle: – **Class 8 > 33,000 lbs.** – **12-13L platform**	**Tech costs in 2021 $**		**Inflation adjusted @ 2%**	
	MY 2027	**MY 2031**	**MY 2027**	**MY 2031**
Total incremental cost per vehicle *(relative to MY21 baseline costs)*	**$18,483**	**$31,153**	**$20,815**	**$37,975**
Direct costs	**$2,504**	**$2,504**	**$2,819**	**$3,052**
1 Engine technology	$1,110	$1,110	$1,250	$1,353
2 Aftertreatment technology	$1,311	$1,311	$1,477	$1,599
3 Vehicle side changes	$82	$82	$93	$100
Indirect costs	**$15,980**	**$28,649**	**$17,996**	**$34,923**
4 Extended useful life	$6,049	$12,682	$6,812	$15,459
5 Extended warranty of ERC	$9,739	$15,654	$10,967	$19,082
6 Research and development	$112	$224	$126	$273
7 On-board diagnostics	$36	$45	$40	$55
8 Laboratory & equipment	$39	$39	$44	$47
9 In-Use Testing	$5	$5	$6	$7

90% NOx reduction along with CARB Omnibus UL (12yr/800k (10yr/600k mi) will lead to an incremental cost of $35k p.u. for

Scenario 3: HHDDE Incremental cost per vehicle

HHDDE: Incremental costs per vehicle: – Class 8 > 33,000 lbs. – 12-13L platform	Tech costs in 2021 $		Inflation adjusted @ 2%	
	MY 2027	MY 2031	MY 2027	MY 2031
Total incremental cost per vehicle *(relative to MY21 baseline costs)*	**$21,214**	**$34,682**	**$23,890**	**$42,277**
Direct costs	**$4,765**	**$4,765**	**$5,366**	**$5,809**
1 Engine technology	$1,989	$1,989	$2,240	$2,424
2 Aftertreatment technology	$2,588	$2,588	$2,915	$3,155
3 Vehicle side changes	$188	$188	$212	$229
Indirect costs	**$16,449**	**$29,917**	**$18,524**	**$36,469**
4 Extended useful life	$6,102	$13,011	$6,872	$15,860
5 Extended warranty of ERC	$9,989	$16,268	$11,249	$19,830
6 Research and development	$262	$529	$296	$645
7 On-board diagnostics	$50	$65	$56	$79
8 Laboratory & equipment	$39	$39	$44	$47
9 In-Use Testing	$6	$6	$7	$8

Engine technologies required to meet 0.02g/bhp-hr. NOx will l incremental costs

Direct cost: Engine technology incremental cost per vehicle

All costs are in 2021 dollars ($) and incremental to MY 2021 baseline costs	Scenario 1		
	MY 2027	MY 2031	MY 20
1 Total engine technology incremental cost	**$1,989**	**$1,989**	**$1,11**
Cylinder deactivation	**$1,512**	**$1,512**	**$812**
EGR cooler bypass	**$211**	**$211**	**$117**
Other required incremental engine technologies	**$266**	**$266**	**$181**

– Cylinder deactivation and EGR cooler bypass have large ranges in incremental costs due to differences in higher stringency and durability

– Ricardo understands the need for confidentiality and feels that OEMs will adopt individual nuances in engi seen are relatively closely aligned

  – Depending on engine-out emissions of their current baseline engines, some OEMs indicated the re

  – 'Other' technologies can be characterized as ones reducing parasitic engine losses and enabling hi

Implementing SwRI's "Stage 3" aftertreatment on HHDDE plat
$2.6k p.u. increase in aftertreatment costs

Direct cost: Aftertreatment technology incremental cost

All costs are in 2021 dollars ($) and incremental to MY 2021 baseline costs	Scenario 1		
	MY 2027	MY 2031	MY 20
(2) Total after-treatment tech. incremental cost	$2,588	$2,588	$1,31
LO-SCR	$1,480	$1,480	$772
ASC + SCRs	$529	$529	$297
DOC	$0	$0	$0
DPF	$0	$0	$0
Sensors and dosing	$470	$470	$181
Other electrical components	$47	$47	$30
Advanced controls and calibration	$62	$62	$32

- Study assumed SwRI's 'Stage 3' demonstrator solution to be sufficient for meeting NOx stringency require
  solutions in this cost study. OEMs provided incremental cost data for implementing the stage 3 solution ov
- OEMs have commented that the SwRI 'Stage 3' demonstrator has not been adequately tested to meet CA
  useful life. Thus, the actual in-vehicle solution can be very different from the assumed stage 3 demonstrat
- Ricardo believes that rigorous engineering development is required to optimize after-treatment conversion
  minimizing incremental weight and cost, and each manufacturer will come to a unique specific solution tha

Vehicle design changes required to package larger AT solutic additional $188 p.u. in vehicle costs

Direct cost: Vehicle side incremental cost

All costs are in 2021 dollars ($) and incremental to MY 2021 baseline costs	Scenario 1		
	MY 2027	MY 2031	MY 20
3 Total vehicle side incremental cost	**$188**	**$188**	**$82**
Vehicle changes	**$188**	**$188**	**$82**

- Implementing a new after-treatment(AT) solution required modifications to the vehicles. Costs included he insulation. These modifications are needed to accommodate the increase in AT size and weight and assist
- Ricardo agrees there will be differences between emission reductions from the engine relative to the AT sy necessitate unique vehicle installation requirements
- OEMs have indicated that implementing 'stage 3' solution will require a significant redesign of the vehicle c vehicle redesigns have not been included in the scope of this study

Extension of UL life to 12yr/800k miles for MY31 HHDDEs will incremental cost of $13k p.u.

Indirect cost: Extended useful life incremental cost (1/2)

All costs are in 2021 dollars ($) and incremental to MY 2021 baseline costs	Scenario 1		
	MY 2027	MY 2031	MY 20
4 Total extended UL incremental cost	$774	$6,937	$6,04
Incremental cost for existing components	$0	$532	$491
R&D for extending UL of existing components	$0	$59	$53
R&D for testing and validating UL of existing components	$0	$58	$83
Replace/maintain ERC within UL	$657	$5,942	$5,29
Replace/maintain non ERCs, essential for functioning of ERCs within UL	$117	$327	$117
Other costs	$0	$18	$12

- Range of responses for extended useful life reflects some OEM's confidence in current-practice durability, validation periods will be required for MY 2031
- Incremental ERC costs to extend useful life ranges between 15% to 25% of current baseline component c components within the extended useful life period
- Depending on a OEMs amortization schedule and yearly volumes, R&D cost ranged from $2.5M - $25M
- Based on experience with similar components, Ricardo believes that 20% is a reasonable estimate for inc amortization period of R&D costs

Extension of UL life to 12yr/800k miles for MY31 HHDDEs will incremental cost of $13k p.u.

Indirect cost: Extended useful life incremental cost (2/2)

- Some OEMs are confident in their product offering and believe the extension of useful life requirements wi
- Most OEMs have determined it will be necessary to replace components within the extended useful life, ar
  - Costs include component costs, dealer labor, and markups
  - Based on the historical performance of the engine and AT components, the expected replacement f shared
- OEMs have cautioned that packaging of the final AT design can lead to significant variation in some of the

Extension of ERC warranty to 10yr/600k miles will lead to an i $16k p.u. for MY31 HHDDEs

Indirect cost: Extended warranty for ERC incremental cost

All costs are in 2021 dollars ($) and incremental to MY 2021 baseline costs	Scenario 1		
	MY 2027	MY 2031	MY 20
5 Total extended warranty incremental cost	**$0**	**$5,962**	**$9,73**
Existing ERC component reliability improvement	**$0**	**$554**	**$2,11**
ERC warranty of existing components	**$0**	**$2,203**	**$3,18**
ERC warranty costs of new components compared to baseline warranty provision	**$0**	**$1,983**	**$2,81**
Emission warranty information reporting	**$0**	**$11**	**$18**
Incremental cost for recalls	**$0**	**$1,203**	**$1,48**
Other costs	**$0**	**$9**	**$121**

– All OEMs are expecting a significant increase in total warranty replacement costs for ERC. These costs in and new components through the extended warranty periods, increased costs due to additional recalls, ar handle additional warranty/recall programs

– For incremental cost determination, most OEMs shared detailed warranty data by components while other

– Ricardo believes analysis based on existing warranty data by components provides an accurate method fo components. Warranty associated with new components need to be estimated based on experience with s

R&D costs related to NOx reduction technologies amount to a
$530 p.u. for MY31 HHDDEs

Indirect cost: R&D incremental cost (incremental to 'typical' R&D spe

All costs are in 2021 dollars ($) and incremental to MY 2021 baseline costs	Scenario 1		
	MY 2027	MY 2031	MY 20
6 Total R&D incremental cost	$260	$260	$112
Engineering costs associated with commercializing incremental technology	$14	$14	$14
Development, verification, durability, vehicle testing, customer field testing, calibration, certification and DF testing	$217	$217	$71
Cost of incorporating new procedure for Low Load Cycle	$22	$22	$23
Cost of incorporating new procedures for In-Use Testing	$3	$3	$3
Other costs	$4	$4	$1

- Majority of R&D is spent on the engineering and validation of durability and performance over an extended
- Ricardo believes the best practice is to assume additional engineering headcount and other investments a and efficiency over an extended period

OBD incremental costs are mainly for engineering to ensure s term compliance and are amortized over 4 years production

Indirect cost: On-board diagnostics incremental cost

All costs are in 2021 dollars ($) and incremental to MY 2021 baseline costs	Scenario 1		
	MY 2027	MY 2031	MY 20
7 **Total OBD incremental cost**	**$41**	**$41**	**$36**
Evaluating effectiveness of existing strategies and defining new strategies	**$4**	**$4**	**$3**
OBD strategy development and calibration for new technologies	**$21**	**$21**	**$17**
Cert demonstration tests expanded due to additional OBD monitors	**$14**	**$14**	**$12**
Other OBD related costs	**$2**	**$2**	**$3**

- Since the cost of OBD is small compared to the components themselves, and the investments required ar unit are modest
- Engineering costs for more stringent requirements with longer durability periods again constitutes majority
- Assumptions for investments in engineering range from no incremental spend or included in other categor
- Best practice is to estimate additional engineering headcount and test cell usage or CAPEX and amortize

Increased use of enhanced lab equipment will add $40 p.u. fo stringent requirements with greater durability

Indirect cost: Laboratory investments incremental cost

All costs are in 2021 dollars ($) and incremental to MY 2021 baseline costs	Scenario 1		
	MY 2027	MY 2031	MY 20
8 Total laboratory investment incremental cost	$36	$36	$39
Improved measurement capability	$16.74	$16.74	$16.7
IUT simulation (CO2-based)	$0.00	$0.00	$0.0
LLC programming	$0.18	$0.18	$0.0
Motoring dynos	$8.50	$8.50	$11.1
Test vehicles and Gen2 PEMS	$0.43	$0.43	$0.4
CVS cells	$0.12	$0.12	$0.1
Other equipment	$9.85	$9.85	$10.3

- Investments in upgraded lab equipment ranged from just under $5M to just over $6.5M
  - IUT simulation capability upgrades ranged from no investment needed to $3M; Investment for LLC OEM's required no incremental motoring dynos while others invested up to nearly $4M; PEMS equ while test vehicle costs ranged from nothing to almost $2M; CVS cells costs ranged from no additio
- Other equipment included additional certification and aging cell upgrades to electrification measurement u
- Ricardo believes lab equipment should be upgraded as needed and amortized over 4 years as best practi

In-use monitoring costs averaged $6 p.u. with some OEMs as and equipment, and others no change

Indirect cost: In-use compliance incremental cost

All costs are in 2021 dollars ($) and incremental to MY 2021 baseline costs	Scenario 1		
	MY 2027	MY 2031	MY 20
9 Total in-use compliance incremental cost	$5	$5	$5
Incremental cost of performing regulated in-use test	$0.83	$0.83	$0.8
In-use vehicle fleet operation cost	$2.38	$2.38	$2.3
Cost of acquiring the test vehicle	$0.27	$0.27	$0.2
PEMS and other monitoring system installation and monitoring	$1.15	$1.15	$1.1
Compliance monitoring and analysis	$0.23	$0.23	$0.2
Other compliance cost	$0.47	$0.47	$0.4

– Monitoring greater in-use compliance requirements required no increase from some OEMs up to $2.7M in investments from others

Contents

Assumptions used for defining 3 scenarios for medium heavy platform

Assumptions for MHDDE

Assumptions	Scenario 1: 90% NOx reduction, ~50% Extended UL and CARB "Step 1" Warranty		Scenario 2: 50% NOx reducti Warranty aligned with CARE	
	MY 2027	MY 2031	MY 2027	M
Engine and vehicle class	7-9L diesel engines; class 6-7 vehicles; 19.5-33k lbs. vehicle weight			
NOx stringency	• FTP/RMC-SET(Federal Test Procedure/Ramped Modal Cycle): 0.020 g/bhp-hr. NOx • LLC(Low Load Cycle): 0.050 g/bhp-hr. NOx • Idling: 5 g/hr. NOx • HDIUT(Heavy-Duty In-Use Test): o Method: 3-Bin Moving average window with cold start o Threshold: 1.5x Standards		• FTP/RMC-SET(Federal Test Procedure/Ramped Modal Cycle hr. NOx • LLC(Low Load Cycle): 0.25 g/bh • Idling: 15 g/hr. NOx • HDIUT(Heavy-Duty In-Use Test): o Method: 3-Bin Moving averag with cold start o Threshold: 1.5x Standards	
Useful life	No change from current (10yr/185k mi)	11yr/270k mi	11yr/270k mi	12yr/350k
Extended warranty	No change from current (5yr/100k mi)	5yr/150k mi	7yr/220k mi	10yr/280k

90% NOx reduction, 10yr/185k mi UL, and 5yr/100k mi extende to an incremental cost of $7.3k p.u. for MHDDEs

Scenario 1: MHDDE Incremental cost per vehicle

MHDDE: Incremental costs per vehicle: – Class 6-7 > 19,501-33,000 lbs. – 7-9L platform	Tech costs in 2021 $		Inflation adjusted @ 2%	
	MY 2027	MY 2031	MY 2027	MY 2031
Total incremental cost per vehicle *(relative to MY21 baseline costs)*	**$4,255**	**$7,323**	**$4,792**	**$8,927**
Direct costs	**$3,854**	**$3,854**	**$4,341**	**$4,699**
Engine technology	$1,498	$1,498	$1,687	$1,826
Aftertreatment technology	$2,082	$2,082	$2,344	$2,537
Vehicle side changes	$275	$275	$310	$335
Indirect costs	**$401**	**$3,469**	**$451**	**$4,228**
Extended useful life	$171	$1,722	$193	$2,100
Extended warranty of ERC	$0	$1,517	$0	$1,849
Research and development	$181	$181	$204	$221
On-board diagnostics	$21	$21	$23	$25
Laboratory & equipment	$24	$24	$27	$29
In-Use Testing	$4	$4	$4	$4

50% NOx reduction along with CARB Omnibus UL (12yr/350k (10yr/280k mi) will lead to an incremental cost of $9.3k p.u. fo

Scenario 2: MHDDE Incremental cost per vehicle

MHDDE: Incremental costs per vehicle: – Class 6-7 > 19,501-33,000 lbs. – 7-9L platform	Tech costs in 2021 $		Inflation adjusted @ 2%	
	MY 2027	MY 2031	MY 2027	MY 2031
Total incremental cost per vehicle *(relative to MY21 baseline costs)*	**$6,648**	**$9,377**	**$7,487**	**$11,430**
Direct costs	**$1,975**	**$1,975**	**$2,225**	**$2,408**
Engine technology	$749	$749	$843	$913
Aftertreatment technology	$1,041	$1,041	$1,172	$1,269
Vehicle side changes	$186	$186	$209	$227
Indirect costs	**$4,672**	**$7,401**	**$5,262**	**$9,022**
Extended useful life	$1,706	$2,790	$1,921	$3,401
Extended warranty of ERC	$2,810	$4,326	$3,165	$5,273
Research and development	$116	$243	$131	$296
On-board diagnostics	$11	$14	$12	$17
Laboratory & equipment	$26	$26	$29	$31
In-Use Testing	$4	$4	$4	$4

90% NOx reduction along with CARB Omnibus UL (12yr/350k (10yr/280k mi) is estimated to cause an incremental cost of $1

Scenario 3: MHDDE Incremental cost per vehicle

MHDDE: Incremental costs per vehicle: – Class 6-7 > 19,501-33,000 lbs. – 7-9L platform	Tech costs in 2021 $		Inflation adjusted @ 2%	
	MY 2027	MY 2031	MY 2027	MY 2031
Total incremental cost per vehicle *(relative to MY21 baseline costs)*	**$8,628**	**$11,494**	**$9,716**	**$14,011**
Direct costs	**$3,854**	**$3,854**	**$4,341**	**$4,699**
Engine technology	$1,498	$1,498	$1,687	$1,826
Aftertreatment technology	$2,082	$2,082	$2,344	$2,537
Vehicle side changes	$275	$275	$310	$335
Indirect costs	**$4,773**	**$7,639**	**$5,375**	**$9,312**
Extended useful life	$1,714	$2,878	$1,930	$3,509
Extended warranty of ERC	$2,810	$4,326	$3,165	$5,273
Research and development	$202	$383	$228	$467
On-board diagnostics	$17	$22	$19	$27
Laboratory & equipment	$26	$26	$29	$31
In-Use Testing	$4	$4	$4	$5

Contents

Assumptions used for defining 3 scenarios for LHD gasoline

Assumptions for LHD Gasoline

Assumptions	Scenario 1: 90% NOx reduction, ~50% Extended UL and CARB "Step 1" Warranty		Scenario 2: 50% NOx reducti Warranty aligned with CARE	
	MY 2027	MY 2031	MY 2027	MY
Engine and vehicle class	6-8L gasoline engines; >14k lbs. vehicle weight			
NOx stringency	• FTP/RMC-SET(Federal Test Procedure/Ramped Modal Cycle): 0.020 g/bhp-hr. NOx • LLC(Low Load Cycle): 0.050 g/bhp-hr. NOx • Idling: 5 g/hr. NOx • HDIUT(Heavy-Duty In-Use Test): o Method: 3-Bin Moving average window with cold start o Threshold: 1.5x Standards		• FTP/RMC-SET(Federal Test Procedure/Ramped Modal Cyc g/bhp-hr. NOx • LLC(Low Load Cycle): 0.25 g/b • Idling: 15 g/hr. NOx • HDIUT(Heavy-Duty In-Use Test o Method: 3-Bin Moving avera with cold start o Threshold: 1.5x Standards	
Useful life	No change from current (10yr/110k mi)	12yr/155k mi	12yr/155k mi	15yr/200k
Extended warranty	No change from current (5yr/50k mi)	5yr/75k mi	7yr/110k mi	10yr/160k

90% NOx reduction, 12yr/155k mi useful life, and 5yr/75k mi w incremental cost of $2.5k p.u. for LHD gas engines

Scenario 1: LHD Gas Incremental cost per vehicle

LHD Gas: Incremental costs per vehicle: – **> 14,000 lbs.** – **6-8L platform**	**Tech costs in 2021 $**		**Inflation adjusted @ 2%**	
	MY 2027	**MY 2031**	**MY 2027**	**MY 2031**
Total incremental cost per vehicle *(relative to MY21 baseline costs)*	**$2,274**	**$2,475**	**$2,561**	**$3,017**
Direct costs	**$1,923**	**$1,923**	**$2,166**	**$2,344**
Engine technology	$488	$488	$549	$595
Aftertreatment technology	$1,389	$1,389	$1,565	$1,694
ORVR (Onboard refueling vapor recovery)	$42	$42	$47	$51
Vehicle side changes	$4	$4	$5	$5
Indirect costs	**$351**	**$552**	**$396**	**$672**
Extended useful life	$0	$13	$0	$16
Extended warranty of ERC	$0	$183	$0	$224
Research and development	$304	$306	$342	$373
On-board diagnostics	$9	$10	$10	$12
Laboratory & equipment	$5	$5	$5	$6
In-Use Testing	$33	$35	$38	$43

50% NOx reduction along with CARB Omnibus UL (15yr/200k (10yr/160k mi) will lead to an incremental cost of $1.7k p.u. fo

Scenario 2: LHD Gas Incremental cost per vehicle

LHD Gas: Incremental costs per vehicle: – **> 14,000 lbs.** – **6-8L platform**	**Tech costs in 2021 $**		**Inflation adjusted @ 2%**	
	MY 2027	**MY 2031**	**MY 2027**	**MY 2031**
Total incremental cost per vehicle *(relative to MY21 baseline costs)*	**$1,572**	**$1,718**	**$1,770**	**$2,094**
Direct costs	**$995**	**$995**	**$1,120**	**$1,213**
Engine technology	$246	$246	$278	$300
Aftertreatment technology	$703	$703	$791	$856
ORVR (Onboard refueling vapor recovery)	$42	$42	$47	$51
Vehicle side changes	$4	$4	$5	$5
Indirect costs	**$577**	**$723**	**$650**	**$881**
Extended useful life	$12	$45	$14	$55
Extended warranty of ERC	$228	$338	$256	$412
Research and development	$292	$294	$329	$358
On-board diagnostics	$7	$7	$8	$8
Laboratory & equipment	$5	$5	$5	$6
In-Use Testing	$33	$35	$38	$43

90% NOx reduction along with CARB Omnibus UL (15yr/200k (10yr/160k mi) will lead to an incremental cost of $2.7k p.u. fo

Scenario 3: LHD Gas Incremental cost per vehicle

LHD Gas: Incremental costs per vehicle: – **> 14,000 lbs.** – **6-8L platform**	**Tech costs in 2021 $**		**Inflation adjusted @ 2%**	
	MY 2027	**MY 2031**	**MY 2027**	**MY 2031**
Total incremental cost per vehicle *(relative to MY21 baseline costs)*	**$2,521**	**$2,713**	**$2,839**	**$3,307**
Direct costs	**$1,923**	**$1,923**	**$2,166**	**$2,344**
Engine technology	$488	$488	$549	$595
Aftertreatment technology	$1,389	$1,389	$1,565	$1,694
ORVR (Onboard refueling vapor recovery)	$42	$42	$47	$51
Vehicle side changes	$4	$4	$5	$5
Indirect costs	**$598**	**$790**	**$674**	**$963**
Extended useful life	$12	$45	$14	$55
Extended warranty of ERC	$237	$393	$267	$479
Research and development	$304	$306	$342	$373
On-board diagnostics	$7	$7	$8	$8
Laboratory & equipment	$5	$5	$5	$6
In-Use Testing	$33	$35	$38	$43

Contents

Investments in electrification & autonomous technologies are
resources. OEMs are likely to pass regulation driven increase

Purchase price impact

1. Regulations for reducing NOx emissions, extending UL and warranty for heavy duty vehicles has significant cost ramifications

2. Historically, OEMs pass these increased costs on to customers at the point of sale

3. Pricing practices of individual OEMs and their respective costs have significant bearing on purchase pricing

4. Customers that have historically purchased extended warranty packages will experience lesser cost increases

Te

Ext

Extended

Prici

Contents

Pre-buy/No-buy scenarios historically result from the risk-ave avoiding the new technologies and higher costs resulting fro

Multitude of factors impact scale of pre-buys

Finance

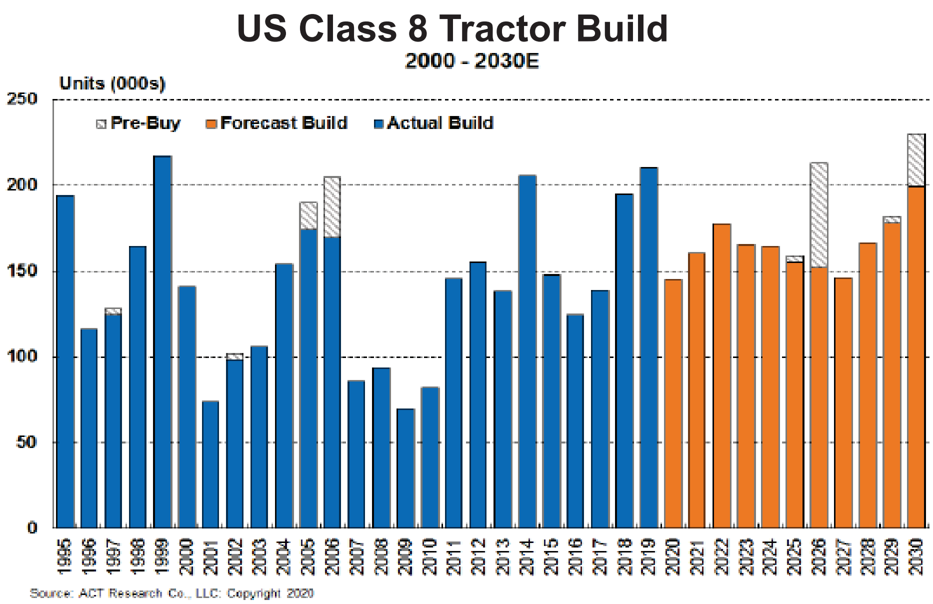
- Availability of capital
- Cost of money
- Lease vs Buy
- Tax incentives

Fleet

- Average fleet age
- Private vs Public

Vehicle

- Reliability
- Fuel economy/Co
- Maintenance cost
- Incremental purch



- Fleet owners use different strateg ultimately impacts pre-buy volum
  - E.g., Lower average fleet a with fuel-efficient trucks
- **Historical pre-buys estimates;**
  - **EPA 2004:** Resulted in high introduced during start of e buy units in 2002 and 2003
  - **EPA 2007:** Resulted in high profitability for trucking indu
  - **EPA 2010:** Significant price capacity and softer profitab 15k pre-buy units in 2008 a

Incremental costs due to increased stringency of NOx emissi extended warranty & UL requirements are expected to cause

Expected pre-buy volume as % of market

	2027		2031		2027		2031		2
	2025	2026	2029	2030	2025	2026	2029	2030	2025
HHDDE	0.67%	9.83%	2.85%	18.55%	2.09%	30.88%	2.98%	19.38%	2.40%
MHDDE	2.05%	16.13%	1.24%	4.34%	3.21%	25.20%	1.10%	3.86%	4.17%
LHD Gasoline	Estimated pre-buy volumes is lower than 1% for MY27 and MY31fo								
	Scenario 1: 90% NOx reduction, ~50% Extended UL and CARB “Step 1” Warranty				Scenario 2: 50% NOx reduction, UL and Warranty aligned with CARB Omnibus				Scena UL a

- ACT Research performed pre-buy analysis to assess the impact of CARB’s Omnibus Low NOx rulemakin trucks
- Ricardo analysis makes use of the ACT Research pre-buy analysis and scales it appropriately based on i
  - Assumes all other factors (micro or macro economic) remain the same

Incremental costs due to increased stringency of NOx emissi extended warranty & UL requirements are expected to cause

Expected pre-buy volume

	2027		2031		2027		2031		2
	2025	2026	2029	2030	2025	2026	2029	2030	2025
HHDDE	1,472	21,755	6,574	42,729	4,626	68,360	6,869	44,649	5,309
MHDDE	2,529	19,852	1,589	5,563	3,951	31,017	1,414	4,948	5,127
LHD Gasoline	Estimated pre-buy volumes is lower than 1% for MY27 and MY31fo								
	Scenario 1: 90% NOx reduction, ~50% Extended UL and CARB "Step 1" Warranty				**Scenario 2: 50% NOx reduction, UL and Warranty aligned with CARB Omnibus**				**Scena UL a**

- ACT Research performed pre-buy analysis to assess the impact of CARB's Omnibus Low NOx rulemakin trucks
- Ricardo analysis makes use of the ACT Research pre-buy analysis and scales it appropriately based on i
  - Assumes all other factors (micro or macro economic) remain the same

Low-buy phenomenon is expected in 2027 and 2031 due to ex phenomenon prior to MY2027 and MY2031 in HHDDE and MH

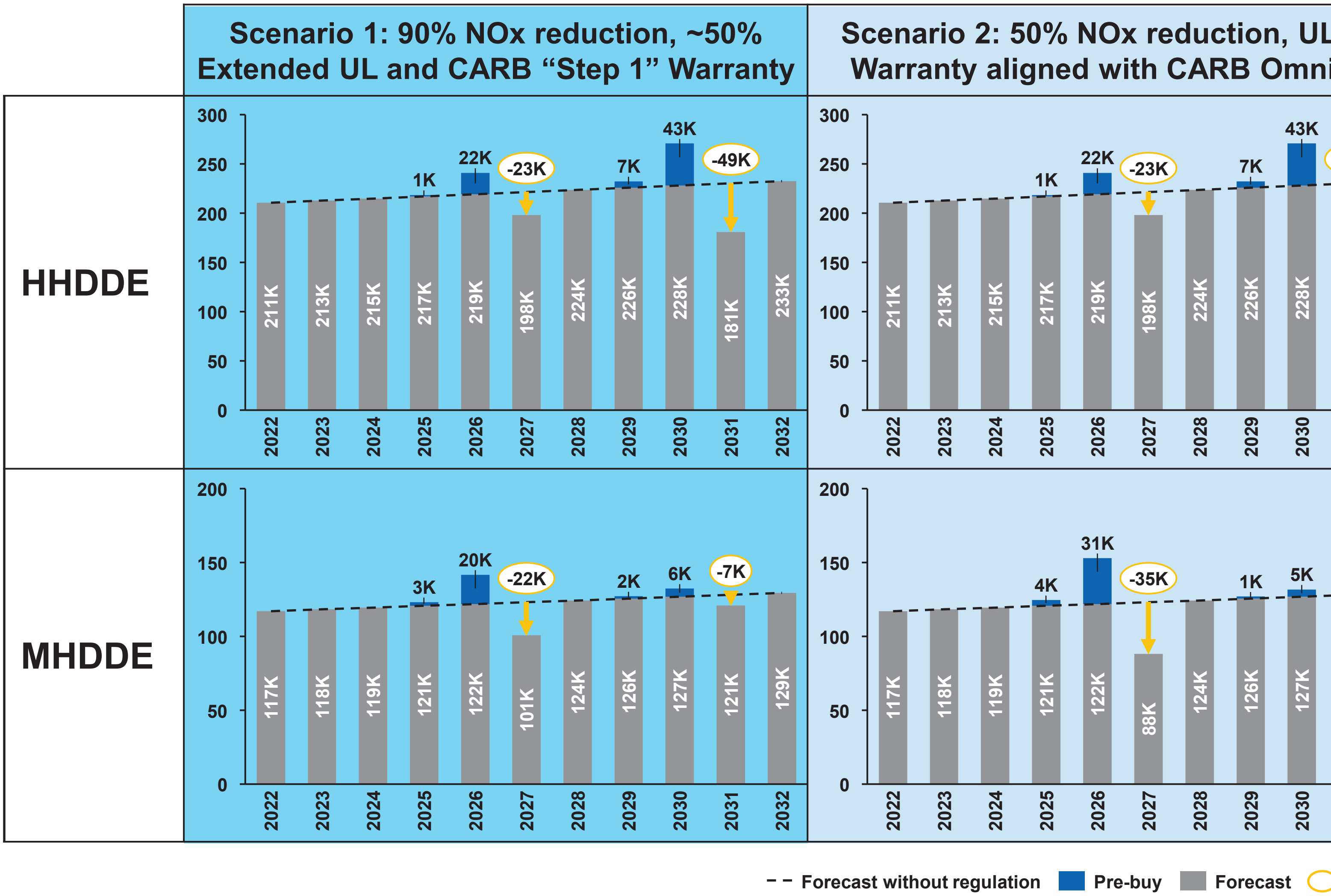
Expected low-buy volume

	2027	2031	2027	2031	2
	2027	2031	2027	2031	2
HHDDE	23,227	49,303	72,986	51,518	8
MHDDE	22,381	7,152	34,968	6,362	4
LHD Gasoline	Low-buy phenomenon not anticipated				
	Scenario 1: 90% NOx reduction, ~50% Extended UL and CARB "Step 1" Warranty		**Scenario 2: 50% NOx reduction, UL and Warranty aligned with CARB Omnibus**		**Scena UL a**

- Ricardo analysis assumes that the low-buy scale (volume) will be similar to the pre-buy and will occur in t

Pre-buy and low-buy estimates for potential next-tier EPA HD regulations in HHDDE and MHDDE segment

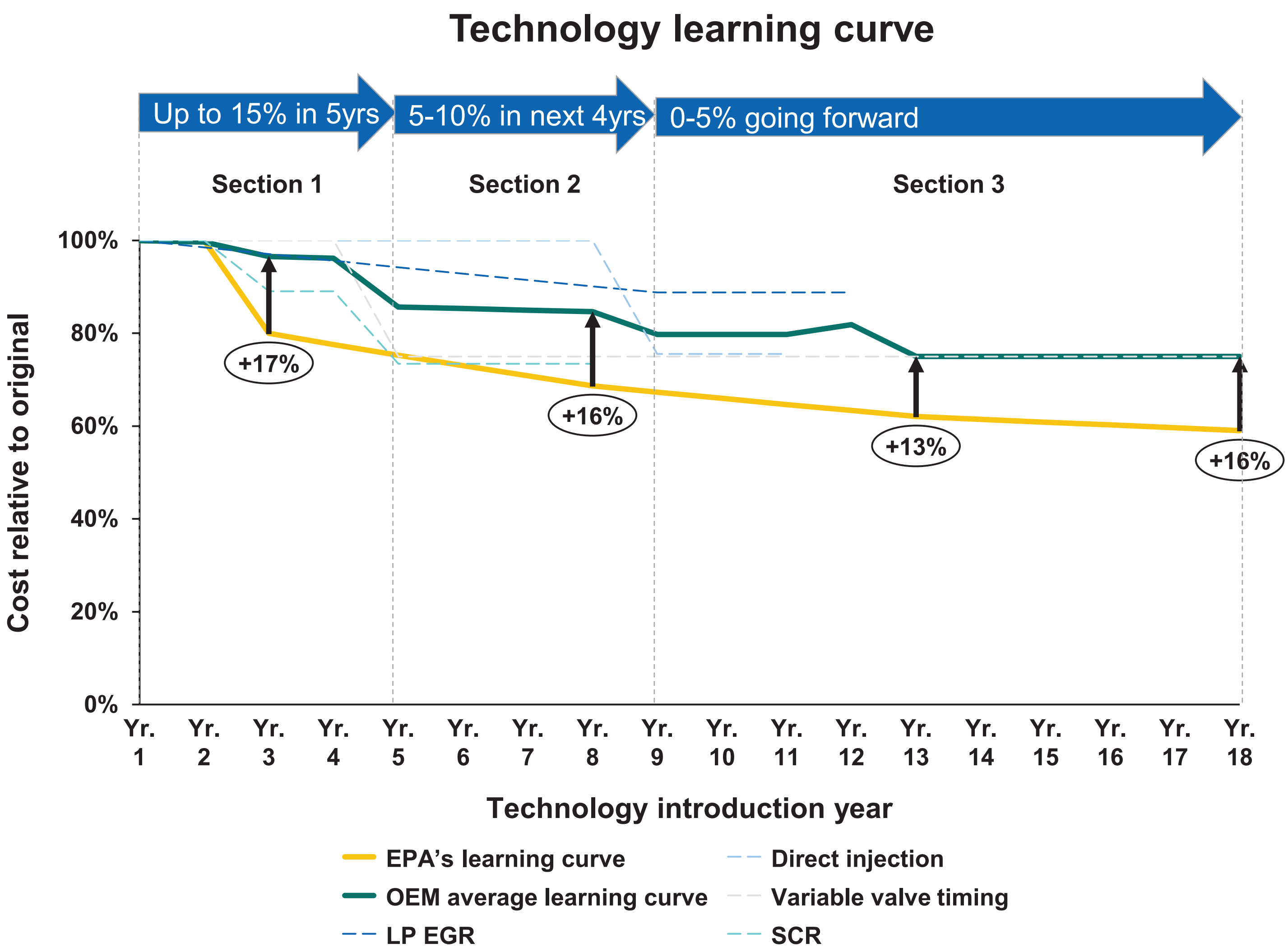
Expected pre-buy and low-buy volume



Contents

Most OEMs do not experience the steep learning cost reducti in its analysis

Technology learning curves – Actual 'new technology' cost progressi



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NERA
ECONOMIC CONSULTING

Potential Air Quality Benefits of a 90%/75% Reduction in NO_x Emissions from New Heavy-Duty On-Highway Vehicles

– Conceptual Summary of Methods and Key Results

Prepared for the Truck and Engine Manufacturers Association

August 2021

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Contents

List of Figures

List of Tables

List of Acronyms

ACE	Affordable Clean Energy
BCA	Benefit-Cost Analysis
BenMAP	Benefits Mapping and Analysis Program
CAMx	Comprehensive Air Quality Model with Extensions
C-R	Concentration-Response
EMA	Truck and Engine Manufacturer's Association
EPA	Environmental Protection Agency
FTP	Federal Test Procedure
GVWR	Gross Vehicle Weight Rating
HDOH	Heavy-Duty On-Highway
HHD	Heavy Heavy-Duty Vehicle; Class 8a and 8b Trucks (GVWR > 33,000 lbs)
LHD2b3	Light Heavy-Duty Vehicle; Class 2b and 3 Trucks ((8,500 lbs < GVWR <= 14,000 lbs)
LHD45	Light Heavy-Duty Vehicle; Class 4 and 5 Trucks (14,000 lbs < GVWR <= 19,500 lbs)
LML	Lowest Measured Level
MHD	Medium Heavy-Duty Vehicle; Class 6 and 7 Trucks (19,500 lbs < GVWR <= 33,000 lbs)
MOVES3	Motor Vehicle Simulator 3
NAAQS	National Ambient Air Quality Standards
NERA	NERA Economic Consulting
NOx	Nitrogen Oxides
OMB	Office of Management and Budget
$PM_{2.5}$	Fine Particulate Matter (that have a diameter of less than 2.5 micrometers)
RIA	Regulatory Impact Analysis

I. Introduction

The U.S. Environmental Protection Agency (EPA) has announced a "Clean Trucks Plan " (CTP) to consider lowering the current federal nitrogen oxide (NO_x) standards for heavy-duty on-highway (HDOH) trucks under the provision of the Clean Air Act that authorizes such standards. A Notice of Proposed Rulemaking for the CTP is expected to be released before the end of 2021.

Under the Clean Air Act, federal NO_x emissions standards for heavy-duty vehicles may be revised "taking costs into account,"[1] One approach for determining an appropriate cost level (and the one used by EPA in past rulemakings) is to conduct a benefit-cost analysis (BCA) of the tighter NO_x standard. Such BCAs are typically presented in the Regulatory Impact Analyses (RIAs) that EPA must prepare for every economically significant rulemaking.[2]

To obtain insight into the range of potentially justifiable tighter HDOH NO_x standards, the Truck and Engine Manufacturers Association (EMA) engaged NERA Economic Consulting (NERA) to prepare estimates of the air quality benefits that EPA is likely to be able to attribute to a tighter NO_x standard, focusing specifically on the beneficial impacts attributable to a 90% reduction in the current NO_x FTP standard, which EMA estimated could lead to a 75% reduction in the in-use NO_x emissions from new HDOH trucks. This report provides a conceptual overview of NERA's approach and a summary of the main conclusions. More technical details of the data and calculations that NERA utilized are provided in a separate NERA report being released at the same time.

In the case of an air quality regulation, such as that for a lower HDOH emissions standard, the main quantifiable benefits reported in the associated RIA are the societal value of potential improvements in health outcomes from reduced exposures of the U.S. population to the relevant ambient pollutants.[3] Typically, RIAs estimate the total benefits projected to occur in one or more specific future years, after several years of implementation and phase-in of the new emission standard. Those annual estimates are compared to estimates of the annualized incremental costs incurred in the same future years to assess the extent to which benefits are projected to exceed costs. Although there is no formal determination on this matter, one would reasonably expect that benefits must exceed costs (*i.e.*, the benefit-to-cost ratio must be greater than 1:1) in order to conclude that the regulation's costs have been appropriately taken into account (absent other offsetting or non-quantifiable impacts deemed to be a major concern).

The standard approach that EPA takes in RIAs uses several types of complex models and detailed data inputs, all of which are updated for each new regulatory analysis.[4] This is a highly complex process, and also difficult to emulate in advance of EPA's own analysis without having access to the specific updated models and data that will be used. One rarely even knows the specific future year(s) that EPA will select as the focus for its benefit and cost calculations. Therefore, a simpler and quicker approach is needed to

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[1] Clean Air Act Section 202(a)(3)(B).

[2] RIAs are required under Executive Orders for every economically significant proposed and final rulemaking of an executive branch agency, such as EPA. An economically significant rulemaking is defined as a new regulation whose costs would exceed $1 million per year. Among other required contents, RIAs must provide estimates of the potential social benefits and costs of a regulation and their implications for the net benefits of the rule. BCAs can, of course, be prepared to evaluate an appropriate cost level outside of a formal RIA, but the upcoming truck emissions rulemaking can be expected to require a formal RIA.

[3] In RIAs, the term "benefit" refers to the monetized societal value that is assigned to a physical estimate of the health risk or environmental damage reduction from a regulation.

[4] The models involved just for the benefits portion of the analysis include emissions inventories and emissions projections models such as MOVES3, 3-dimensional fate and transport models such as CAMx, and health risk analysis models such as BenMAP.

develop approximate estimates of the maximum per-truck cost that EPA might expect to be able to justify with a full BCA, in order to provide preliminary guidance on which new emission control technologies, and their associated costs, are reasonable to account for in a proposed rule.

NERA has developed such an initial and more straightforward approach, which is described in high-level terms in this report. Our "scoping" approach has been designed around the fact that it will be quicker to categorize the array of potential control technologies in terms of their total cost *per truck* than to estimate what those costs will be when projected over the entire future HDOH fleet and annualized for some specific (yet to be known) future year. The scoping approach also takes into account that if annualized incremental costs in any future year will be less than the annual benefits, then the total lifecycle cost per truck will also have to be less than the present value of the benefit that will be produced (on average) by each truck that would be affected by the rule. Thus, NERA has developed a simplified approach that gauges the potential benefits *per truck* from the assumed tighter NO_x standard. Such per-truck benefits estimates can help identify the scope of the maximum per-truck compliance cost that will be likely to pass muster under a full BCA of the proposed tighter NO_x standard.

We emphasize that the estimates we summarize in the following sections of this report reflect an effort to anticipate what the Agency would estimate if it applied its own usual assumptions and analysis methodologies. In making our estimates of NO_x reduction benefits per truck, we have used analysis input assumptions that we believe are within the range of those that EPA would likely use. Of course, we do not know what may arise with updated EPA models, data, and input assumptions, but we have sought out the most recent studies and documents on air pollutants that EPA has released. Our estimates are nevertheless subject to revision as more up-to-date information is released. The specific assumptions that we have used for the present analyses are the subject of NERA's separate technical report, while this report provides a more qualitative description of the approach and its most central results. Were we to undertake this type of benefits analysis without regard to what EPA is expected to do, it is likely that we would utilize different methods and assumptions.

II. Description of Methodology

The following are the specifics of the new anticipated federal HDOH low-NO_x standard that NERA analyzed:

- A 90% reduction in the Federal Test Procedure (FTP) standard from its current level of 0.2 g/hp-hr down to 0.02 g/hp-hr. For NERA's analysis, EMA provided the assumption that the 90% reduction in the FTP-standard would result in a 75% reduction in baseline in-use emissions for the categories of new HDOH trucks being analyzed.[5]

- Inclusion of all truck-types defined in EPA's emissions inventory model as heavy-duty-diesel and on-road. Specifically, those truck-types include long-haul and short-haul combination trucks, long-haul and short-haul single unit trucks, refuse trucks, school buses, transit buses, and intercity buses (a total of 8 types).

- Implementation of the new lower federal NO_x standard starting in 2027.

Given the above assumptions regarding the standard to be analyzed, we calculate the benefits per truck associated with a 75% reduction in those trucks' in-use NO_x emissions. The primary purpose of such a

[5] This was based on guidance from EMA that the reduction in emissions associated with a 90% FTP standard reduction would be roughly equivalent to a 75% reduction in in-use emissions.

low-NO_x emission standard would be to achieve reductions in ambient ozone and fine particulate matter ($PM_{2.5}$) to help states attain or maintain attainment with the NAAQS standards for those two pollutants. Thus, we focus our benefits calculations on the value of projected health risk reductions from the projected reductions in ambient ozone and $PM_{2.5}$ exposures across the U.S. that would result from reduced HDOH truck NO_x emissions across the U.S. due to the implementation of a tighter HDOH NO_x standard.[6] Based on a long history of such benefits calculations (by EPA and many other entities), approximately 98% of estimated health benefits from reductions in ozone and $PM_{2.5}$ is due to reductions in mortality risks. Thus, we simplified our benefit-per-truck estimates by estimating only mortality risk benefits, having confidence that this simplification has no meaningful impact on our numerical conclusions.

In order to obtain per-truck benefit estimates, we first calculate the tons of NO_x emissions reductions from an average new truck that would be purchased in 2027 meeting the tighter NO_x standard, accounting for a potential life of up to 30 years. We do this calculation for each of the 8 truck types covered by the assumed standard. That computation is carried out for each year of a truck's operational life. We assess the average truck's continued operation in each future year based on truck survival rates over time.[7] The emissions reductions in each future year are then translated into a dollar estimate of each year's health benefits using a simple "reduced form" method in which the precursor emissions changes are multiplied by a "benefit per ton" value. EPA routinely uses such an approximation when it wishes to avoid a full, complex benefits analysis.[8]

The result of this methodology is a timeline from 2027 through 2057 of annual benefits per truck in each year of the average 2027-vintage truck's operating life that varies across time (generally declining) as the truck ages. This stream of benefits is discounted to obtain the present value of benefits per truck for each of the 8 truck types. Those 8 values are then combined into a single sales-weighted average benefit-per-truck estimate. It is the latter value that can then be compared to the incremental compliance cost per truck to determine whether the costs of the regulation-driven low-NO_x technology is likely to pass a

6 In this context, the emitted NO_x is called a "precursor" emission because it contributes to the formation of ambient concentrations of ozone and $PM_{2.5}$.

7 NERA's analysis of the future emission reductions of vintage-2027 trucks extends through 2057, allowing at least some trucks in each category to last at least 30 years. However, those later-year reductions have minimal impact due to there being only a small fraction of trucks surviving that long (hence very few tons of reduction in the later years), and also because the benefits of any emissions reductions in the later years are heavily discounted. The survival rates in that dataset differ for each of the 8 truck-types, and so too in our analysis. Documentation of how we calculated the tons of reduction by year and the specific data sources is available in NERA's separate technical report.

8 A full benefit analysis requires that the specific projected precursor emissions changes be run through an air quality fate and transport model to project geographical changes of the relevant ambient pollutant concentrations. That map of pollutant concentration changes must then be run through a demographic health risk model, with the result being total benefits. The "reduced form" approach provides an approximation by conducting the full linked-model runs for a specific (but generic) number of tons of emissions reduction of a specific type of precursor, then dividing the estimated total benefits for that generic scenario by the tons of reduction. This yields an estimate of benefits stated in dollars per ton. This "benefit per ton" value is then multiplied by the tons of reduction of that precursor predicted for any of a variety of different policies to directly (but very approximately) produce an estimate of total benefits without undertaking the complex steps of another full analysis. EPA has already produced and published several "benefits per ton" estimates. Although we considered those existing estimates, NERA followed the standard reduced form estimation process described above to derive its own estimates of benefits per ton, enabling us to apply more up-to-date assumptions that we believe will be used in a full BCA, to enable us to derive more geographically disaggregated estimates of benefits per truck, and to provide a range of estimates that vary in their qualitative confidence levels. When using the same underlying epidemiological risk relationship, NERA's per-ton benefits estimates are comparable to those published by EPA. The specific methods and resulting estimates of benefits per ton are documented in NERA's separate technical report.

robust benefit-cost test. Consistent with OMB and EPA guidance, we provide benefit-per-truck estimates that are calculated using discount rates of 3% and 7%.

III. Benefit-per-Truck Estimates Prior to Confidence-Weighting

The most important input that drives the benefit-per-ton estimates, and hence the benefit-per-truck estimates, is the assumption about the increase in mortality risk per unit change in ozone and $PM_{2.5}$ concentration. That is usually based on a statistically derived association between mortality risk and observed pollutant concentrations or exposures called a concentration-response (C-R) coefficient. The assumed C-R coefficient is usually obtained from one or more of many existing epidemiological studies and associated peer-reviewed papers. EPA tends to change this mortality risk assumption as new epidemiology papers are published and as each NAAQS review cycle is conducted. We reviewed statements in EPA's recent Policy Assessments for $PM_{2.5}$ and ozone (EPA, 2020 and 2019c) as well as the current health impact functions library in EPA's risk analysis tool, BenMAP, to attempt to anticipate which assumptions EPA may adopt in future RIAs. Without commenting on the appropriateness of any such studies, we decided it would be reasonable to provide a range of estimates for each pollutant. For $PM_{2.5}$ benefits per ton, the lower end of the range is based on a low C-R coefficient for all-cause mortality risk from chronic exposures from the Di *et al*. (2017) study, and the higher end of the range is based on an alternative higher C-R coefficient estimate from the same long-term exposure risk study. For ozone, the prior ozone NAAQS review documents gave less causal credence to all-cause mortality risks than in the past, and provided no quantitative risks based on epidemiological evidence. The ozone Policy Assessment document did, however, identify several epidemiological studies of respiratory health effects for its evidence-based evaluation of potential NAAQS levels, and those C-R relationships are now also provided in the current BenMAP library of health impact functions. We therefore focused on those studies for anticipating what the Agency might use if it should include quantified ozone benefits in future RIAs. As a result, we base our range of benefit-per-truck estimates for ozone on low and high risk estimates for respiratory mortality from acute exposure from the Zanobetti and Schwartz (2008) study.

There are significant scientific uncertainties introduced when using such statistical associations from epidemiological studies to predict risks for different populations and under different air quality conditions. There are methods for identifying how the uncertainties may be reduced to derive benefits estimates having a higher degree of confidence. That is a complex issue that will be discussed in detail in the next section. However, Table 1 first presents our benefit-per-truck estimates *prior to any adjustment for confidence*. That is, the following raw per-truck benefits estimates assume that the epidemiological estimates of the increase in mortality risk per unit of ambient pollutant concentration are equally reliable no matter what the level of baseline pollutant exposures might be for the population being assessed in the risk analysis. The ranges reflect the range of point estimates across multiple epidemiological estimates (as discussed above) and should not be interpreted as evidence of statistical confidence ranges.

Table 1: National Ozone and $PM_{2.5}$-Related Benefit-per-Truck Estimates with No Adjustment for Confidence

	Ozone	$PM_{2.5}$
National Benefits per Truck (3% Discount Rate)	\$530 - \$810	\$4,650 - \$6,340
National Benefits per Truck (7% Discount Rate)	\$390 - \$590	\$3,460 - \$4,710

IV. Benefit-per-Truck Estimates with Qualitative Confidence-Weighting

As mentioned above, the mortality risk estimates for $PM_{2.5}$ and ozone are computed using statistically derived estimates of associations between ambient pollutant levels in different locations or on different days and their respective mortality rates, often summarized in the form of a C-R coefficient. The statistical methods of deriving those C-R coefficient estimates make extensive effort to control for a wide range of other drivers of mortality risk to avoid a spurious inference that a positive statistical association implies a causal relationship between the pollutant and elevated mortality risk. Nevertheless, even if there is a sufficiently "causal" relationship within the range of observed pollutant levels, any use of that unit risk estimate to predict changes in risks in different locations and under different levels of exposure necessarily involves extrapolation outside of the original range of data. Extrapolation always introduces uncertainties that are not included in any of the original study's statistical measures of confidence. The more extreme is the extrapolation that a risk analysis requires into exposure and population conditions not representative of the original study, the less qualitative confidence one would have in the derived risk estimate.

Such extrapolation can be a particular problem when using studies of air pollutant-health associations from even the relatively recent past to predict risk in a future year because of the rapid declines in pollutant concentrations that have taken place, and which are projected to continue in the future. For example, based on EPA's Air Trends dataset, the annual average concentration of $PM_{2.5}$ in the U.S. fell by about 30% even during the period 2000 to 2012 over which the mortality risk levels of the individuals studied in Di *et al*. (2017) were being observed.[9] Furthermore, the EPA air quality projection we have used in this analysis indicates population-weighted $PM_{2.5}$ levels in 2035 are expected to be about 35% lower (*before* any reductions due to a tightened HDOH NO_x standard) than the average exposures occurring during the Di *et al*. study's period. As a result, a significant fraction of the $PM_{2.5}$ health benefit estimate reported in Table 1 above requires assuming that the risk association estimated over the historically higher range of pollutant exposures in the Di *et al.* (2017) study will continue to exist when the relevant pollutant levels are far below the originally observed range. That important fact necessarily diminishes the qualitative confidence one can have in the estimates of Table 1, whether at the higher or lower end of the ranges reported in that table.

It is possible to adjust the calculated risk estimates to exclude the portions that involve the most extreme amounts of extrapolation from the original study. As the amount of extrapolation in the benefits estimate is reduced, confidence in the resulting estimate is qualitatively improved. This creates a sliding scale of benefits estimates from least confident to most confident. In contrast, the estimates shown in Table 1 above make no exclusions of the calculated risk estimates at all, allowing extrapolation of the risk relationship even where projected baseline concentrations are lower than the lowest measured level (LML) of the original study and hence represent the least confident end of the full spectrum of benefits estimates.[10]

We assess how much the benefit-per-truck estimates may be reduced if one were to constrain the degree of extrapolation outside of the range of exposures in the original epidemiological study using a sliding

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[9] See https://www.epa.gov/air-trends/particulate-matter-pm25-trends. (Based on Air Trends data, the average $PM_{2.5}$ concentration was 13.5 µg/m^3 in 2000 and 9.2 µg/m^3 in 2012. Di *et al.* used a different set of exposure data, but the paper provides only the average concentration values over all the years studied. That makes it difficult to be aware of this declining trend from the paper alone, the but average concentration reported—*i.e.,* 11.0 µg/m^3—is consistent with the average of the Air Trends data.)

[10] The Agency uses the acronym LML to denote the 0th percentile of the distribution of exposures in the original study.

confidence scale. On that sliding scale, the "more confident" end of the spectrum of mortality risk estimates is calculated by excluding those portions of the underlying risk calculations that apply the original study's risk association to baseline $PM_{2.5}$ pollutant exposures below the 25th percentile of the originally-observed range of $PM_{2.5}$ exposures. The 25th percentile of a dataset is generally viewed as the point where sparseness of observations begins to undercut the ability to determine if an average slope detected over the entire set of originally observed exposure levels remains at the lowest of those levels.

Comparison of the exposure distributions in Figure 1 and Figure 2 (below) illustrates the degree of extrapolation involved in our benefits analysis with respect to the $PM_{2.5}$ benefits estimates.

- Figure 1 shows the population-weighted frequency of observed $PM_{2.5}$ concentrations in the Di *et al*. (2017) epidemiology study (using annual average concentrations across the entire follow-up period, during 2000-2012). This shows that mean concentrations during the follow-up period of the epidemiology study were about 11 $\mu g/m^3$ and that about 75 percent of those observations were higher than about 9 $\mu g/m^3$ (*i.e.*, higher than the dotted line indicating the 25th percentile). Similarly, 95% of those observations were higher than about 6 $\mu g/m^3$ (*i.e.*, higher than the dotted line indicating the 5th percentile).

- Figure 2 depicts the population-weighted frequency of $PM_{2.5}$ concentrations in California and Rest of U.S. (which comprises the conterminous U.S. other than California) that EPA projects will occur in 2035 (which is the period in which a majority of the anticipated HDOH low-NO_x benefits will be accruing).[11] The vertical dotted lines indicate the 5th, 10th and 25th percentiles of the original Di study's pollutant observations (*i.e.*, same as in Figure 1). For the Rest of U.S., EPA has projected that the population-weighted mean $PM_{2.5}$ concentration will be about 7 $\mu g/m^3$, and (as the figure shows) about 95% of the 2035 population is projected to face exposures lower than the original epidemiological study's 25th percentile of $PM_{2.5}$ concentrations. Projected $PM_{2.5}$ levels in California are, as expected, significantly higher than in the Rest of the U.S., but even so, more than half of the 2035 California population is projected to be exposed to $PM_{2.5}$ levels lower than the 25th percentile of the original epidemiological study.

[11] These 2035 projections of $PM_{2.5}$ are based on the 12-km cell air quality grids that EPA used for its benefits analyses in EPA (2019a).

Figure 1: Range of Exposures During 2000-2012 Used in the Di *et al.* (2017) Epidemiology Study to Estimate the C-R Relationship Used for Benefits Calculations in this Analysis

(Source: Derived from data provided to EPA by the study authors, available in EPA, 2019b)

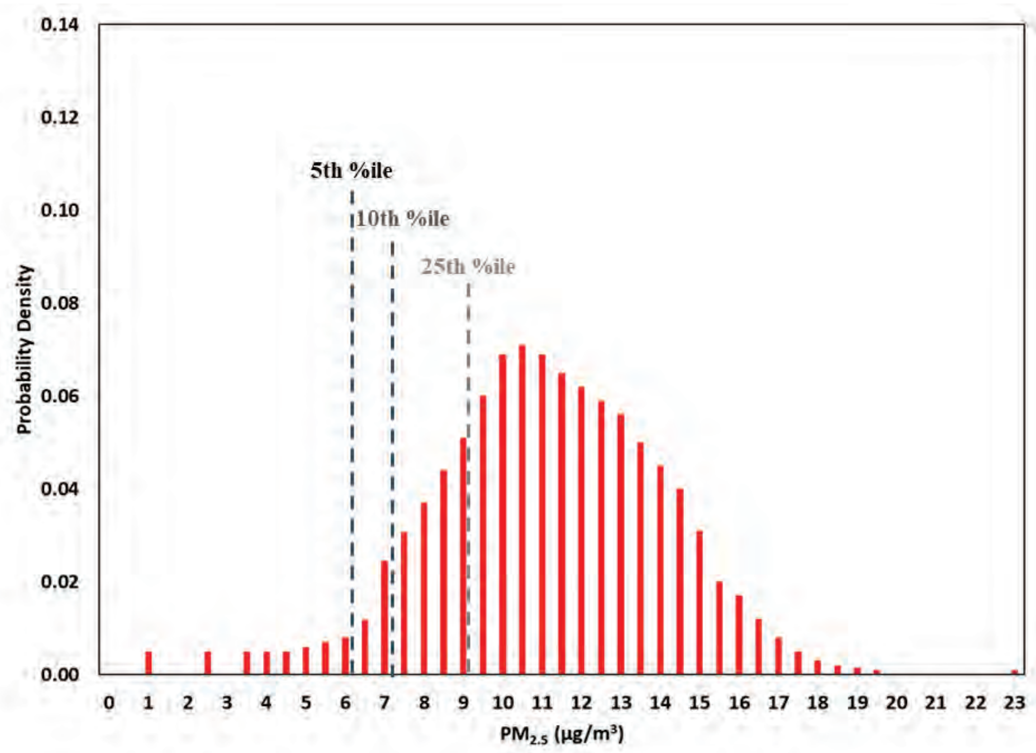
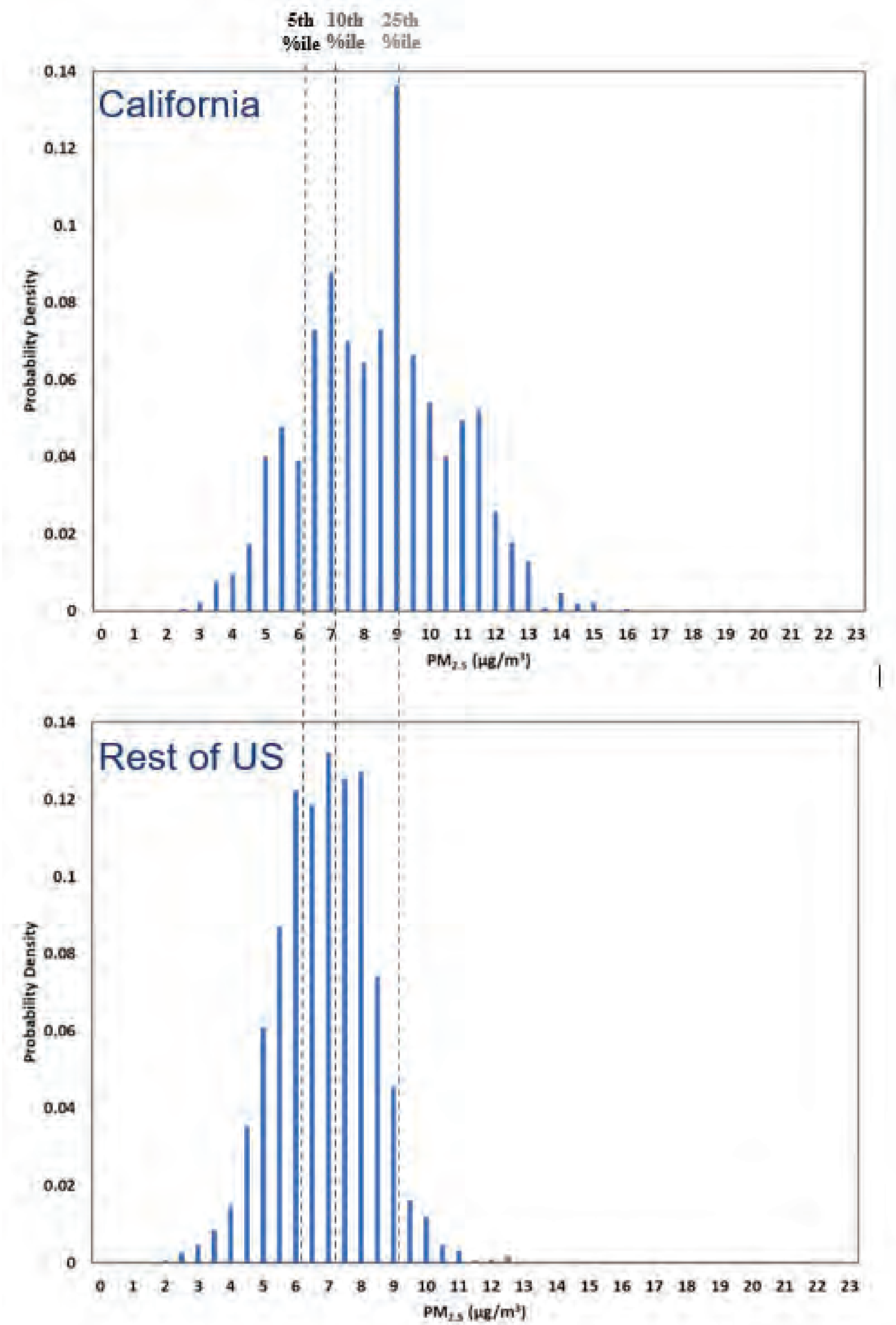


Figure 2: Distributions of $PM_{2.5}$ Concentrations Projected in 2035 (for California and Rest of U.S.) Compared to 5th, 10th, and 25th Percentiles in the Di *et al*. Study (from Figure 1).



Thus, the reliability of predicted risk reductions in our benefits analysis is affected by a significant degree of extrapolation outside of the exposure range of the original epidemiology study that provided an indication (and quantification) of a risk relationship. We next provide alternative estimates of our benefit-per-truck estimates in Table 1 that limit this extrapolation to varying degrees. In applying these confidence-weighting adjustments, we compare our $PM_{2.5}$ and ozone exposure data for the year 2035 to each respective original studies' distribution of exposures.[12]

Table 2 (below) presents our sliding scale of $PM_{2.5}$-related benefit-per-truck estimates for $PM_{2.5}$ adjusted for confidence by this method, and Table 3 presents the equivalent confidence-weighting scale for our ozone benefit-per-truck estimates. The first column in each table contains the same estimates reported in Table 1 (*i.e.,* calculated without any limitations on extrapolation in the risk calculation) and the values in the columns to the right show estimates that have increasingly higher confidence (due to progressively reduced reliance on extrapolation), up to the point where only benefits in areas with exposures at or above the 25th percentile of the original epidemiological study are included. Clearly, requiring more confidence in the benefit-per-truck estimates causes the estimates to decline since we exclude benefits that are in areas with projected baseline concentrations that are below various percentile levels of the pollutant observations in the original study (up to the 25th percentile). For instance, the unadjusted benefit-per-truck estimate of $4,650 for the lower $PM_{2.5}$ estimate (using the 3% discount rate) declines to about $650 at the "more confident" end of the exposure spectrum (*i.e.*, the lower estimate in last column of Table 2). This is a substantial reduction and suggests that the unadjusted risk estimates for future air quality based on epidemiological studies with earlier, higher exposure levels are subject to potential error because they require extrapolation outside of the epidemiological study's range of observed exposures and study populations.[13]

There is less effect of confidence-weighting on the ozone benefit-per-truck estimates. This is because ozone concentrations have not been declining and are not projected to decline in the future as much as $PM_{2.5}$. Thus, use of prior epidemiological studies to project ozone benefits in other locations and years is not as prone to extrapolation.

[12] We use the distribution in Figure 1 to develop confidence-weighted adjustments for both our lower and higher estimates of $PM_{2.5}$ benefits per truck because both are based on a risk association reported in the Di *et al*. (2017) study. We use information on the distribution of city-specific average ozone concentrations in the Zanobetti and Schwartz (2008) study for adjusting our estimates of ozone benefits per truck.

[13] The use of modeled rather than monitored $PM_{2.5}$ data in Di *et al.* (2017) raises its own risk estimation uncertainties in place of a reduction in the out-of-sample extrapolation error that we address here. We make no attempt to adjust for those other uncertainties in this analysis, as we are only attempting to emulate methods that the Agency has itself used in its prior RIAs. (We note that a large portion of the modeled exposures in Di *et al*. are lower than any of the exposures in the Agency's modeling of current U.S. $PM_{2.5}$ levels, which indicates a methodological inconsistency that merits future attention.)

Table 2: National $PM_{2.5}$ Benefit-Per-Truck Estimates (2019$) by Confidence Level and Discount Rate (Range Repor Based on Low and High C-R Estimates from Di *et al*., 2017)

Less confident | More confi

	No Adjustment	LML and Above	1st Percentile and Above	5th Percentile and Above	10th Perc and Ab
3% Discount Rate	$4,650-$6,340	$4,650-$6,340	$4,650-$6,340	$3,930-$5,360	$2,670-$
7% Discount Rate	$3,460-$4,710	$3,460-$4,710	$3,460-$4,710	$2,930-$3,980	$1,980-$

LML = Lowest Measured Level, meaning the minimum observed $PM_{2.5}$ concentration in the original epidemiological study

Table 3: National Ozone Benefit-Per-Truck Estimates (2019$) by Confidence Level and Discount Rate (Range Rep Is Based on Low and High C-R Estimates from Zanobetti and Schwartz, 2008)

Less confident | More confi

	No Adjustment	LML and Above	1st Percentile and Above	5th Percentile and Above	10th Perc and Ab
3% Discount Rate	$530-$810	$530-$810	$530-$810	$530-$810	$440-$
7% Discount Rate	$390-$590	$390-$590	$390-$590	$390-$590	$320-$

LML = Lowest Measured Level, meaning the minimum observed ozone concentration in the original epidemiological study

There is no way to select a single “best” cut-off point for limiting extrapolation uncertainties. In its 2013 $PM_{2.5}$ NAAQS decision, the Administrator discussed how insufficient confidence in the continued existence of health risk associations would arise somewhere between the 10th to 25th percentiles of a study’s range of observations. She chose to set the standard near the lowest of the 25th percentiles of available studies. Based on that precedent, one could consider choosing to limit the benefit-per-truck estimates to those occurring in locations with exposures at or above the 25th percentile. In that case, our analysis indicates that the national average total benefits per truck *might be between $900 and $1,270* if using a 3% discount rate.[14] It would be somewhat lower if using a 7% discount rate. If one were instead to use the 10th percentile as the confidence cut-off, our analysis indicates that the national average total benefits per truck *might be between $3,110 and $4,310* if using a 3% discount rate, and somewhat lower still if using a 7% discount rate.[15]

The main conclusion is that a national average estimate of the combined $PM_{2.5}$ and ozone benefits per truck that includes adjustments for extrapolation-related uncertainties consistent with prior Administrator judgments would not likely exceed $4,500 per truck.

The above statement is based on a national average estimate of benefits, which is the typical way that EPA conducts its BCAs. Note, however, that Figure 2 shows significant differences in the projected $PM_{2.5}$ concentration distributions that are projected to exist between California and Rest of U.S. This suggests that there could be significantly different patterns in the confidence that this method would assign to the benefit-per-truck estimates for those two regions. It also suggests that even the raw (unadjusted) benefit per truck might be significantly higher for trucks operating in California than for those outside of California.

To understand this better, we have recomputed our benefits-per-truck for California and for the Rest of the U.S. separately. The results, including respective effects of confidence-adjustments, are provided in Table 4 (for $PM_{2.5}$) and Table 5 (for ozone). Those tables highlight the wide disparity in the benefit-per-truck estimates that exist for the two regions, *with total per-truck benefits possibly as high as $14,650 in California* even with a moderate confidence adjustment (*i.e.*, using the 10th percentile cut-off and a 3% discount rate), *while the equivalent per-truck benefits for the Rest of U.S. would likely not exceed $3,290*.[16]

[14] This range includes both ozone and $PM_{2.5}$ benefits and is the sum of the values in the last column of Tables 2 and 3.

[15] This is computed by summing the values in the penultimate columns of Table 2 and Table 3.

[16] These estimates sum the respective values in the penultimate columns of Table 4 and Table 5.

**Table 4: Geographically Disaggregated $PM_{2.5}$ Benefit-Per-Truck Estimates (2019$) by Confidence Level and Disc
Each Confidence Level Is Based on Low and High C-R Estimates from Di *et al*., 201**

	No Adjustment	LML and Above	1st Percentile and Above	5th Percentile and Above	10th Perc and Ab
3% Discount Rate					
California	$9,330-$12,700	$9,330-$12,700	$9,330-$12,700	$8,870-$12,080	$7,880-$1
Rest of U.S.	$4,260-$5,810	$4,260-$5,810	$4,260-$5,810	$3,510-$4,780	$2,190-$
National	$4,650-$6,340	$4,650-$6,340	$4,650-$6,340	$3,930-$5,360	$2,670-$
7% Discount Rate					
California	$6,820-$9,290	$6,820-$9,290	$6,820-$9,290	$6,490-$8,840	$5,760-$
Rest of U.S.	$3,180-$4,330	$3,180-$4,330	$3,180-$4,330	$2,620-$3,560	$1,640-$
National	$3,460-$4,710	$3,460-$4,710	$3,460-$4,710	$2,930-$3,980	$1,980-$

LML = Lowest Measured Level, meaning the minimum observed $PM_{2.5}$ concentration in the original epidemiological study

Table 5: Geographically Disaggregated Ozone Benefit-Per-Truck Estimates (2019$) by Confidence Level and Disc
Each Confidence Level Is Based on Low and High C-R Estimates Zanobetti and Schwartz

	No Adjustment	LML and Above	1st Percentile and Above	5th Percentile and Above	10th Perc and Ab
3% Discount Rate					
California	$2,920-$4,480	$2,920-$4,480	$2,920-$4,480	$2,920-$4,480	$2,560-$
Rest of U.S.	$250-$390	$250-$390	$250-$390	$250-$390	$190-$
National	$530-$810	$530-$810	$530-$810	$530-$810	$440-$
7% Discount Rate					
California	$2,140-$3,280	$2,140-$3,280	$2,140-$3,280	$2,140-$3,280	$1,870-$
Rest of U.S.	$190-$290	$190-$290	$190-$290	$190-$290	$150-$
National	$390-$590	$390-$590	$390-$590	$390-$590	$320-$

LML = Lowest Measured Level, meaning the minimum observed ozone concentration in the original epidemiological study

V. Conclusion

If a BCA is to be used to assess the level of cost that might be warranted to implement a tighter HDOH NO_x standard, it is reasonable, as an initial scoping exercise, to attempt to assess the maximum lifecycle cost per truck that might be justifiable before a specific HDOH standard is proposed and a more complex, resource-intensive full BCA is prepared. Having such *ex ante* scoping insights can help guide regulators towards regulatory proposals that will readily pass the more rigorous BCA test. To that end, NERA has developed rough estimates of the potential per-truck lifecycle benefits that one might expect to result from such a complete BCA and has addressed issues of confidence that might be associated with such estimates. Our analysis has limitations but has been based on data and studies that are currently available and has taken into consideration the current status of Agency discussions regarding the health risks driving $PM_{2.5}$ and ozone NAAQS decisions. In this report, we have explained our approach at a conceptual rather than technical level. The many assumptions that we have used, and the studies and data that we applied to set those assumptions, are documented in a separate technical report.

The goal of our analysis has been to develop approximate estimates of the per-truck lifecycle benefits associated with a 90% reduction in the FTP NO_x standard for HDOH trucks, and a corresponding 75% reduction in in-use NO_x emissions. We emphasize that the estimates we report here reflect an effort to anticipate what the Agency itself would estimate if it applied its own usual assumptions and analysis methodologies in a formal RIA, expected to be released later in 2021. We also note that our estimates have been based on data and modeling that the Agency has released in the past. Those will probably be replaced by updated information developed as part of the upcoming HDOH RIA. As there is no publicly available information on the nature of such updates, our present estimates are imprecise and subject to revision as such updated information becomes available. As noted above, were we to undertake this type of benefits analysis without regard to what we anticipate EPA is likely to do, it is likely that we would utilize different methods and assumptions.

We find that, *prior to any confidence weighting*, the Agency might determine that a 90% reduction in the FTP NO_x standard for HDOH (with a corresponding 75% reduction in-use NO_x emissions) would result in national average benefits per truck for 2027 model year trucks in the range of (roughly) \$5,200 to \$7,200 (for $PM_{2.5}$ and ozone combined). When confidence-adjusted for the multiple uncertainties associated with statistical extrapolations from the underlying epidemiological evidence of health risks, the Agency might project national average total per-truck benefits of about \$4,300 at the 10^{th} percentile exposure cut-off. This suggests that a NO_x-control technology to achieve the estimated HDOH NO_x reductions would need to cost less than about \$4,500 per truck to pass a robust benefit-cost test.

Extensive changes are now expected to occur in the mix of HDOH trucks that will be sold in the future, with a potentially significant transition away from ignition-based power trains to electric or fuel-cell trucks. Our analysis of the *per-truck* benefits before any confidence-weighting will not be affected by such a change, but this transition might lower the baseline future $PM_{2.5}$ and ozone concentrations and thus increase the degree of extrapolation, resulting in some lowering of confidence-weighted estimates. More importantly, however, such a transition might have more effect on the per-truck *cost* to which our benefits estimates ought to be compared. That is, the total investment costs of developing, designing, and retooling to meet a tighter HDOH diesel NO_x standard need to be spread over all of the affected fleet; if the projected size of the future fleet of diesel trucks is much reduced, the estimate of the cost *per truck* for use in a scoping analysis should be adjusted upwards accordingly.

In conducting this scoping analysis, we also noted that ozone benefits per ton were much higher for California than the rest of the U.S. We have thus also provided per-truck benefits estimates for California and separately for the Rest of the U.S.[17] In this disaggregated analysis, we estimate that EPA's future analyses might estimate per-truck benefits for trucks operating in California as high as $17,180 at the least-confident level, and as high as about $14,650 for a relatively moderate degree of increased confidence (*i.e.,* at the 10th percentile exposure cut-off). At the same time, of course, the equivalent benefit-per-truck estimates for Rest of U.S. would be reduced to about $6,200 (least confidence) and to about $3,290 (greater confidence). Although this finding could be used to justify a tighter standard for California trucks than for the rest of the U.S., it would be inappropriate to use the higher California-specific benefits estimates in a benefit-cost analysis of a standard that would be applied to other states.

In all the numerical summaries in the paragraphs above, we rely on the 3% discount rate and the higher end of our $PM_{2.5}$ benefits ranges, which are the combination of assumptions that produces the highest benefits estimates. Use of a 7% discount rate generally reduces the per-truck benefits by about 25%. We also note that our analysis has assumed, based on input from EMA, that a 90% reduction in the FTP standard would reduce *in-use* HDOH NO_x emissions by75%. NERA offers no opinion on what the correct in-use reduction percentage should be, but it would be straightforward to make adjustments to accommodate alternative assumptions. For example, if one expects *in-use* emissions to be reduced by the full 90% of the FTP standard's reduction, the benefit-per-truck estimates could increase by about 20%.

Finally, it should be noted that the benefits estimates we report are conservative or, stated differently, weighted to the high side. That conservative approach stems from the fact that in conducting our analyses we have assumed that: there is no exposure threshold to $PM_{2.5}$ or ozone below which mortality effects are no longer evident; it is still appropriate to include benefits associated with ozone-related mortality impacts; the slope of the C-R function for mortality is linear; it is appropriate to account for and credit potential health effects benefits at exposure levels below the NAAQS for $PM_{2.5}$ and ozone; the statistical associations observed in the relevant epidemiological studies between exposure to air pollution and mortality effects are sufficient to infer causality, notwithstanding unresolved issues relating to manipulative or interventional causation; and it is appropriate to assess quantified benefits values at the 10th percentile of the exposure levels at issue in the underlying epidemiological studies, as opposed to utilizing a cut-point at the 25th percentile of exposures. Applying different assumptions regarding any of the foregoing points would lead to a reduction in the calculated benefits estimates.

[17] The latter estimate is for the average over the 47 other conterminous U.S. states.

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Potential Air Quality Benefits of a 90%/75% Reduction in NO_x Emissions from New Heavy-Duty On-Highway Vehicles

– Technical Details of Analysis and Assumptions

Prepared for the Truck and Engine Manufacturers Association

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Contents

List of Figures

List of Tables

List of Acronyms

ACE	Affordable Clean Energy
BCA	Benefit-Cost Analysis
BenMAP	Benefits Mapping and Analysis Program
CAMx	Comprehensive Air Quality Model with Extensions
C-R	Concentration-Response
EMA	Truck and Engine Manufacturer's Association
EPA	Environmental Protection Agency
FTP	Federal Test Procedure
GVWR	Gross Vehicle Weight Rating
HDOH	Heavy-Duty On-Highway
HHD	Heavy Heavy-Duty Vehicle; Class 8a and 8b Trucks (GVWR > 33,000 lbs)
LHD2b3	Light Heavy-Duty Vehicle; Class 2b and 3 Trucks ((8,500 lbs < GVWR <= 14,000 lbs)
LHD45	Light Heavy-Duty Vehicle; Class 4 and 5 Trucks (14,000 lbs < GVWR <= 19,500 lbs)
LML	Lowest Measured Level
MHD	Medium Heavy-Duty Vehicle; Class 6 and 7 Trucks (19,500 lbs < GVWR <= 33,000 lbs)
MOVES3	Motor Vehicle Emission Simulator 3
NAAQS	National Ambient Air Quality Standards
NERA	NERA Economic Consulting
NO_x	Nitrogen Oxides
OMB	Office of Management and Budget
$PM_{2.5}$	Fine Particulate Matter (that have a diameter of less than 2.5 micrometers)
RIA	Regulatory Impact Analysis

I. Introduction

This report provides a description of the data, assumptions and modeling that NERA Economic Consulting (NERA) conducted in its analysis for the Engine and Truck Manufacturers Association (EMA) of the potential per-truck air quality benefits of a possible tightening of the NO_x emissions standard for heavy-duty on-highway (HDOH) trucks. This report serves as a technical supplement to a separate NERA report subtitled *Conceptual Summary of Methods and Key Results* (hereafter called the "Summary Report") that provides a policy-oriented discussion of the purpose of the analysis and summarizes key results. In addition to documenting the analysis steps in more technical detail, this report provides a more disaggregated view of the key results. We recommend that one first read the Summary Report, as that contains more general background on the context for this analysis and its policy implications than what is found in this technical documentation.

II. Objective of This Analysis

As discussed in the accompanying Summary Report for this study, past practice of the U.S. Environmental Protection Agency (EPA or the Agency) in implementing Clean Air Act provisions regarding truck emissions standards suggests that any proposal for a tightening of those standards will need to have estimated benefits that exceed its estimated costs. That is usually demonstrated though a benefit-cost analysis (BCA) that is documented in a regulatory impact analysis (RIA) that the Agency must prepare for every economically significant rulemaking. The approach that EPA typically follows in RIAs to estimate national health benefits of regulations affecting ambient air quality such as fine particulate matter ($PM_{2.5}$) and ozone includes several steps:

A. Estimating the incremental emission reductions from implementation of the regulation (and their geographical locations);
B. Estimating the ambient ozone and $PM_{2.5}$ changes across the U.S. as a result of the reduction in emissions;
C. Estimating the population-wide health risk improvements from lower ambient ozone and $PM_{2.5}$ concentrations; and
D. Estimating the societal value in dollars of the estimated health risk improvements – which are referred to as the potential "benefits" of the regulation.

In RIAs, those benefit calculations are typically carried out for a specific future calendar year (usually when the regulation in question is fully implemented) and are compared to estimates of the annualized costs at that point in time.[1] That is a complex and resource-intensive type of analysis that requires specific assumptions about the evolution of markets affected by the regulation (such as the projected future demand for trucking services). Without knowledge of those baseline assumptions, and which specific year will be analyzed, it is not possible to approximate the specific benefits estimates that will be reported in a future RIA. Even if this could be done, the results would provide little insight without a comparable estimate of the total annualized regulatory costs in that particular year – also a complex calculation. However, it is important to develop some rough understanding of the incremental lifecycle cost of a new truck that is likely to pass a RIA's benefit-cost test before anchoring a rulemaking process around a particular degree of stringency. A scoping analysis is therefore valuable to undertake in the

[1] Less frequently, RIAs compute benefits and costs as present values over the duration of the policy implementation period. The analysis we describe in this report is relevant to that type of benefit-cost comparison as well.

preliminary stage of rulemaking, before any specific new standard levels are ready to be proposed. NERA's analysis, documented here, was developed for use in such a scoping exercise.

In developing a simpler analysis method that could produce such scoping-level insights, NERA noted that preliminary information on a new standard's potential cost will be available in the form of its impact on the lifecycle cost per new truck. We also note that if the annual benefits of that new standard will be able to pass a BCA in any future year, then the benefits that each individual truck is likely to provide over its operational lifespan also will need to exceed the incremental costs of that truck, or, at least, that this net benefit condition will be achieved on average over all new trucks. Thus, NERA has prepared an initial scoping analysis that estimates of the present value of benefits over the operating life of an average new truck purchased in 2027 (the first year that the anticipated standard is likely to be binding) that meets a hypothetical 90% reduction in the NO_x FTP emissions standard. Those per-truck benefits estimates can then be compared to per-truck compliance costs to obtain preliminary insight on whether that particular standard is likely to pass a full BCA.

We emphasize that the estimates we have made in this analysis reflect an effort to anticipate what the Agency would estimate if it applies its own usual assumptions and analysis methodologies. That is, we have used analysis input assumptions that we believe are within the range of those that EPA would likely use. Of course, we do not know what may arise with updated EPA models, data, and input assumptions, but we have sought out the most recent studies and documents on air pollutants that EPA has released. Our estimates are nevertheless subject to revision as more up-to-date information is released. Were we to undertake this type of benefits analysis without regard to what EPA is expected to do, it is likely that we would utilize different methods and assumptions.

III. Overview of Methodology

The process by which we estimate per-truck benefits is summarized in this section. The remaining sections of this report then describe the data, assumptions and models we have used for each step of the process.

First, we calculate the tons of NO_x emissions reductions over time from new trucks that meet the tighter NO_x standard, if purchased in 2027. (We assume all model year 2027 trucks will fully meet the hypothetical 90% FTP standard reduction, which, based on assumptions provided by EMA, will yield 75% reductions in in-use emissions). Recognizing that some of the new trucks will operate longer than others, we consider the average tons across all new trucks expected to be purchased in 2027 for each year over a potential life of up to 30 years (*i.e.*, through 2057). That calculation is carried out for each of the eight truck types covered by the assumed standard.[2]

Next, the per-truck emissions reductions in each future year are translated into a dollar estimate of each year's health benefits using a simple "reduced-form" method in which the precursor (*e.g.*, NO_x) emissions changes are multiplied by an estimated "benefit-per-ton" value. The result of this calculation is a timeline from 2027 through 2057 of annual benefits per truck in each year of the average 2027–vintage truck's operating life.

That stream of benefits then is discounted to obtain the present value of benefits per truck for each of the eight truck types. Those eight values are combined into a single sales-weighted average benefit-per-truck

[2] These eight truck types correspond to regulatory class IDs - 41 (LHD2b3), 42 (LHD45), 46 (MHD), 47 (HHD), 48 (Urban Bus), 49 (Glider Vehicles) per EPA's emissions inventory model (MOVES3) documentation (https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1011TF8.pdf).

estimate.[3] Consistent with OMB and EPA guidance, we provide benefit-per-truck estimates that are calculated using annual discount rates of 3% and 7%.

Finally, we calculate how these per-truck benefits are affected by changing the allowed extent of extrapolation from original health effects studies, providing a sliding scale of the per-truck benefits estimates with different degrees of qualitative confidence. We refer to this process as "confidence-weighting."

The resulting scale of estimates with varying degrees of confidence weights represents our scoping-level estimate of the average lifecycle benefits per truck; they can then be compared to estimates of the incremental per-truck compliance cost to determine whether that anticipated standard is likely to pass a benefit-cost test after a more detailed BCA.[4]

IV. Calculation of Reduction in Tons Emitted

To obtain estimates of the tons of NO_x reduced per truck, we relied on EPA's mobile source emissions model, MOVES3. Those calculations were done by truck type and by state for each state of the conterminous U.S. states (excluding the District of Columbia). We used the MOVES3 data to estimate how long the average truck purchased in 2027 is expected to continue to operate, and to quantify the average operational characteristics of the still-operating trucks as a function of truck age.

Specifically, for each of the eight heavy-duty truck types, we tracked a set of 100 new hypothetical vehicles purchased in 2027 and used the MOVES3 assumptions regarding the percent of vehicles surviving through each of the next 30 years, the average miles the surviving trucks are driven in each year (which is age-dependent), and their associated baseline (current standard) NO_x emissions.[5] Each year's reduction in tons of NO_x per truck was then calculated as a 75% reduction from the respective year's baseline NO_x emissions (*i.e.*, the sum of baseline NO_x emissions from all operational modes), divided by the number of vehicles surviving in that year. This computation was carried out in each year of the truck's assumed operational life to obtain tons of NO_x reduced per truck by year.

Figure 1 illustrates the resulting estimate of reduction in NO_x emissions for an average model-year 2027 truck in each year of its operational life.[6] Those reductions decline as the trucks age because in each year

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[3] We weighted the present value estimate of the per-truck benefit obtained for each of the eight truck types by the new vehicle sales in 2027 for each of the truck types projected in MOVES3.

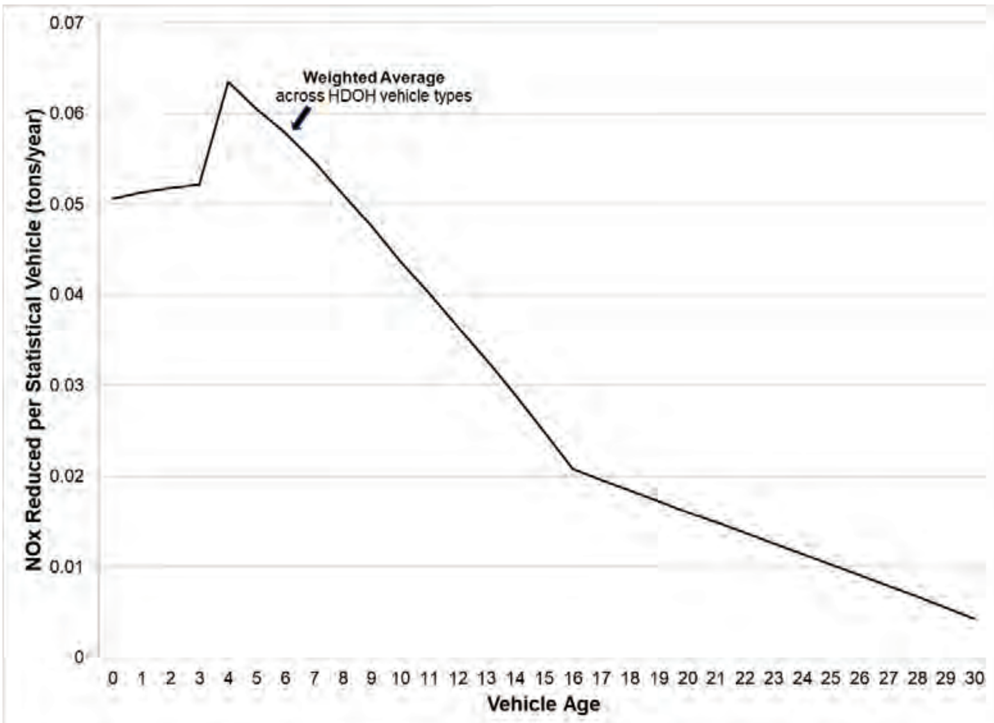
[4] Extensive changes are now expected to occur in the mix of HDOH trucks that will be sold in the future, with a potentially significant transition away from ignition-based power trains to electric or fuel-cell trucks. Our analysis of the *per-truck* benefits before any confidence-weighting will not be affected by such a change, but this transition might lower the baseline future $PM_{2.5}$ and ozone concentrations and thus increase the degree of extrapolation, resulting in some lowering of confidence-weighted estimates. More importantly, however, such a transition might have more effect on the per-truck *cost* to which our benefits estimates ought to be compared. That is, the total investment costs of developing, designing, and retooling to meet a tighter HDOH diesel NO_x standard need to be spread over all of the affected fleet; if the projected size of the future fleet of diesel trucks is much reduced, the estimate of the cost *per truck* for use in a scoping analysis should be adjusted upwards accordingly.

[5] The baseline NO_x emissions for each HDOH truck analyzed were calculated for each of the operational modes (running exhaust, start exhaust, extended idle exhaust, and auxiliary power exhaust) which were then summed up to yield the total baseline NO_x emissions. The baseline emissions from running exhaust were calculated using running exhaust emission rates (specified in units of grams of NOx/hr) and the number of hours the truck was operating in running exhaust mode. The baseline emissions from the other operational modes – start exhaust, extended idle exhaust, and auxiliary power exhaust – were calculated using their respective emissions rates (specified in units of grams of NOx/vehicle) and the number of vehicles operating in that year.

[6] The weights used to compute the average across the different HDOH vehicle types analyzed are the projected new vehicle sales for each of the truck types from MOVES3 in 2027.

some of the trucks are removed from service, and trucks that are still in service are used less intensively as they age. The estimated annual reduction in NO_x emissions per "statistical" vehicle ranges from a low of 0.004 tons at age 30 to a high of 0.063 tons at age 4.

Figure 1: NO_x Emissions Reduced per Statistical Vehicle (Average per Year per Vehicle)



We also used MOVES3 to estimate the aggregate annual reductions in NO_x emissions across the lower-48 states that would result from implementation of the tighter NO_x standard in every model year from 2027 through 2057. That result could be of use if one were to conduct an analysis of benefits for specific future years rather than on the per-truck basis that is the focus of this scoping analysis.

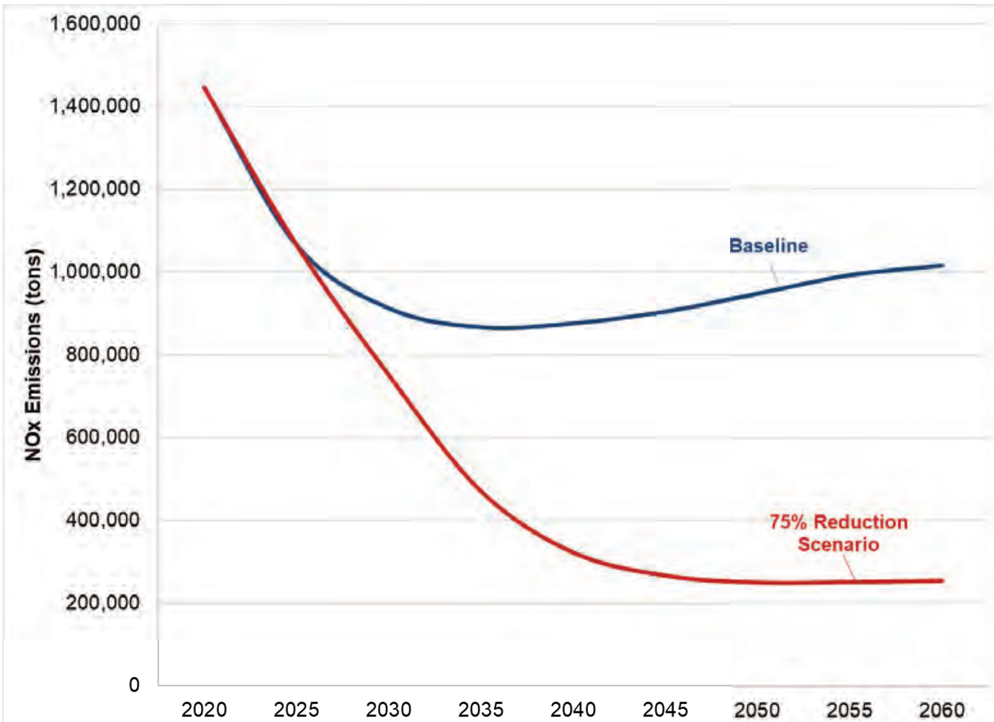
To compute the total annual tons of reduction over time, we extracted projected baseline NO_x emissions from MOVES3 for each of the eight truck-types and all operational modes by state and by year from 2020 through 2050. To calculate the reductions in NO_x emissions, we reduced the baseline emissions across all the eight truck types by 75% in each year from 2027 onwards (where 2027 is the year in which the tighter NO_x standard is assumed to be implemented).[7]

The aggregated results are shown in Figure 2, while the results for each individual state are provided in Appendix A. The total baseline emissions across the U.S. for the eight HDOH truck types analyzed are

[7] To keep the analysis simple, we did not apply any phase-in period for the standard. However, the effect of the standard (a 50% reduction in in-use emissions across the entire fleet), does take time to emerge as the standard is not applied to trucks purchased prior to 2027. Those pre-2027 trucks are assumed to remain in the fleet without any changes in their baseline operational or turnover assumptions.

projected to reach about 1.02 million tons by 2060, while emissions under the assumed scenario (*i.e.*, with implementation of a 90% tighter NO_x FTP standard that provides 75% reduction in in-use emissions) are projected to reach about 0.25 million tons by 2060. Thus, by 2060 the annual reduction in NO_x emissions projected from the affected HDOH diesel trucks is projected to be about 0.75 million tons.[8]

Figure 2: Baseline and Scenario Emissions Across All HDOH Truck Categories



V. Development of Benefit-per-Ton Values and Benefit-per-Truck Estimates

A benefit-per-ton value measures the projected health benefits associated with projected changes in precursor emissions (*e.g.*, NO_x). The approach typically employed to compute those estimates involves running specific projected precursor emission changes through a full air quality fate-and-transport model (*e.g.*, CAMx) to project spatial changes in the relevant ambient pollutant concentrations. Those pollutant concentration changes are then provided as input to a demographic health risk analysis model (*e.g.*, BenMAP), along with specific assumptions about the concentration-response (C-R) relationship and social value per health effect incident to produce total monetized benefits. Those total benefits are then

[8] This aggregate reduction assumes the current MOVES3 baseline of sales of HDOH diesel trucks. If that baseline does not reflect the significant transition away from ignition-based power trains to electric and fuel cell power trains that is now widely expected to occur over the same time period, it overstates the total tons of reduction that a new NO_x HDOH standard for diesel trucks will actually produce. While it would not affect the *per-truck* benefits estimates prior to any confidence-weighting adjustments, it could cause overstatement of the estimates on the higher-confidence end of our scale of results, because a lower baseline of emissions would imply greater amounts of extrapolation, as explained in more detail in the Summary Report.

divided by the assumed change in tons of the precursor emission to yield a benefit-per-ton estimate stated in dollars.

This is called a "reduced-form" benefits estimate. The Agency and other groups often approximate total benefits of a potential emissions-reduction action by simply multiplying an available (and relevant) benefit-per-ton value by the number of tons of emissions reduction associated with that action. While subject to heightened uncertainty and inaccuracy, this approach avoids the great time and cost of conducting the air quality modeling step. We do not suggest that EPA will or should use this reduced-form approach in its own RIA for a future HDOH rulemaking, but we consider it a reasonable approach for the type of scoping-level approximation of benefits per truck that is the objective of our analysis.

While EPA has already published several such "reduced-form" benefit-per-ton estimates, we chose to derive our own estimates. By computing them ourselves, we can perform a wide range of sensitivity analyses that would not be possible using those published by others. For example, in our analysis, we (a) apply more up-to-date assumptions relating to baseline ambient pollutant concentrations;[9] (b) derive and explore the implications of more geographically disaggregated benefit-per-truck estimates; (c) use newer and different C-R assumptions that the Agency might use in its future benefits analyses; and (d) provide a range of benefit-per-truck estimates that vary in the extent to which they rely on extrapolation outside of the range of data supporting the original estimation of the C-R coefficients being applied.

We had to use different data sources to develop our estimates for ozone and $PM_{2.5}$. The rest of this section therefore describes the methods and the data that we used to compute our benefit-per-ton and associated benefit-per-truck estimates for ozone and $PM_{2.5}$ separately. It also provides state-specific detail to supplement the more aggregated estimates presented in the accompanying Summary Report. All of the results reported in this section give full weight to risk estimates from exposures as low as zero and make no adjustment for declining confidence associated with extrapolation of the C-R relationship to concentrations at the low end of the range of observations in the original epidemiological study. Our method for assessing the quantitative sensitivity to alternative limits on the degree of such extrapolation is described in Section VI of this report.[10]

A. $PM_{2.5}$ Calculations

To develop our "reduced-form" benefit-per-ton estimates for $PM_{2.5}$, we relied upon air quality modeling used to produce a set of mobile-source benefit-per-ton estimates reported in Wolfe *et al.* (2018). That study was of particular relevance to our analysis because it provided $PM_{2.5}$ benefit-per-ton estimates specifically due to NO_x emissions from HDOH trucks.[11] The paper reported average national and regional ("East" and "West") benefit-per-ton estimates, using a baseline $PM_{2.5}$ concentration grid and associated baseline NO_x emissions projected to occur in 2025. The benefit-per-ton estimates reported in the paper are calculated using two C-R functions – from Krewski *et al.* (2009) and Lepeule *et al.* (2012) – and using BenMAP's demographic assumptions for the year 2025.

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[9] For our analysis, we used 2035 baseline ozone and $PM_{2.5}$ grids from a recent air RIA (EPA, 2019a), which were the BenMAP inputs with the most up-to-date air quality modeling that we were able to identify in the public domain. The concentrations in these grids also are broadly reflective of the concentrations of ozone and $PM_{2.5}$ projected to occur in the years during which the tighter standard would be having most of its incremental impact (*i.e.*, in the 2030s and 2040s).

[10] The case for this latter type of sensitivity analysis, which we call "confidence weighting," is explained in more detail in the accompanying Summary Report.

[11] The species of $PM_{2.5}$ associated with NO_x precursor emissions is particulate nitrate.

EPA provided NERA with the BenMAP grids of 2025 HDOH nitrate contributions and the associated NO_x emissions (by state) employed by Wolfe *et al*. Using those data and the same C-R relationships, NERA ran the BenMAP model to confirm we could replicate the nitrate benefit-per-ton estimates due to HDOH trucks, both at the national and the regional level.

To better understand the degree of potential variation in such values on a geographic basis, NERA then used BenMAP and those same air quality and emissions data to develop benefit-per-ton estimates on a more disaggregated basis, generally state by state (which was the smallest disaggregation available for the emissions data.) However, recognizing that much of the ambient $PM_{2.5}$ in very small states would be attributable to emissions in surrounding states, several of the smallest Eastern states were aggregated into subregions about the size of the larger states.[12]

Like Wolfe *et al.*, we estimate a range for the $PM_{2.5}$ benefits-per-ton using two alternative C-R relationships for mortality risk. Rather than use the same two C-R relationships that Wolfe *et al.* used, we chose to update those inputs to reflect what one might expect the Agency to use in a future RIA. To decide on the C-R estimates to define the lower and higher ends of our range, we reviewed EPA's recent Policy Assessment for $PM_{2.5}$ (EPA, 2020) and also the C-R relationships for $PM_{2.5}$ that currently exist in the BenMAP health impact functions library Based on the review, we decided to rely on two C-R relationships from a study by Di *et al.* (2017).[13] Also, consistent with EPA practice for long-term $PM_{2.5}$ benefits calculations, we applied EPA's standard twenty-year segmented cessation lag (EPA, 2004) to the estimates developed using the Di *et al.* low and high C-R relationships.[14]

The year-2050 benefit-per-ton estimates calculated using the low Di *et al.* C-R relationship are illustrated as a map in Figure 3, and as a population-weighted cumulative distribution in Figure 4 (two pages hence). State-specific estimates range from less than $100 per ton to more than $19,000 per ton (2019$) around a national average of $7,500 per ton.[15] This range primarily reflects variations in population densities, and also regional differences in the amount of change in ambient $PM_{2.5}$ per ton of HDOH NO_x emissions. While this is a very wide range around the national average, there are no clear outliers on the range. However, California and several midwestern states account for the highest values. The values in these figures are based on year-2050 demographic assumptions, but the variation from state to state is generally

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[12] The two multi-state regions are called North East and Mid-Atlantic. The North East region comprises Connecticut, Massachusetts, New Hampshire, New York, Rhode Island and Vermont. The Mid-Atlantic aggregate region comprises Delaware, Maryland, New Jersey, Pennsylvania, Virginia and West Virginia. The benefit-per ton-estimates for these aggregate regions are calculated by the dividing the aggregate benefits for the region by the aggregate NO_x emissions reduction for the region.

[13] For the low end of the range, we employed a C-R coefficient for all-cause mortality of 0.0059, based on a relative risk of 1.061 per 10 µg/m3 change in $PM_{2.5}$ (Two-pollutant analysis, Analysis based on data from nearest monitoring site). For the high end of the range, we employed a C-R coefficient for all-cause mortality of 0.0081, based on a relative risk of 1.084 per 10 µg/m3 change in $PM_{2.5}$ (Single-pollutant analysis). Both these relative risk estimates are obtained from Table 2 of the Di et al. study (p. 2518). The C-R relationships apply to people ages 65 years or older, and our BenMAP calculations have used this older population when applying the Di *et al*. coefficients.

[14] This structure assumes a 30% reduction in premature mortality in the first year, a 50% reduction over years 2 through 5 and a 20% reduction over years 6 through 20 after the reduction in $PM_{2.5}$ concentration.

[15] In addition to relying on Di *et al.* C-R estimates rather than either the Krewski *et al.* or Lepeule *et al.* C-R functions, these estimates apply year-2050 demographic conditions, whereas Wolfe *et al.* applies year-2025 demographic assumptions, which produce lower per-ton values. Also, these are stated in 2019 real dollars, whereas Wolfe *et al.* states its estimates in 2015 real dollars, which also results in lower numerical values. As noted earlier, our analysis methods do replicate the estimates reported Wolfe *et al.* when we apply the same C-R and demographic assumptions and state the results in same-year real dollars.

similar for other demographic years. The numerical values estimated for the 2030, 2040, and 2050 demographic assumptions are provided in Appendix B.

Our year-2050 national average benefit per ton of reduction in HDOH NO_x emissions calculated using the high Di *et al.* (2017) C-R relationship is about $10,000 per ton (2019$). The geographic variation around that average is presented in Figure 5 and Figure 6 on the next page, and is very similar to that using the low Di *et al.* C-R relationship. Numerical values behind these figures, and for 2030 and 2040 are also provided in Appendix B.

As explained in the prior section, our estimates of the *per-truck* benefits apply our estimates of benefits per ton in each year from 2027 through 2057[16] to our estimates of the per-truck tons of reduction each respective year, and take a present value of that stream of annual values. Figure 7 and Figure 8 below present the maps and cumulative distributions, respectively, of $PM_{2.5}$ benefit-per-truck estimates computed using the low C-R relationship from the Di *et al.* (2017) epidemiological study and applying a 3% discount rate. Figure 9 and Figure 10 present the same information using instead the high C-R relationship from the Di *et al.* (2017) epidemiological study (also applying a 3% discount rate). The national average $PM_{2.5}$ estimates (for a 3% discount rate) are $4,650 per truck based on the low C-R relationship from the Di*et al.* study and $6,340 per truck based on the high C-R relationship from the Di *et al.* study. As with the distributions presented in Figure 4 and Figure 6, the states with the highest benefit-per-truck estimates are in the Midwest and California.

The corresponding maps and distributions for the $PM_{2.5}$ benefit-per-truck estimates computed using a 7% discount rate are presented in Appendix C. For each state, those benefits estimates are about 25% lower than their respective 3% discount rate estimates, leaving the geographical variations much the same as presented in the figures below.

[16] For each year's specific benefit-per-ton value, we interpolated linearly between our 2030 and 2050 per-ton values. We considered this a reasonable approximation for our scoping analysis. However, we note that use of a more refined interpolation that incorporates year-2040 values appears to increase per-truck benefits estimates by less than 5%.

Figure 3: Map of $PM_{2.5}$-Only Benefits per Ton by State Using the Low Di *et al.* (2017) C-R Coefficient (2050)

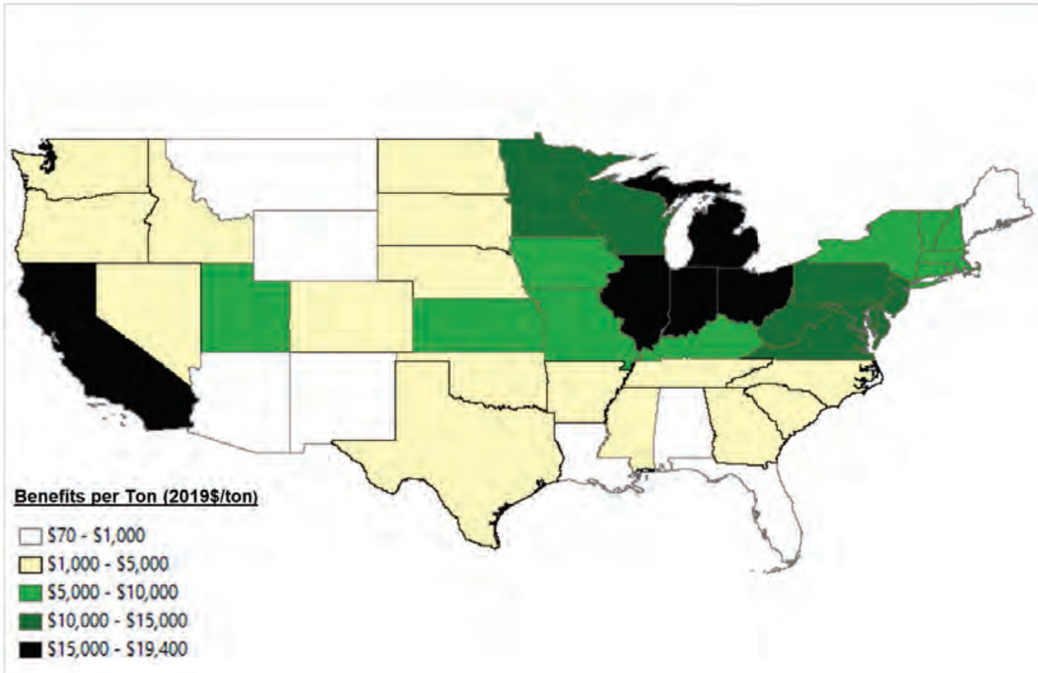


Figure 4: Cumulative Distribution of $PM_{2.5}$-Only Benefits per Ton by State Using the Low Di *et al.* (2017) C-R Coefficient (2050)

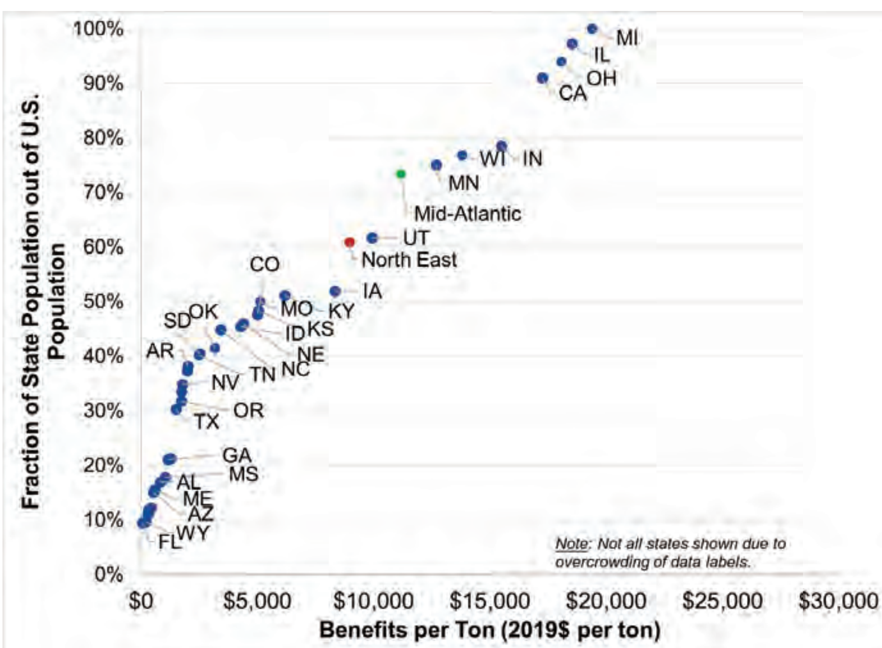


Figure 5: Map of $PM_{2.5}$-Only Benefits per Ton by State Using the High Di *et al.* (2017) C-R Coefficient (2050)

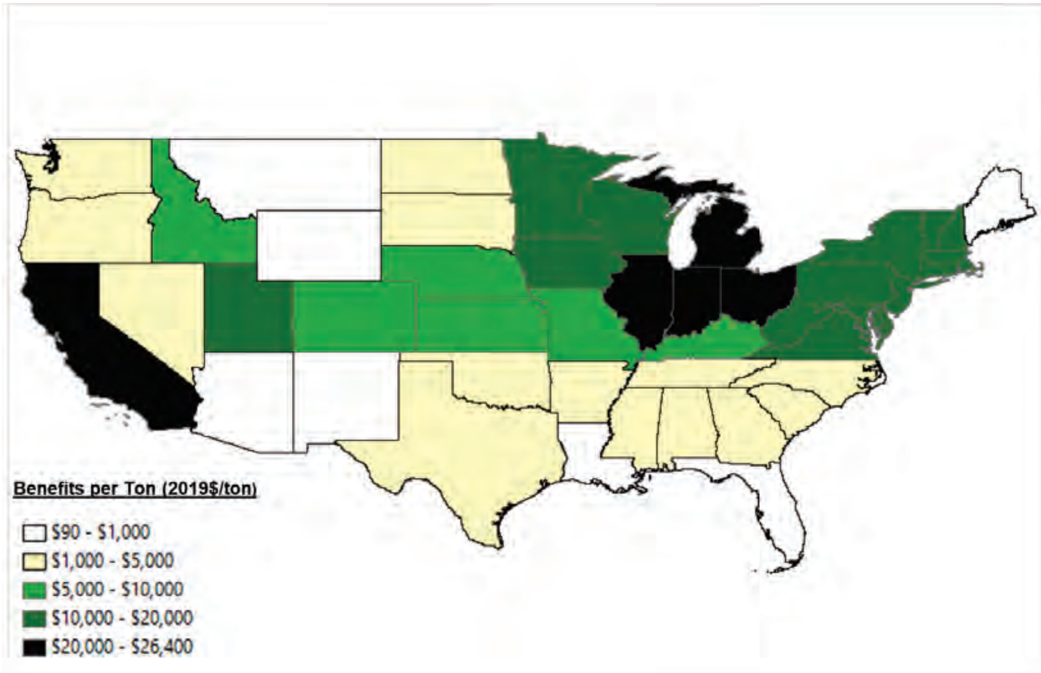


Figure 6: Cumulative Distribution of $PM_{2.5}$-Only Benefits per Ton by State Using the High Di *et al.* (2017) C-R Coefficient (2050)

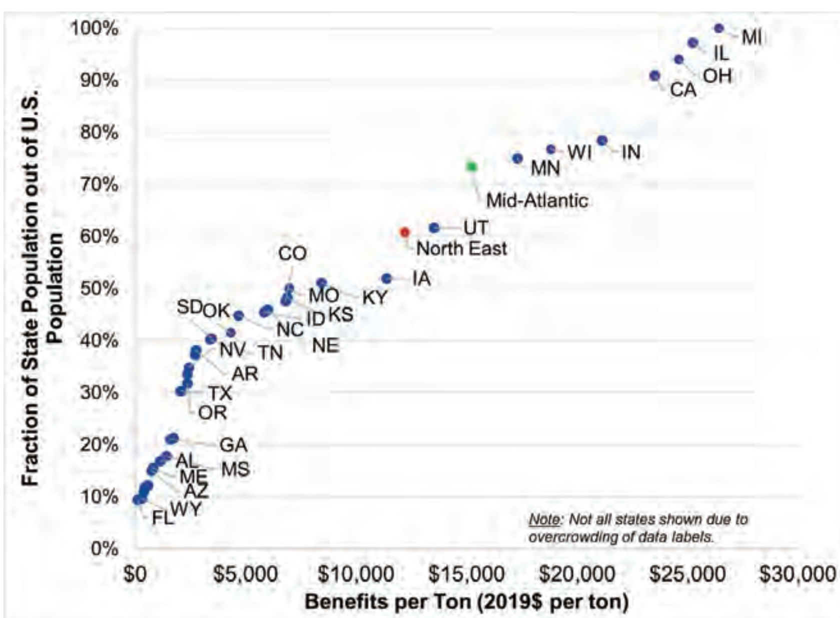


Figure 7: Map of $PM_{2.5}$-Only Benefits per Truck by State Using the Low Di et al. (2017) C-R Coefficient, 3% Discount Rate

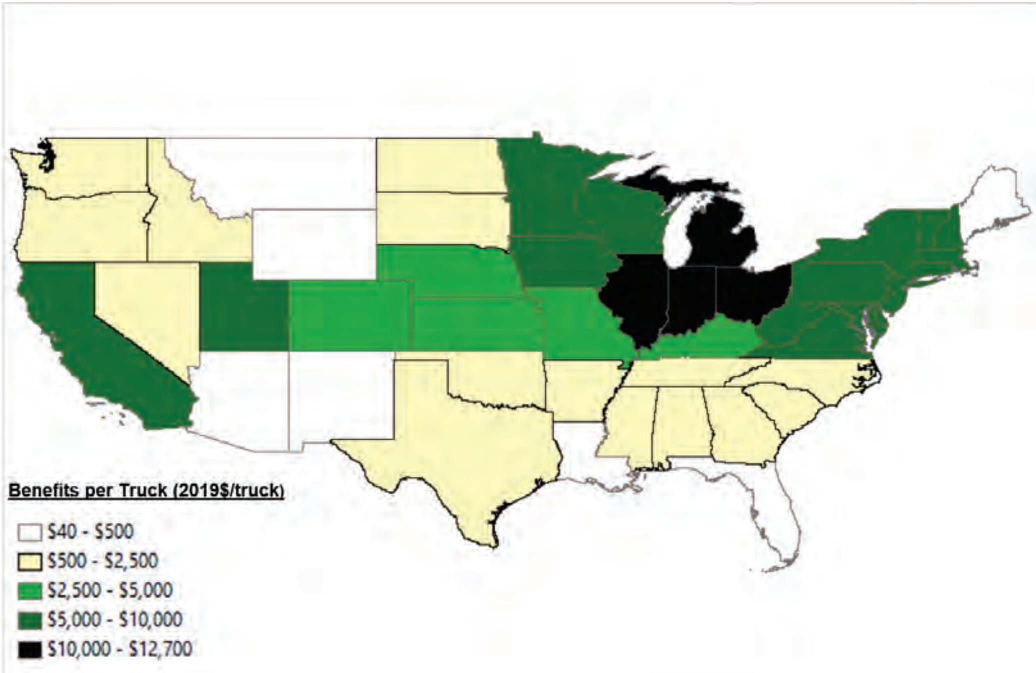


Figure 8: Cumulative Distribution of $PM_{2.5}$-Only Benefits per Truck by State Using the Low Di et al. (2017) C-R coefficient, 3% Discount Rate

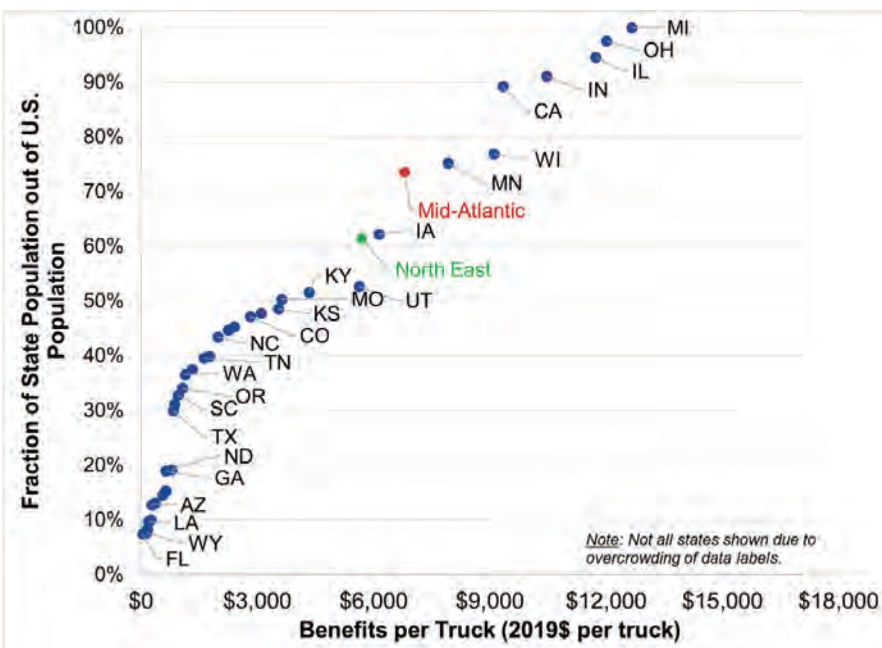


Figure 9: Map of $PM_{2.5}$-Only Benefits per Truck by State Using the High Di *et al.* (2017) C-R Coefficient, 3% Discount Rate

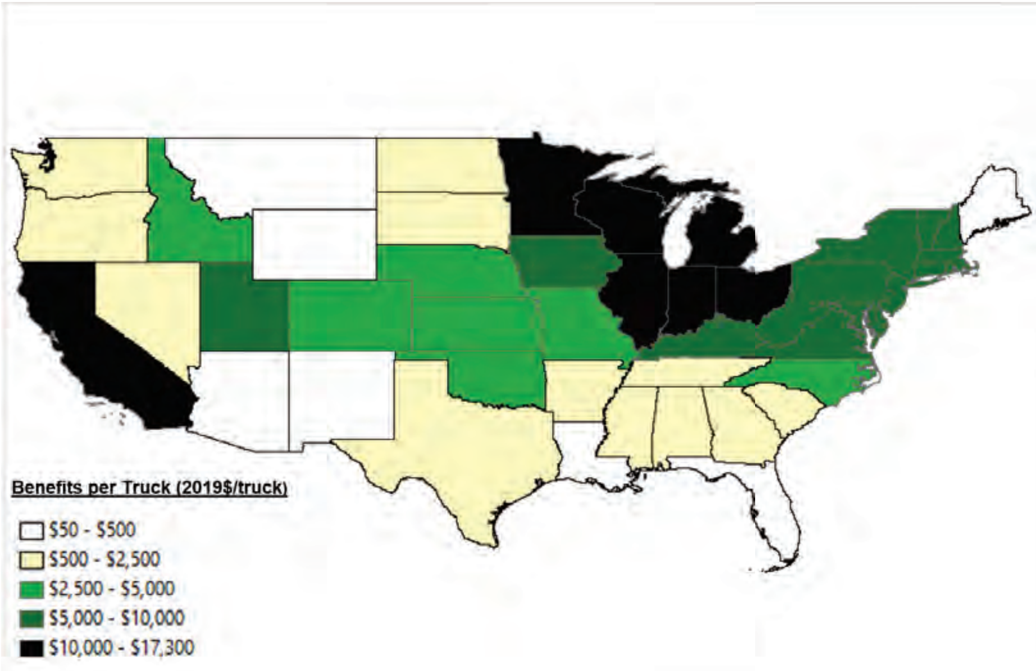
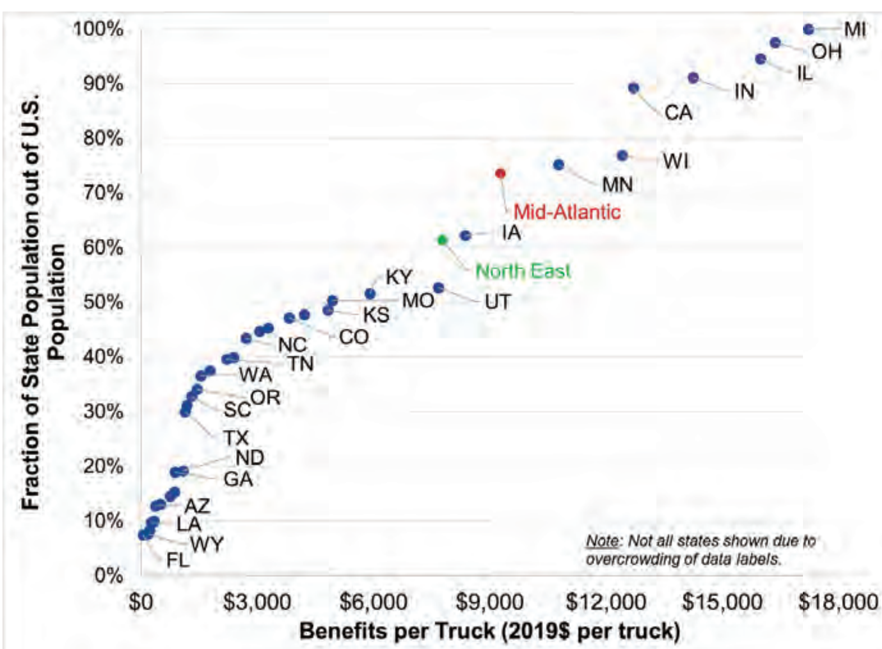


Figure 10: Cumulative Distribution of $PM_{2.5}$-Only Benefits per Truck by State Using the High Di *et al.* (2017) C-R Coefficient, 3% Discount Rate



B. Ozone Calculations

Wolfe *et al.* (2018) does not provide any benefit-per-ton estimates for ozone. Also, there appears to be only one example among EPA's past RIAs that used the "reduced-form" benefit-per-ton methodology for ozone – the RIA for the Clean Power Plan (EPA, 2015a). Because those estimates were based on NO_x reductions from electricity generating units, which have a very different geographic distribution than vehicle emissions, they are not relevant for use in our HDOH benefits scoping analysis. All the other past RIAs we reviewed that contained estimates of ozone-related health benefits had based those estimates on full-scale US-wide air quality modeling of the specific emissions reductions projected for that regulation. One can develop a rough estimate of the average ozone benefit per ton *implied* in those remaining RIAs by dividing the RIA's estimate of total ozone benefits by its estimated tons of NO_x emissions reductions. Of those remaining RIAs, the one that is most relevant to an HDOH NO_x reduction regulation is the RIA for the Tier 3 Light-Duty Vehicle standards from 2014 (EPA, 2014a). We find that the approximate national average ozone benefit per ton implied in that RIA (stated in 2019$) ranges from about $3,800 per ton when using an all-cause mortality C-R relationship from Bell *et al.* (2004) to about $17,300 per ton when using an all-cause C-R relationship from Levy *et al.* (2005). A more relevant but older RIA is that for the prior HDOH NO_x emissions rulemaking (EPA, 2000). Its implied national average ozone benefit per ton was $824 (2019$). That estimate was based on a C-R function for hospital admissions rather than mortality. Clearly there is a wide range, but none of those estimates reflects the Agency's current thinking about ozone-related health risks that could be viewed as a likely basis for ozone benefits calculation in a future RIA. Below we describe how we developed our own reduced-form estimates for ozone benefits, and their implications for per-truck benefits.

EPA's current draft Policy Assessment for ozone (EPA, 2019c) does not provide epidemiology-based risk calculations for any health effect, and it specifically casts doubt on ozone's potential mortality risk. This suggests that a future RIA might not attribute any mortality benefits to ozone reductions. In the spirit of providing a range of estimates, however, we decided to employ a low and a high coefficient for respiratory mortality from Zanobetti and Schwartz (2008). This choice reflects the facts that EPA did cite several epidemiological studies addressing respiratory health risks in an appendix of the draft ozone Policy Assessment and that the most recent (2021) health impact functions library in BenMAP also contains several C-R relationships for respiratory health risks; of those cited, Zanobetti and Schwartz provided the clearest option for C-R coefficients specifically for respiratory mortality risk.[17]

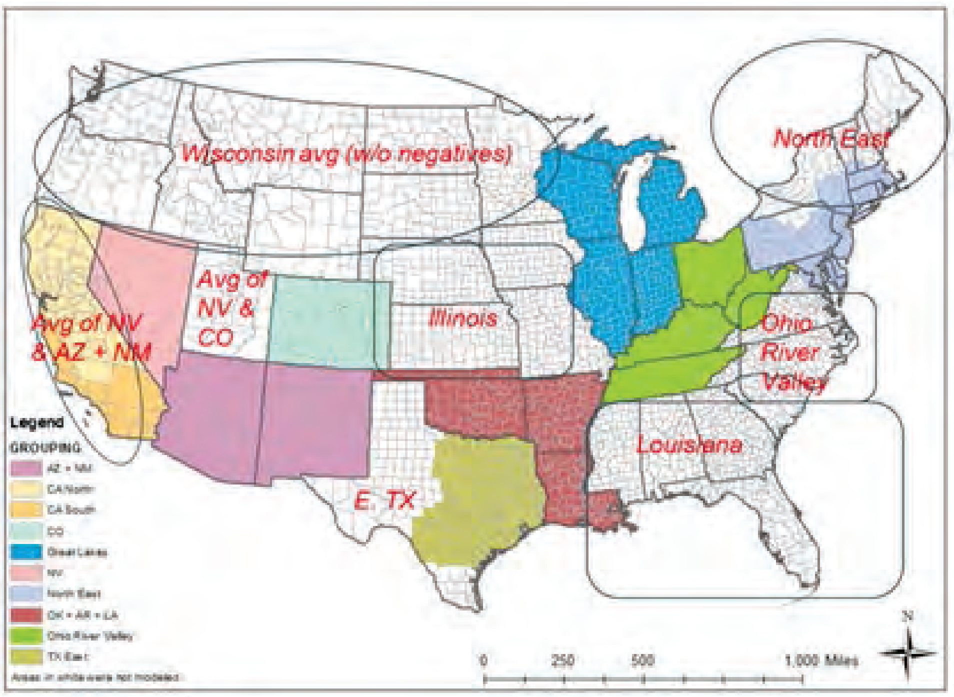
Also challenging to this part of our analysis was a lack of a specific grid of ambient ozone concentrations associated with a specific quantity of tons of NO_x emissions, such as was available for $PM_{2.5}$ from the Wolfe *et al.* study. We instead had to rely on less nationally comprehensive results from prior air quality modeling sensitivity cases that had been prepared for the 2015 Ozone RIA (EPA, 2015b). For that RIA, EPA conducted several sensitivity runs with CAMx for specific regions of the U.S. that the Agency had projected would need to make NO_x reductions to attain an ozone NAAQS down to 65 ppb. Some of those sensitivity runs simulated the ambient ozone impacts of "across-the-board" 50% reductions in anthropogenic NO_x emissions, which thus, at least in part, included mobile source emissions reductions. We consider those specific sensitivity runs to be the most relevant for our analysis. They had been run for eight U.S. regions, identified by the colored areas (excluding the two in California) in Figure 11, which is

[17] For the low end of the range, we employ a low C-R coefficient for respiratory mortality of 0.00054, based on a relative risk of 1.0054 per 10 ppb change in 8-hr ozone from the 0-day lag model. For the high end of the range, we employ a low C-R coefficient for respiratory mortality of 0.00082, based on a relative risk of 1.0083 per 10 ppb change in 8-hr ozone from the 0-3 day lag model. Both these relative risk estimates are obtained from Table 1 of the Zanobetti and Schwartz study (p. 186).

copied from EPA (2015b).[18] The outputs of those sensitivity runs that were reported in a technical support document spreadsheet (EPA, 2015c) were ozone design values at each existing monitor across the U.S. for the base case and for each of the sensitivity cases and the NO_x emissions changes between the two cases. Following guidance in that document, we used those outputs to calculate "ozone response factors" for each of the sensitivity cases by dividing the projected change in the ozone design value at each monitor across the U.S. by the tons of NO_x emissions reduction assumed for that case.

Figure 11: Basis for Estimating Ozone Response Factors for Each State

(Source: EPA (2015b), Figure 2-2, with red font text added by NERA, as explained in text.)



Note: For northern states west of WI, "Wisconsin avg (w/o negatives)" means that monitors in WI with a negative response factor were not included in the average estimated for these states. Negative values imply local ozone formation is VOC-limited, which does occur in parts of WI (near the lake), but which we assume does not occur in northern states west of WI.

For each state where emissions were reduced in one of the eight relevant sensitivity runs, we extracted the ozone response factors for all the monitors in that state and adopted the simple average of those values as our analysis's assumption for that state's change in ambient ozone due to a ton of NO_x emitted by HDOH trucks in that state.

Although EPA's data provided response factors for all monitors throughout the entire U.S., we did not use response factor data for monitors that were not within the region for which emissions had been cut.[19] For areas of the U.S. that were not included in any of EPA's sensitivity cases (*i.e.*, the white areas in Figure 11), we adopted an average ozone response factor from one of the modeled regions, selecting a region that we judged to have relatively similar ozone forming attributes (*e.g.*, temperature, sunlight, *etc.*). For

[18] None of the sensitivity cases run for the two California regions involved the 50% across-the-board NO_x reductions that we considered relevant for our analysis.

[19] We did confirm that response factors for monitors outside of the region of the simulated emissions reductions were generally very much smaller than those for monitors within the region.

example, for Missouri, we used an ozone response factor (*i.e.*, the average ppb change in Missouri per ton of NO_x emitted in Missouri) that was the same as EPA's modeling indicated for Illinois. The red text on Figure 11 identifies the assignments we made for each of those areas that were not included in one of EPA's sensitivity cases.[20] The state-specific values of our resulting set of ozone response factors are provided in Appendix D.

We multiplied our state-specific ozone response factors by the state-specific NO_x emission reductions that we also estimated (as described in Section IV, and reported in Appendix A) to obtain rough estimates of projected changes in ozone design values expected to occur in each state with the implementation of the hypothetical tighter HDOH NO_x standard. We further assumed that changes in average seasonal ozone concentrations would be equal to the estimated changes in design values that was the basis of our estimates of ozone response factors.[21] Using BenMAP, we applied those estimates of absolute changes in ambient ozone to the baseline ozone levels in every 12-km grid cell in each respective state to compute ozone benefit-per-ton estimates. As noted above, we used two C-R relationships for acute respiratory mortality risk during the summer months (June – August) estimated by a multi-city study and reported in Zanobetti and Schwartz (2008).[22] Those calculations were carried out for the U.S. and by state for 2030, 2040, and 2050. The benefit-per-ton estimates obtained for the U.S. and by state are provided in Appendix B, with the year-2050 estimates summarized below.

Our estimate of the national average ozone benefit per ton for 2050 computed using the low C-R relationship from the Zanobetti and Schwartz (2008) study is $926 per ton (2019$).[23] Figure 12 and Figure 13 present the state-specific results, which show California far higher than any other state: about $5,250 per ton –nearly 6 times the U.S. average. If California is removed from the data, the average for the remaining 47 states is about $430 per ton. Using the high C-R relationship from the Zanobetti and Schwartz (2008) study, we obtain a national average ozone benefit per ton estimate for 2050 of $1,420 per ton (2019$). Figure 14 and Figure 15 present the state-specific results, obtained using the high C-R relationship. The estimate for California is about $8,050 per ton while for the average for the remaining 47 states (excluding California) is about $660 per ton.

Figure 16 and Figure 17 graph the *per-truck* benefit estimates obtained using the low C-R relationship from the Zanobetti and Schwartz (2008) study when applying a 3% discount rate. The national average ozone benefit-per-truck estimate is $530 per truck (2019$). California's estimate is $2,920 per truck, while the average for Rest of U.S. is $250 per truck. Figure 17 and Figure 18 graph the *per-truck* benefit estimates obtained using the high C-R relationship from the Zanobetti and Schwartz (2008) study when

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[20] Because the sensitivity cases for California were not appropriate for our analysis needs, we made an assignment for California too, as identified in red font in the figure.

[21] We surmise that this assumption causes our analysis to overstate the projected changes in ozone in most locations, as it is quite likely that absolute changes in average ozone will be smaller than absolute changes in the highest levels of ozone. If so, this also means that our benefit-per-truck estimates for ozone will be overstated. As those estimates have turned out quite small even if they may be overstated due to this assumption, we have not attempted to further refine the assumption or to conduct sensitivity analyses for it.

[22] Consistent with EPA's methods for estimating risk from ozone exposures measured only during ozone-season months, our benefits calculations are for June through August. An adjustment factor of 0.25 was applied to BenMAP's year-round counts of avoided respiratory mortality. This factor reflects the fraction of the days in the year covered by those months.

[23] This is low compared to the ozone benefit-per-ton values implied in the Tier 3 Light-Duty Vehicle Standards RIA (EPA, 2014a). The primary reason for the large reduction is that our benefits calculations are for respiratory mortality only, whereas the 2014 RIA used C-R relationships for all-cause mortality, which the Agency now views as not likely causal. We also suspect (but cannot confirm) that the 2014 RIA applied a seasonal C-R relationship to mortality risk across the entire year. The Agency did not make such an extrapolation in its Health Exposure and Risk Assessment for that ozone NAAQS review (EPA 2014b).

applying a 3% discount rate. We obtain the national average ozone benefit-per-truck estimate to be $810 per truck (2019$). The estimate for California is obtained to be $4,480 per truck while the average for the Rest of the U.S. is obtained to be $390 per truck.

The corresponding maps and distributions for the ozone benefit-per-truck estimates computed using a 7% discount rate are presented in Appendix C. For each state, those benefits estimates are about 25% lower than their respective 3% discount rate estimates, with the geographical variations much the same as presented in the figures below.

Figure 12: Map of Ozone-Only Benefits per Ton by State Using the Low Zanobetti and Schwartz (2008) C-R Coefficient (2050)

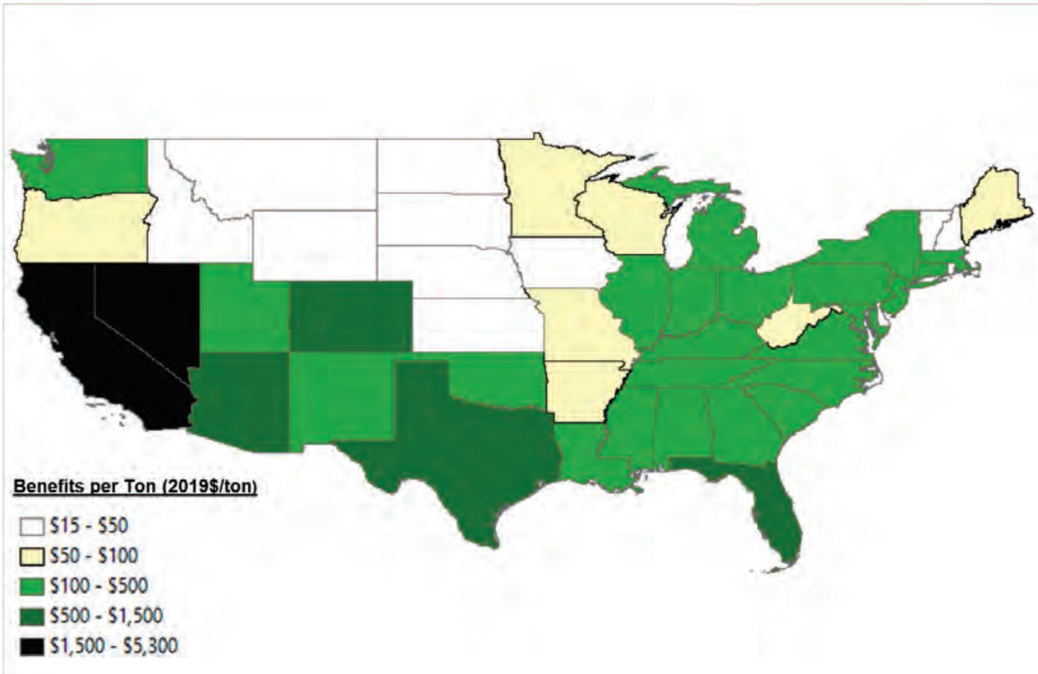


Figure 13: Cumulative Distribution of Ozone-Only Benefits per Ton by State Using the Low Zanobetti and Schwartz (2008) C-R Coefficient (2050)

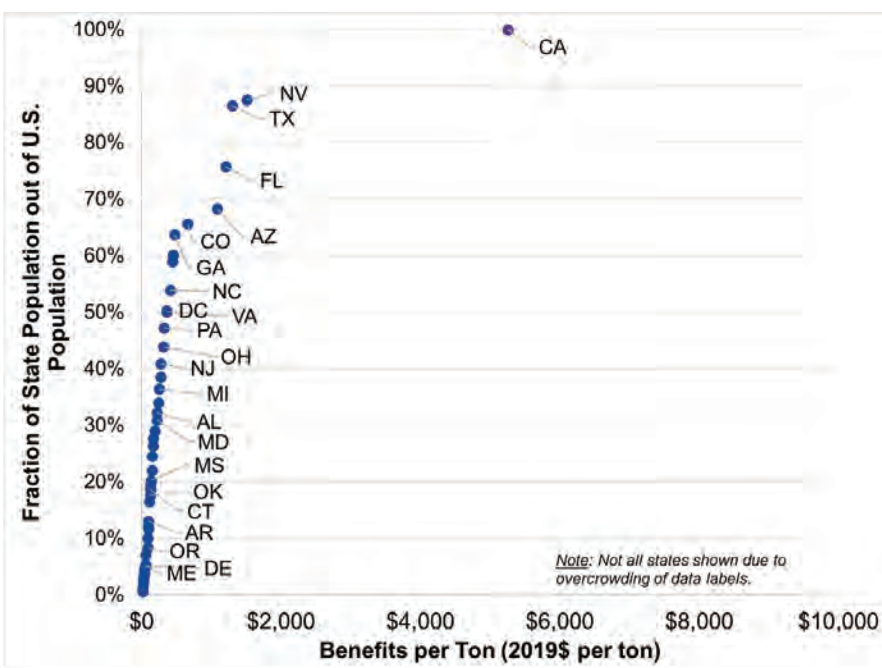


Figure 14: Map of Ozone-Only Benefits per Ton by State Using the High Zanobetti and Schwartz (2008) C-R Coefficient (2050)

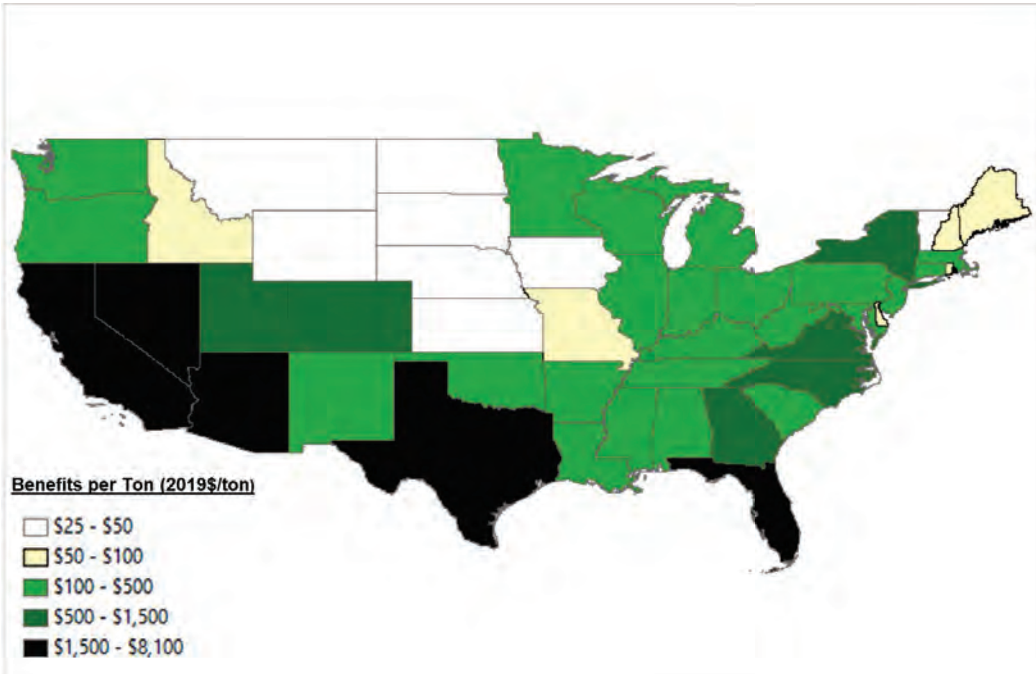


Figure 15: Cumulative Distribution of Ozone-Only Benefits per Ton by State Using the High Zanobetti and Schwartz (2008) C-R Coefficient (2050)

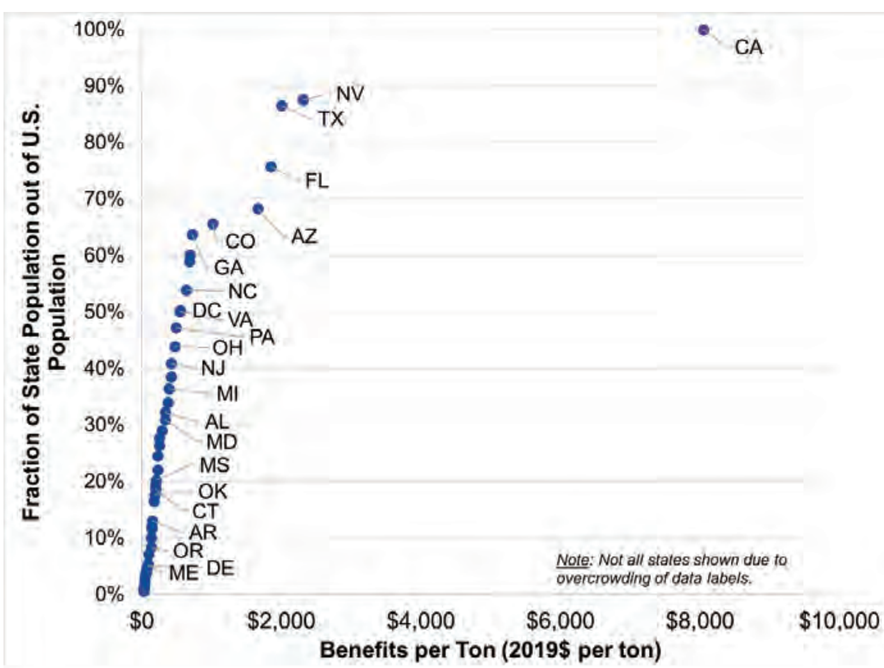


Figure 16: Map of Ozone-Only Benefits per Truck by State Using the Low Zanobetti and Schwartz (2008) C-R Coefficient, 3% Discount Rate

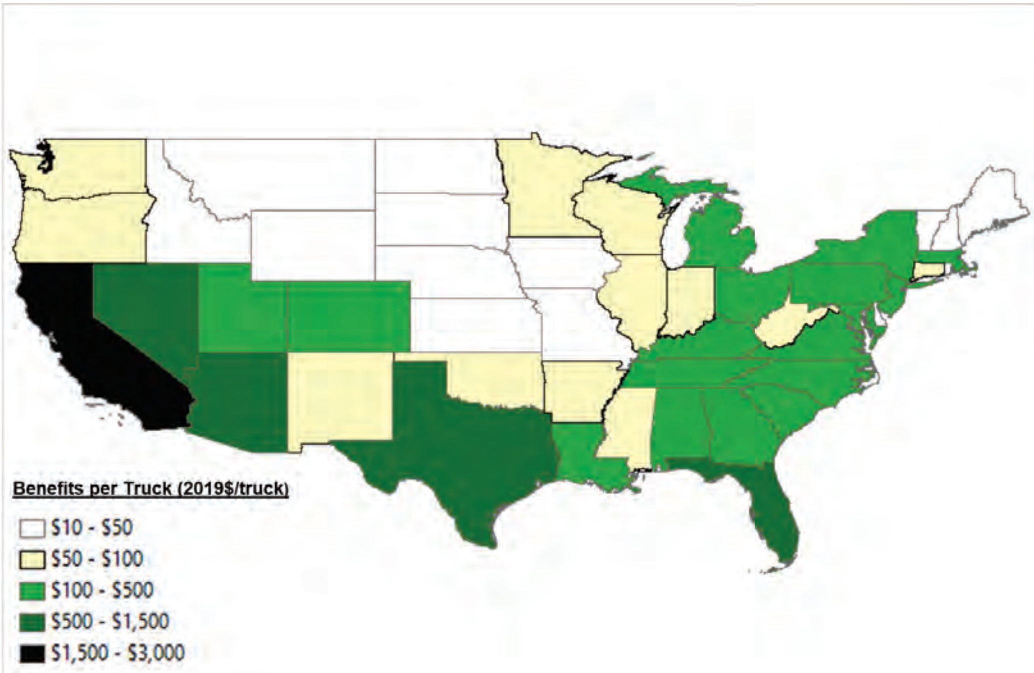


Figure 17: Cumulative Distribution of Ozone-Only Benefits per Truck by State Using the Low Zanobetti and Schwartz (2008) C-R Coefficient, 3% Discount Rate

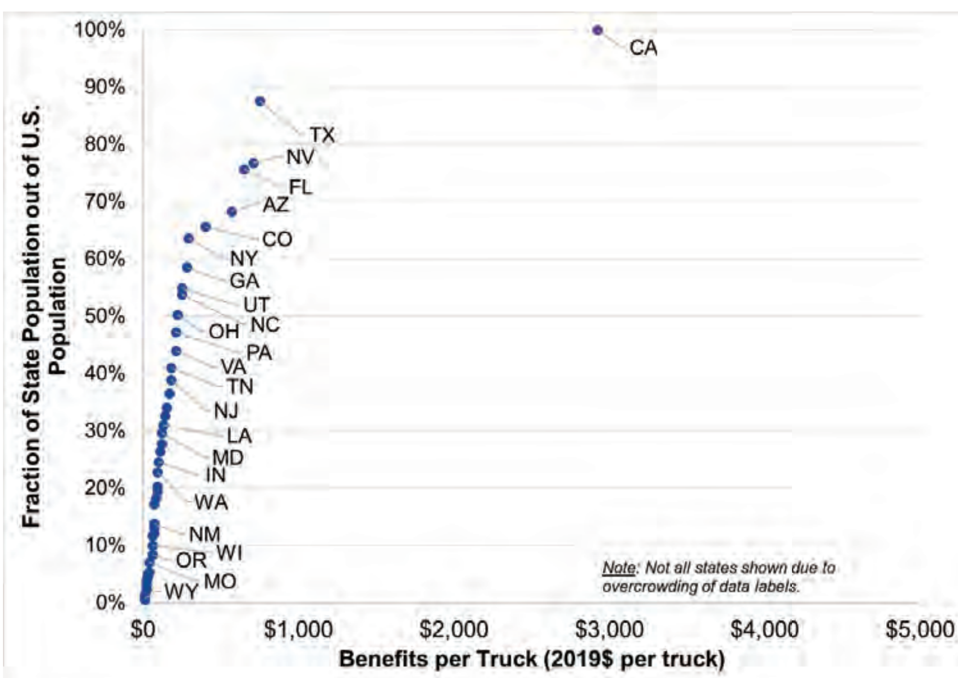


Figure 18: Map of Ozone-Only Benefits per Truck by State Using the High Zanobetti and Schwartz (2008) C-R Coefficient, 3% Discount Rate

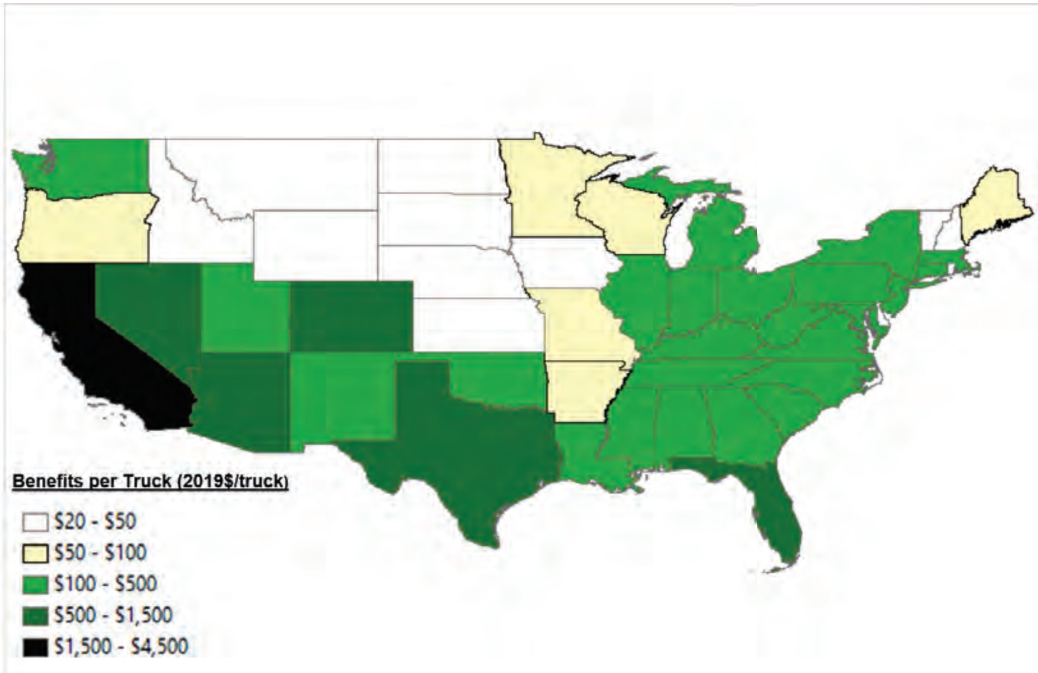
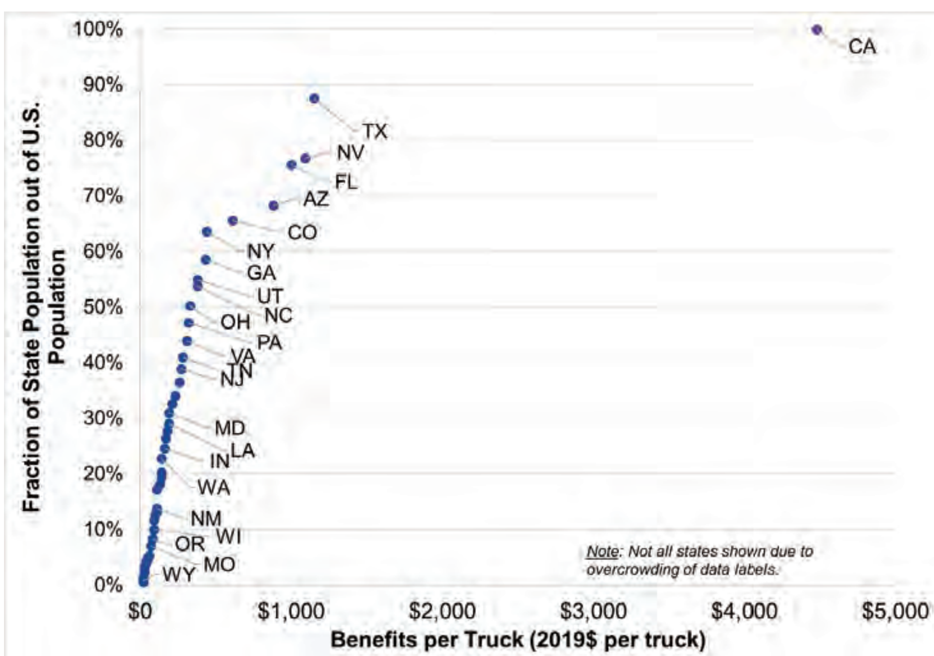


Figure 19: Cumulative Distribution of Ozone-Only Benefits per Truck by State Using the High Zanobetti and Schwartz (2008) C-R Coefficient, 3% Discount Rate



VI. Benefit-per-Truck Estimates with Varying Confidence Levels

An important input that drives the benefit-per-ton estimates and thus the benefit-per-truck estimates is the C-R coefficient, which is an assumption about the increase in health risk per unit change in ozone and $PM_{2.5}$ concentration. That assumption is usually based on a statistically derived association reported in one of many existing epidemiological papers. There are significant scientific uncertainties introduced when using these statistical associations to predict risks under different population and air quality conditions than those analyzed in the papers, since it involves extrapolation outside the range of observed exposures. The accompanying Summary Report of our analysis provides a detailed explanation of this concern with extrapolation in benefits analyses.[24] It also discusses an approach to quantify the sensitivity of benefits estimates to various amounts of limitations on the amount of extrapolation allowed in their computation, which we have applied to the benefit-per-truck estimates of our scoping analysis.

We provide alternative estimates of benefits per truck associated with varying levels of extrapolation-related confidence. Estimates at the "more confident" end of the spectrum exclude benefits calculated to occur in areas with projected baseline concentrations below the 25th percentile of the range of observations in the original C-R estimation data. Estimates at the "less confident" end of the spectrum make no exclusions at all, allowing extrapolation of the C-R relationship even where projected baseline concentrations are lower than the lowest measured level (LML) in the original epidemiological study.[25] Estimates that fall between these two ends of the spectrum exclude benefits that are in areas with projected baseline concentrations that are below percentile levels lower than the 25th percentile of the pollutant observations in the original study (such as the 1st, 5th, 10th percentiles of the original study's observed exposure levels). Thus, we create a sliding scale of per-truck benefits estimates with increasing levels of qualitative confidence.[26]

To apply this method, two sets of data are needed. First, the relevant baseline concentrations associated with the regulation's benefits, C_b, must be identified. Second, the concentrations associated with each selected population-weighted percentile p in the original epidemiological study must be obtained. These values are denoted C_p, which we apply for p=0, 1st, 5th, 10th, and 25th percentiles. The estimated benefits are placed into bins according to the baseline concentration level, C_b, from which they have been computed. Total benefits associated with each percentile level p are then recomputed by summing up benefits in only those bins with baseline concentrations $C_b \geq C_p$. This results in gradually declining benefits-per-ton estimates as the percentile cut-off p rises – implying greater qualitative confidence that the benefits included in the computation are not the result of speculative extrapolation outside of the range of observed exposures.

An appropriate set of baseline exposures would be those projected to be in effect during the time period when the new regulation is taking effect. For our analysis, that would be from 2027 through 2057. The most relevant air quality projections usable in BenMAP that we could identify in the public domain are those prepared for the RIA for finalizing the repeal of the Clean Power Plan (EPA, 2019a), which include projected $PM_{2.5}$ and ozone levels nationally for the years 2025, 2030, and 2035. We obtained those BenMAP air quality grids from EPA. We chose to use the 2035 projections for our analysis, as most of

[24] See Section IV of that Summary Report.

[25] The Agency uses the acronym LML to denote the 0th percentile of the distribution of exposures in the original study.

[26] The values along this scale bear no relationship to statistical measures of significance or confidence intervals; nor do the ranges provided within each segment of the scale, which reflect only high and low point estimates of the C-R relationship from different estimation methods.

the per-truck benefits occur in the years 2027 through 2040, although about 20% do occur after 2040, when baseline exposures will probably be lower still.

For each of the C-R relationships that we use in our scoping analysis, we obtained the concentrations associated with each percentile (*i.e.*, the C_p values) from the respective original study. We use the population-weighted exposure distribution from Di *et al.* (2017) to develop the values of C_p for our low and high$PM_{2.5}$ benefit-per-truck estimates, and we use the distribution of ozone exposures in the Zanobetti and Schwartz (2008) study to develop confidence-weighting adjustments for our low and high ozone benefit-per-truck estimates. The percentiles in the Di *et al.* study are available in supplemental materials to the original paper but are more precisely listed in a $PM_{2.5}$ docket entry (EPA, 2019b). We use information on the distribution of city-specific average ozone concentrations reported in Table 2 of the online supplement to Zanobetti and Schwartz (2008) study.

For the two epidemiological studies that we have relied upon, Tables 1 through 4 below identify (in the first row) the ambient concentration levels (C_p values) for each of the above percentile cut-off levels that we have used to explore sensitivities to extrapolation-related confidence weighting. The second row of each table identifies the percentage of the respective study's total avoided premature statistical deaths that lie *within* each alternative confidence range. (These sum to 100% across the row.) The last two rows of each table report the benefit-per-truck values associated with each confidence level when applying, respectively, a 3% and 7% discount rate to the present value calculation. The first column in each table reports the national average estimates unadjusted for confidence (which we reported in the previous section), while the values in the columns to the right show the estimates that have increasingly higher confidence, up to the point where only benefits in areas with exposures at or above the 25th percentile of the original epidemiological study are included.

Table 1 and 2 present the $PM_{2.5}$ benefit-per-truck estimates calculated using low and high C-R coefficients from Di *et al.* (2017). It shows that about 14% of the benefits are projected to occur in locations that have exposures greater than the 25th percentile of all the exposures in the epidemiological study. As shown in Table 1, the unadjusted estimate of $4,650 per truck (obtained using the low C-R coefficient) that was reported in the prior section of this report declines to $650 per truck at the "more confident" end of the spectrum.[27] If we were to use the 10th percentile as a less conservative confidence cut-off, the associated benefit-per-truck estimate would be $2,670 with about 57% of the benefits projected to occur in locations that have exposures greater than the 10th percentile of all the study exposures.[28] As shown in Table 2, the unadjusted estimate of $6,340 per truck (obtained using the high C-R coefficient), declines to $890 per truck at the "more confident" end of the spectrum. At the 10th percentile confidence cut-off, the benefit-per-truck estimate is $3,640 per truck. As before, the estimates computed using a 7% discount rate are about 25% lower than the respective 3% discount rate estimates.

Table 3 and 4 present the ozone benefit-per-truck estimates calculated using low and high C-R coefficients from the Zanobetti and Schwartz (2008) study. The pattern observed in the drop-off of the benefit-per-truck estimates is significantly different from that for $PM_{2.5}$. As shown in Table 3, the unadjusted estimate of $530 per truck (obtained using the low C-R coefficient) remains unchanged through the 5th percentile confidence cut-off because almost none of the U.S. is projected to have ozone

[27] The benefit-per-truck estimate of $650 is calculated by multiplying the unadjusted estimate by the fraction of benefits that can be attributed to locations with exposures greater than the 25th percentile of the study exposures: 14%*$4,650.

[28] 57% is computed as the sum of the percentages of the total deaths that can be attributed to locations with exposures greater than the 25th percentile of the study exposures (*i.e.*, the sum of the last two columns, 43%+14%). This sum is then multiplied by the unadjusted estimate (*i.e.*, 57%*$4,650) to obtain the 10th percentile confidence-weighted estimate of $2,670.

concentrations below 23.4 ppb in our baseline air quality grid, even though Zanobetti and Schwartz data indicate that about 5% of the cities in their study had lower average ozone levels.[29] The confidence-weighted ozone benefit estimate declines to $250 per truck at the highest confidence end of the spectrum with 47% of our estimated ozone benefits projected to occur in locations with exposures above the 25th percentile of all the cities observed in the original Zanobetti and Schwartz study. As shown in Table 4, the unadjusted estimate of $810 per truck (obtained using the low C-R coefficient), declines to $380 per truck at the highest confidence end of the spectrum. As before, the estimates computed using a 7% discount rate are about 25% lower than the respective 3% discount rate estimates.

[29] We have no explanation for such a discrepancy at this time, which seems surprising given that our estimates of baseline exposure are more disaggregated than those of Zanobetti and Schwartz's observations (12-km grid resolution *vs.* city-wide averages) and they occur later in time (2035 *vs.* 1989-2000) when tighter ozone standards will be in place.

Table 1: Avoided Premature Statistical Deaths (%) and National $PM_{2.5}$ Benefits per Truck (2019$) by Confidence
C-R Coefficient from the Di *et al.* (2017) Epidemiology Study and Applying 3% and 7% Discount

	Below LML (<0.02)	LML to 1st Percentile (≥0.02 & <3)	1st to 5th Percentile (≥3 & <6.2)	5th to 10th Percentile (≥6.2 & <7.3)	10th to 25th Percentile (≥7.3 & <9.1)
			Avoided Premature Statistical Deaths (%)		
National	0%	0%	15%	27%	43%
			Benefit per Truck (2019$)		
3% Discount Rate	$4,650	$4,650	$4,650	$3,930	$2,670
7% Discount Rate	$3,460	$3,460	$3,460	$2,930	$1,980

LML = Lowest Measured Level, meaning the minimum observed $PM_{2.5}$ concentration in the original epidemiological study

Table 2: Avoided Premature Statistical Deaths (%) and National $PM_{2.5}$ Benefits per Truck (2019$) by Confidence
C-R Coefficient from the Di *et al.* (2017) Epidemiology Study and Applying 3% and 7% Discount

	Below LML (<0.02)	LML to 1st Percentile (≥0.02 & <3)	1st to 5th Percentile (≥3 & <6.2)	5th to 10th Percentile (≥6.2 & <7.3)	10th to 25th Percentile (≥7.3 & <9.1)
	Avoided Premature Statistical Deaths (%)				
National	0%	0%	15%	27%	43%
	Benefit per Truck (2019$)				
3% Discount Rate	$6,340	$6,340	$6,340	$5,360	$3,640
7% Discount Rate	$4,710	$4,710	$4,710	$3,980	$2,700

LML = Lowest Measured Level, meaning the minimum observed $PM_{2.5}$ concentration in the original epidemiological study

Table 3: Avoided Premature Statistical Deaths (%) and National Ozone Benefits per Truck (2019$) by Confidence
C-R Coefficient from the Zanobetti and Schwartz (2008) Epidemiology Study and Applying 3% and 7% D

Less confident ← **More confident**

	Below LML (<15.1)	LML to 1st Percentile (=15.1)	1st to 5th Percentile (>15.1 & <23.4)	5th to 10th Percentile (≥23.4 & <35.6)	10th to 25th Percentile (≥35.6 & <44.0
			Avoided Premature Statistical Deaths (%)		
National	0%	0%	0%	17%	36%
			Benefit per Truck (2019$)		
3% Discount Rate	$530	$530	$530	$530	$440
7% Discount Rate	$390	$390	$390	$390	$320

LML = Lowest Measured Level, meaning the minimum observed ozone concentration in the original epidemiological study

**Table 4: Avoided Premature Statistical Deaths (%) and National Ozone Benefits per Truck (2019$) by Confidence
C-R Coefficient from the Zanobetti and Schwartz (2008) Epidemiology Study and Applying 3% and 7% D**

	Below LML (<15.1)	LML to 1st Percentile (=15.1)	1st to 5th Percentile (>15.1 & <23.4)	5th to 10th Percentile (≥23.4 & <35.6)	10th to 25th Percentile (≥35.6 & <44.0
			Avoided Premature Statistical Deaths (%)		
National	0%	0%	0%	17%	36%
			Benefit per Truck (2019$)		
3% Discount Rate	$810	$810	$810	$810	$670
7% Discount Rate	$590	$590	$590	$590	$490

LML = Lowest Measured Level, meaning the minimum observed ozone concentration in the original epidemiological study

As illustrated previously, significant differences exist between the projected concentrations in California and the Rest of U.S., which points to the existence of different patterns in the decline of the benefit-per-truck estimates moving from the "less confident" to the "more confident" end of the benefits estimates scale.[30] Table 5 through 8 present the benefit-per-truck estimates separately for California and Rest of the U.S. in the same format as that presented above for the national estimates. These tables show that California benefit-per-truck estimates decrease at a slower rate than the Rest of the U.S estimates do, which further widens the significant disparities that were noted in the unadjusted estimates in the prior section.

Table 5 and 6 present the $PM_{2.5}$ benefit-per-truck estimates calculated using low and high C-R coefficients from the Di *et al.* (2017) study for these two regions. As shown in Table 5, the unadjusted estimate using a 3% discount rate (obtained using the low Di *et al.* (2017) C-R coefficient) declines from $9,330 to $5,570 per truck for California, while it declines from $4,260 to $180 per truck for the Rest of the U.S. While the estimates for California are about 2 times higher than those for the Rest of the U.S. at the "less confident" end of the spectrum, they are 30 times higher at the "more confident" end. About 60% of the benefits in California are projected to occur in locations with baseline concentrations greater than the 25th percentile of the original study; in contrast, the corresponding fraction for benefits estimates across the Rest of the U.S. is about 4%. As shown in Table 6, the unadjusted estimate using a 3% discount rate (obtained using the high Di *et al.* (2017) C-R coefficient) declines from $12,700 to $7,580 per truck for California, while it declines from $5,810 to $250 per truck for the Rest of the U.S. The relationship between the California and the Rest of the U.S. estimates are similar to those obtained using the low C-R coefficient.

Table 7 and 8 present the ozone benefit-per-truck estimates calculated using low and high C-R coefficients from the Zanobetti and Schwartz (2008) study for the two regions. The unadjusted estimate using a 3% discount rate (obtained using the low Zanobetti and Schwartz (2008) C-R coefficient) declines from $2,920 to $1,690 per truck for California, while it declines from $250 to $80 per truck for the Rest of the U.S. The confidence unadjusted estimate using a 3% discount rate (obtained using the high Zanobetti and Schwartz (2008) C-R coefficient) declines from $4,480 to $2,600 per truck for California, while it declines from $390 to $130 per truck for the Rest of the U.S. Compared to the $PM_{2.5}$ estimates, a larger disparity in the estimates for the two regions is observed at the "less confident" end of the spectrum. That is, the California benefit-per-truck estimates are about 12 times higher than those for the Rest of the U.S. before confidence-weighting and are about 21 times higher at the other end of the confidence-weighting spectrum.

Although this finding that California has substantially higher benefits per truck could be used to justify a tighter standard for California trucks than for the rest of the U.S., it would be inappropriate to use the higher California-specific benefits estimates in a benefit-cost analysis of a standard that would be applied to other states.

[30] The Rest of U.S. region includes all states across the conterminous U.S. except for California.

Table 5: Avoided Premature Statistical Deaths (%) and $PM_{2.5}$ Benefits per Truck (2019$) for California and Rest
Level Using the Low C-R Coefficient from the Di *et al.* (2017) Epidemiology Study and Applying 3% and 7%

	Below LML (<0.02)	LML to 1st Percentile (≥0.02 & <3)	1st to 5th Percentile (≥3 & <6.2)	5th to 10th Percentile (≥6.2 & <7.3)	10th to 25th Percentile (≥7.3 & <9.1)
			Avoided Premature Statistical Deaths (%)		
California	0%	0%	5%	11%	25%
Rest of U.S.	0%	0%	18%	31%	47%
			Benefit per Truck (2019$)		
3% Discount Rate					
California	$9,330	$9,330	$9,330	$8,870	$7,880
Rest of U.S.	$4,260	$4,260	$4,260	$3,510	$2,190
7% Discount Rate					
California	$6,820	$6,820	$6,820	$6,490	$5,760
Rest of U.S.	$3,180	$3,180	$3,180	$2,620	$1,640

LML = Lowest Measured Level, meaning the minimum observed $PM_{2.5}$ concentration in the original epidemiological study

Table 6: Avoided Premature Statistical Deaths (%) and $PM_{2.5}$ Benefits per Truck (2019$) for California and Rest Level Using the High C-R Coefficient from the Di *et al.* (2017) Epidemiology Study and Applying 3% and 7

Less confident ← **More confident**

	Below LML (<0.02)	LML to 1st Percentile (≥0.02 & <3)	1st to 5th Percentile (≥3 & <6.2)	5th to 10th Percentile (≥6.2 & <7.3)	10th to 25th Percentile (≥7.3 & <9.1)
			Avoided Premature Statistical Deaths (%)		
California	0%	0%	5%	11%	25%
Rest of U.S.	0%	0%	18%	31%	47%
			Benefit per Truck (2019$)		
3% Discount Rate					
California	$12,700	$12,700	$12,700	$12,080	$10,730
Rest of U.S.	$5,810	$5,810	$5,810	$4,780	$2,990
7% Discount Rate					
California	$9,290	$9,290	$9,290	$8,840	$7,850
Rest of U.S.	$4,330	$4,330	$4,330	$3,560	$2,230

LML = Lowest Measured Level, meaning the minimum observed $PM_{2.5}$ concentration in the original epidemiological study

Table 7: Avoided Premature Statistical Deaths (%) and Ozone Benefits per Truck (2019$) for California and Rest Level Using the Low C-R Coefficient from the Zanobetti and Schwartz (2008) Epidemiology Study and Applying Rates

Less confident ← **More confident**

	Below LML (<15.1)	LML to 1st Percentile (=15.1)	1st to 5th Percentile (>15.1 & <23.4)	5th to 10th Percentile (≥23.4 & <35.6)	10th to 25th Percentile (≥35.6 & <44.0
Avoided Premature Statistical Deaths (%)					
California	0%	0%	0%	12%	30%
Rest of U.S.	0%	0%	0%	24%	44%
Benefit per Truck (2019$)					
3% Discount Rate					
California	$2,920	$2,920	$2,920	$2,920	$2,560
Rest of U.S.	$250	$250	$250	$250	$190
7% Discount Rate					
California	$2,140	$2,140	$2,140	$2,140	$1,870
Rest of U.S.	$190	$190	$190	$190	$150

LML = Lowest Measured Level, meaning the minimum observed ozone concentration in the original epidemiological study

Table 8: Avoided Premature Statistical Deaths (%) and Ozone Benefits per Truck (2019$) for California and Rest Level Using the High C-R Coefficient from the Zanobetti and Schwartz (2008) Epidemiology Study and Applying Rates

	Below LML (<15.1)	LML to 1st Percentile (=15.1)	1st to 5th Percentile (>15.1 & <23.4)	5th to 10th Percentile (≥23.4 & <35.6)	10th to 25th Percentile (≥35.6 & <44.0
			Avoided Premature Statistical Deaths (%)		
California	0%	0%	0%	12%	30%
Rest of U.S.	0%	0%	0%	24%	44%
			Benefit per Truck (2019$)		
3% Discount Rate					
California	$4,480	$4,480	$4,480	$4,480	$3,920
Rest of U.S.	$390	$390	$390	$390	$300
7% Discount Rate					
California	$3,280	$3,280	$3,280	$3,280	$2,870
Rest of U.S.	$290	$290	$290	$290	$220

LML = Lowest Measured Level, meaning the minimum observed ozone concentration in the original epidemiological study

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Appendix A: Estimated Total NO_x Emissions Reductions Including All Model Years, by Sta

	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
U.S.	39,268	79,207	119,691	161,341	212,912	262,076	309,543	354,311	395,691	433,610	468,668	500,585	528,674	553,267
Alabama	781	1,575	2,380	3,208	4,234	5,212	6,156	7,047	7,869	8,623	9,320	9,954	10,512	11,000
Arizona	1,069	2,156	3,258	4,391	5,796	7,136	8,429	9,649	10,776	11,809	12,763	13,632	14,398	15,067
Arkansas	495	999	1,509	2,034	2,683	3,301	3,898	4,460	4,979	5,454	5,893	6,293	6,644	6,951
California	4,017	8,102	12,245	16,506	21,785	26,818	31,679	36,266	40,507	44,396	47,993	51,270	54,156	56,685
Colorado	703	1,418	2,142	2,887	3,810	4,689	5,538	6,339	7,079	7,757	8,384	8,955	9,457	9,896
Connecticut	346	698	1,055	1,423	1,879	2,313	2,734	3,130	3,497	3,833	4,145	4,428	4,678	4,897
Delaware	121	245	370	499	660	813	961	1,101	1,231	1,349	1,459	1,559	1,647	1,725
Florida	2,089	4,214	6,370	8,588	11,349	13,984	16,531	18,935	21,161	23,203	25,094	26,819	28,339	29,674
Georgia	1,299	2,620	3,959	5,337	7,047	8,677	10,251	11,736	13,109	14,369	15,533	16,594	17,528	18,346
Idaho	249	502	758	1,022	1,346	1,656	1,954	2,235	2,495	2,733	2,952	3,151	3,327	3,480
Illinois	1,323	2,669	4,033	5,437	7,178	8,838	10,442	11,955	13,354	14,637	15,823	16,904	17,855	18,690
Indiana	935	1,887	2,851	3,843	5,071	6,241	7,370	8,436	9,420	10,322	11,155	11,914	12,581	13,166
Iowa	518	1,045	1,579	2,128	2,806	3,452	4,075	4,663	5,205	5,701	6,159	6,576	6,942	7,262
Kansas	458	923	1,395	1,880	2,478	3,048	3,597	4,115	4,593	5,030	5,434	5,801	6,124	6,406
Kentucky	711	1,435	2,167	2,921	3,847	4,730	5,581	6,383	7,123	7,800	8,426	8,994	9,494	9,930
Louisiana	634	1,279	1,932	2,604	3,435	4,227	4,991	5,712	6,378	6,988	7,552	8,065	8,517	8,912
Maine	221	445	672	905	1,194	1,469	1,733	1,983	2,213	2,424	2,618	2,795	2,951	3,086
Maryland	697	1,407	2,126	2,866	3,784	4,660	5,506	6,304	7,043	7,720	8,346	8,917	9,420	9,861
Massachusetts	646	1,304	1,970	2,657	3,512	4,328	5,117	5,862	6,552	7,186	7,773	8,308	8,780	9,195
Michigan	1,349	2,722	4,113	5,544	7,320	9,013	10,649	12,191	13,617	14,924	16,132	17,233	18,201	19,050
Minnesota	792	1,597	2,413	3,252	4,293	5,285	6,242	7,145	7,979	8,744	9,450	10,092	10,657	11,152
Mississippi	503	1,014	1,532	2,065	2,723	3,351	3,957	4,527	5,054	5,537	5,982	6,388	6,744	7,055
Missouri	958	1,932	2,918	3,933	5,178	6,364	7,507	8,585	9,579	10,488	11,328	12,091	12,762	13,347
Montana	219	442	668	900	1,187	1,461	1,725	1,974	2,203	2,413	2,607	2,783	2,938	3,074
Nebraska	322	649	980	1,321	1,740	2,140	2,525	2,888	3,223	3,530	3,813	4,070	4,296	4,493
Nevada	311	628	949	1,279	1,688	2,079	2,456	2,812	3,141	3,442	3,722	3,976	4,200	4,396
New Hampshire	186	375	566	763	1,007	1,239	1,463	1,674	1,869	2,048	2,213	2,363	2,496	2,611
New Jersey	865	1,745	2,637	3,557	4,705	5,801	6,862	7,864	8,792	9,644	10,433	11,153	11,789	12,348
New Mexico	387	779	1,178	1,587	2,092	2,573	3,037	3,475	3,879	4,248	4,590	4,900	5,173	5,411

	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
New York	1,363	2,750	4,155	5,602	7,396	9,107	10,759	12,318	13,760	15,083	16,306	17,420	18,402	19,262
North Carolina	1,321	2,666	4,028	5,430	7,166	8,821	10,420	11,927	13,320	14,597	15,777	16,852	17,798	18,626
North Dakota	154	310	469	632	833	1,025	1,209	1,383	1,544	1,691	1,827	1,950	2,058	2,153
Ohio	1,419	2,863	4,326	5,831	7,692	9,467	11,179	12,794	14,287	15,655	16,919	18,070	19,082	19,969
Oklahoma	644	1,300	1,964	2,646	3,491	4,295	5,070	5,802	6,477	7,095	7,666	8,186	8,642	9,041
Oregon	492	991	1,498	2,019	2,665	3,281	3,875	4,435	4,953	5,427	5,866	6,265	6,616	6,924
Pennsylvania	1,325	2,672	4,037	5,442	7,177	8,832	10,429	11,935	13,326	14,601	15,779	16,851	17,795	18,620
Rhode Island	97	196	296	398	526	648	766	877	980	1,074	1,161	1,241	1,311	1,373
South Carolina	786	1,584	2,394	3,227	4,255	5,236	6,182	7,074	7,898	8,652	9,349	9,983	10,541	11,029
South Dakota	172	347	524	706	930	1,143	1,348	1,541	1,719	1,882	2,032	2,169	2,288	2,393
Tennessee	954	1,923	2,906	3,918	5,169	6,361	7,512	8,598	9,601	10,521	11,371	12,144	12,825	13,421
Texas	3,377	6,812	10,295	13,878	18,319	22,554	26,643	30,500	34,066	37,335	40,358	43,111	45,534	47,657
Utah	393	793	1,198	1,614	2,129	2,620	3,094	3,540	3,953	4,331	4,681	4,999	5,279	5,524
Vermont	113	228	344	464	611	751	886	1,014	1,131	1,239	1,338	1,428	1,507	1,576
Virginia	1,140	2,299	3,474	4,682	6,176	7,598	8,972	10,266	11,463	12,558	13,571	14,492	15,303	16,012
Washington	793	1,600	2,418	3,259	4,299	5,290	6,246	7,148	7,981	8,745	9,451	10,093	10,658	11,153
West Virginia	274	552	835	1,125	1,483	1,825	2,154	2,464	2,751	3,013	3,256	3,476	3,670	3,839
Wisconsin	933	1,882	2,844	3,833	5,057	6,222	7,347	8,407	9,386	10,283	11,111	11,864	12,526	13,104
Wyoming	155	312	471	635	836	1,027	1,211	1,384	1,544	1,690	1,825	1,948	2,055	2,149

Appendix A: Estimated Total NO_x Emissions Reductions Including All Model Years, by Sta

	2045	2046	2047	2048	2049	2050	2051	2052	2053	2054	2055	2056	20
U.S.	637,703	651,097	663,996	675,926	686,947	697,645	707,782	714,754	723,940	732,727	741,297	749,692	759,
Alabama	12,675	12,940	13,196	13,439	13,658	13,870	14,071	14,262	14,445	14,619	14,789	14,956	15,
Arizona	17,360	17,723	18,071	18,403	18,701	18,989	19,262	16,826	17,051	17,266	17,476	17,683	17,9
Arkansas	7,999	8,164	8,322	8,474	8,609	8,739	8,863	8,981	9,093	9,199	9,303	9,405	9,5
California	65,402	66,790	68,129	69,406	70,554	71,669	72,727	73,738	74,702	75,625	76,526	77,410	78,4
Colorado	11,405	11,644	11,874	12,093	12,290	12,480	12,661	12,833	12,997	13,154	13,307	13,457	13,6
Connecticut	5,655	5,776	5,893	6,005	6,106	6,204	6,297	6,386	6,471	6,553	6,632	6,711	6,8
Delaware	1,992	2,035	2,077	2,117	2,152	2,187	2,221	2,252	2,283	2,312	2,340	2,368	2,4
Florida	34,306	35,050	35,769	36,457	37,079	37,684	38,259	38,811	39,338	39,844	40,340	40,827	41,3
Georgia	21,164	21,613	22,046	22,459	22,831	23,192	23,534	23,862	24,174	24,473	24,765	25,051	25,3
Idaho	4,000	4,082	4,160	4,234	4,300	4,364	4,424	4,482	4,536	4,587	4,638	4,687	4,7
Illinois	21,562	22,020	22,461	22,881	23,259	23,626	23,975	24,307	24,624	24,928	25,224	25,515	25,8
Indiana	15,167	15,484	15,788	16,079	16,339	16,591	16,830	17,057	17,274	17,480	17,682	17,879	18,
Iowa	8,349	8,520	8,684	8,841	8,980	9,115	9,242	9,363	9,478	9,588	9,695	9,799	9,9
Kansas	7,365	7,516	7,660	7,798	7,920	8,038	8,149	8,255	8,356	8,452	8,545	8,636	8,7
Kentucky	11,411	11,643	11,864	12,075	12,261	12,442	12,612	12,773	12,926	13,071	13,212	13,350	13,5
Louisiana	10,266	10,480	10,686	10,882	11,058	11,228	11,389	11,542	11,689	11,828	11,964	12,097	12,2
Maine	3,546	3,618	3,687	3,753	3,812	3,868	3,922	3,973	4,021	4,067	4,112	4,155	4,2
Maryland	11,383	11,626	11,861	12,085	12,287	12,483	12,669	12,847	13,017	13,180	13,339	13,496	13,6
Massachusetts	10,637	10,869	11,094	11,309	11,504	11,694	11,875	12,048	12,214	12,374	12,530	12,683	12,8
Michigan	21,966	22,430	22,877	23,304	23,687	24,060	24,413	24,750	25,071	25,379	25,679	25,974	26,3
Minnesota	12,845	13,113	13,371	13,618	13,839	14,054	14,258	14,452	14,636	14,813	14,985	15,154	15,3
Mississippi	8,116	8,283	8,444	8,597	8,734	8,866	8,991	9,111	9,224	9,332	9,438	9,541	9,6
Missouri	15,335	15,645	15,942	16,224	16,473	16,714	16,941	17,156	17,360	17,554	17,742	17,926	18,
Montana	3,533	3,605	3,674	3,369	3,420	3,470	3,517	3,561	3,603	3,643	3,681	3,719	3,7
Nebraska	5,163	5,267	5,368	5,463	5,547	5,629	5,706	5,779	5,849	5,915	5,979	6,041	6,1
Nevada	5,072	5,180	5,284	5,383	5,472	5,558	5,640	5,718	5,793	5,864	5,934	6,002	6,0
New Hampshire	3,006	3,069	3,129	3,186	3,238	3,287	3,335	3,379	3,422	3,463	3,503	3,542	3,5
New Jersey	14,293	14,607	14,912	15,205	15,471	15,730	15,977	16,215	16,442	16,661	16,876	17,087	17,3
New Mexico	6,222	6,349	6,471	6,587	6,690	6,790	6,884	6,974	7,059	7,140	7,218	7,295	7,3

	2045	2046	2047	2048	2049	2050	2051	2052	2053	2054	2055	2056	20
New York	22,228	22,701	23,157	23,592	23,984	24,365	24,726	25,071	25,401	25,716	26,024	26,326	26,6
North Carolina	21,469	21,920	22,355	22,769	23,141	23,502	23,845	24,171	24,482	24,780	25,070	25,354	25,6
North Dakota	2,473	2,523	2,571	2,617	2,658	2,697	2,734	2,769	2,803	2,835	2,866	2,896	2,9
Ohio	23,008	23,489	23,952	24,393	24,789	25,172	25,535	25,881	26,210	26,525	26,832	27,132	27,4
Oklahoma	10,402	10,617	10,823	11,019	11,195	11,365	11,525	11,678	11,824	11,962	12,098	12,230	12,3
Oregon	7,977	8,144	8,305	8,458	8,596	8,729	8,855	8,975	9,090	9,200	9,306	9,411	9,5
Pennsylvania	21,449	21,896	22,326	22,735	23,101	23,455	23,791	24,111	24,415	24,705	24,988	25,265	25,5
Rhode Island	1,585	1,619	1,652	1,683	1,712	1,739	1,765	1,790	1,814	1,837	1,860	1,882	1,9
South Carolina	12,696	12,958	13,211	13,451	13,666	13,874	14,071	14,258	14,436	14,606	14,771	14,933	15,1
South Dakota	2,745	2,800	2,852	2,902	2,945	2,988	3,027	3,065	3,100	3,134	3,167	3,198	3,2
Tennessee	15,465	15,789	16,101	16,397	16,663	16,921	17,165	17,398	17,620	17,832	18,038	18,240	18,4
Texas	54,959	56,121	57,242	58,311	59,272	60,206	61,091	61,937	62,743	63,515	64,269	65,008	65,8
Utah	6,364	6,496	6,624	6,746	6,854	6,960	7,059	7,154	7,245	7,331	7,415	7,498	7,5
Vermont	1,810	1,846	1,881	1,914	1,944	1,972	1,999	2,024	2,048	2,071	2,094	2,115	2,1
Virginia	18,438	18,821	19,190	19,541	19,854	20,158	20,446	20,720	20,980	21,229	21,471	21,708	21,9
Washington	12,849	13,117	13,375	13,621	13,841	14,054	14,256	14,448	14,631	14,805	14,976	15,142	15,3
West Virginia	4,415	4,506	4,593	4,676	4,749	4,821	4,889	4,953	5,014	5,072	5,129	5,184	5,2
Wisconsin	15,078	15,390	15,689	15,974	16,229	16,476	16,709	16,932	17,143	17,345	17,541	17,733	17,9
Wyoming	2,465	2,514	2,561	2,605	2,644	2,682	2,717	2,751	2,782	2,812	2,841	2,869	2,9

Appendix B: Estimated Benefits per Ton, by State

	Zanobetti and Schwartz (2008); Ozone Respiratory Mortality (2019$/ton) (Low)			Zanobetti and Schwartz (2008); Ozone Respiratory Mortality (2019$/ton) (High)			Di *et al.* (2017); PM$_{2.5}$ All-Cause Mortality (2019$/ton) (Low)			Di M
	2030	2040	2050	2030	2040	2050	2030	2040	2050	2
U.S.	$666	$816	$926	$1,023	$1,252	$1,420	$6,552	$7,558	$7,842	$8
Alabama	$209	$225	$218	$320	$345	$334	$746	$836	$821	$1
Arizona	$705	$905	$1,085	$1,082	$1,388	$1,665	$326	$439	$532	$
Arkansas	$93	$101	$99	$143	$155	$152	$1,743	$1,991	$2,013	$2
California	$3,662	$4,546	$5,249	$5,620	$6,973	$8,050	$11,572	$14,687	$17,241	$1
Colorado	$513	$609	$661	$788	$934	$1,015	$3,543	$4,374	$4,987	$4
Connecticut	$111	$128	$128	$170	$197	$196	$7,315	$8,544	$8,581	$9
Delaware	$41	$48	$50	$63	$74	$77	$18,053	$21,794	$23,129	$2
Florida	$803	$1,020	$1,205	$1,232	$1,565	$1,850	$44	$58	$69	$
Georgia	$361	$433	$472	$554	$665	$724	$805	$1,024	$1,157	$1
Idaho	$32	$38	$41	$50	$59	$63	$3,023	$3,793	$4,276	$4
Illinois	$101	$112	$112	$154	$173	$172	$15,512	$17,921	$18,514	$2
Indiana	$144	$154	$146	$221	$237	$224	$14,172	$15,821	$15,491	$1
Iowa	$30	$31	$28	$46	$48	$44	$8,574	$9,102	$8,334	$1
Kansas	$28	$29	$26	$43	$44	$41	$4,870	$5,308	$5,036	$6
Kentucky	$166	$175	$164	$256	$269	$252	$5,947	$6,501	$6,176	$8
Louisiana	$169	$187	$186	$260	$287	$286	$252	$283	$287	$
Maine	$49	$57	$56	$76	$87	$86	$468	$573	$594	$
Maryland	$158	$195	$217	$242	$299	$333	$10,277	$12,838	$14,470	$1
Massachusetts	$145	$164	$162	$223	$252	$248	$4,448	$5,077	$5,048	$6
Michigan	$233	$257	$252	$358	$394	$387	$16,936	$19,343	$19,381	$2
Minnesota	$83	$95	$92	$127	$146	$142	$10,405	$12,486	$12,684	$1
Mississippi	$126	$137	$135	$193	$210	$207	$823	$968	$1,025	$1
Missouri	$61	$65	$60	$94	$100	$92	$4,994	$5,438	$5,111	$6
Montana	$25	$29	$30	$38	$45	$47	$309	$381	$421	$
Nebraska	$17	$18	$16	$26	$27	$25	$4,242	$4,625	$4,397	$5
Nevada	$829	$1,129	$1,504	$1,273	$1,733	$2,309	$1,009	$1,366	$1,781	$1
New Hampshire	$33	$40	$40	$51	$61	$62	$1,716	$2,137	$2,212	$2

	Zanobetti and Schwartz (2008); Ozone Respiratory Mortality (2019$/ton) (Low)			Zanobetti and Schwartz (2008); Ozone Respiratory Mortality (2019$/ton) (High)			Di et al. (2017); PM2.5 All-Cause Mortality (2019$/ton) (Low)			Di e M
	2030	2040	2050	2030	2040	2050	2030	2040	2050	2
New Jersey	$233	$269	$273	$357	$413	$419	$12,678	$14,931	$15,409	$1
New Mexico	$88	$109	$129	$134	$167	$197	$200	$258	$315	$
New York	$388	$436	$443	$595	$670	$680	$9,447	$10,832	$11,238	$1
North Carolina	$323	$383	$412	$496	$588	$632	$2,531	$3,128	$3,427	$3
North Dakota	$16	$19	$20	$25	$30	$30	$1,048	$1,228	$1,261	$1
Ohio	$297	$321	$310	$455	$492	$476	$16,177	$18,207	$18,060	$2
Oklahoma	$129	$133	$124	$198	$205	$191	$3,086	$3,320	$3,171	$4
Oregon	$72	$82	$89	$111	$126	$136	$1,378	$1,598	$1,722	$1
Pennsylvania	$281	$318	$318	$432	$488	$489	$13,961	$16,313	$16,676	$1
Rhode Island	$40	$45	$45	$61	$69	$69	$8,404	$9,731	$9,821	$1
South Carolina	$172	$211	$241	$264	$324	$371	$1,190	$1,506	$1,732	$1
South Dakota	$16	$18	$17	$25	$28	$27	$2,407	$2,651	$2,520	$3
Tennessee	$249	$275	$273	$383	$422	$419	$2,177	$2,478	$2,484	$2
Texas	$951	$1,159	$1,303	$1,460	$1,779	$1,999	$1,036	$1,318	$1,498	$1
Utah	$313	$386	$452	$480	$592	$693	$7,120	$8,730	$9,917	$9
Vermont	$17	$20	$20	$26	$30	$30	$1,634	$2,049	$2,230	$2
Virginia	$262	$322	$356	$401	$494	$546	$2,409	$3,128	$3,641	$3
Washington	$117	$138	$150	$180	$212	$230	$1,430	$1,761	$1,979	$1
West Virginia	$97	$100	$94	$149	$153	$144	$3,483	$3,742	$3,622	$4
Wisconsin	$82	$93	$89	$126	$142	$137	$12,233	$14,082	$13,799	$1
Wyoming	$14	$16	$17	$21	$25	$26	$164	$196	$206	$

Appendix C: Benefit-per-Truck Estimates by State, 7% Discount Rate

Figure 20: Map of $PM_{2.5}$-Only Benefits per Truck by State Using the Low Di *et al.* (2017) C-R Coefficient, 7% Discount Rate

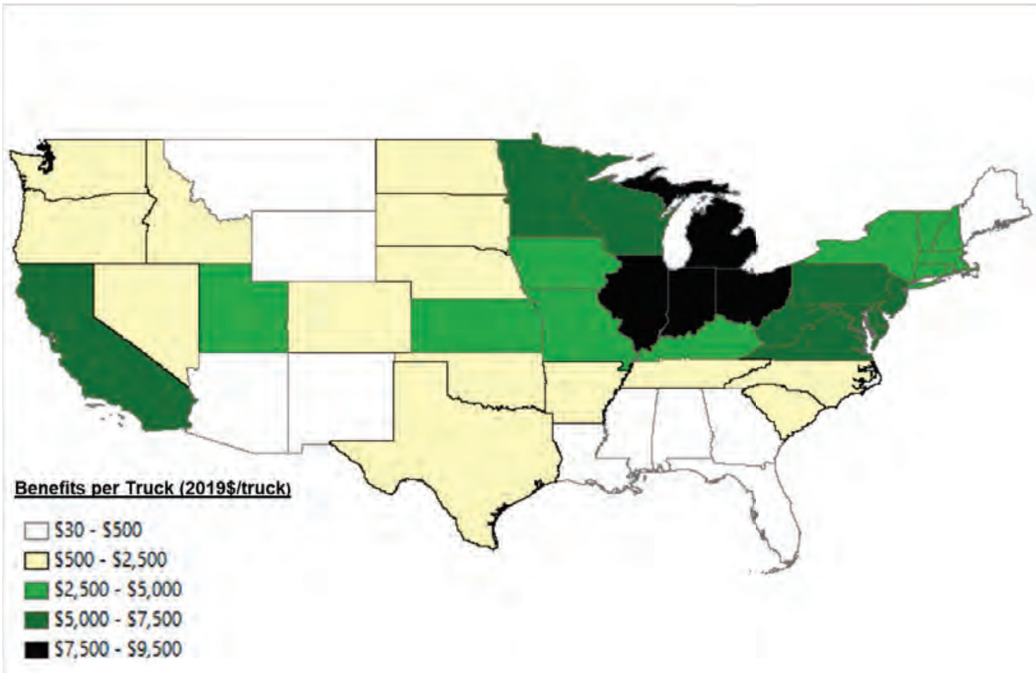


Figure 21: Cumulative Distribution of $PM_{2.5}$-Only Benefits per Truck by State Using the Low Di *et al.* (2017) C-R Coefficient, 7% Discount Rate

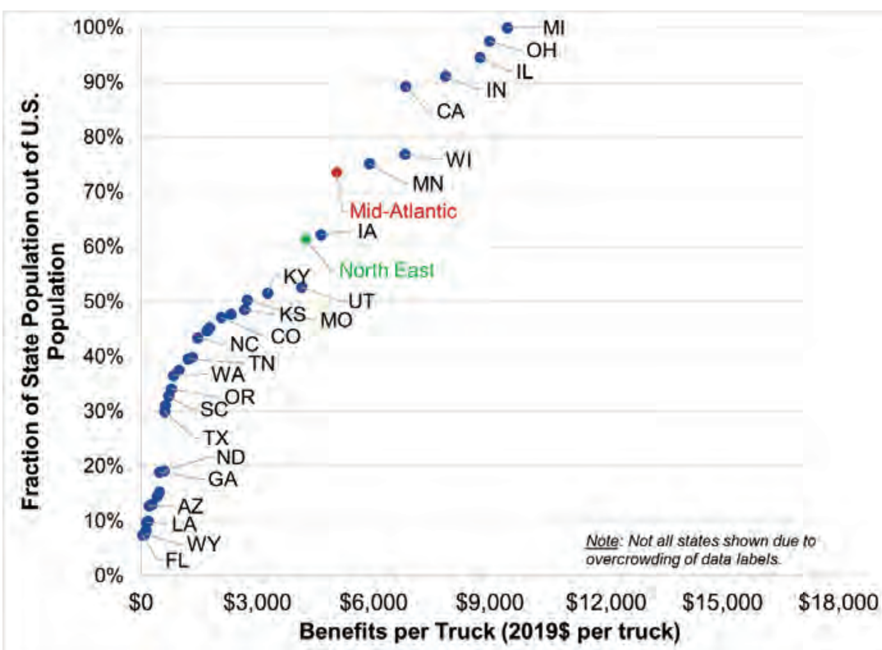


Figure 22: Map of $PM_{2.5}$-Only Benefits per Truck by State Using the High Di *et al.* (2017) C-R Coefficient, 7% Discount Rate

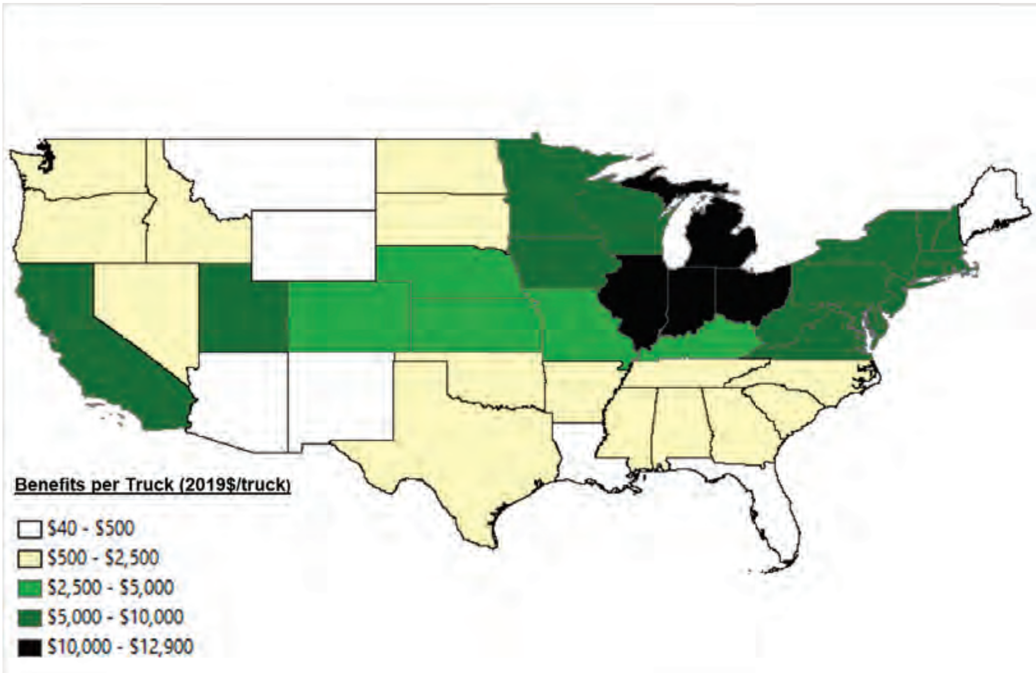


Figure 23: Cumulative Distribution of $PM_{2.5}$-Only Benefits per Truck by State Using the High Di *et al.* (2017) C-R Coefficient, 7% Discount Rate

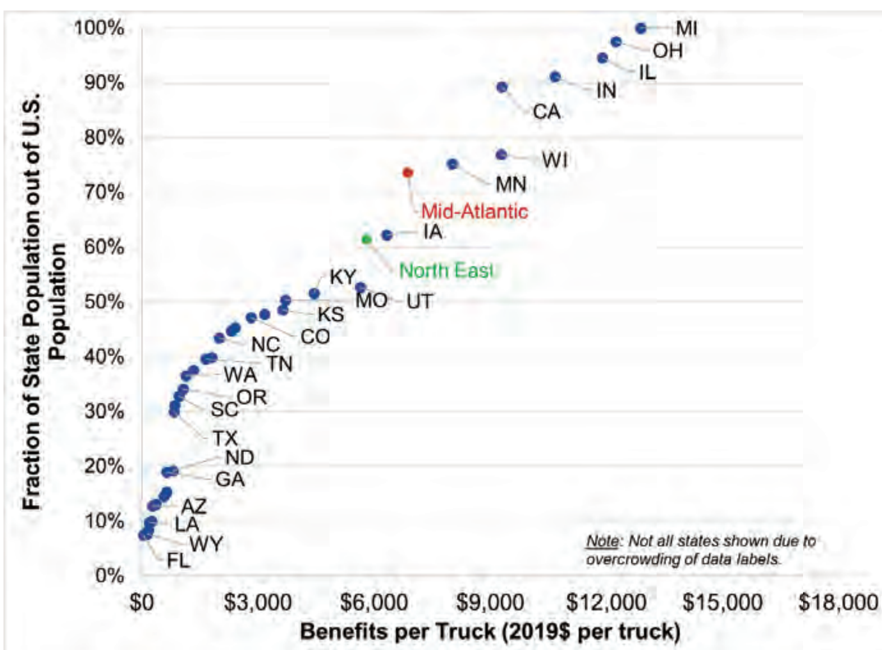


Figure 24: Map of Ozone-Only Benefits per Truck by State Using the Low Zanobetti and Schwartz (2008) C-R Coefficient, 7% Discount Rate

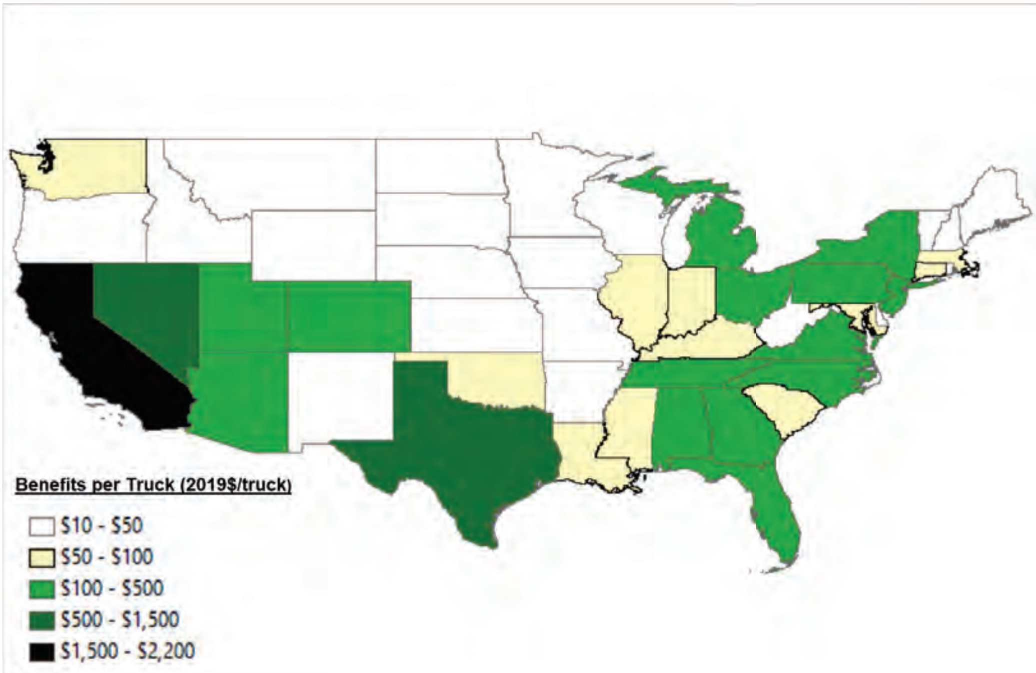


Figure 25: Cumulative Distribution of Ozone-Only Benefits per Truck by State Using the Low Zanobetti and Schwartz (2008) C-R Coefficient, 7% Discount Rate

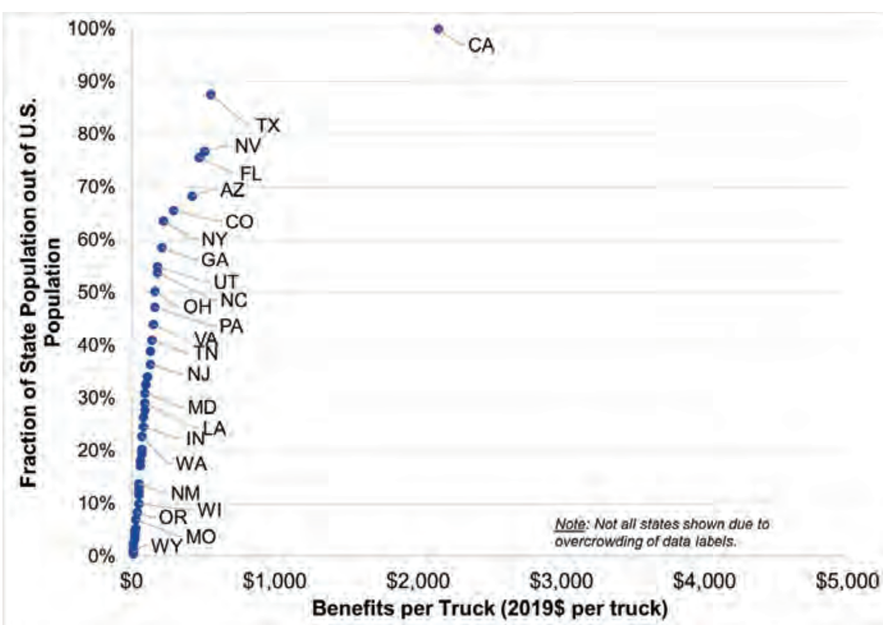


Figure 26: Map of Ozone-Only Benefits per Truck by State Using the High Zanobetti and Schwartz (2008) C-R Coefficient, 7% Discount Rate

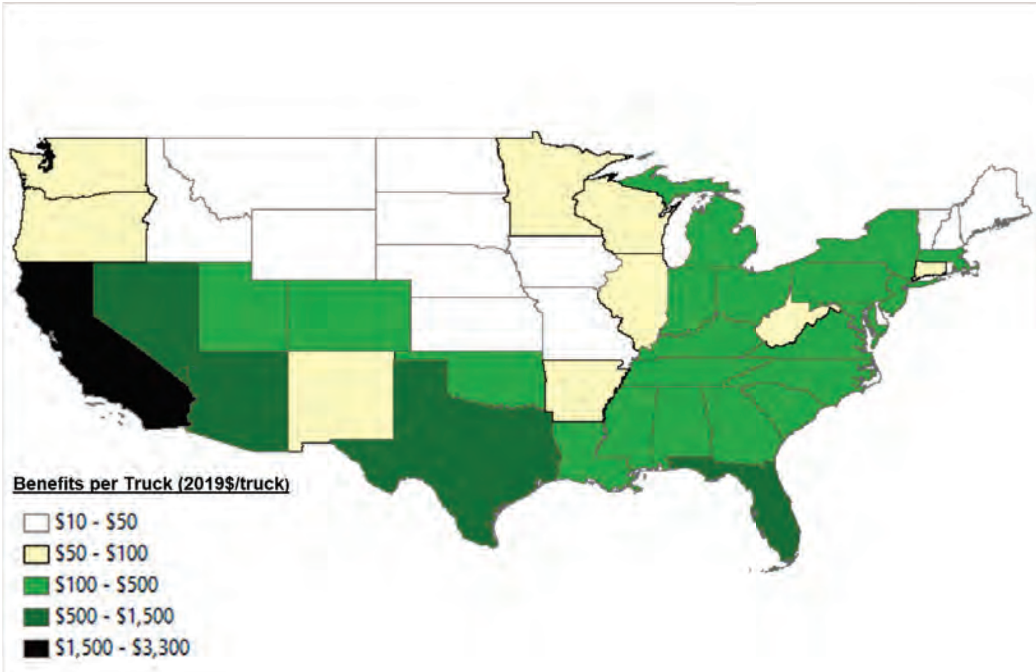
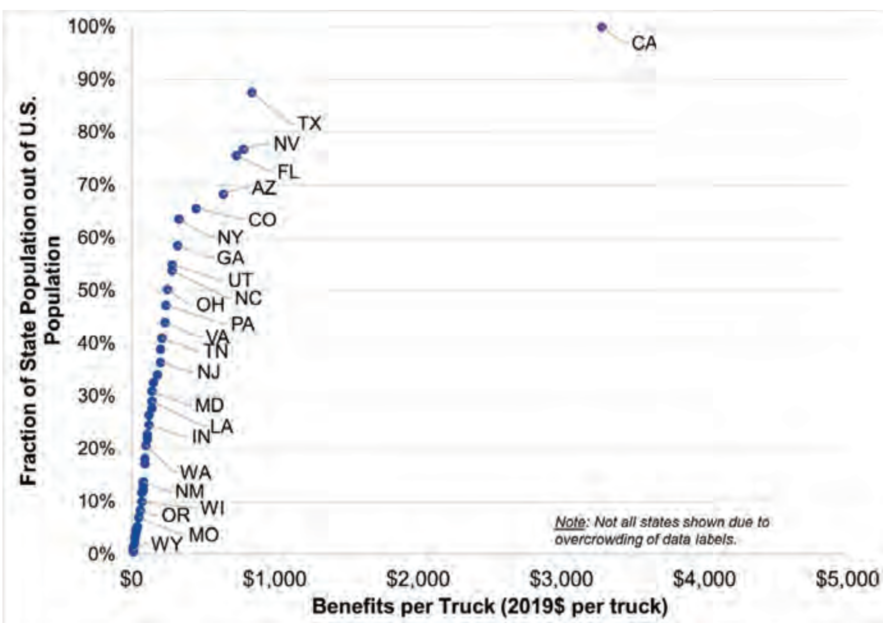


Figure 27: Cumulative Distribution of Ozone-Only Benefits per Truck by State Using the High Zanobetti and Schwartz (2008) C-R Coefficient, 7% Discount Rate



Appendix D: Estimated Average Ozone Response Factors by State

State	Ozone Response Factor (ppb/ton)
Alabama	0.000022
Arizona	0.000061
Arkansas	0.000014
California	0.000072
Colorado	0.000061
Connecticut	0.000019
Delaware	0.000017
Florida	0.000022
Georgia	0.000022
Idaho	0.000011
Illinois	0.000005
Indiana	0.000012
Iowa	0.000005
Kansas	0.000005
Kentucky	0.000017
Louisiana	0.000022
Maine	0.000016
Maryland	0.000019
Massachusetts	0.000015
Michigan	0.000014
Minnesota	0.000011
Mississippi	0.000022
Missouri	0.000005
Montana	0.000011
Nebraska	0.000005
Nevada	0.000135
New Hampshire	0.000012
New Jersey	0.000019
New Mexico	0.000021
New York	0.000015
North Carolina	0.000017
North Dakota	0.000011
Ohio	0.000014
Oklahoma	0.000018
Oregon	0.000011
Pennsylvania	0.000012
Rhode Island	0.000019
South Carolina	0.000017
South Dakota	0.000011
Tennessee	0.000019
Texas	0.000025
Utah	0.000098
Vermont	0.000010
Virginia	0.000020

State	Ozone Response Factor (ppb/ton)
Washington	0.000011
West Virginia	0.000019
Wisconsin	0.000009
Wyoming	0.000011

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