Achieving a Zero Emission Truck Fleet: Final Report

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Executive summary

This report uses economic reasoning, data and models to evaluate alternative policy approaches for achieving California's stated objectives to transition its medium and heavy-duty trucking fleet to entirely zero-emission trucks (ZETs) by 2045. The recently finalized Advanced Clean Fleet (ACF) rule regulates large fleets, drayage trucks, and public fleets. This report considers the remaining trucks, which comprise somewhere between one-third to one-half of the total fleet for larger trucks, and a larger proportion of the smallest commercial vehicles.[1] We refer to these trucks as the non-ACF fleet. The objective of policy is to transition the non-ACF fleet to be zero-emission at the lowest possible cost. A secondary objective is to mitigate the burden on small businesses or lower-income communities that may be caused by a transition.

Our analysis takes a set of existing policies as given. It assumes that the ACF remains in place and is unchanged. We also assume that the useful life provision, which restricts the ability of the California Air Resources Board (CARB) to require the retirement of existing trucks until they have reached specific age and mileage thresholds, remains in place.

A focus of the report is in drawing distinctions between what we call "command and control" approaches and "market-based approaches." Command and control policies operate by prohibiting purchase, registration or use of specific vehicles. Or, a command and control approach might proscribe penetration rates of ZETs on set timelines that each operator must meet. Under this definition, the ACF is a command and control regulation.

Market-based approaches, in contrast, use pricing mechanisms or tradable permits to create economic incentives that are designed to alter market outcomes while maintaining as much flexibility as possible as to how the market chooses to respond to the incentives. Market-based approaches can range from mileage-based or annual fees to green zones to subsidies for charging infrastructure. What they have in common is that they aim to create price signals in the market and then allow each fleet operator to respond flexibly, by either making changes to their fleet or paying a fee (or foregoing a subsidy). Note that a fleet penetration requirement like the ACF with permits that are tradable across firms would be categorized as a market-based mechanism because it allows different operators to respond differently through trading. Annual differentiated registration fees, which are another market based mechanism, were determined to be of particular interest, and so these policies are a major focus of the report.

The report also draws a categorical distinction between "pro-retirement policies" and "pro-adoption policies," both of which are market-based instruments. Pro-retirement policies foster a ZET transition by raising the cost of operating incumbent diesel trucks. In contrast, pro-adoption policies foster a ZET transition by lowering the cost of owning and operating ZET trucks. Figure

[1] These estimates are taken from a CARB fact sheet.

1 is a simple representation of this policy taxonomy.

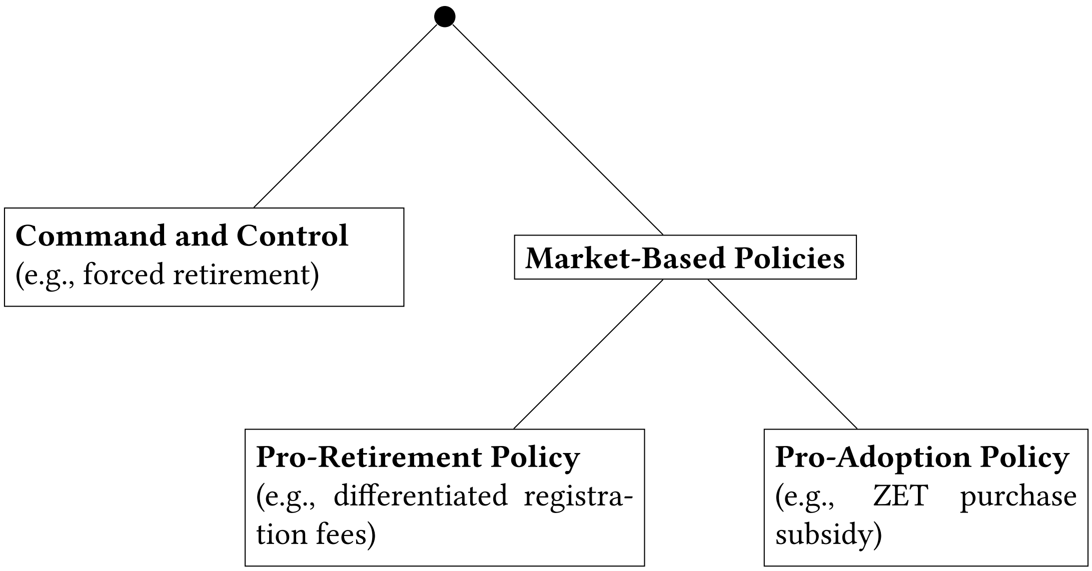


Figure 1: Policy Options

The main findings of the report include the following:

1. **Command and control approaches risk being ineffective, but even where they are able to move the market, they will be less efficient (higher cost) than feasible market-based mechanisms.** The potential for ineffective rules stems from constraints imposed by the useful life provision. In terms of inefficiency, we highlight three main sources of cost escalation—timing, unintended consequences, and incentive alignment. We next describe each of these further.

2. **Command and control approaches will be ineffective unless they restrict entry of used diesel trucks into the state.** A 100% new ZET sales target and forced retirement at the end of useful life is insufficient to transition the non-ACF fleet because operators could perpetually import lightly used diesels from out of state and operate them until the end of their useful life. We refer to this as the "used truck carousel." Non-ACF operators already routinely purchase used trucks, and many trucks in the California fleet are imported from another state. Thus, to be effective, a command and control regulation must directly limit the ability of operators to bring additional used diesel trucks into service in the state.

   We develop an aggregate model that quantifies how mileage accrued by vehicles beyond their useful life might be replaced if those vehicles are forced to retire. If there are no new restrictions on the importation of used diesels, the mileage of diesel trucks past their useful life could be completely replaced by younger diesels, but even when all of those miles are replaced entirely by ZET trucks, this leads to only 6.1% of diesel mileage switching to zero emission modes given current industry patterns. Put differently, only a small share of miles are driven by trucks past their useful life, so forcing their retirement without impacting the usage of younger diesel trucks does little to move the market. To get greater penetration of ZET mileage, policy must restrict the introduction of additional used diesels into California are necessary. Even a new sales mandate of 100% is insufficient, so long as operators can import used diesels.

3. **Command and control approaches raise cost by forcing artificially early restrictions on the entry of diesels, due to the useful life provision.** Because the useful life provision guarantees trucks a lifespan between thirteen and eighteen years, a command and control approach that respected this rule would need to entirely prohibit additional diesel trucks from entering the state within the next few years in order to ensure a fully ZET fleet by 2045. Forcing such early change for smaller operators and sharply restricting their acquisition choices before 2030, while the infrastructure is still developing and capital costs are still relatively high, raises costs unnecessarily. In particular, many non-ACF fleets routinely acquire used trucks, but use ZETs are not available today. Used ZETs will become widely available only after the new market share of ZETs rises for several years (due to cost declines, the ACF, and the EPA Phase 3 program) and the initial owners start to turn over their fleet.

   A major problem with command and control approaches is this mistiming. In contrast, market-based mechanisms can be strengthened over time, as ZETs become more available and affordable.

   This point is worth emphasizing. There is momentum in the ZET market and a potential that it will mature quickly, but this has not happened yet. There is still need for production to increase, for options to expand in key segments, for cost to come down with competition and learning, for infrastructure to be built, and for industry to learn to adapt practices to a new power source. Once these things happen, there is still a phase-in period before a mature used ZET market exists. All of this is poised to occur, but the exact timing is uncertain. Market based mechanisms, which can be dialed up or down, offer policy makers greater flexibility to adjust as the market evolves and take up is observed, as opposed to command and control approaches constrained by the useful life provision.

4. **Compared to feasible market based mechanisms, command and control approaches will create more unintended consequences that raise overall cost.** All command and control approaches that we know of will lead to unintended consequences in the form of pre-buying, lifetime extensions, and lock in. Pre-buying occurs when operators expand

inventory ahead of a regulation, which has already been shown to occur for trucks around federal emissions changes (Rittenhouse and Zaragoza-Watkins, 2018). Lifetime extension occurs when operators expand the lifetime of vehicles because regulation makes their replacement cost higher. This phenomenon is well document in the light-duty fleet (Jacobsen and van Benthem, 2015). Lock-in occurs when operators keep vehicles in the California fleet instead of following standard churn in order to maintain the largest possible eligible fleet.

Our empirical analysis of registration data in the state in the body of the report gives reason to believe that these factors will be significant distortions that raise the cost of command and control approaches. Regulators have an opportunity to learn about these phenomenon by studying how operators respond to drayage fleet restrictions created by the ACF that will begin in 2024.

5. **Command and control approaches are less able to align incentives for truck retirement with social value, which escalates cost.** Efficiency requires that the trucks that have the lowest net value (the value to operators minus their pollution impact) are retired first. Command and control regulations align retirements based on age and mileage, not pollution damages and market value, and thus fail to achieve ZET penetration cost effectively. Market based mechanisms improve the alignment and thus lower costs, without requiring the regulator to gather any new information.

   To estimate how much cost could be increased we use an aggregate quantitative model to first analyze a case where a system of subsidies and fees is used to find the lowest-cost switchers to ZET. We compare that to a case where a command-and-control policy mandates the same number of switches to ZET but, instead of finding the lowest-cost switchers, falls on trucks with an average cost of switching. For a case with 16% conversion to ZET in 2030 this leads to costs that are approximately 6 times higher for command-and-control than for a subsidy and fee system. To the extent the command-and-control system is well or poorly designed, and so falls on lower-than-average or higher-than-average cost switchers, the ratio would adjust accordingly but never fall below 1.

6. **A command and control approach would likely end up looking very similar to the ACF, but such a policy will be especially costly for smaller operators.** The ACF set very aggressive timelines for the elimination of additional diesel trucks, but it offers operators an alternative pathway that meets phase-in milestones for an operator's fleet. The milestone pathway essentially forces the retirement of trucks before their useful life expires, but this is allowable because the milestone pathway is an option that is voluntarily selected by operators.

A command and control approach for the non-ACF fleet would likely end up taking the same approach for the same reason; otherwise it will be required to completely eliminate additional diesels before 2030, which is implausibly fast, especially given the reliance on used trucks among non-ACF operators. Thus, the command and control pathway looks like it will actually become either (a) a plan to fold all trucks into the ACF, or (b) a parallel regulation that mimics the ACF on a delayed timeline for smaller fleets.

The problem with this approach is its high cost and the risk of an exaggerated burden on the smallest operators. An ACF-style policy would suffer from the inefficiencies described above. We expect these inefficiencies to be of greater concern for smaller firms than for the ACF-regulated firms because smaller firms will have more trouble smoothing costs over their fleet, higher costs of borrowing to finance the transition, and more heterogeneity in compliance costs.

7. **The ideal market based mechanism, which effectively prices pollution, is feasible but would require new administrative capacities.** According to economic theory, the most efficient way to foster the ZET transition is to price pollution and then allow operators to make adoption decisions once they bear the full social cost of their choices. In practice, this ideal policy would assess fees on diesel trucks that vary with class, age, mileage and driving location. We argue that this is technologically and administratively feasible, but we recognize that it requires new data collection and administrative capacity. Such a scheme would have myriad efficiency benefits. It would likely impose larger burdens, however, on smaller operators who own older trucks. This could be mitigated by using some of the revenue raised to offset costs.

8. **Addition of compliance trading to an ACF-style regulation would have important efficiency benefits.** Rather than require each firm to hit ZET penetration milestones, a regulation could allow firms to trade compliance credits, so that the industry as a whole achieves the milestones. We do not have the necessary information to quantify the efficiency gains for allowing trading among trucks, but there is substantial evidence from other trading markets demonstrating that trading substantially lowers costs. Such a system is similar to well established policies in California including cap and trade for carbon, the Low-Carbon Fuel Standard, and the Advanced Clean Car II rule. In effect, this option transforms an ACF-style rule for the non-ACF fleet from a command and control policy into a market based mechanism in order to lower cost while preserving policy outcomes.

9. **Alternative market based mechanisms require little or no new administrative capacity and can be expected to deliver key cost savings.** As a practical matter, regulators

may prefer alternative market-based policies that deviate from the ideal policy and have lower administrative or data collection burdens. The report discusses a variety of alternatives, including both pro-retirement policies (e.g., annual taxes on used diesel vehicles) and pro-adoption policies (e.g., capital subsidies for ZETs). These policies provide a spectrum of options that differ in their cost of implementation and expected efficiency gains. Relative to command and control approaches, these policies systematically offer improvements in incentive alignment, reduce or eliminate unintended consequences related to pre-buying, lifetime extension and lock in, and they relax the undesirable timing constraints that plague command and control rules (i.e., they can be phased in over time).

10. **Differentiated annual registration fees based on pollution damages would be large enough to have a significant effect on the market while producing efficiency gains compared to command and control.** The annual pollution damages associated with trucks is large, even for newer diesels: it ranges in 2030 from $0.14 per mile for newer Class 4-7 trucks to $0.42 per mile for older Class 8 trucks. These estimates use a lower estimate of damages per unit of pollution. This means that fees based on these pollution damages are large enough to move the market in substantial ways while simultaneously improving economic efficiency via the principle of pricing pollution.

    Fees based on pollution damage can be significant relative to other parts of operating cost, especially for older diesel trucks, leading to relatively large quantity changes compared to a world without these fees. In the report we calculate a low and high damage estimate based on alternative values of pollution impacts. In an aggregate quantitative model calibrated to the lower estimate of damages and relatively conservative (small) demand elasticities we find that in 2030 14-19% (over a range of elasticity assumptions) of diesel demand would shift to ZETs. This fraction rises to 34-47% in 2030 if fees are set equal to a higher estimate of pollution damages.

    In 2037 the fees become smaller because new diesels are progressively cleaner, but there are also greater numbers of used ZETs available. The latter effect slightly dominates, and the now-smaller fees create a 17-30% shift to ZETs with fees set at the lower estimate of pollution damages.

    Pollution damages vary substantially with the age and vintage of trucks, with Class 8 diesels over 4 years old in 2030 creating 48% more damage than newer models in the same year. Similar gaps exist for other classes and years. This means that policies that ignore these differences, by only targeting overall ZET penetration rates as the ACF does, will be inefficient because they fail to send accurate price signals that encourage retirement of the most polluting vehicles on route to achieving a 100% ZET penetration goal.

Differentiated annual registration fees improve efficiency relative to a world where all diesel vehicles are treated the same, but we note additional efficiency improvements are possible if fees can be further differentiated based on intensity of use (mileage) or driving location.

11. **Pro-adoption policies (e.g., subsidies for ZETs) can achieve some of the same benefits as pro-retirement policies (e.g., taxes for diesels), but they have some important efficiency drawbacks.** First, subsidies require revenue, which must be raised in a costly way from public funds. This suggests the possibility of combining subsidies with differentiated registration fees to maintain revenue balance. As ZETs become mainstream, an increasing share of subsidies will go to "inframarginal" purchases—to operators who would have bought a ZET even without the incentive, which escalates cost.

    Second, subsidies are less efficient because it is harder to accurately calibrate the optimal difference in subsidy size across vehicles. The optimal subsidy, in theory, to a particular new ZET depends on which type of vehicle—what age and vintage—someone is foregoing in order to choose the ZET. This counterfactual is generally not observed.

12. **Market based mechanisms provide more flexibility that can be used to ensure equity and prevent harm to specific firms or communities as compared to command and control approaches, if they are designed with this goal in mind.** Generally, all policies that accelerate the phase out of diesel trucks risk placing burdens on operators and the communities that rely on them. Moreover, we expect greater burdens for operators who have higher costs of changing their vehicle types, which typically be true for smaller operators and for those who currently rely most on older trucks.

    Both market based mechanisms and command and control approaches are likely to place greater burdens on these types of operators (with an important exception being retirement buyouts or other subsidy programs that directly benefit operators), but market based mechanisms offer more flexibility that can be used to mitigate these burdens for target populations.

    For example, tradable permits can be granted for free on a sliding scale to particular operators, fees can be offset, and generally all of these tools can be phased in more gradually. (Note that it is possible to preserve efficiency while providing discounts and free allocation, but only when the policy is designed carefully.) It is conceptually possible to do these same forms of compensation with command and control approaches, but such policies will generally be less flexible, especially in dealing with small firms that have only a few vehicles.

13. **Location specific policies have important potential efficiency benefits, in particular when used as a complement to another policy.** Greenhouse gas emissions from

trucks are independent of location, but the local air pollution damages from diesel trucks are large and vary substantially across location. The ideal pricing policy would differentiate emissions fees by location to account for the differences in damages caused by ambient conditions and the proximity of vulnerable populations. Assuming an alternative policy is adopted, a location specific pricing policy (e.g., a Green Zone with tolls) or a prohibition on diesel usage in specific locations (e.g., some form of an Indirect Source Rule, akin to the drayage carve out in the ACF) could therefore enhance efficiency while ensuring protection of specific communities. We are not able to quantify those benefits in the current report, but we do demonstrate the vast differences in damages per mile traveled across locations which makes clear that such a policy could overcome limitations of other feasible instruments.

Overall, these conclusions point to the potential role of market based mechanisms to lower cost, and in particular they argue for attention on pro-retirement policies that can improve efficiency while raising revenue that can be used to fund infrastructure or otherwise compensate industry. The report considers many additional design considerations and details that differentiate among these policy alternatives.

1 The objective of this report

The objective of this report is to answer the following question:

> *What are the lowest cost options to encourage the adoption of zero-emission trucks among the California fleets that are not covered by the Advanced Clean Fleet rule, on a schedule consistent with the state's goals, taking existing policies as given?*

In this report, "lowest cost" means taking into account both the cost to industry and the broader economic cost to society. Cost-effectiveness of policy is our primary concern, but we also consider distributional considerations (who is burdened more under possible alternatives?) where possible.

By taking "existing policies as given" we presume that the Advanced Clean Fleet rule, the Advanced Clean Truck rule, the useful life provision, and the federal Environmental Protection Agency's Phase 3 rules (all of which we discuss below) are all in place and unchanging. The focus of the report is on the remaining portion of the fleet that is not controlled by the Advanced Clean Fleet rule. At times, we do comment on how different policy approaches could influence the cost of compliance of the ACF fleet, as well as how state policies may influence the efficacy of federal rules, but this is not our primary focus.

The explicit aim of this report is to explore a range of policy options and to assess their strengths and weaknesses, given the motivating question. The focus is on "qualitative assessment" (which policies are more or less cost-effective, and are the differences large?), but we also develop a set of internally consistent cost comparisons using a simplified model for specific policies of interest. We provide a short overview of a variety of policy ideas and more depth on topics of particular interest, as explained to us by CARB staff.

1.1 Policy context

The state's target: The analysis in this report is heavily shaped by the existing policy context, starting with California's ambitious environmental goals related to medium and heavy-duty trucks. The state has plans to reduce local air pollution and greenhouse gas emissions from the sector. For this report, the key policy targets a goal of turning over the entire truck fleet, both new and used, to be zero emission by 2045 where feasible, which is embodied in a 2020 Executive Order from the Governor.[2] We presume this outcome is desirable for purposes of the report and limit our discussion to how it can be achieved at lowest cost, rather than how it might be modified.

[2] See the executive order here.

Existing policies in California: To meet the 2045 target, state agencies need to develop a suite of policies that will help move the market towards the desired outcome. Some are already in place.

A first step was the Advanced Clean Truck (ACT) rule, under which manufacturers of trucks must sell zero-emission trucks (ZETs) that represent a share of their overall annual sales. The required share rises through 2035. This regulation is poised to accelerate the move to zero-emission trucks, but it is insufficient to achieve the 2045 goals. Mandated ZET shares top out at 75% for Class 4-8 straight trucks and 40% for truck tractors, and the rule does not directly force the turnover of the used truck fleet or prohibit the importation of used vehicles from out of state.[3]

The second critical step is the Advanced Clean Fleet (ACF) rule, which was finalized in 2023. This rule expands the ACT rule to establish 100% ZET sales targets for manufacturers as of 2036. This ensures that new truck sales will be zero emission. To address the used fleet, the ACF rule creates new rules that govern truck operators (fleet owners), rather than vehicle manufacturers, who are the obligated parties under the ACT and the ACF's rules governing new truck sales.

The ACF sets rules for three types of fleet operators: drayage trucks, public fleets, and high-priority fleets. High-priority fleets are businesses that operate more than 50 trucks or that have more than $50 million in annual revenue. ARB estimates that the operator fleet requirements of the ACF will cover two-thirds of Class 7-8 tractors and around half of larger vocational vehicles, but only about one out of eight smaller medium-duty trucks.

The remaining fleet, which we refer to throughout as the "non-ACF fleet" consists of the non-drayage trucks operated by smaller, private firms. Non-ACF operators will be free to continue operating fossil fuel vehicles and to continue acquiring additional ones into the future. Even with 100% new sales targets in 2036 for manufacturers in California, operators would be able to import used diesel vehicles from out of state in the future. Our focus is on policy approaches that can encourage ZET adoption among these operators.

The useful life provision: CARB is limited in its ability to simply force the retirement of older fossil-fueled vehicles by the so-called useful life provision (State of California, 2017), a law which prohibits forced retirement of commercial motor vehicles until they have reached 13 years of age and 800,000 miles, or 18 years of age at any mileage.[4]

In the extreme, the useful life provision implies that the state would have to prohibit both the sale of any new trucks and the importation of used trucks as early as 2027 in order to ensure that no used vehicles with useful life remaining are in the state by 2045. As this is infeasible, the useful life provision is a key force motivating additional policy exploration.

EPA Phase 3: The federal government also has nationwide goals related to ZET adoption.

[3] See CARB's fact sheet here.

[4] A brief explanation is here, and the provision can be found in California's Health and Safety Code, Section 43021.

The EPA is currently taking comments on a proposed new rule, often called Phase 3, that imposes new limits on fleetwide greenhouse gas emissions by manufacturers. The rule does not regulate the used fleet. The proposed rule does not mandate the use of zero-emission technologies, but EPA projects that ZET market shares ranging from 25% for sleeper cabs to 50% for vocational vehicles by 2032 are a plausible compliance pathway for manufacturers.

For our purposes, the EPA Phase 3 rule is most important to the extent that it affects the availability of used ZETs and tightens the market for used diesel trucks in future years. The policy may also be important if it helps push down the cost of zero-emission technologies by encouraging nationwide adoption.

At the same time, nested federal and state regulations create a greater possibility for leakage. Because the California fleet is part of the national fleet, faster adoption of new ZETs in California reduces the need for manufacturers to sell ZETs outside of California because the ZET sales in California do more to satisfy nationwide requirements. Prior analysis of this type of leakage under nested regulations for the light-duty market suggested that the leakage was quite large Goulder et al. (2012). We do not pursue this question in the report, but we flag as a substantial concern that more aggressive action within California will implicitly weaken the impact of federal policy unless federal policy is strengthened further.

1.2 Policies we consider

To organize our analysis, we delineate the policy alternatives into three broad categories: command and control approaches that mandate retirement, pro-retirement policies that use market mechanisms to encourage scrappage of diesels, and pro-adoption policies that use market incentives to encourage adoption of ZETs. Within each category there are many variations, and use of policies from each category are not mutually exclusive—the optimal design likely involves a mix. The delineation is, however, useful in highlighting the strengths and weaknesses of different approaches.

In the broadest terms, there are three ways of achieving ZET adoption. First, policy can simply require adoption (command and control). Second, policy can make the alternative to ZETs (incumbent diesel trucks) less appealing to operate. This can be achieved either by making the up-front capital more expensive (taxing new truck sales), by raising the annual operating cost (diesel or mileage taxes, registration fees), or by limiting the use value of the trucks (green zones). Third, policy can make the ZETs more appealing, by lowering their purchase price (capital subsidies) or lowering operating costs (improving fueling infrastructure).

The report discusses many variations within these policy classes that vary in their impacts, but we believe framing these three broad alternatives is a useful way to conceptualize the policy

Table 1: Three broad classes of policy

Class of policy	*Examples*
Command and control	Regulation requiring fossil trucks to retire after useful life
Pro-retirement	Differentiated registration fees
	Mileage tax
	Scrappage subsidies
	Green zones
	Diesel tax surcharge
Pro-adoption	Capital subsidies
	Fuel infrastructure subsidies

menu at the highest level.

1.3 The useful life provision creates inefficient compromises that increase the value of market based mechanisms

This report takes the useful life provision at face value and assumes it will remain in place. We would be remiss, however, if we did not point out the challenges that it creates from the point of view of economic efficiency and cost minimization. The main challenge created is that the provision forces much more aggressive early action in order to achieve full transition of the fleet to zero-emission by 2045. Working backward, if some trucks are going to be allowed to operate for 18 years, the state would have to lock out all new diesel trucks by 2027, and then disallow importation of lightly used trucks by age on a phase-in schedule. This is inefficient and raises the cost of achieving the goals. What is more efficient is to allow for a smoother glidepath where adoption is set to rise as cost falls with learning. The ACF does this through its milestone compliance option, but this has to be setup as an optional compliance pathway because of the useful life provision.

Economic incentives, like the ones explored below, can help by allowing incentives to ramp up over time and allows for direct impacts on the full fleet of vehicles, regardless of their useful life status. But, those incentives may have to become much stronger in order to guarantee a complete elimination of diesel vehicles, where the goal of a fully transitioned fleet by 2045 is taken literally. A combination of incentives over the next decade with an option to simply eliminate residual vehicles with command and control options in later years as needed would be more flexible, but may be unavailable because of the provision.

1.4 Caveats

The scope of this report limits our attention to a number of key issues, which we call out here before proceeding.

We do not analyze the ACF: To ensure cost-effectiveness, economists advocate for the use of flexible, market-based mechanisms that allow market actors to comply with policy objectives in ways that are consistent with their own private information about benefits and costs. The ACF rule allows flexibility in some dimensions, but it deviates substantially from the economic ideal, which would involve some form of flexible compliance trading across fleets. Reforms in that direction seem imminently feasible. For example, the ACF could be amended to allow licenses to register a fossil vehicle in a given year that could be traded across firms. This would lower compliance costs. It would also make it more feasible to incorporate the non-ACF fleet into the existing regulation, rather than requiring a new set of policies to address them. We understand, however, that reforms to the ACF are outside the scope of this report and so do not pursue them.

Similarly, economic analysis is often able to identify and quantify possible unintended consequences of policy design, where market actors are able to comply with rules in ways contrary to the intentions of policy. The ACF has several provisions that may invite "creative compliance" through ownership changes, reshuffling of fleets, and strategic registration of vehicles in and out of the state. We understand these to also fall outside the scope of this report and so mention them only as they relate to policy alternatives addressing the non-ACF fleet.

We focus on California, not global emissions: If California's ZET goals simply lead to the displacement of diesel trucks to other locations, where they continue to emit greenhouse gas emissions, then achieving decarbonization goals could have limited or no actual climate benefits. This sort of "leakage" could be quite important in practice, but our focus in this report is on achieving California's internal goals. Addressing leakage is a critical topic for future work.

2 Data sources and definitions

DMV data— Analysis below is based on a truck fleet database provided by CARB staff. The database contains anonymized vehicle and industry information from the California department of motor vehicles (DMV) and Dun and Bradstreet, which cannot be used to identify any single truck or company. This data is only used in support of the work done as part of this agreement/contract. The DMV registration data covers calendar years 2013 - 2019[5] for vehicles with Bureau of Automotive Repair (BAR) ranks T6 (Class 4 - 7, Gross Vehicle Weight Rating, or GVWR, between 14,001 and 33,000 lbs) and T7 (Class 8, GVWR over 33,000 lbs). Throughout, we refer

[5] Two datasets, one from 2013 - 2016, and another, from 2017 - 2019, are appended. These datasets are slightly different due to updated processing by CARB.

to trucks by their class category. Appendix A details data cleaning procedures that drop or alter values for a small number of trucks.

Attributes include engine year, county, fleet grouping type, fuel type, and Dun and Bradstreet firm data. Additional data fields are merged in, assigning each vehicle-year an estimated miles traveled (i.e., accrual) and emissions rates from the Emissions Factors (EMFAC) model managed by CARB. The total truck population by registration year and class, according to our DMV data, is shown in Figure 2.

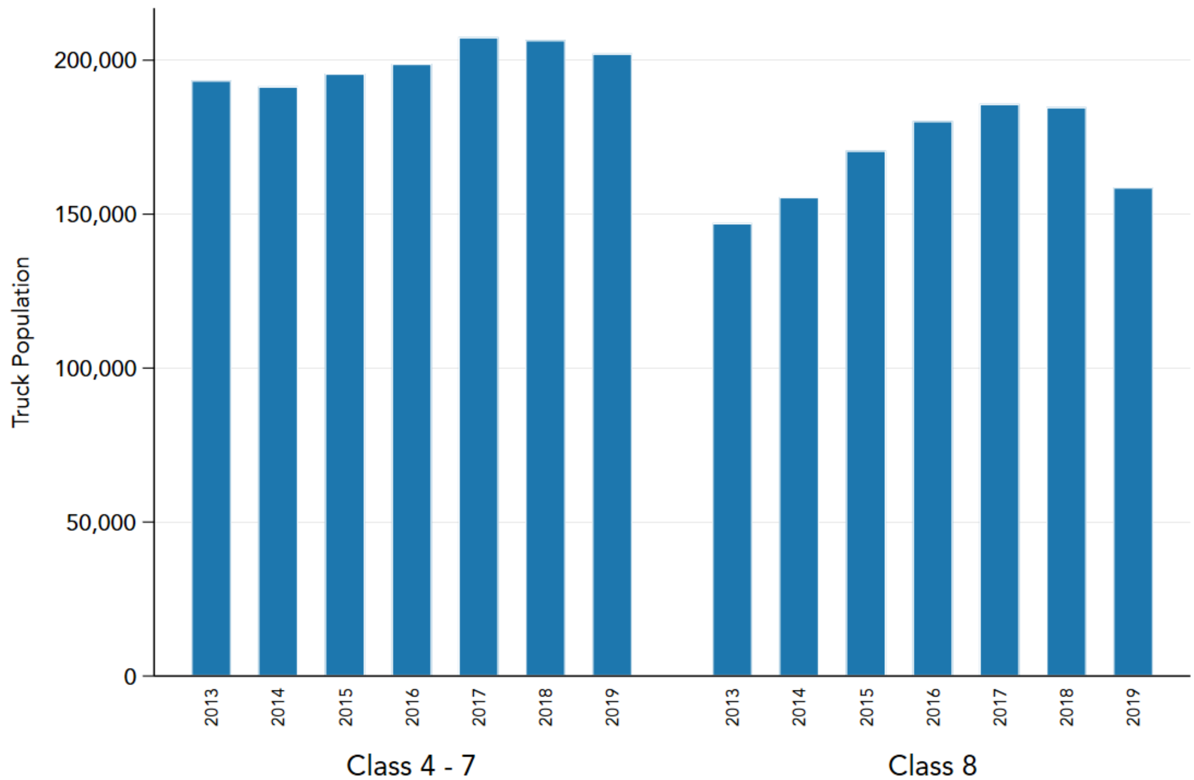


Figure 2: 2013 - 2019 Truck Population by Class

Note: This figure displays the historical compositions of the Class 8 and Class 4-7 truck populations from 2013 to 2019. These data come from DMV registration data provided by CARB.

Dun and Bradstreet data—Registration data from years 2017 - 2019 also includes Dun and Bradstreet (D&B) anonymized firm data, which gives us information about industry type, firm fleet size and financial information. Registration data are matched to D&B data by vehicle owner name and address, but the matches are not always perfect. CARB gives us match quality scores for names and addresses using a simple natural language model for string matching. Average address similarity was 75%, with 60% of matched observations being perfect matches. The equivalent statistics for name similarity were 53% and 28%.

ACF status—Critical to our analysis is evaluating whether a given truck is likely to be covered by the ACF. The ACF will cover public fleets, drayage vehicles, and large fleets, defined as fleets that operate 50 or more trucks or that have at least 50 million in annual revenue.

For our analysis, we define a truck in calendar years 2017 through 2019 as "ACF covered", by calendar year, if any of the following are true:

1. it is a drayage truck (travels to the Port of Oakland or Port of LA),
2. its fleet reports total sale revenue over $50M, or
3. its fleet has 50 or more Class 4 - 8 vehicles registered.

Just over half of trucks in the three final years of DMV registration data are ACF-regulated, by our estimation. The ACF-regulated fraction increases slightly, from 53% in 2017 to 56% in 2019. The fraction within Class 4 - 7 vehicles is consistently lower than the fraction within Class 8 vehicles, partially due to Drayage trucks which are both always Class 8 and always ACF-regulated. See Table 2 for a more detailed breakdown of the ACF-regulated population in 2017 - 2019 observational DMV registration data.

Table 2: ACF-Regulated Population By Calendar Year and Weight Category

CY	*Weight Category*	*% ACF*	*Count ACF*
2017	Class 4 - 7	0.49	102,391
	Class 8	0.57	106,176
2018	Class 4 - 7	0.50	104,065
	Class 8	0.57	104,420
2019	Class 4 - 7	0.54	109,612
	Class 8	0.58	92,385

EMFAC data—The DMV data do not include direct measures of odometer readings or annual mileage. We use data from EMFAC to assign mileage based on a vehicle class, vintage and year. We also use EMFAC to assign emissions per mile to vehicles based on class, vintage and year.

We also use the 2021 EMFAC data to model the fleet in future years, which we use for analysis of policy impacts.[6] Wherever possible, we use population estimates which assume all existing regulations are imposed, which includes the Truck and Bus rule and the ACF. A picture of the fleet size by class and ACF status in future years, according to EMFAC, is displayed in Figure 3.

[6]Specifically, we pulled data from EMFAC201 version v1.0.2, specifying Onroad Emissions, setting the region to Statewide. The data were downloaded here.

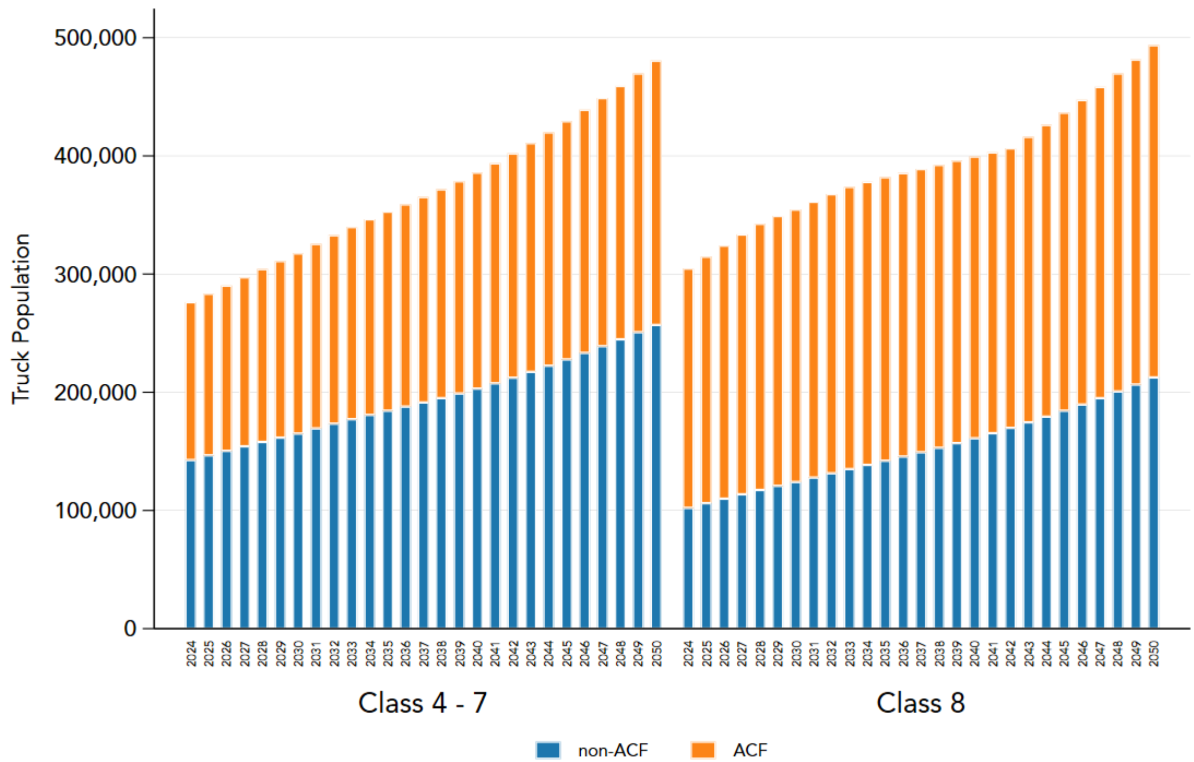


Figure 3: 2024 - 2050 Truck Population by Class & ACF Classification

Note: This figure displays the projected compositions of the Class 8 and Class 4-7 truck populations from 2024 to 2050. These values come from the EMFAC 2021 model.

Damage estimates—We use damage estimates from the academic literature and the Federal EPA to assign a dollar value per unit of emissions.

For damages associated with PM2.5 and PM2.5 precursors, we use the US EPA's Benefits Mapping and Analysis Program (BenMAP) data product.[7] These data include damages estimated for ammonia (NH_3), nitrogen oxides (NO_x), $PM_{2.5}$, and sulfur dioxide (SO_2). We use the values for damages in calendar year 2030 (in $2020).

We retrieve damage values for for carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) from the US Government's Interagency Working Group (IWG) on the Social Cost of Greenhouse Gases (SC-GHG). We use the 2021 IWG report which provides interim values to be used until a new IWG report is published, as ordered by the Biden administration.[8] Like the EPA estimates, these values are for damages in calendar year 2030 (in $2020).

We use damage estimates for carbon monoxide (CO) from Matthews and Lave (2000). These values are in $1992/ton and are adjusted to $2020. These three data sources and alternative damage estimates are described in more detail in Appendix B.

In one additional piece of analysis, we leverage the Air Pollution Emission Experiments and Policy analysis (APEEP) model, also known as the AP3 model, to estimate damages by county. The integrated assessment model links emissions of air pollution to exposures, physical effects, and monetary damages in the contiguous United States. These county-level damages are used only in Figure 13.

3 Key facts about California's truck fleet that influence evaluation of policy

In this section, we use the aforementioned data to establish key observations about the California truck market. This list of observations is curated to be relevant to the policy comparisons below. We delineate these observations as a list of "facts" that we then cite where relevant in evaluating policy alternatives.

Fact 1 *It is common practice for used trucks to be imported into the state, more so for the non-ACF fleet, within which nearly two-thirds of trucks come into California used.*

Figure 4 illustrates the distribution of ages at which vehicles enter the ACF and non-ACF fleets. Both fleets see a large number of "new" vehicles (DMV age equal to 0 or 1) entering but maintain fat tailed distributions indicating that the number of used vehicles is large as well. If we

[7] The BenMAP data are available here.

[8] The 2021 IWG SC-GHG report can be found here.

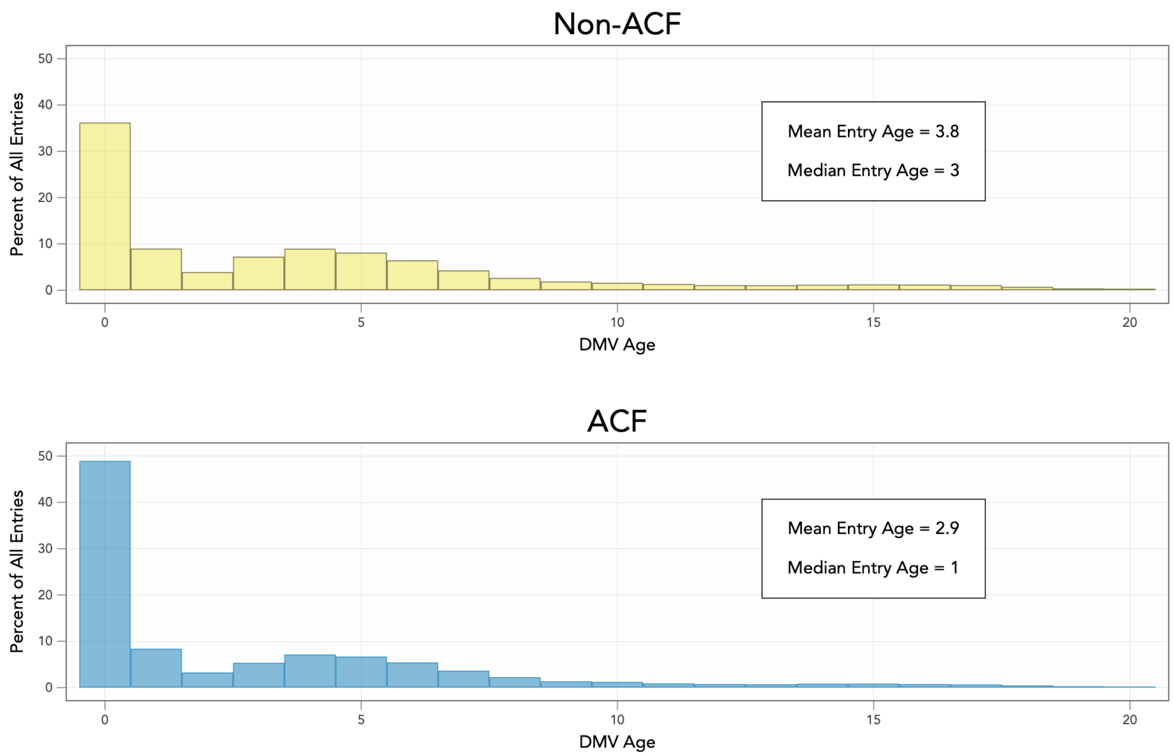


Figure 4: Vehicle Entry Ages for ACF and Non-ACF Fleets

Note: This figure displays the age distribution of vehicles entering the ACF and non-ACF fleets between 2013 and 2018. The non-ACF fleet has higher mean and median entry ages than the ACF fleet implying more used vehicles being imported into the state for the non-ACF fleet. DMV age is calculated by subtracting the vehicle's model year from the calendar year in which it enters the fleet. This figure was generated using DMV registration data provided to us by CARB.

group entry age into two bins, as in Figure 5, we see that the number of used vehicles entering actually exceeds new for the non-ACF fleet by a large margin. For every truck that enters the non-ACF fleet as new, two trucks enter from out of state as used.

This is important because it demonstrates that it is common practice for vehicles to begin in another state and be imported into California as a used vehicle, especially for non-ACF operators. This matters because one threat to command and control policies is a perpetual importation of used diesel trucks that can then be used until their useful life expires. Even when 100% of new sales are ZETs, a command and control regulation that forced retirement at useful life might have little impact on the used ZET fleet because operators would continue to import used diesels from out of state. We call this the "used truck carousel." Policy would have to prevent importation in order to be effective.

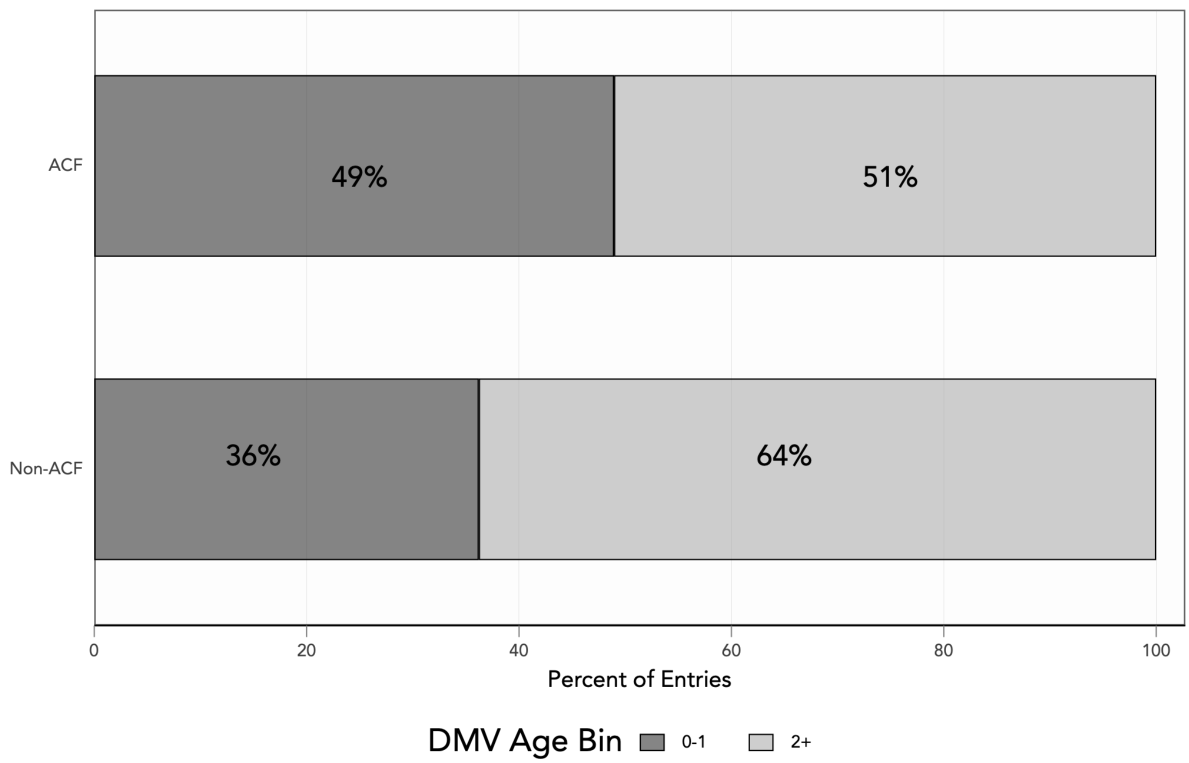


Figure 5: Binned Entry Ages

Note: This figure displays the fraction of the ACF and non-ACF fleets that enter at 0-1 years of age and at 2 or more years of age between 2013 and 2018. DMV age is calculated by subtracting the vehicle's model year from the calendar year in which it enters the fleet. This figure was generated using DMV registration data provided to us by CARB.

Fact 2 *Most vehicles exit the state before the limits proscribed by the useful life provision.*

Figure 6 illustrates the distribution of ages at which vehicles in the ACF and non-ACF fleets exit the California fleet according to our data. (We say a vehicle has exited if it is present in one year and absent from the registration data the next year.) While the useful life provision requires exit by 13 or 18 depending on mileage, we see a mass of exits for both fleets prior to the age of 10. Additionally, we see substantial bunching around the 18 year mark for the ACF fleet. This is less pronounced for the non-ACF fleet. We draw attention to this fact because if regulation is able to plug the used truck carousel, it will create an incentive for operators to elongate the lifespan of vehicles. This phenomenon, which we below call the Gruenspecht effect, is an unintended consequence of a command and control regulation. If ZET requirements make replacement of an existing truck more expensive, operators will tend to hold their existing fleet longer.

If most vehicles typically stayed in the state until the end of their useful life already, then operators would not be able to expand vehicle lifetimes in this way. But, the data show that there is considerable "headroom"—most vehicles are retired well ahead of the useful life thresholds, so they would be able to expand their lifetimes in response to policy.

Market based mechanisms that create price incentives are not constrained by the useful life provision in the same way, so this fact points to an efficiency weakness of command and control approaches. Market based mechanisms could encourage exit of diesel vehicles across the age distribution. For example, they would encourage operators who purchased new trucks and sell them at intermediate ages to export these out of state rather than to sell them in state.

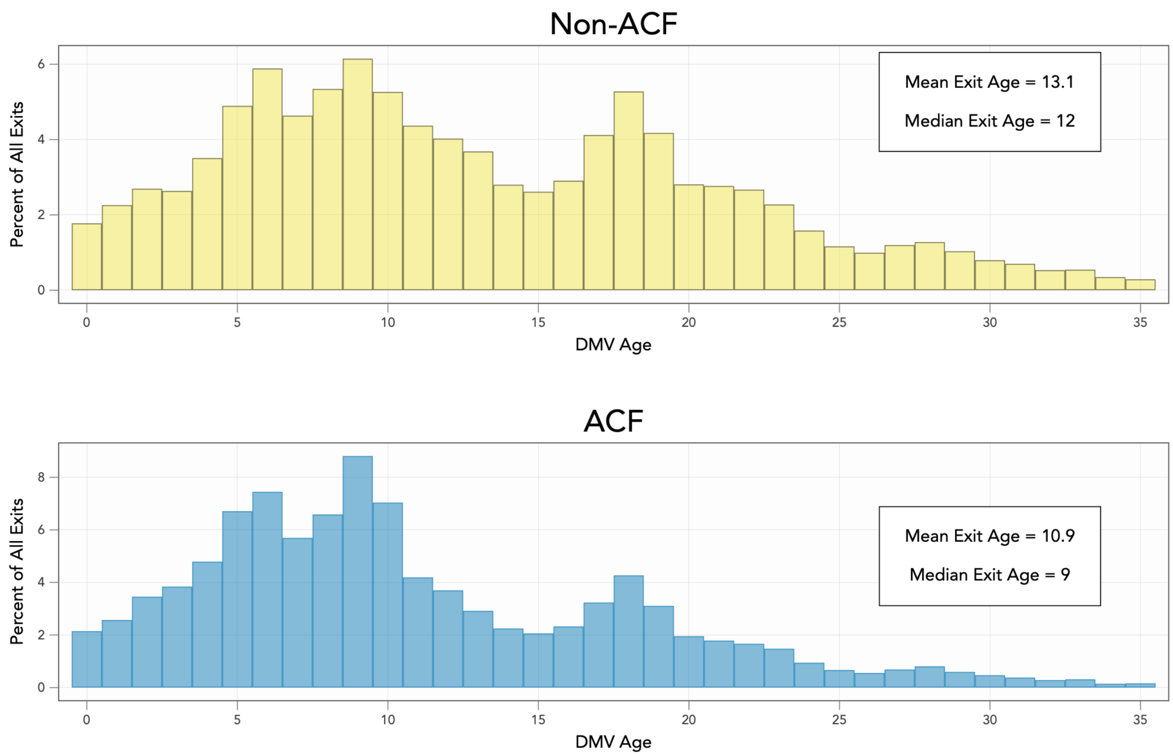


Figure 6: Vehicle Exit Ages for ACF and Non-ACF Fleets

Note: This figure displays the age distribution of vehicles exiting the ACF and non-ACF fleets between 2013 and 2018. In both the ACF and non-ACF fleets, the median exit age is before the 13 or 18 year cut-offs imposed by the useful life provision. DMV age is calculated by subtracting the vehicle's model year from the calendar year in which it enters the fleet. This figure was generated using DMV registration data provided to us by CARB.

Fact 3 *Non-ACF fleets systematically operate older trucks; non-ACF trucks are three years older than ACF trucks on average.*

Figure 7 illustrates the differences in the operating age distributions between ACF and non-ACF fleets. For the ACF fleet, we see a mass of vehicles operating below 5 years of age whereas the non-ACF fleet's mass is much more spread out with slight bunching below 10 years. The both median and mean ages are about at least 3 years higher for the non-ACF fleet than for the ACF fleet. We highlight these differences as it is useful just to understand that even though the ACF covers a lot of the fleet, the non-ACF sector has a disproportionate share of the older trucks. This also makes clear that the non-ACF fleet finds it economical to use older trucks. An aggressive regulation is thus likely to pose higher costs on this group as it forces more change from their normal course of operations. In turn, this means that a move to ZET vehicles for this fleet may be most economical when used ZETs are available, which will require a delay compared to the transition of the ACF fleet.

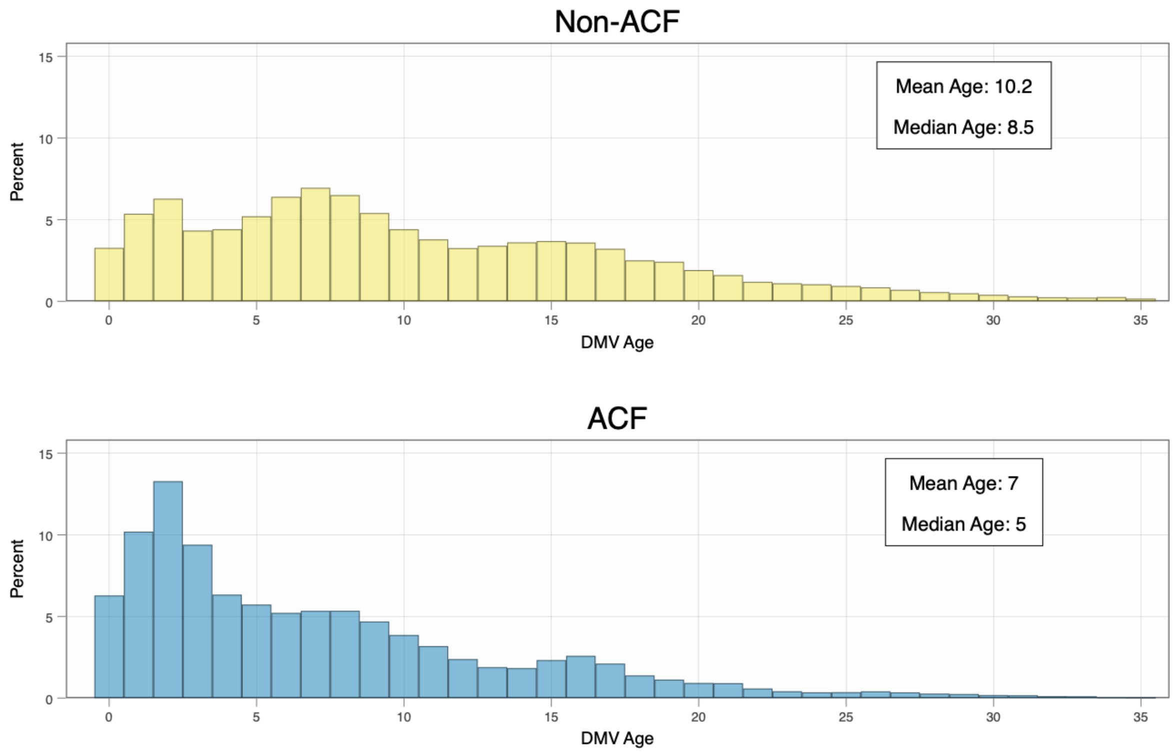


Figure 7: Operating Ages for ACF and Non-ACF Fleets

Note: This figure displays the age distribution of vehicles operating in the ACF and non-ACF fleets between 2013 and 2019. The non-ACF fleet systematically operates older trucks with mean and median ages about 3 years higher than those of the ACF fleet. DMV age is calculated by subtracting the vehicle's model year from the calendar year in which it enters the fleet. This figure was generated using DMV registration data provided to us by CARB.

Fact 4 *Non-ACF trucks frequently enter and leave the state within their normal lifecycle.*

Across just seven years of DMV data (2013 through 2019), 50% of VINs exit the dataset (for example, a VIN observed in 2013 but not in 2014) at least once. Among those exits, 20% re-appear (for example, a VIN observed in 2013, not in 2014, and then again in a later year). Overall, 10.6% of VINs exit the dataset and then re-appear in a later year.

This sort of churn in and out of the state appears to be part of the normal business operations for operators. A command and control policy that prohibits use of new trucks creates added cost because it will "lock in" vehicles—if it is impossible or costly to add a diesel to the California fleet, operators will be disinclined to let a truck exit the state, knowing that they cannot simply have it reenter in the future. Below, we do not attempt to quantify the cost of this lock in effect, but given the substantial churn that we see as part of normal business operations, we would expect this inefficiency to be material to the industry.

Fact 5 *A substantial fraction of overall truck usage in California is from trucks registered out of state, but this usage is much smaller for medium trucks.*

Roughly one-third of all heavy-duty truck miles driven in 2030 are projected to be from out-of-state (OOS) trucks, according to EMFAC's 2021 baseline projection. Based on these projections, in calendar year 2030, Class 8 trucks drive the majority of the total heavy-duty truck VMT and 40% of Class 8 VMT is from OOS trucks. For Class 4-7 trucks, the fraction of OOS VMT is only 2%.

This is important because operators could possibly respond to regulations by altering the location of registration as a strategic response to policy, unless the policy treats out of state vehicles in a manner commensurate with its usage in the state. The non-ACF fleet is tilted towards Class 4-7 trucks, and the usage from out of state for this fleet is expected to be small, so this is less of a concern. For Class 8 trucks, however, it is critical that policy affect out of state vehicles in a like manner, or else operators could simply strategically register vehicles out of state and then use them in state.

Fact 6 *Similar trucks are driven significantly different miles per year.*

Figure 8 illustrates the substantial heterogeneity in average annual mileage for Class 8 and Class 4-7 trucks according to data from the California Vehicle Inventory Use Survey (CAVIUS). The blue and yellow shaded areas indicate 1 standard deviation above and below the mean mileage. The grey shaded area identifies vehicles that have exceeded the guidelines of the useful life provision, i.e., they are 13 years old with over 800,000 miles or are 18 years old. We highlight this fact because it affects the efficiency of annual fees that do not differentiate vehicles by their annual mileage. These differences in mileage also imply that there would be substantial variation in the remaining asset value of different trucks of the same age. This in turn implies heterogeneity in the cost of turning over diesel trucks, even of the same age and vintage, and replacing them with ZETs at a given point in time. As such, these differences imply an inefficiency in milestone turnover policies that might be used in a command and control policy, as well as some inefficiency in market based mechanisms that impose fees that do not vary with mileage.

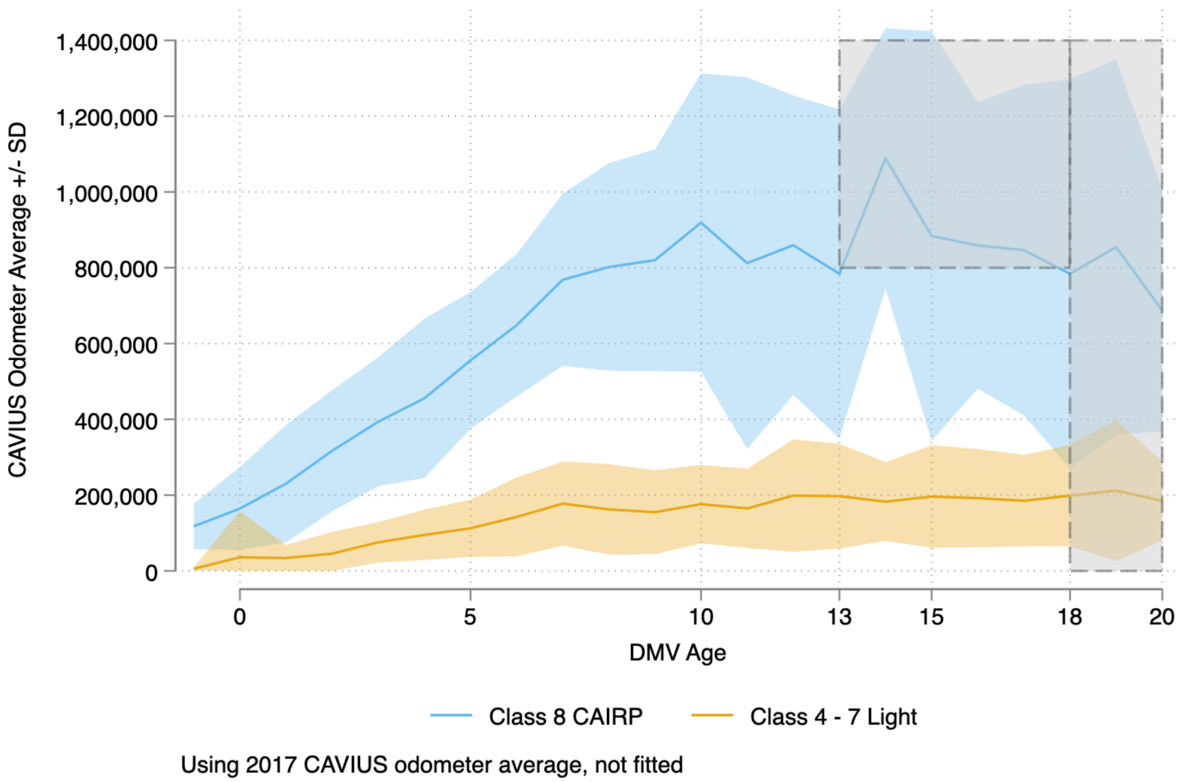


Figure 8: Heterogeneity in Annual Mileage

Note: This figure displays the variation in annual mileage for class 8 and class 4-7 trucks. Class 8 trucks drive many more miles per year and with much more mileage variation within the fleet. This figure was generated using 2017 CAVIUS data.

Fact 7 *Pollution damages per mile vary significantly by vehicle age and vintage, but annual damage estimates vary less.*

Pollution damages per truck vary across vintages (model years) and age (calendar years). Variation per mile is substantial due to differences in emission control technologies and because of depreciation of those systems over the life of a vehicle. Variation in damages per year differ because of these per mile differences, and because different trucks are driven different numbers of miles. This variation is important because it determines the efficiency gain from differentiation. Were damages per mile uniform, then a uniform per mile fee would be fully efficient. Were damages per year uniform, then an annual fee that was the same for all diesel trucks would be fully efficient.

Figure 9 illustrates projected annual VMT per Class 8 CAIRP truck in calendar years 2030-2040 for vintages newer than and including 2020. For a given vintage (model year) of truck, VMT per truck is generally projected to decrease over time (i.e., numbers decline along the x-axis). Alternatively, within a given calendar year, newer trucks are projected to drive more miles. Details differs across vehicle classes, and this segment is especially high mileage, but the qualitative pattern that newer vehicles are driven more is common across vehicle types.

Damages per mile also vary by vintage and age. Figure 10 illustrates damages in dollars per hundred miles driven by Class 8 CAIRP trucks. We see that as vehicles age, their damages per mile increase. Likewise, newer vintages of truck have lower damages per mile. These results reflect both technology changes and modeled depreciation with age. (These figures report damages assuming high damage estimate parameters, which are explained further below.)

The mileage differences and the differences in pollution per mile work in opposite directions, so the annual damages can either decline or rise with vehicle age. For Class 8 CAIRP vehicles, older vehicles usually have more damages per year than younger vehicles because the damages per mile effects dominate,k but this is not always true in later years. This is shown in Figure 11. For any given year, the annual damages across vehicles in the fleet can be see by looking in a vertical column. In most cases, newer trucks (higher in the chart on the y-axis) will have lower damages and would thus garner a lower pollution-based annual fee.

Compared to the substantial differences in damages per mile, however, the differences across vehicles is significantly compressed. This means that a uniform annual fee may be less inefficient than one might have expected.

It is also important to note that the combined effects of the damage/mile and miles/truck ratios could lead to higher expected damages per truck for *newer* trucks in some instances. For example, Figure 12 illustrates damages per truck for Class 4-7 CAIRP trucks. We see that newer vehicles are expected to have the highest per-truck damages because they are expected to drive so many more miles per year than older trucks in this category.

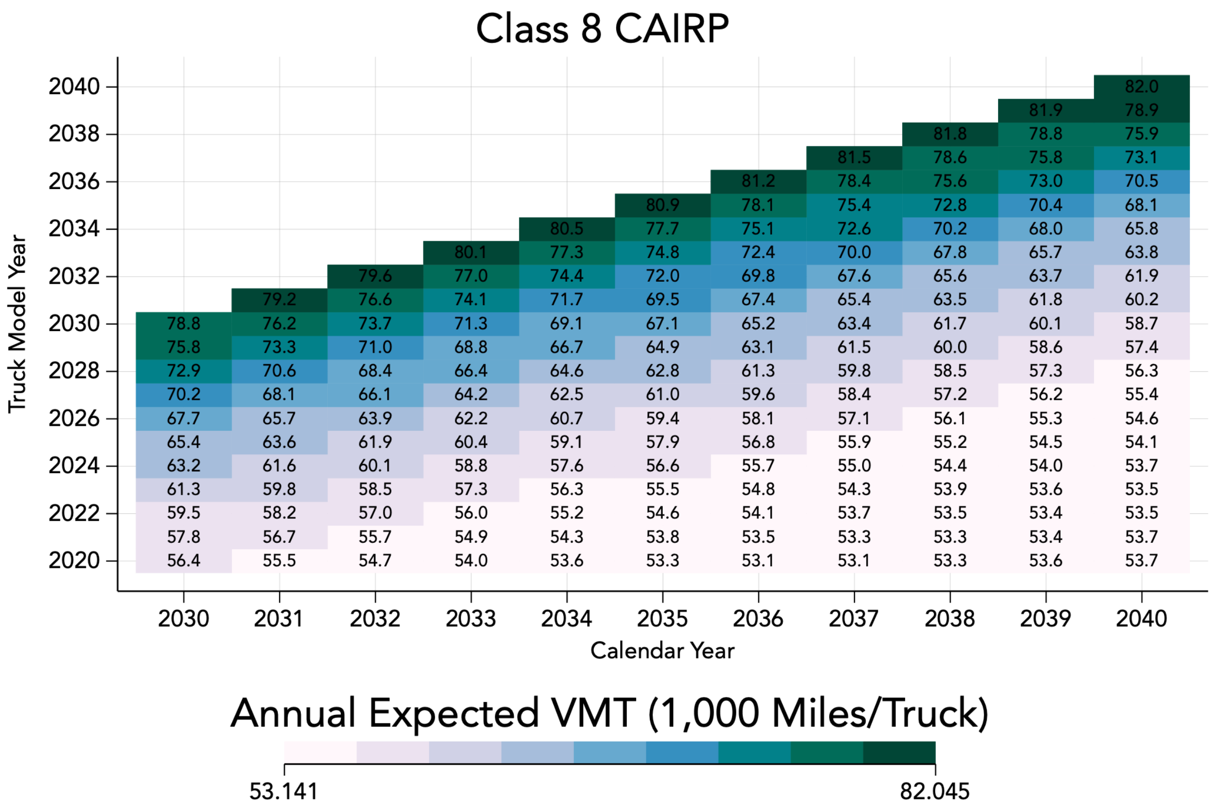


Figure 9: Heterogeneity in Annual Mileage Per Truck - Class 8 CAIRP

Note: This figure displays projected annual vehicle miles traveled per truck for Class 8 CAIRP trucks in calendar years 2030-2040 and for model years 2020-2040. VMT projections come from the EMFAC 2021 model.

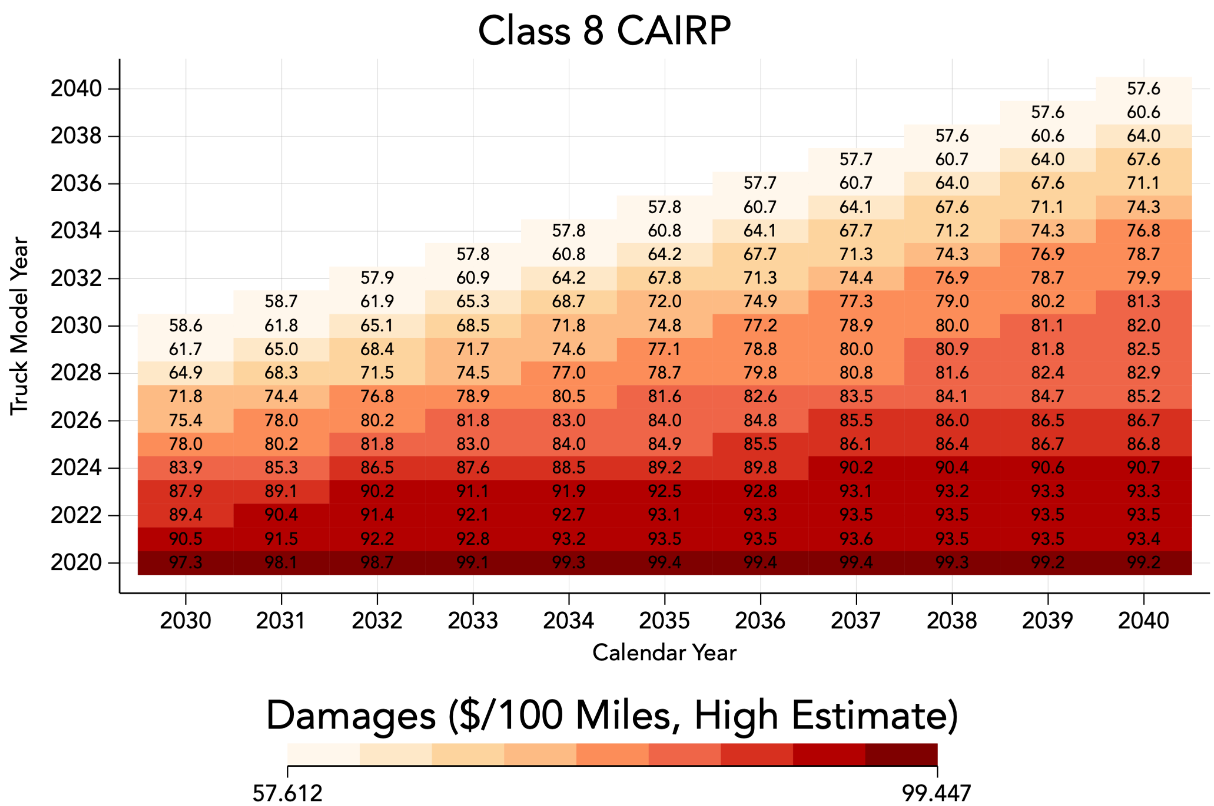


Figure 10: Heterogeneity in Damages Per 100 Miles Traveled - Class 8 CAIRP

Note: This figure displays projected annual damages per 100 miles driven for Class 8 CAIRP trucks in calendar years 2030-2040 and for model years 2020-2040. Damages shown here are calculated as the sum of per-mile damages from CO_2*,* CH_4*,* NO_x*,* NH_3*,* $PM_{2.5}$*, and* SO_x*. This figure uses the high damage estimates outlined in Table 3.*

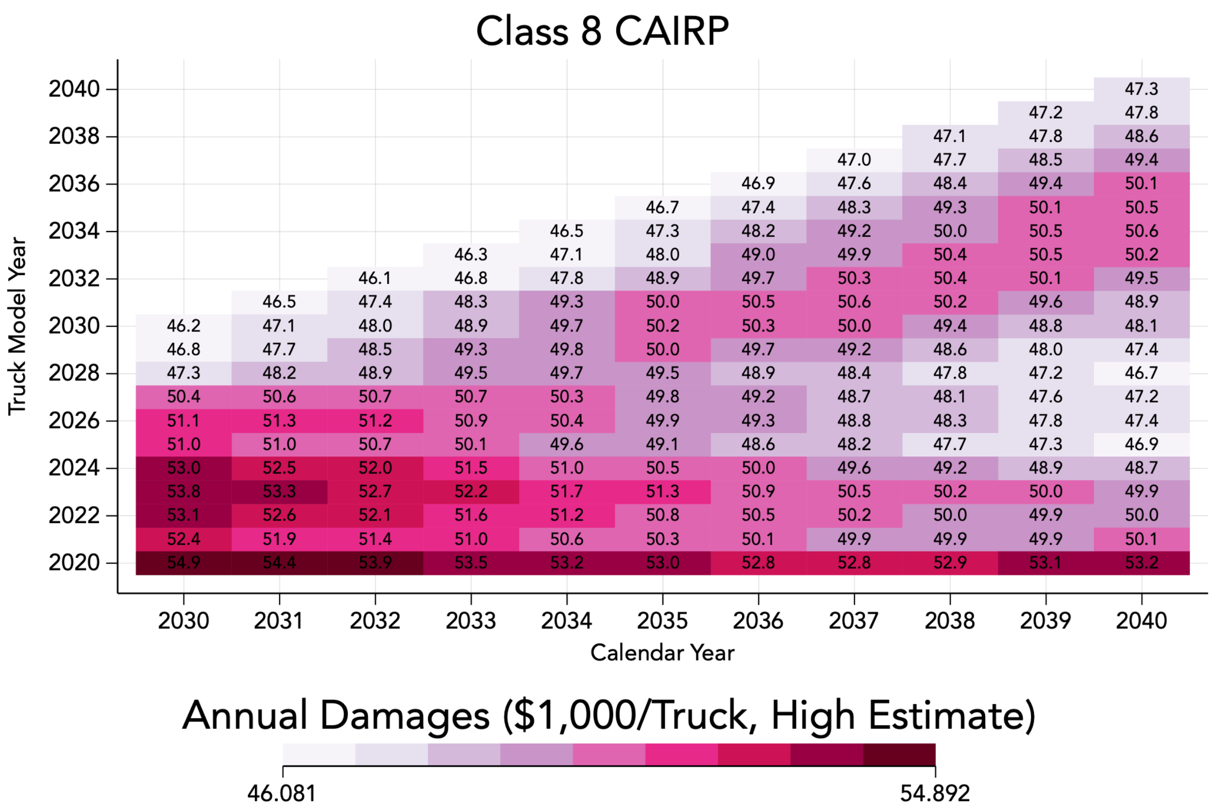


Figure 11: Heterogeneity in Damages Per Truck - Class 8 CAIRP

Note: This figure displays projected annual damages per truck for Class 8 CAIRP trucks in calendar years 2030-2040 and for model years 2020-2040. Damages shown here are calculated as the sum of per-truck damages from CO_2, CH_4, NO_x, NH_3, $PM_{2.5}$, *and* SO_x. *This figure uses the high damage estimates outlined in Table 3.*

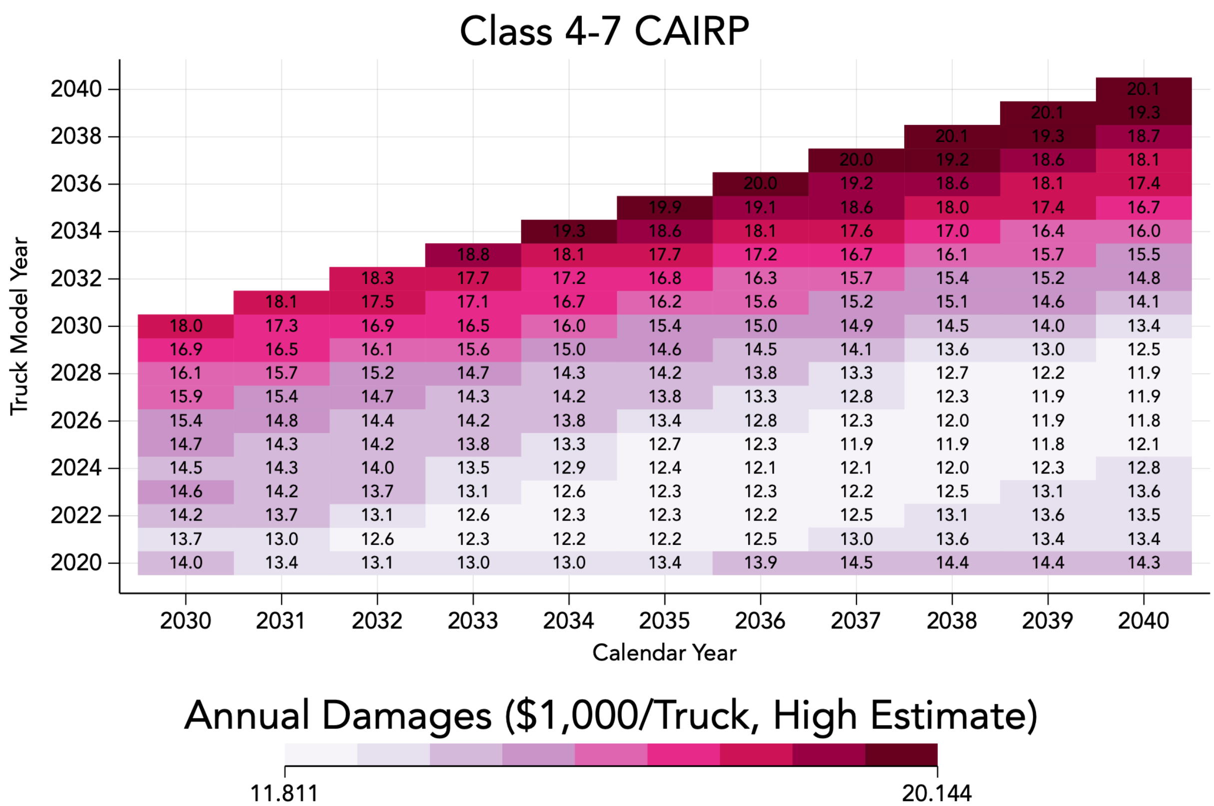


Figure 12: Heterogeneity in Damages Per Truck: Class 4-7 CAIRP

Note: This figure displays projected annual damages per truck for Class 4-7 CAIRP trucks in calendar years 2030-2040 and for model years 2020-2040. Damages shown here are calculated as the sum of per-truck damages from CO_2*,* CH_4*,* NO_x*,* NH_3*,* $PM_{2.5}$*, and* SO_x*. This figure uses the high damage estimates outlined in Table 3.*

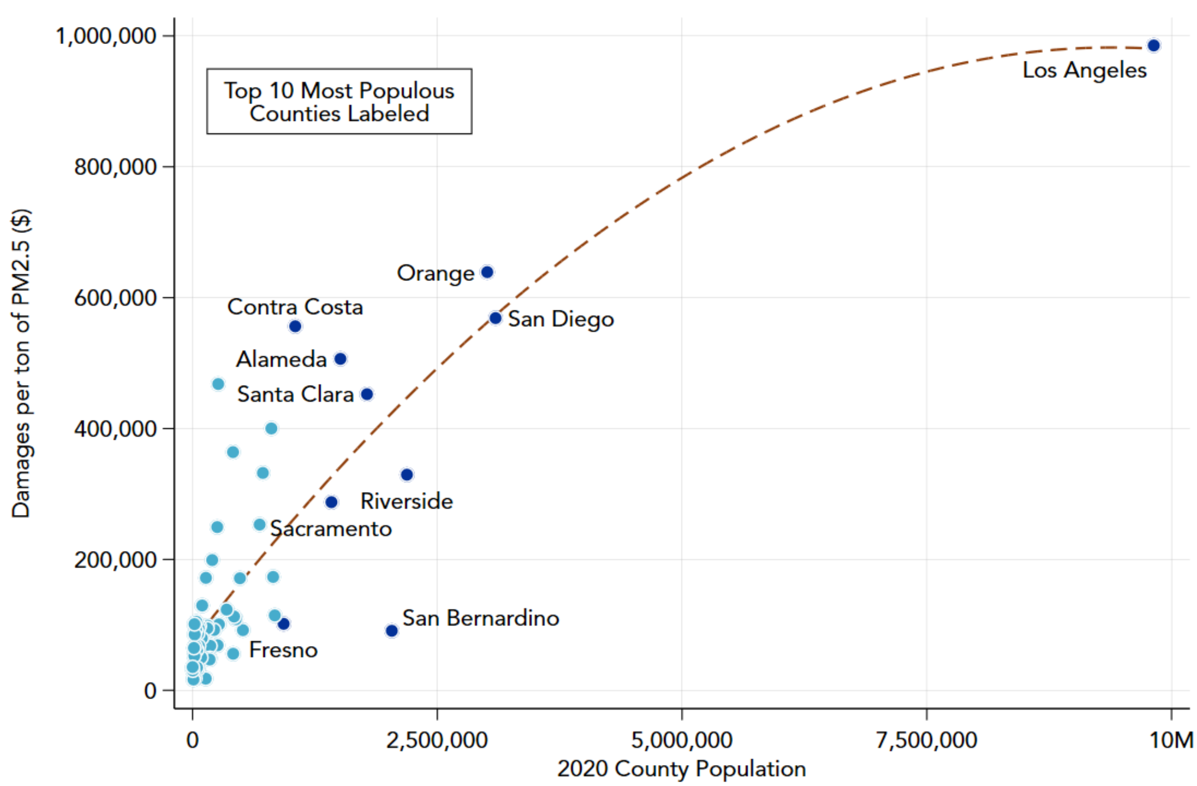
Fact 8 *Pollution damages vary significantly across space.*

The policies that are our main focus in this report do not treat vehicles differently depending on *where* they are driven. The main exceptions are Green Zones, discussed below.

The lack of spatial differentiation is important because damages per ton of emission do vary a great deal across space, primarily because there are differences in the number of people exposed to the pollution.

To illustrate this, Figure 13 plots the damage per ton of PM 2.5 by county in California on the vertical axis against county population on the horizontal axis.[9] Damages differ by a factor of five or ten between large and small counties, and even among the most populous counties, damages can easily be 100% different across space. At a more granular level, damages would differ even more. This is indicative of the potential benefits of spatially-differentiated policies.

Figure 13: $PM_{2.5}$ Damages, by County Population



Note: The figure above uses $PM_{2.5}$ damages from the AP3 model, calculated by county.

[9]These estimates come from the AP3 model. We use that model here because damages at the county level are available, whereas our primary source of damages from the EPA provide only California-average affects. The damage numbers in AP3 and EPA differ, so this figure is most useful as a reference of the difference across space.

4 Efficient policy benchmark

Economic models demonstrate that the most cost-effective way to reduce some source of pollution is typically to price that pollution. Pricing can be accomplished through taxation or through a cap-and-trade system. To be fully efficient, the price needs to be as close as possible to the actual pollution. The reason that pollution pricing is cost-effective is that it gives all market actors the same incentive on the margin to reduce pollution using any available methods or means. Market actors have private information about the costs and benefits of reducing pollution through various actions that the regulator may not know or be able to anticipate, especially as market conditions and technologies evolve. Pollution pricing allows maximum flexibility in compliance and aligns incentives so that market forces will tend to cause the cost-effective abatement activities to occur. This minimizes the cost of achieving a given environmental outcome without requiring the policymaker to have enough detailed information and foresight to proscribe exactly the right set of actions. A command and control regulation that proscribes the same actions or compliance pathways for a diverse set of actors will necessarily raise costs by failing to allow flexibility that respects the heterogeneity of costs and opportunities across actors.

In terms of timing, a consistent price on pollution allows market actors to make adjustments on a timeline that minimizes costs. If costs of compliance are declining over time because of technological improvement, for example, then market actors will decide when to implement changes so as to minimize costs. In contrast, a command and control approach that specifies a compliance pathway can cause costs to rise.

In the case of pollution from medium and heavy-duty trucks, the economic ideal benchmark is to put a price on emissions that reflect the damages they create. As such, the price would vary with the amount of pollution emitted and, for local air pollution, the location of the emissions relative to vulnerable populations. This ideal emissions tax is an important benchmark because the cost-effectiveness of alternatives can be understood in terms of the extent to which they replicate these incentives.

The benchmark emissions tax would impose a fee on a truck that depends on how many miles it is driven in a period, its emissions per mile, and the location of those miles. Such a fee would create an incentive for owners and operators to reduce pollution by:

- switching to lower emission technologies (including both shifting among diesel trucks towards cleaner models and switching toward ZETs), as well as better maintaining engines to reduce emissions;
- adjusting mileage, including by changing loading practices to reduce the number of trips;
- changing routes to avoid vulnerable populations;

- doing all of this on a timeline that minimizes total cost, inclusive of private cost and pollution damages.

In terms of a goal of retiring diesel vehicles and replacing them with ZETs, the pollution pricing benchmark would be cost-effective because it would allow each truck owner to evaluate the private benefit they receive from operating a vehicle in the optimal (that is, taking the incentives into account) manner and compare those to the private costs of using the vehicle plus the pollution costs.

The net social value of a vehicle can be denoted as:

$$\text{Net Social Value} = \text{Private Value} - \text{Private Costs} - \text{Pollution Damage}. \tag{1}$$

If the regulator wants to encourage cost-effective vehicle retirement that follows a proscribed trajectory, it can use a pollution tax that is some portion of total damages θ and scale that value up or down in order to achieve the desired retirement speed, in a cost-effective manner. In such a policy, individual operators will face a net value equal to:

$$\text{Net Social Value} = \text{Private Value} - \text{Private Costs} - \theta\text{Pollution Damage}, \tag{2}$$

where retirement would occur when the net value becomes negative. That is, an operator will retire a vehicle when the net private benefits minus the policy incentive become negative.

Market actors will vary widely in their private value and private costs of utilizing given trucks, including trucks of identical vintage and class, and the regulator has no plausible way of measuring that heterogeneity. The cost-effective solution orders vehicles and retires them according to their net social benefits. This can be achieved even when the regulator does not know the private information about costs and benefits but instead deploys a pollution-based tax as described here. All other policies will deviate from cost effectiveness to the degree that there is heterogeneity in net social benefits of each truck that cannot be captured accurately by policy incentives.

Even more importantly, many of the unintended consequences created by command and control regulations will not be induced by a pollution tax. This lowers the cost of achieving policy goals.

4.1 The ideal pollution tax is a realistic policy option

This theoretical ideal is not easy to implement, but it should not be dismissed too quickly. The barrier to implementation is knowing (a) the location of driving of a truck over a year and (b) the emissions per mile of that truck. It is quite costly to measure emissions per mile directly on an individual vehicle, but a reasonable proxy can be derived by assigning an emissions rate based on class and vintage. This creates some inaccuracies, but it would capture a great deal of the meaningful variation and thus boost cost-effectiveness.

Regarding location and driving data, state agencies do not currently have access to those data. But, these data already exist for many trucks and the cost of installing GPS tracking and logging systems is modest. By 2030, it is reasonable to assume that a majority of vehicles would already have telematics or could be equipped with them at an acceptable cost. The greater barrier may be privacy concerns or other resistance to sharing data that already exist. If that is the case, a straightforward solution is to offer firms an option to pay a higher presumptive fee on driving or to share telematics data in order to get a more favorable rate. Such an opt-in scheme can be designed to encourage participation, so that firms voluntarily join in increasing rates over time (Borenstein, 2013; Cicala et al., 2022). Alternatively, an extension of the existing camera network could create a reasonable estimate of mileage and could certainly be used to measure travel in key locations of greatest concern.

Given the relative feasibility of such an idealized tax, it should be mentioned as a possibility. Given agency guidance, however, we focus our attention on some alternatives below, but use this policy primarily as a benchmark against which to understand the incentives created by alternatives.

5 Policy options for spurring decarbonization

In this section, we describe the three main policy approaches and variations within them. Here we aim to simply explain how alternatives might be implemented. We discuss the strengths and weaknesses of the approaches in section 6. In that section, we provide additional details where relevant. Here we aim to delineate possible policy approaches at a high level.

5.1 Command and control

Our first class of policies is distinguished by relying on neither price incentives nor tradable quantity systems. Instead, they are approaches that rely on scheduling retirements directly and disallowing registrations based on a truck's age.

1. Forced retirement at useful life: A first policy option is to simply impose a ban on all fossil-fueled vehicles that have exceeded their useful life. The ACF imposes such a limitation on the fleets that it covers, so this policy would simply extend that rule to cover the remainder of the fleet. Taken in isolation, however, this provision would do nothing to prevent a perpetual flow of used vehicles into the state. So, some additional component is likely required.

2. Forced retirement with additional restrictions: A second option is to ban fossil trucks beyond their useful life, combined with some additional restrictions that makes it impossible for operators to simply register additional used trucks.

3. Extend the ACF: A third option is to simply include the rest of the fleet in the ACF. As discussed below, this could potentially be paired with a policy that assesses fees on fossil trucks, and compliance with the ACF could be an opt-in alternative to the fees.

The rationale for not including all trucks in the ACF in the first place is (at least in part) the difficulty of complying with a fleet phase-in scheme for operators with only a few vehicles. This suggests an alternative tradable quota scheme, which we include under the pro-retirement policies.

5.2 Pro-retirement market-based policies

One fundamental way to encourage truck owners and operators to move away from legacy fossil-fueled trucks is to make them more expensive or less appealing to operate in California. We consider five distinct policy options that all follow this theme.

4. Annual registration fees: The first pro-retirement option is to assess annual registration fees. These fees would be differentiated by some set of vehicle characteristics, most likely vintage and class, but they would not vary with the usage of a given truck. That is, conditional on its vintage and class, a truck will be assigned a fee, but if that truck is driven more or less in a given time period, that fee would not change. Such fees could be administered through the existing vehicle registration fee system. Below, we focus on differentiated fees that are proportional to the pollution created by each type (vintage and class) of truck.

5. Mileage fees: A second pro-retirement option is to assess fees based on vehicle mileage. Such a fee could be assessed annually, but we distinguish it from annual registration fees that do not depend on the usage pattern of a specific vehicle and do not require new administrative systems or data. Mileage fees, in contrast, would require a new administrative system that collects mileage information. We focus attention on a mileage fee that is associated with the pollution damages per mile traveled, which could be differentiated across vintage and class where emissions per mile are known to differ, but do not vary with location of driving. Where a fee is assessed based on mileage as well as the location of driving, we group this under the theoretical ideal of a damage-based fee.

6. Fuel taxation: A third pro-retirement option is to increase taxes on diesel fuel used for transportation. This can be implemented through a change to existing tax structures and would discourage use of legacy vehicles by making them more expensive to operate. We focus attention on a fuel tax designed to reflect the pollution damages per gallon of fuel.

7. Tradable quantity systems: The prior three pro-retirement policies are all forms of price incentives—they raise the price of registering or using a diesel truck in California. It is possible to instead restrict the quantity (or the proportion) of fossil trucks in operation directly through a quota system. Where the quota system is tradable, we consider this a pro-retirement market-based policy rather than a command and control option. The most appealing option for a tradable-quantity system is probably when it is used as an alternative to an annual registration fee.

8. Diesel buy out programs: Rather than taxing diesel truck usage, policy could foster retirement by offering buy outs for diesel truck retirements. Buyouts offer a political appeal of transferring funds in a direct and salient way to operators, but they pose a substantial risk of unintended consequences. Compared to fees, buyouts boost the asset value of the existing fleet of diesel trucks and would thus encourage important of used diesels into the state, where they would be able to benefit from the buyout in a future year. Designing a policy to avoid these unintended incentives would be difficult.

9. Green zones: The final pro-retirement option that we consider is the use of so-called "green zones" within which fossil trucks are not allowed to enter, or can enter for a fee. The basic idea here is to encourage a shift to ZETs by limiting the usefulness of fossil trucks (or raising the cost of their operation). The major distinction for green zones is that they allow for spatial differentiation, which is important because damages per ton of pollutant vary a great deal across locations depending on the proximity of populations. Among the policy alternatives we consider, only the ideal tax and green zones capture this spatial dimension. (When mileage taxes are made to vary by location, we consider this close enough to the ideal emissions tax that we group it under that category.) Note that green zones can be combined with other policies. One version of green zones is a complete prohibition on travel into specific locations. This might be achieved under some form of Indirect Source Rule.

5.3 Pro-adoption policies

Broadly, instead of making legacy diesel trucks more expensive or less appealing to operate, policy can encourage ZET adoption by making ZETs less expensive or more appealing. We call these pro-adoption policies.

10. Capital subsidies: A first approach to pro-adoption policies is to directly subsidize the up-front cost of purchasing or financing a new ZET. Such a subsidy can be targeted and limited.

11. Infrastructure and fueling support: A second approach is to ensure that fueling infrastructure for ZETs is inexpensive and available. This can take the form of the build-out and subsidization of public charging options or private options. The main distinction we draw here is that this is something that affects the operating cost, rather than the capital cost, but does not directly target the per unit cost of the fuel itself.

12. Fuel subsidies, including rate reform: A third approach is to affect the operating cost of the ZETs through fuel prices. For electric trucks, this can include policy that lowers the volumetric rate for electricity, as well as restructuring of utility rates, including demand charges, that may make refueling unappealing. For hydrogen or other options, this may involve direct subsidies or investment in a hydrogen system.

6 Strengths and weaknesses of policy alternatives

We now lay out the main strengths and weaknesses, with a focus on minimizing the cost of meeting policy objectives, organizing our discussion by the three broad classes of policy.

6.1 Evaluating command and control approaches

1. Forced retirement at useful life: The most basic approach is to simply ban registration of all non-ACF trucks once they have met their useful life, which we denoted as policy option 1. The main benefit of this approach is its simplicity. It is also relatively low cost to administer, provided that the DMV will disallow registration for targeted vehicles. There are two very large drawbacks to this approach, however.

First, this approach will not be cost-effective. Except to the extent that value is correlated with useful life rules, it does nothing to ensure that the trucks with the greatest value to the market are preserved the longest. Put differently, it does nothing to target the retirement of the trucks that are the lowest cost to retire and convert to ZETs.

The ideal benchmark policy puts a fee on vehicles that scales with pollution and varies across usage and emissions per mile, and then allows fleet operators to choose the vehicles that are lowest cost to retire, taking those incentives into account. The ban at useful life approach amounts to putting a zero tax on all trucks until they reach their useful life, and then assessing an infinite tax. This will be a very poor approximation of the actual value. We know from our descriptive analysis of the market that many vehicles exit the state well before their useful life (Fact 2). This policy approach does nothing to accelerate the retirement of trucks that are close to their natural time of turnover and is thus clearly not cost-effective.

Second, the base approach will be subject to what we call the **"used truck carousel."** To comply with the useful life policy, operators could simply buy used trucks from out of state and use them until they meet the useful life threshold. Our data analysis shows that this is already typical market behavior—non-ACF fleets appear to acquire a large fraction of their trucks from outside California as used trucks (Fact 1) and there is regular churn in this market, with vehicles moving in and out of the state within the normal course of a lifecycle (Fact 4). Given that this is already standard market behavior even before any regulatory incentives are put in place, it is quite likely that a policy that relies on decarbonizing the non-ACF fleet just by relying on the useful life threshold, without some additional measure that prevents the used truck carousel from fully circumventing the intention of the policy, will have minimal effect.

2. Forced retirement with additional restrictions: The second alternative is to combine a ban beyond useful life with some sort of policy that prevents the "used truck carousel." We are unclear how this would be achieved. One option would be to simply ban the importation of used trucks—but this seems overly restrictive and costly. It might be possible to somehow require vehicles that are retired to be replaced by ZETs, but this invites potential gaming of ownership and creates complications for entry of new firms, which could prove costly to industry.

That said, we suppose that some innovation is adopted so that the used truck carousel is not a problem, and in fact, a restriction on useful life provisions is put into practice. But, we assume that the solution does not resemble a fleet average ZET standard like the ACF (that possibility is considered next). In that case, a command and control approach could be effective, but it will not be cost-effective both because it does not harness differences in value across trucks in choosing which to retire (discussed above) and because it suffers from additional inefficiencies.

The first problem is what economists call the **Gruenspecht effect**, and what we call here **lifetime extension**. Environmental regulation that makes new capital more expensive, or unavailable, creates a strong incentive to elongate the usage of old capital. This is known as the Gruenspecht effect, after Gruenspecht (1982). This effect has been considered in analysis of automobiles (Gruenspecht, 1982; Jacobsen and van Benthem, 2015; Jacobsen et al., 2023) and power plants (Gruenspecht and Stavins, 2002; Stavins, 2006; Bushnell and Wolfram, 2012).

In the case of command and control restrictions that reduce the availability of new fossil-fueled vehicles, the Gruenspecht effect will come from the existing used fleet extending their lifetime. Our analysis of the truck fleet indicates that many vehicles are normally retired well before their Useful Life Provision benchmarks (Fact 2). This means that there is considerable space for them to elongate their lives within the Useful Life Provision's protective window. In sum, under a command and control system, we would expect vehicles to live longer than they currently do, which creates an inefficient, unintended consequence.

The Gruenspecht effect can be thought of as a form of **lock in** distortion. To illustrate, consider the treatment of drayage vehicles under the ACF. Starting in January 2024, no new diesel trucks can be registered as drayage vehicles. An operator who might normally use a particular vehicle for 5 years for drayage and then move it to another use or sell it to another operator will now have an incentive to maintain that vehicle and ensure that it visits a port annually in order to maintain its drayage status. When that vehicle might have normally been retired, the operator now has an incentive to maintain that vehicle's use for longer, keeping it for option value if nothing else.

A second problem with this policy approach is that it creates significant incentives to **pre-buy**, or more generally to **pre-register**. A command and control system constrained by the Useful Life Provision creates an incentive for firms to buy extra vehicles ahead of policy introduction or phase-in, building up an extra stock of vehicles that can be drawn down over time. This is economically wasteful and can increase pollution. This tendency to pre-buy was documented empirically in Rittenhouse and Zaragoza-Watkins (2018). The authors found a significant increase in Class 8 trucks in the months immediately prior to the EPA's 2007 new engine standards policy. This resulted in over 30 thousand more trucks being purchased prior to the regulation than would have been otherwise, resulting in an estimated $100 million in environmental damages.

Note that, as we understand these policy restrictions, pre-buying could take the form of "pre-registering" vehicles in the state that might otherwise have been owned and operated but registered in another state. To the extent that this sort of selective decision on where to register the existing fleet of trucks ahead of compliance years impacts the policy status of vehicles, regulators should be especially wary because it could be very low cost for many operators to rapidly expand in-state registrations if it provides them a benefit under the rules.

As with the Gruenspecht effect, drayage fleets under the ACF provide a relevant example. The restriction on new fossil vehicles after January 2024 creates a very strong "pre-buy" ("pre-register") incentive, so we should expect operators to register additional vehicles ahead of the deadline. Regulators have an opportunity to learn about the severity of these potential concerns in the near term by studying industry response to the drayage rules.

3. Extend the ACF: In general terms, economists advocate the use of pricing instruments or regulations with considerable flexibility rather than command and control approaches. Rather than mandate retirement by a specific year, economists will generally argue that a policy that prices pollution or creates tradable quotas for the remaining fleet are preferable because they allow market participants to choose compliance options that are best for them. This will matter most when there is heterogeneity in the value of maintaining vehicles of different vintages across operators, which there surely is, though we do not have a ready way to quantify that heterogeneity in costs.

That being said, there is no immediate economic reason to favor a regulation that covers only part of the fleet, as the ACF does. By dividing the fleet into regulated and unregulated sectors, the ACF creates the possibility of economic distortions between those fleets. For example, business structures might be reinvented so that large operators contract out to smaller operators who are not covered by the ACF. Or, municipal governments might subcontract to private firms rather than operate their own fleet.

If a command and control alternatives could be designed to fold the entire fleet into a common framework, this would have some benefits of coherence as well as potential efficiency benefits due to avoiding those types of coverage distortions. Note that an expansion of the ACF could be setup as a voluntary opt-in policy. Uncovered firms could, for example, be given the option to pay differentiated registration fees or opt in to the ACF and become covered. This type of voluntary opt-in would create selection bias, but the incentives could be designed to ratchet up so as to encourage mass participation and the ACF policy could be designed to automatically adjust given the opt-in rate. This sort of ratcheting design has been discussed around opt-in dynamic pricing for electricity (Borenstein, 2013) and for carbon accounting (Cicala et al., 2022).

Presumably the main reason to have exempted vehicles from the ACF in the first place was out of a belief that compliance would be difficult and more costly for smaller firms. Larger firms that operate a bigger fleet can smooth their transitions over more vehicles. Larger firms will have lower borrowing costs on average so they are better positioned to invest in new capital. Larger firms are also more likely to purchase new vehicles (see Fact 5), so they can switch to ZETs more readily in the short term before a used stock is available. Finally, larger firms may be better equipped to manage refueling through an internal system, whereas smaller operators may rely more heavily on public charging/fueling options that are as yet unavailable. In addition, the phase-in of ZET shares for larger firms specified in the ACF apply poorly to a small firm that operates a single truck, or even only a handful of vehicles. (A solution to this last point is to pool firms in compliance to create a tradable registration quota system. We discuss that option separately below.)

6.1.1 Summary of command and control

Command and control approaches are appealing in terms of simplicity and in requiring little or no new administrative capacities. They, however, have significant drawbacks:

- Command and control approaches will either be highly ineffective (if the used truck carousel is an easy compliance option) or they will induce unintended distortions via lock-in and by elongating the life of existing vehicles (Gruenspecht effect).
- Command and control approaches are not cost-effective because they do not account for heterogeneity in valuation across trucks.
- Command and control approaches do not raise revenue.

This last point on revenue is a critical departure from pro-retirement policies, most of which are designed to raise revenue. One reason that revenue is important is that it can be used to compensate operators or communities that experience greater harm from a regulation.

In terms of the conclusions about efficiency, our analysis of the registration data from California leads us to believe that these drawbacks would be substantial. This leads us to consideration of market based mechanisms.

6.2 Evaluating pro-retirement market-based policies

The next category of policy options are policies that impose a fee or restriction on the use of diesel trucks. In all cases, we propose fees that are based in some way on pollution damages, so that the policy creates some approximation of condition 2, repeated here:

$$\text{Net Social Value} = \text{Private Value} - \text{Private Costs} - \theta\text{Pollution Damage}. \quad (3)$$

This gives this class of policy a significant edge in cost effectiveness compared to command and control regulations, but these policies still fall short of the ideal damage-based tax.

The reason is that the policies discussed in this section will create fees that are only partial approximations of pollution damages. For example, an annual registration fee will fail to distinguish between two trucks of the same class and vintage that are driven a different number of miles, or where one truck is driven only in remote areas (and thus causes less damage per ton of emission) and the other is used in a densely populated location. The difference in cost effectiveness across policy alternatives within this class hinges on the degree to which the pollution damage variation reflected in the policy captures more or less of the true variation in damages.

A key defining characteristic of all of the policies discussed below is that they affect the cost of *operating* a truck in California. This means that the policies cannot be evaded through a used truck carousel (any truck brought into the state at any age will pay the fees), nor do they create pre-registration distortions, nor do they create an unintended incentive to elongate the life of existing diesel trucks.

They all generally provide less certainty about the exact phase out of diesel trucks because they depend on market choices that can fluctuate with fuel prices, demand for shipping, and the evolution of subsidies and truck prices. But, they have the advantage that they can be dialed up or down over time as the market evolves in order to calibrate outcomes to the desired transition pathway.

4. Annual registration fees: A simple and transparent way of tilting market incentives towards ZETs and away from fossil-fueled trucks is to impose annual registration fees that are differentiated by truck type, which we will call "differentiated registration fees" (DRFs). Differentiated registration fees can be added to existing annual registration fees, which means that there would be minimal new administrative costs required to implement them.

Fees also have the advantage of raising revenue, which can either be used to fund subsidies for ZETs or ZET infrastructure, or used to compensate communities or operators most affected by regulation, or simply be used to support the general fund. As such, differentiated registration fees can be used to fund complementary policies that target distributional concerns or to fund pro-adoption policies.

There are many potential variations on the basic idea of differentiated registration fees. We focus our attention here on a scheme that is pollution-based, in which the goal is to assign an annual fee to each vehicle that is commensurate with the expected environmental damages it creates per year, put into dollar terms. For each vehicle class and vintage, this tax scheme would assign an annual fee based on expected pollution damages. This is an appealing starting point according to economic theory because it follows the principle of "pricing pollution." Prior work has modeled the fees following this structure for the light-duty vehicle market and concluded they would lead to large efficiency gains (Jacobsen et al., 2023).

From an economic efficiency point of view, the problem with alternative policies is that they create incentives for only a subset of these many margins of action. For example, an annual registration fee gives the operator of a diesel truck no incentive to reroute their vehicle (so long as they decide it is worth paying the fee and operating the vehicle for the year). It thus falls to other policies to try to account for these other margins—for example, separate rules applied to drayage trucks aim to force operators to allocate cleaner trucks towards higher population routes.

Annual registration fees are appealing because they are easy to implement—vehicles already pay them, and an environmental surcharge can be added on with little administrative burden. But, they do not create incentives for mileage reduction, rerouting, improved maintenance, or improved operational efficiency.

They also create uneven burdens that could be the source of objection. We propose class by vintage specific annual tax rates, but within class and vintage, some vehicles create substantially more damage than others due to (a) mileage, (b) emissions factors, and (c) location of driving. These are important limitations, as is apparent from the fact that mileage varies substantially (Fact 6) and because damages across space vary greatly (Fact 8). We do not have direct information on variation in the in situ emissions per mile ratings of vehicles of the same vintage and class, but this variation in the light-duty fleet is very large because of differences in the breakdown of pollution control equipment over the life of a vehicle (Knittel and Sandler, 2018; Jacobsen et al., 2023).

We do not see a feasible way to impose a fee on each vehicle distinctly according to how its emissions per mile differs from other vehicles in its vintage and class, which would require either on-board systems or a wide-ranging emissions check system. But, it may be feasible to make progress on the other dimensions, especially if the first implementation is not until 2030.

One potential concern of differentiated registration fees is whether they could be avoided or reduced through strategic registration of trucks out of state. In the extreme, if an operator could avoid an annual fee by simply changing the domicile of a vehicle to another state, but was able to continue to operate the truck in California, this would be a significant weakness.

Trucks that operate in multiple states already pay a mixture of fees across locations based on the fraction of their mileage through the International Registration Plan (IRP) system. Our understanding of IRP rules implies that any new pollution-based annual fee would be apportioned in the same way—so an interstate truck that drove 50% of its miles in California would pay 50% of the fee amount. This aligns incentives properly and would not create distortions. But we acknowledge this as a point of uncertainty, as we have not been able to confirm this is how IRP would work. If differentiated registration fees could be easily avoided by strategic registration location, this would be a significant concern.

5. Mileage fees: One potential improvement is to tax vehicles annually based on their mileage. This would have an efficiency benefit in that it would give owners and operators an incentive to reduce the usage of vehicles in accordance with true costs and benefits of operation. It would also have a fairness benefit in that it would charge more to those who pollute more, and vice versa, for different trucks within a class and vintage.

Fact 6 shows that there is a great deal of variation in mileage across vehicles that have the same class and vintage. Annual differentiated registration fees that do not vary with mileage will thus create fees that are imprecise measures of pollution at the level of the individual truck, and they likewise fail to encourage mileage reductions. Mileage fees could overcome these limitations.

This would require, however, verified odometer readings, which the state does not currently acquire in a systematic way. Most trucks capture telemetry data already today, so the relevant information exists. It is simply a matter of finding a way that these data can be shared in a verifiable way at low administrative costs, voluntarily.

One possibility is to consider an opt-in provision. Operators could submit a verified odometer record, or some record subject to audit, in order to qualify for the mileage-based schedule instead of the flat fee. This will induce selection bias—trucks that operate fewer miles will have an incentive to opt in. But, the flat fee can be set to take this into account and can be designed to create a virtuous cycle.

If the flat fee is set according to the expected mileage of the fleet that did not opt in, then it will rise as more trucks opt into the mileage-based fee. In each iteration, as more trucks opt in, the expected mileage of the remaining fleet will be higher, and this leads to further escalation of the flat fee, and yet more trucks will opt in. Such a mechanism has been considered around opt-in dynamic pricing for electricity (Borenstein, 2013) and for carbon accounting (Cicala et al., 2022).

6. Fuel taxation Instead of taxing vehicles according to their mileage each year, the state could simply increase the diesel fuel tax. This has the direct effect of creating a price on greenhouse gas emissions, which are directly proportional to fuel usage. It would create a significant benefit in that it charges vehicles more or less depending on their emissions.

It would not, however, not capture the differences in local pollution per ton of diesel that exist across vehicles of different classes and vintages. We conjecture that the diesel tax is more challenging to change due to administrative procedures and political considerations, so at present, we focus on annual fees. But, we emphasize that a diesel tax has some key benefits, and a combination of an annual differentiated registration fee and a diesel surcharge would greatly improve the ability of policy to approximate efficient incentives.

7. Tradable quantity system: Economists make a critical distinction between price and quantity instruments. The state's ZET goals are structured as quantity targets, but differentiated registration fees are a price instrument. This is a mismatch. Because we cannot be certain of how the market will respond to a given set of taxes (prices), we do not know if a given tax scheme will be sufficient to achieve a desired quantity outcome (the number of remaining fossil-fueled trucks).

Instead of a tax, one could imagine a quantity-based policy that would function by limiting the number of registrations of diesel trucks. We call this a "license to register" system. In effect, CARB would issue a fixed number of licenses to register a diesel truck in a given year, whereas zero emission trucks could be registered with one of these licenses.[10] Without a license, an operator could not register a vehicle in the state. To gain the cost-effectiveness of a market-based instrument, the permits would be tradable between operators. They could be auctioned to stakeholders, or allocated for free based on past registration histories, but auctioning them has a number of benefits.

Note that these sorts of quotas for automobiles have been used in a number of countries, including Singapore and China. Economic theory suggests that such a policy would deliver the cost effectiveness of a tax policy, while creating greater certainty about the quantity of trucks and hence progress towards specific ZET targets.

Economists normally believe that tradable permit programs can achieve the same efficiency as price policies, but have the added benefit of providing assurance on quantity targets. But, in this case, if the tradable permits apply only to new vehicles, then all of the same problems cited above may manifest again. Thus, it is likely necessary to build a permit program that covers used trucks as well.

One approach would require a "license to register" for all used trucks. This would offer maximum control over the fleet. This would, however, likely run afoul of the Useful Life Provision.

[10]A possible variation is to structure this as an intensity standard (performance standard) that requires a given fraction of the fleet be ZET in a given year. This is already implemented for new vehicles under existing law; the challenge is to think through how this could be constructed for the used fleet.

Given the Useful Life Provision, a quota policy would probably need to be restricted to new trucks. In that case, the original license could be attached to a particular truck and be valid for its useful life and then immediately expire.

Allowing a license to be transferred between trucks would allow a tradable system of licenses to register to overcome some of the other inefficiencies of a command and control system. For example, a license could come with a specified number of remaining years or miles, and these are depleted each year based on the utilization of trucks that were registered via that particular license. This creates a number of interesting possibilities, but note that it also means that some trucks that would be retired early from the fleet would then create a license that could be used for other trucks, thus ensuring that all of the useful life mileage/years of service for each vehicle would end up being used, assuming there is scarcity. In that case, CARB could always be allowed to buy back licenses from the market and retire them, which preserves the rights associated with the Useful Life Provision while giving CARB an option for accelerating retirements at a known cost.

Tradable permit systems exist in many markets. One common occurrence is significant price volatility, especially in the early periods of a market (Schmalensee and Stavins, 2017). This can create uncertainty about costs for market participants. Moreover, in practice, cap and trade programs often feature price controls (a ceiling and/or a floor). When these price controls bind, which may be quite often if the demand for permits is hard to forecast, a tradable permit program functions like a price instrument Borenstein et al. (2019).

Tradable permits can also create genuine hassle costs, especially for smaller operators. If the permits are not easily traded on a liquid market, which will be especially likely if they cover only a small portion of the market or are divided into many distinct varieties, then these costs could be a substantial drawback to the approach.

Overall, given that a viable scheme would need to cover used costs, and that this in turn raises a complicated set of interactions with useful life provision, a tradable permit system holds promise, but a number of challenging design issues necessitate deeper exploration to determine if the approach is feasible. For these reasons, pricing approaches seem more straightforward.

8. Diesel buy out programs: An alternative to charging diesel vehicles more for usage in the state is to encourage their retirement by directly paying for it. Such a scrappage subsidy has considerable precedent, both in small scales policies today for trucks (including Hawaii's Diesel Replacement Rebate), and in policies like the so-called Cash for Clunkers program for light-duty vehicles and the vehicle retirement benefit in California's Consumer Assistance Program. In the light duty market, these programs have been analyzed and shown to have some effects, but often to achieve less environmental benefits than anticipated due to reshuffling and selection on take up (Mian and Sufi, 2012; West et al., 2017).

The appeal of a buy-out subsidy program is that it sends money to industry in a direct and salient manner, lowering their costs instead of raising them. This is therefore a direct way to combat concerns about causing undue burdens, particularly for smaller non-ACF operators. In terms of efficiency, buy outs can be effective at encouraging turnover, and they share many of the efficiency benefits of other market based mechanisms by providing flexibility.

The drawback to buy-out programs is first that they require revenue, and second that they are likely to create some unintended consequences by encouraging importation of more used vehicles in California in an interim period. In the extreme, a poorly designed policy could be gamed by operators who would move diesel trucks into California just before they intend to scrap them, and then bringing them into the state in order to claim the buy out. A policy would presumably be designed with rules about how long the truck needed to be in the state in order to qualify, but this just pushes back the possibility that strategic operators would move vehicles into the state at an early time (and then operate it here for the necessary years) in order to qualify.

Even without any intentional gaming, however, a buy out program would encourage operators to keep used trucks in the state longer, until retirement, rather than selling them out of state during the normal life-cycle of the vehicle. The reason is that a diesel that is currently in the state would forfeit the opportunity to earn the buy out if it was sent out state in the interim. But Fact 2 shows that most vehicles do indeed exit the state at earlier ages, indicating that many are resold as used in another state. A generous buyout program could thus backfire substantially by keeping these vehicles in the state longer.

Overall, we think these likely unintended consequences, which are difficult to completely manage around, weigh heavily against buy-outs being used as the principle tool for encouraging retirement.

9. Green zones: A critical weakness of annual registration fees is that they are of limited value in creating geographic differentiation. For greenhouse gas emissions, the location of a ton of a pollutant is irrelevant, but location matters a great deal for local pollutants. Conventional models take into account the proximity of populations as well as ambient pollution and atmospheric conditions in determining how much harm to humans is caused by a ton of emissions in a particular place. Population drives much of these differences. These differences are highlighted in Fact 8.

The ideal economic solution is to put a price on each ton of emission that varies with location. Something approximating this is feasibly given advanced telemetry data or via an expanded network of cameras that can be used to build a rich tolling network. On the other extreme, a limited number of specific cordons, which require a fee or simply ban certain vehicles from entering, is a coarse version of geographic restrictions.

Such a policy could be a toll system, or it could be an outright ban or limitation on use of diesel trucks in specific areas. Our understanding is that an Indirect Source Rule (ISR) could be used as a mechanism for banning use of diesel vehicles in particular locations. These types of policies, which restrict usage of vehicles of a particular vintage of power train, have been shown to be effective at changing behavior and shifting the vehicle fleet in specific locations for light-duty vehicles (Barahona et al., 2020; Wolff, 2014; Adda and Cooper, 2000). An ISR that bans usage is effectively a Green Zone with an extremely high price. Economic reasoning favors the use of a price tied to the exact damages of usage, rather than an outright ban, but an outright ban can be a substantial efficiency improvement over no policy at all.

Green zones could be a powerful instrument for encouraging fleet turnover and for reducing diesel truck usage in key areas, but the implementation depends greatly on details. Green zones could be quite small in size, or they could cover large portions of dense cities like Los Angeles. Green zones could involve tolls or bans.

A Green Zone scheme based on banning specific vehicles from traveling within a specific cordon will be more powerful when the cordon zone is larger. As an extreme example, a green zone encompassing Los Angeles County that banned all diesel trucks after a certain year would indeed be powerful.

On the other hand, a toll-based system can be *less* effective when the area is large because vehicles may cross over the threshold of larger areas less often. The reason is that the if the tolled area is large enough, then a vehicle may need to enter it only once in order to travel many miles. Taking the same example of a green zone for all of Los Angeles County, a truck with a local duty cycle might be able to conduct its entire business within the county, meaning it would pay the fee rarely, or never.

Moreover, there is greater inequity and a loss of efficiency in the tolling applied to larger areas because there is more heterogeneity in the miles traveled (and hence emissions) per trip within larger areas. That is, many trucks would simply pass through a green zone, while others may be making a series of stops and deliveries within the zone. A simple threshold policy treats them the same.

Smaller, more tightly defined green zones invite vehicles to reroute. This can be beneficial so long as the zones are drawn carefully. But, if the overriding consideration here is to encourage fleet turnover, the rerouting margin is of less consequence, which again favors larger zones with steeper fees or bans.

To quantify the impact of a green zone system one would need some sample trip data to describe the typical travel pattern of vehicles. One would want to know what sort of areas would be targeted, and then to have some ability to estimate typical truck traffic through those areas by vehicle class. To calibrate the pollution-based tax for a given green zone, one would need an estimate of the typical miles traveled by a vehicle that crosses into that zone. These data may exist, but we do not currently have access to any version of them.

The foregoing assumes that payment into a green zone is based on crossing a threshold, and not on miles traveled or time spent in the zone. If telemetry data were available to measure the miles traveled within the zone, then it seems like the same data could be used for a more general spatial road charging system, and the concept should not be limited to green zones. It might be possible to charge based on time spent within the zone, but this raises similar fairness questions.

In sum, a spatial rule, whether it is a toll-based Green Zone or an ISR that bans usage in a given cordon, is likely to be of limited effectiveness if implemented alone, but it could be a very efficient complement to another market based policy (or a command and control approach). The key is that spatial differences in damage from local air pollution are very large, and any policy that helps to address these issues is potentially efficiency enhancing. Data on populations and ambient weather conditions are broadly available, so additional research could quantify the benefits of spatial tolls or bans around specific locations in order to provide more detailed guidance.

6.3 Summary of pro-retirement options

Relative to command and control alternatives, the main features of pro-retirement options discussed here are:

- They avoid distortions related to pre-buying, the import and replace carousel, the Gruenspecht effect and lock in because they make operators pay per year of usage of a truck in the state.
- They are more cost-effective because they (partially) price pollution damages, which aligns private incentives with social benefits to ensure that the lowest value trucks are the ones that are first retired from the fleet.
- They raise revenue that can be used for general public priorities or to fund subsidies for ZET infrastructure or adoption. Revenue could also be used to compensate operators or communities most impacted by the regulation.
- They differ in their need for new administrative systems.
- They differ in their degree of cost-effectiveness, depending on how well they capture differences in emissions rates, driving distance, and driving location.
- These policies can be phased in over time by ratcheting up prices, whereas command and control policies that are constrained by the useful life provision will have to make aggressive changes early.

- For policies that do not differntiate by location of use (over space), a combination of one of the fee structures with a Green Zone or ISR policy that creates some spatial differentiation could be a very effective combination of instruments.

A last note is that these sorts of market mechanisms are often more amenable to flexible enforcement that allows the regulator to relax restrictions on constituents of interest.

6.4 Evaluating pro-adoption policies

The flip side of making diesel trucks more expensive or less appealing to operate is to directly lower the cost of purchasing or operating zero-emission trucks. There are myriad variations on this theme, but we delineate them into three groups to emphasize important differences in the incentives they create and the possibility of leakage.

All of the pro-adoption policies discussed below share some of the efficiency benefits of pro-retirement policies when compared to command-and-control alternatives because they all rely on flexible market signals that give actors a common signal and freedom of choice in how to respond. Vehicle capital subsidies, however, suffer from key inefficiencies relative to seemingly similar pro-retirement fees. There are also important potential distinctions between policies that lower up-front capital costs of vehicles versus those that lower the cost of refueling because there is more potential to "export" the benefits out of California in the former case.

10. Capital subsidies for vehicles: The up-front cost of new trucks is and will remain a critical factor in the adoption decision. Policy can lower the cost of new zero-emission trucks by directly subsidizing purchases. Existing policies, which we discuss in more detail in Appendix C, in California, in several other states, and at the federal level do this to some degree.

Subsidies have several advantages. They are a direct and salient mechanism. Industry will naturally favor subsidies because they funnel public funds into the sector. In principle, they are flexible and can be tailored by class and owner. For example, California's existing policies include programs that restrict eligibility based on firm size and allow for truck subsidies that vary by class (see appendix section C.2 for further discussion).

There are several limitations related to subsidies, however. First, subsidies are inherently less precise in targeting efficient turnover than differentiated taxes. The reason is that the optimal subsidy would vary with the pollution savings associated with each vehicle. But, the pollution savings associated with a given vehicle type depend on the counterfactual choices—what truck would that buyer have purchased had they not chosen a ZET, and how much did that vehicle pollute? Differentiated taxes can capture these efficiency differences in a way that subsidies cannot, leading to an efficiency advantage for subsidies relative to taxes. Sallee (2023) points out this efficiency advantage of taxes over subsidies.

Second, subsidies require revenue. Several existing policies are primarily funded by Volkswagen settlement funds, which are capped, and in general, a rapid expansion of the clean truck market would entail far greater revenue.

Combining used truck registration fees with up-front subsidies for ZETs is a variation on what economists and policy analysts call a "feebate," which is a scheme that provides subsidies to clean products, funded by fees on dirty products. In the light-duty vehicle sector, feebates have been implemented in several places including France, Sweden, Singapore, New Zealand, and Canada.[11]

The issue with raising revenue will become significant as the market share of ZETs expands. As a product's adoption rises, more and more of the subsidy goes to "inframarginal" buyers—buyers who would have purchased a ZET even in the absence of a policy (Boomhower and Davis, 2014). This logic implies that the optimal subsidy is shrinking in the baseline market share of a product (DeShazo et al., 2017). More generally, the point is that subsidies would become very expensive, and have low-cost effectiveness when adoption is widespread.

A third concern with subsidies is "leakage," where trucks subsidized in California leave the state. In the extreme, imagine that California had an aggressive subsidy for new zero-emission trucks and the rest of the country did not, but there was nevertheless demand to adopt some zero-emission trucks out of the state because of federal Phase 3 rules, simple market trends, or other factors. In this case, large fleet operators would have an incentive to buy all new zero-emission trucks in California, register them initially in order to receive the subsidy. But, they might drive the vehicles out of state, partly or entirely, or quickly move the registration to another location. In this scenario, California would subsidize all the zero-emission trucks of the entire nation, draining public funds, while receiving only some fraction of the benefit.

Regulators are aware of these potential concerns, which is why some existing policies have requirements that a vehicle remains in a state and be operated primarily in the state in order to maintain eligibility. California's Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP), for example, requires that vehicles be operated in the state for three years, with limitations on mileage outside the state, in order to be eligible. Such provisions are essential, though they are imperfect, as some operators may still strategically manage operations in order to inflate their eligibility for subsidies. This creates an important distinction between the other classes of pro-adoption policies, discussed below, which lower the cost of *operating* a ZET in the state.

A critical design question relates to whether subsidies should be available to all vehicles, or only to the non-ACF fleet. If subsidies are available for all vehicles, as is currently the case,

[11] A brief discussion of these example policies can be found here: https://theicct.org/magic-of-feebate-programs-jun22/. France's program is the most significant of these and has been analyzed in several papers including D'Haultfœuille et al. (2014). Anderson and Sallee (2016) discuss the economics of feebates as compared to other policies.

then those subsidies might do nothing to actual adoption if the ACF provisions are binding, but instead, they would simply shift the cost of compliance from the truck owners and operators onto taxpayers. A binding regulation like the ACF creates what economists call a "shadow price," an increase in cost required to comply with the rule. By subsidizing adoption of heavy-duty trucks explicitly, a subsidy transforms the "shadow price," which is a burden born by the industry, into an explicit subsidy, which is paid for by taxpayers. For example, consider a year in which ACF requires a given class of vehicle to be 10% ZETs. If a subsidy is introduced, a possible outcome is that operator continues to have only 10% ZETs, but now the cost of achieving that is lower by the amount of the subsidy. This is fine if shifting the burden is the intention of policy, but regulators need to understand that when there is a binding regulatory constraint a subsidy, in some cases, will not increase the number of ZETs, it will simply shift who is paying the bill.

A final point of consideration is that regulators should keep in mind that the ultimate benefits of a subsidy for ZETs—which economists call the "incidence" of the subsidy—need not go to the buyer who initially receives the subsidy. A subsidy for new ZET purchases may allow manufacturers to increase the price they charge to buyers because buyers have a higher willingness to pay as a result of the subsidy. Alternatively, some of the benefit may flow to the customers of trucking services, as lower firm costs will manifest into lower shipping costs. As such, some fraction of the ultimate benefits of a subsidy may go to truck manufacturers, and some may go to the consumers of final goods who benefit from lower shipping costs. In the light-duty sector, some evidence suggests that buyers did gain most of the benefit from subsidy programs Gulati et al. (2017); Sallee (2011), but the market structure and strength of competition in the trucking sector may lead to different outcomes.

11. Infrastructure and fueling support: Subsidies for new purchases lower the up-front cost of trucks. A second class of pro-adoption policy aims to lower other costs by improving or subsidizing fuel infrastructure.

For electric vehicles, most operators will want the option of charging their vehicles on their own premises. This will generally require the installation of new fast-charging equipment that can create substantial up-front capital costs. Direct subsidies for this equipment and installation can thus be a direct and effective way of lowering barriers to adoption.

Costs of installing chargers on-site include delays and constraints, not just the up-front costs. Many facilities may require upgrades and interaction with utilities that may not be ready to scale. Charging at specific locations may not be feasible without utility upgrades to the distribution network. Policies that can reduce costs and eliminate utility bottlenecks may be impactful.

Many duty cycles for trucks also require availability of public fast-charging infrastructure along travel corridors. This infrastructure is in its infancy, and policy actions that can accelerate development will be a critical requirement for widespread adoption.

Both direct subsidies for trucks and this class of policy, which targets refueling cost and availability, lower the total operating cost of zero-emission trucks. A key distinction, however, is that infrastructure investments that lower the cost of *operating* a ZET in the state do not create the same concerns for leakage highlighted above. Subsidizing the *purchase* of a ZET in the state encourages operators to buy a vehicle, but they may choose to use it outside the state for much of its life unless precluded by policy, whereas making it cheaper to *operate* ZETs in the state encourages continued usage of vehicles in the state, even if they were purchased initially in another state.

12. Fuel subsidies, including rate reform: A third pro-adoption policy approach is to directly lower the cost of fuel for ZETs. For the case of electricity, which appears at the moment to be the dominant near-term approach, this raises issues of rate design.

In California, the cost of retail electricity is known to be well in excess of the social marginal cost of providing additional electricity to an existing customer (Borenstein et al., 2021). This is due to the fact that all system costs, as well as other costs including wildfire mitigation and liability, as well as some other policy priorities including low-income subsidies and energy efficiency programs, are funded by ratepayers and are recovered in the form of high volumetric (per kWh) prices. For retail customers, Borenstein et al. (2021) estimate that per-kWh prices are two to three times higher than social marginal cost in California. Commercial customers also face demand charges that can complicate and add cost to fleet charging. Utilities do have special rates for businesses using electric vehicles, but there is likely a great deal of space for improvements in these rates to ensure that they do not create a barrier to adoption.

A policy or rate reform that lowers the cost of operating ZETs per mile will, like infrastructure improvements, spur adoption by lowering the total operating cost of ZETs, while avoiding the problems of leakage to other states. Policies that lower fuel costs also have the benefit of encouraging greater utilization of ZETs on the margin, which is different than either class of capital subsidy. That is, if we compare a capital subsidy that results in the same number of ZETs being registered as an electricity subsidy or price reform, we would expect the ZETs to be used to drive more miles in the latter case because fuel cost reforms directly lower the cost per mile. As such, there is a likely additional efficiency benefit of such policies in encouraging a shift of fleet operations towards the ZETs and away from the diesel vehicles during the transition to a fully ZET fleet.

6.4.1 Summary of pro-adoption options

In brief, when compared to command-and-control alternatives, pro-adoption policies have significant efficiency benefits. Taken alone, pro-adoption policies have key inefficiencies relative to pro-retirement policies.

- Capital subsidies for trucks are salient and likely to be effective, but they inherently target pollution less well than do differentiated registration fees, which implies an efficiency advantage for fees.

- Policies that lower the cost of purchasing ZET trucks in California risk having some of the benefits exported out of the state, whereas policies that lower operating costs in the state avoid this concern.

- Subsidy policies require revenue, and in particular subsidies per truck will become increasingly costly and decreasing in their cost effectiveness as market shares rise. This makes subsidies a less appealing instrument for fostering the transition from 2030 and beyond.

- Investment in charging infrastructure is clearly needed to foster the transition, and the exact form of this needed investment of course depends on which fuel sources become dominant. Electric trucks face substantial hassle barriers related to charging installations and utility backlogs, and they are paying fuel prices that are inflated over social marginal cost. Policy that can address these issues could be effective and would be an efficient complement to pro-retirement policies.

In summary, we conclude that per-vehicle subsidies are a reasonable instrument to use at present, but it will suffer critical weaknesses if it is relied upon to be the primary instrument as the market matures. A more appealing policy combination is to use differentiated registration fees or another pro-retirement policy that raises revenue and then support needed infrastructure investments, including possibly subsidies for charging rollout as well programs that can reduce wait and hassle time for installing charging equipment, particularly assuming that electric trucks are the dominant form of ZET.

6.5 Summary of policy comparisons

The exact characteristics of any of the policy options depend on implementation details, but Figure 14 below provides a useful heuristic about the likely characteristics of alternative policy options by category.

The foregoing discussion focused on efficiency and efficacy. Equity concerns were raised at several points, but it is worth reiterating here some of the key insights about equity. First, the burden of complying with a policy that mandates fleet turnover (as in a command and control approach) or prices pollution (as in a differentiated registration fee system) for individual operators will depend on the cost to them of turning over existing vehicles to zero emission trucks. We do not have direct information on these costs, but we expect the cost of upgrading the fleet will depend on truck usage patterns, but also firm size (with a change being more expensive for smaller firms that have to deal with fixed costs of changing, have higher borrowing costs and will be more reliant on public refueling) and for those that currently rely on older trucks (as the capital cost difference will be greatest, particularly as the used ZET fleet matures).

The burden on operators can be minimized by policies that subsidize ZETs directly or that pay for diesel scrappage. Of course, the funds needed come from somewhere else, either through other fees in the industry or from state taxpayers. Thus, the equity considerations ultimately depend on the source of revenue as well.

When comparing pricing or permit systems to command and control approaches, both will place a bigger burden on those with the greatest cost of switching to ZETs, but market based mechanisms will generally provide more flexibility that can be used to control those burdens. For example, tradable permits can be allocated for free to smaller operators, or other groups of concern. Similarly, fees can be waived, or, even better, tradable waivers can be distributed to operators based on past registrations to eligible operators who meet criteria based on their size, location or other attribute of concern. (The reason to provide tradable waivers instead of a firm-specific discount or waivers is to preserve efficiency.)

Figure 14: Policy comparison

	Benefits			**Unintended Distortions**		**Revenue**
Policy alternative	**Cost effectiveness from harnessing industry information**	**Accounts for mileage differences**	**Accounts for spatial differences**	**Induces Gruenspecht effect**	**Induces pre-registering**	**Revenue implication**
Ideal emissions tax	High	Yes	Yes	No	No	Positive
Forced retirement at useful life	Low	No	No	Yes	Yes	Neutral
Forced retirement with additional restrictions on used importation	Low	No	No	Yes	Yes	Neutral
Expand ACF	Low	No	No	Yes	Yes	Neutral
Annual registration fees	Medium	No	No	No	No	Positive
Mileage fees	Medium	Yes	No	No	No	Positive
Fuel taxation	Medium	Yes	No	No	No	Positive
Tradable quantity system	Medium	No	No	No	No	Positive
Diesel buy out programs	Medium	No	No	No	Yes	Negative
Green zones	Medium	Yes	Yes	No	No	Positive/Neutral
Capital subsidies	Medium	No	No	No	No	Negative
Infrastructure and fueling	Medium	No	No	No	No	Negative
Fuel subsidies	Medium	Yes	No	No	No	Negative

7 How large are pollution damages?

As discussed above, economic theory councils that the most cost effective policy will be one that imposes a fee (or subsidy) based on the unpriced pollution, measured in dollars of cost. We thus present an analysis that calculates how large pollution-based fees might be. As a first step, we calculate estimates of the damages associated with the use of fossil-fuel trucks, and in the next section we discuss how this would translate into policy.

Several steps are required to calculate a pollution-based fee. First, from EMFAC, we take the emissions per mile and typical mileage associated with a given year and vintage. These are fields directly available in EMFAC. These allow us to calculate tons of pollutant that are associated with each vehicle class and vintage.

To monetize those tons, we use estimated damages per ton from Internal Combustion Engines in California in 2030, in $2020 dollars, calculated by the US Environmental Protection Agency (EPA). These damage estimates are calculated using estimates of the value of a statistical life, dose-response functions from epidemiology, air transport models of pollution, and demographic information. The EPA projects these estimates out to 2030 based on changes in population and income. The EPA provides a low and high number for most pollutants. We start by using the low numbers, and then show how estimates change when we adopt the higher values.

For carbon emissions, we use the current White House social cost of carbon of $62 per metric ton in 2030 for our baseline analysis, and show results using $187 per metric ton, which is a value recommended in new rulings, in our high damage scenario. Table 3 shows high and low damages per pollutant ton, in $2020 dollars, adjusted to short tons. Please note that the short ton value is used in all below figures and tables.

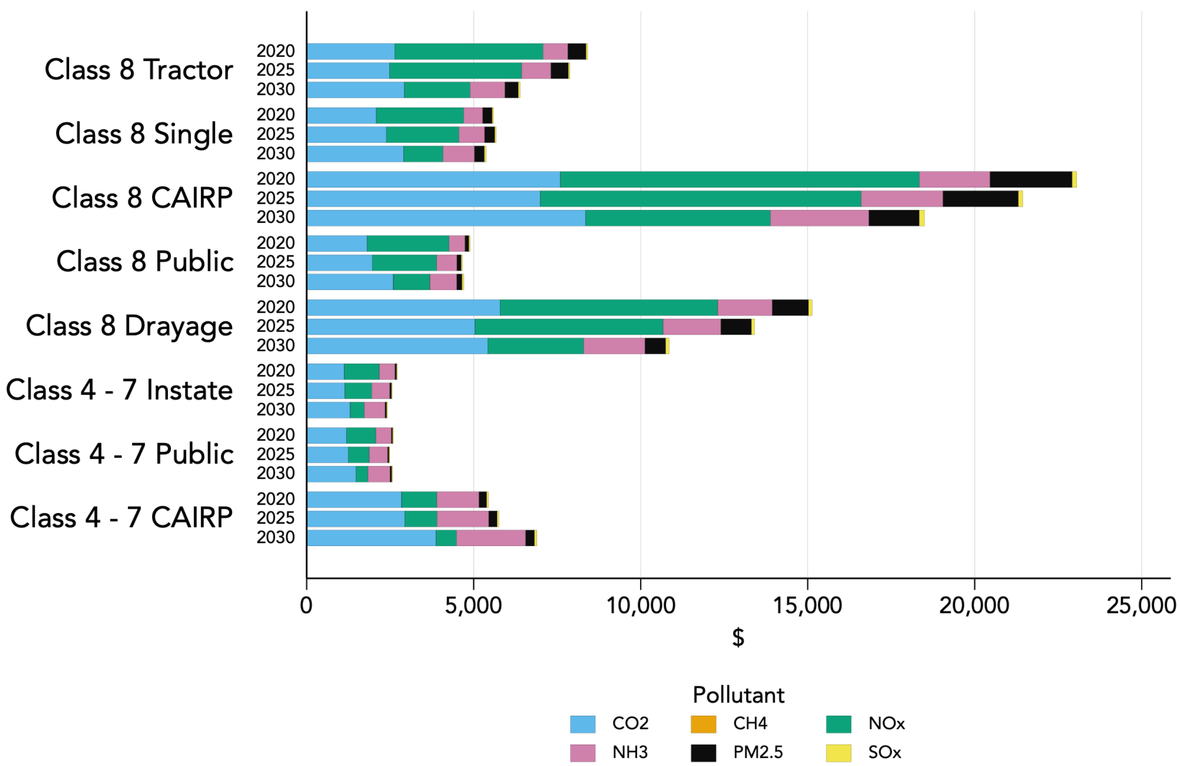
Table 3: Damages ($2020) per pollutant short ton

Estimate	*CO_2*	*CH_4*	*NO_x*	*NH_3*	*$PM_{2.5}$*	*SO_x*
Low	$68	$2,205	$68,366	$154,201	$1,047,058	$134,791
High	$206	$5,732	$141,261	$320,264	$2,167,443	$279,287
Source	White House	White House	EPA	EPA	EPA	EPA

Our proposed annual fee value is thus the pollution damages per ton times the tons of emissions per year associated with a vehicle type. Figure 15 shows the resulting estimated fees in 2031 for 2020, 2025 and 2030 vintage trucks by class.

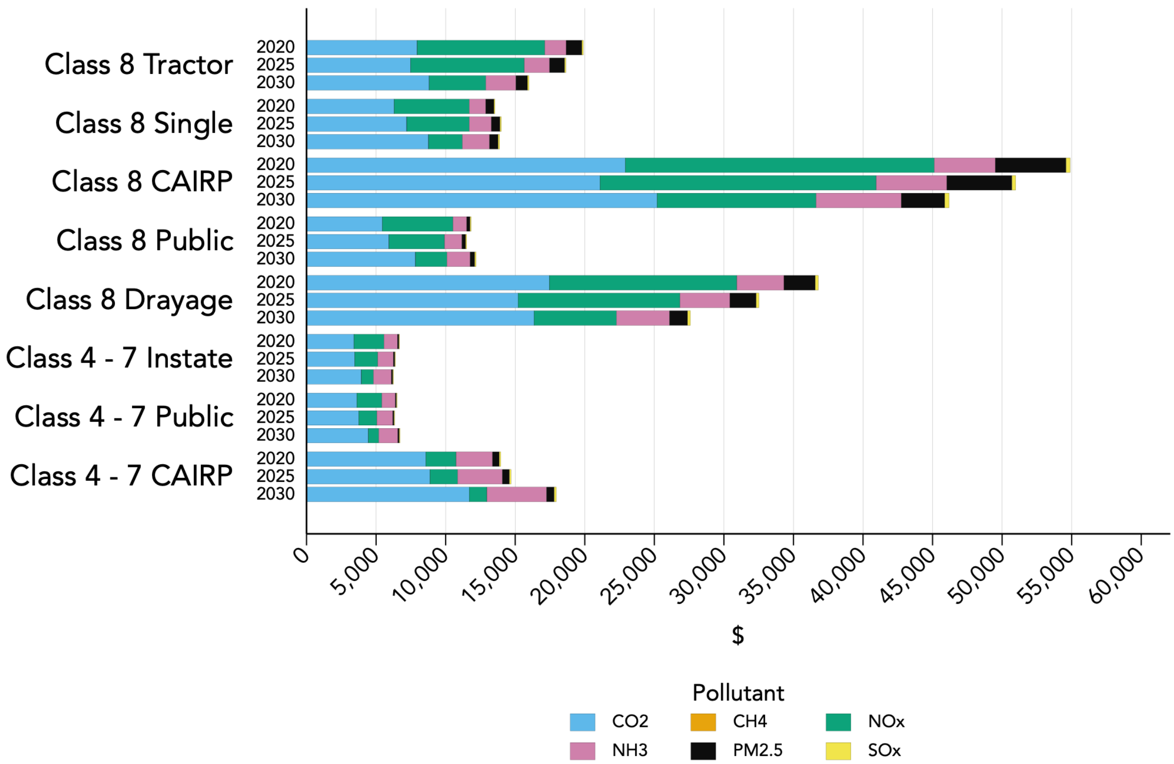
These results show that the annual fees come from a variety of pollutants, all of which make a substantial contribution to damages from truck pollution. As a point of comparison, Class 8 trucks pay on the order of $3,000 per year in registration fees today, mostly due to a weight-based charge.

Figure 15: Annual Per-Truck Damages by Truck Group & Model Year in CY2030 Using EPA's Low Damage Estimates



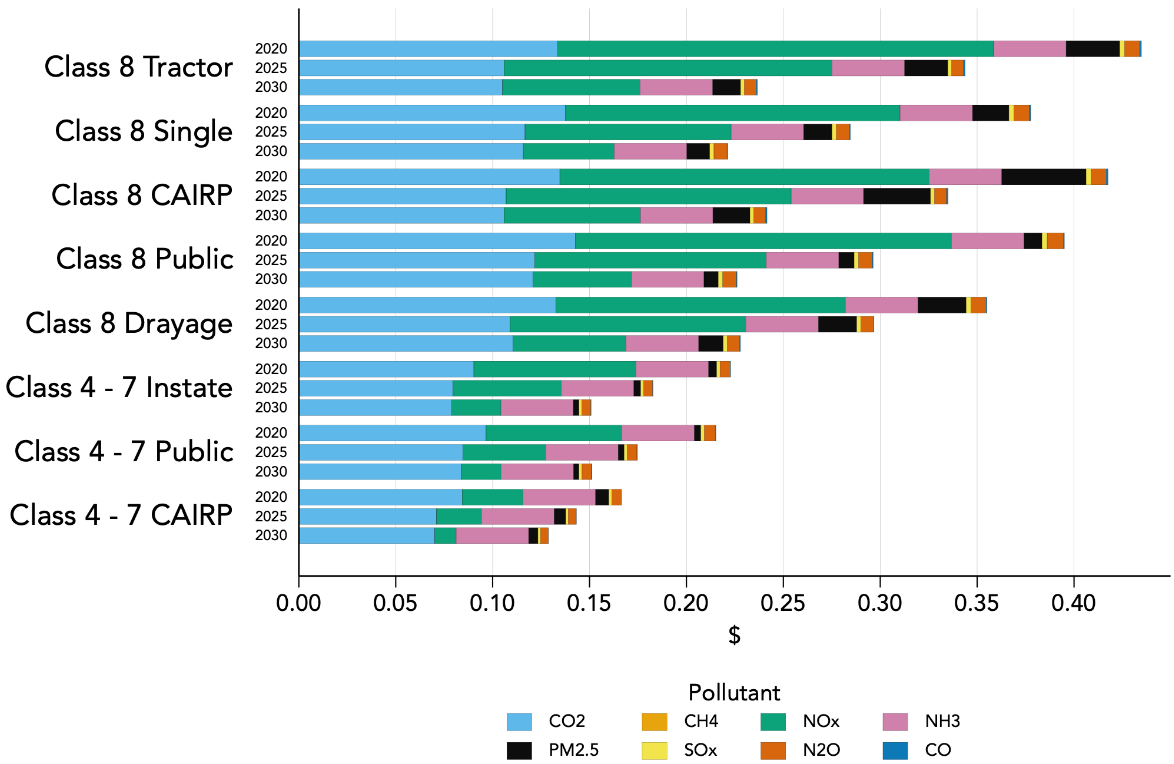
Note: This figure displays projected annual per-truck damages for Class 8 and Class 4-7 trucks in calendar year 2030. This figure uses the low damage estimates outlined in Table 3. Per-truck damages are calculated by multiplying per-ton damages by the tons-per-mile and miles-per-truck projections from the EMFAC 2021 model.

Figure 16: Annual Per-Truck Damages by Truck Group & Model Year in CY2030 Using EPA's High Damage Estimates



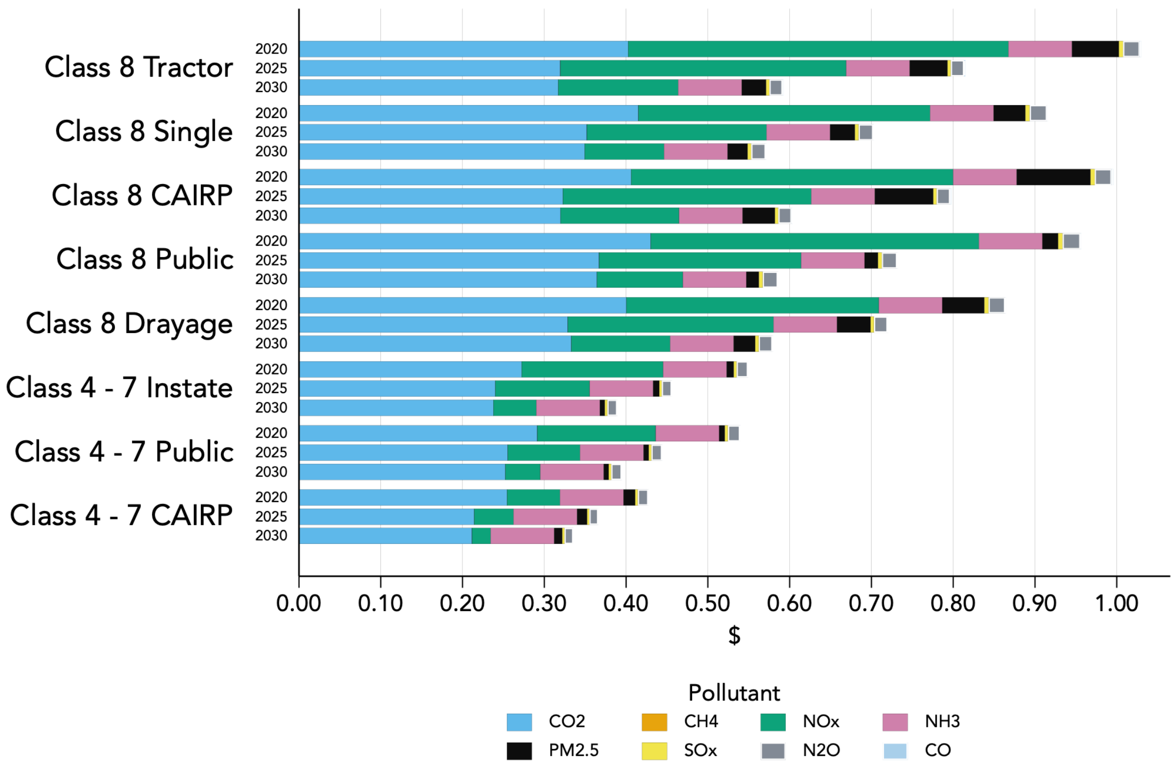
Note: This figure displays projected annual per-truck damages for Class 8 and Class 4-7 trucks in calendar year 2030. This figure uses the high damage estimates outlined in Table 3. Per-truck damages are calculated by multiplying per-ton damages by the tons-per-mile and miles-per-truck projections from the EMFAC 2021 model.

Figure 17: Annual Damages Per Mile by Truck Group & Model Year in CY2030 Using EPA's Low Damage Estimates



Note: This figure displays projected annual per-mile damages for Class 8 and Class 4-7 trucks in calendar year 2030. This figure uses the low damage estimates outlined in Table 3. Per-mile damages are calculated by multiplying per-ton damages by the tons-per-mile estimates from the EMFAC 2021 model.

Figure 18: Annual Damages Per Mile by Truck Group & Model Year in CY2030 Using EPA's High Damage Estimates



Note: This figure displays projected annual per-mile damages for Class 8 and Class 4-7 trucks in calendar year 2030. This figure uses the high damage estimates outlined in Table 3. Per-mile damages are calculated by multiplying per-ton damages by the tons-per-mile estimates from the EMFAC 2021 model.

Figure 16 shows that these annual pollution damages roughly double when using the higher values. Damage estimates based on these higher cost per ton values can exceed $50,000 for the highest mileage Class 8 vehicles.

Figures 17 and 18 show damages on a per mile basis, rather than an annualized amount. Variation across vintages in the annual fees are caused by both differences in emissions per mile and estimated typical mileage. By looking at the per-mile figures, one can separate these effects. Per mile damage estimates also allow comparison to fuel costs.

For comparison, a typical fuel economy for Class 8 trucks is around 6 miles per gallon. At that fuel economy, every $1 increase in the price of diesel translates to an increase in the per mile operating cost of $0.17. Thus, damages that add (social) cost of $0.34 per mile are similar in cost impact to a $2 per gallon increase in the price of diesel, and a $0.70 per mile fee cost is similar to a $4 hike in the price of diesel.

This demonstrates that the air pollution damages associated with truck usage represent a qualitatively large part of the total cost of operating trucks. In the high damage scenario (Figure 18), pollution costs represent a cost to society equivalent to a several-dollar increase in the price of diesel for older vehicles.

8 What impact would differentiated fees likely have?

The foregoing analysis demonstrates that pollution damages associated with truck usage are large, even when we consider future vintages that are expected to be cleaner per mile. In this section, we discuss how fees based on these damages might impact the market. A fee equal to the full annual or per mile damages may be deemed too large for political reasons, though recall that the revenue raised through such fees could be recycled in a way that keeps the industry whole overall while further fostering a cost effective transition to ZETs. In what follows we will assume that a system of fees and subsidies is created such that the money raised from the fees equals that paid out in subsidies. For simplicity we will consider all fees and subsidies as though they are paid on a per-mile basis, though in fact it may be more feasible to collect payments annually or even just once at the beginning of a truck's life based on anticipated miles.[12]

In the analysis, the difference between fees for different vehicles is kept equal to the difference in emissions damages. For example suppose the pollution damages caused by a diesel vehicle are 25 cents per mile. One system might place a 25 cent fee on diesel miles and no fee on ZETs, reflecting the pollution damage. Alternatively, a fee of 10 cents a mile on diesel trucks paired with

[12] A more complex model could consider the differences in incentives depending on payment structure. For example, annual fees on diesel trucks could encourage more intensive utilization during the year. Subsidies to ZETs made using a single payment at the beginning of the truck's life could reduce utilization intensity and encourage ZET exports to other states. We abstract from these effects here. These differences can be important in practice.

a 15 cents per mile subsidy for ZETs maintains the strength of the financial incentive to switch (at 25 cents per mile), but creates a smaller average burden on the truck fleet overall. Again it may be more practical, or helpful to truck buyers who need financing, to pay the expected value of a 15 cents per mile subsidy all at once when the truck is brand new, but we abstract from this choice in the simplified quantitative analysis.

8.1 Qualitative discussion of the magnitude of potential fees

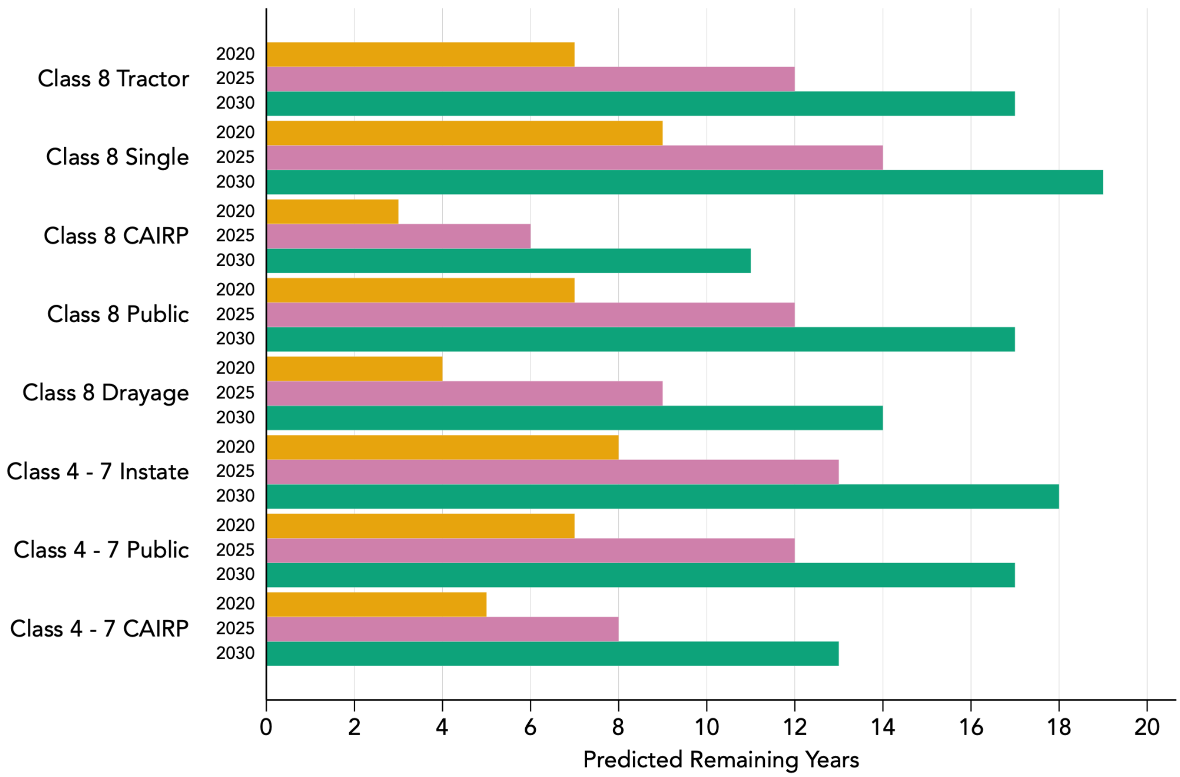
A vehicle owner considering whether to buy or keep a fossil-fueled truck instead of a ZET will consider not just the current fee, but also the value of the future flow of fees. Thus, to judge the full impact of introducing an annual pollution-based registration fee on decisions it is useful to construct the present-discounted value of all fees. To do so, we need an estimate of the remaining lifetime of a truck given its current age, the future schedule of fees, and an assumed discount rate.

To assess the remaining lifetime of a vehicle, we model the typical vehicle survival by age and fleet grouping type among vehicles in the 2024-2050 projected fleet from EMFAC, and then apply these same survival rates to the 2030 fleet. For the time path of fees, we assume that trucks pay the same fee in all remaining years of registration. We assume a 5% discount rate.

Figure 19 shows our estimates of the remaining years of life of vehicles of different vintages and classes in the 2030 fleet. This is relevant as it dictates the potential full lifetime of fees that an owner would expect to pay if they continued to register and operate a diesel vehicle in California. (The idea is that the registration fees will change this decision, but we want to first establish how large an impact the proposed fees have on ownership costs given current behavior to judge how large will be the likely response.)

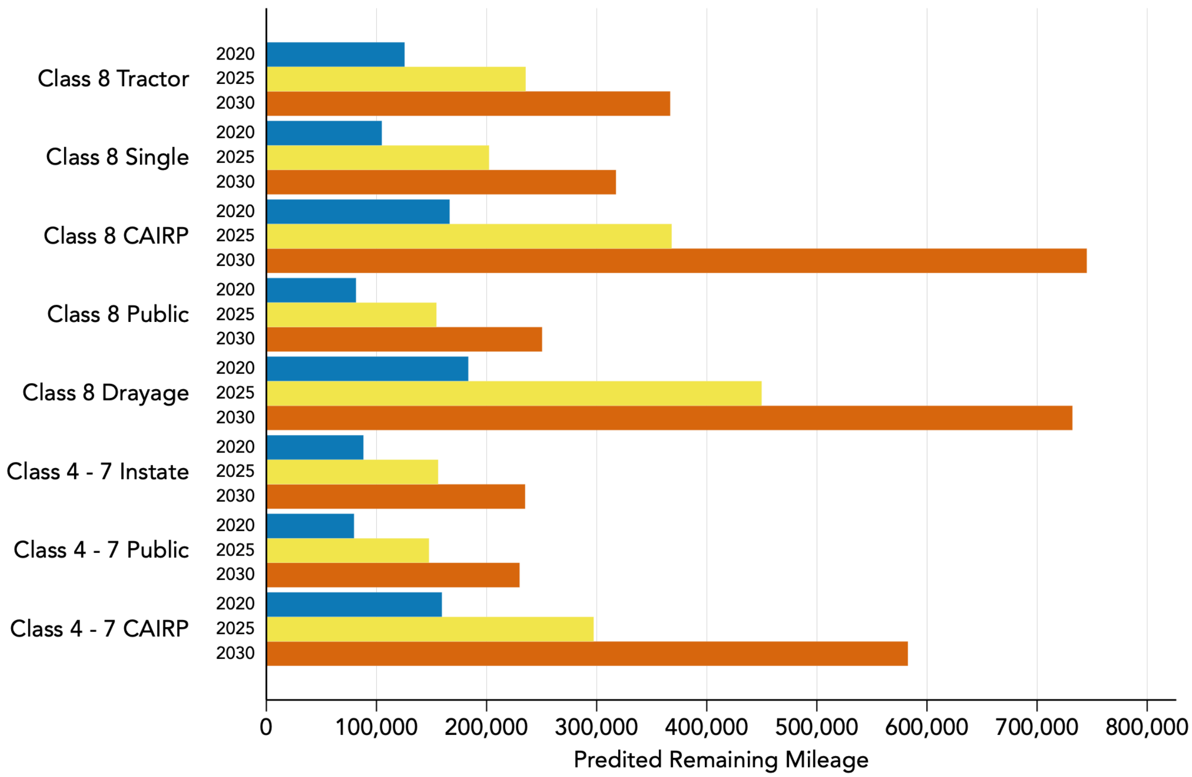
Figure 20 shows remaining mileage, rather than years of life for reference. Generally, these exaggerate the differences because older vehicles are driven less per year.

Figure 19: Predicted Remaining Years of Life by Model Year in CY2030



Note: This figure shows the predicted remaining operating years for Class 8 and Class 4-7 trucks in calendar year 2030. Remaining years of life are calculated using forward looking vehicle population projections for calendar years 2025 to 2050 from the EMFAC 2021 model.

Figure 20: Predicted Remaining Mileage, by Truck Group & Model Year in CY2030



Note: This figure shows the predicted remaining mileage for Class 8 and Class 4-7 trucks in calendar year 2030. Remaining mileage is calculated using forward looking vehicle mileage projections for calendar years 2025 to 2050 from the EMFAC 2021 model.

8.2 Are these fees large enough to move the market?

To assess the plausible effect of pollution-based fees on adoption and turnover decisions, we first compare the annual and cumulative fees to other aspects of the cost of ownership.

First, as we already established above, an annual fee calibrated to the full annual damages per truck per year would equate to a substantial increase in the price of diesel fuel when the annual fees are amortized on a per-mile basis. Truck operators are very sensitive to operating costs, and, in qualitative terms, fees of this order of magnitude can be expected to have a significant impact on demand.

Second, as compared to existing annual registration fees, which top out in the low single thousands for even the largest trucks, these proposed fees are generally larger.

At the same time, the proposed fees are not larger than other operating cost categories. Even at the top of the range, they are still smaller than annual fuel costs.

Another comparison that might be useful is to imagine the impact these fees would have on a buyer considering a new diesel truck in 2030, who would otherwise wish to own and operate the vehicle over its life.[13] How large would be the present-discounted value of the fees they could expect to pay?

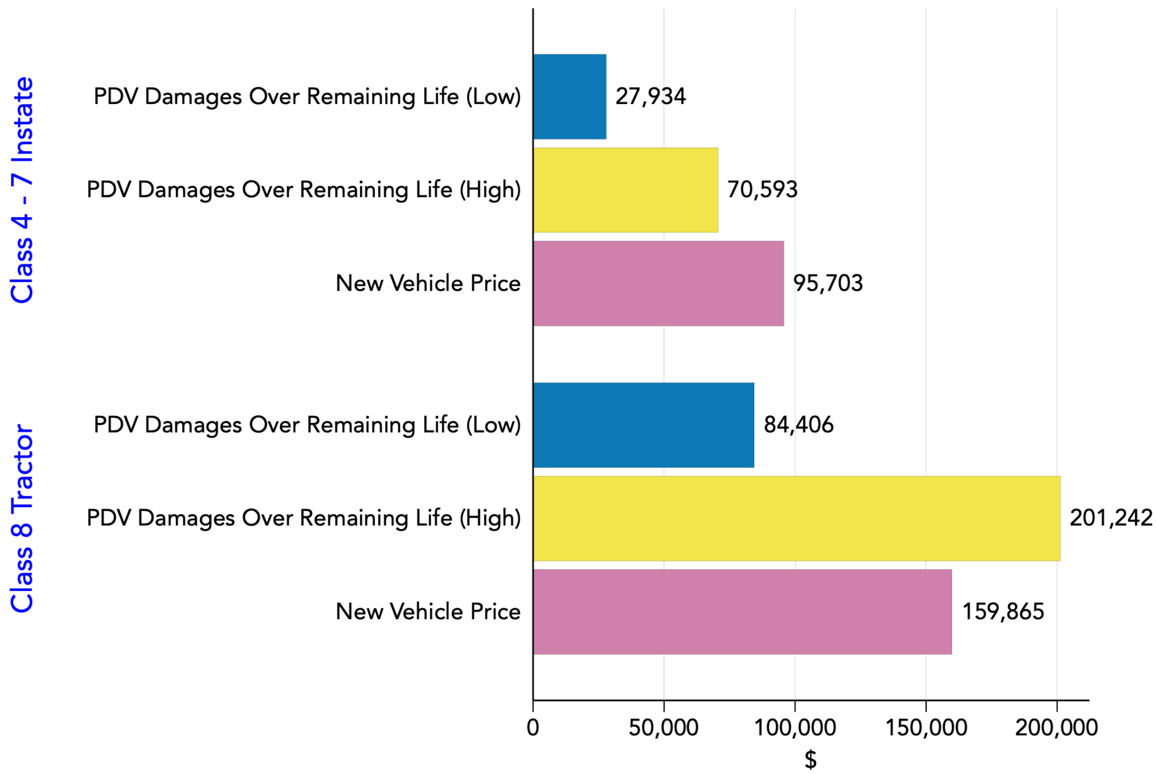
Figure 21 shows these values for the low and high damage estimates and compares them to estimates of the new vehicle price taken from California Air Resources Board (2021). For Class 8 vehicles, the high damage scenario creates fees that are comparable to the entire up front price of a vehicle. This fraction is lower under low damage estimates and for Class 4 through 7s, but in all cases these fees represent a large fraction of the capital costs, and thus could be expected to make a substantial impact on ownership decisions.

Those present-discounted value estimates rely on assuming a vehicle would be operated in California for the rest of a typical life. Another useful perspective is to instead compare the annual fees to the residual value of a vehicle as it ages. We do this using the residual value calculations provided in California Air Resources Board (2021). Figure 22 shows the residual value curve for a Class 8 tractor, against a proposed annual fee from the low damage scenario. As a vehicle ages, the annual fee becomes a substantial fraction of the remaining asset value, which points to the potential for a significant retirement response.

Another way to see this is to simply plot the ratio of the fee to the residual value at different ages. Figure 23 does this for three vehicle types by age for the low damage scenario. This makes clear that, especially for heavy-duty tractors, which depreciate quickly because they tend to accrue many miles, these fees would represent a large ongoing cost compared to the value of the underlying asset.

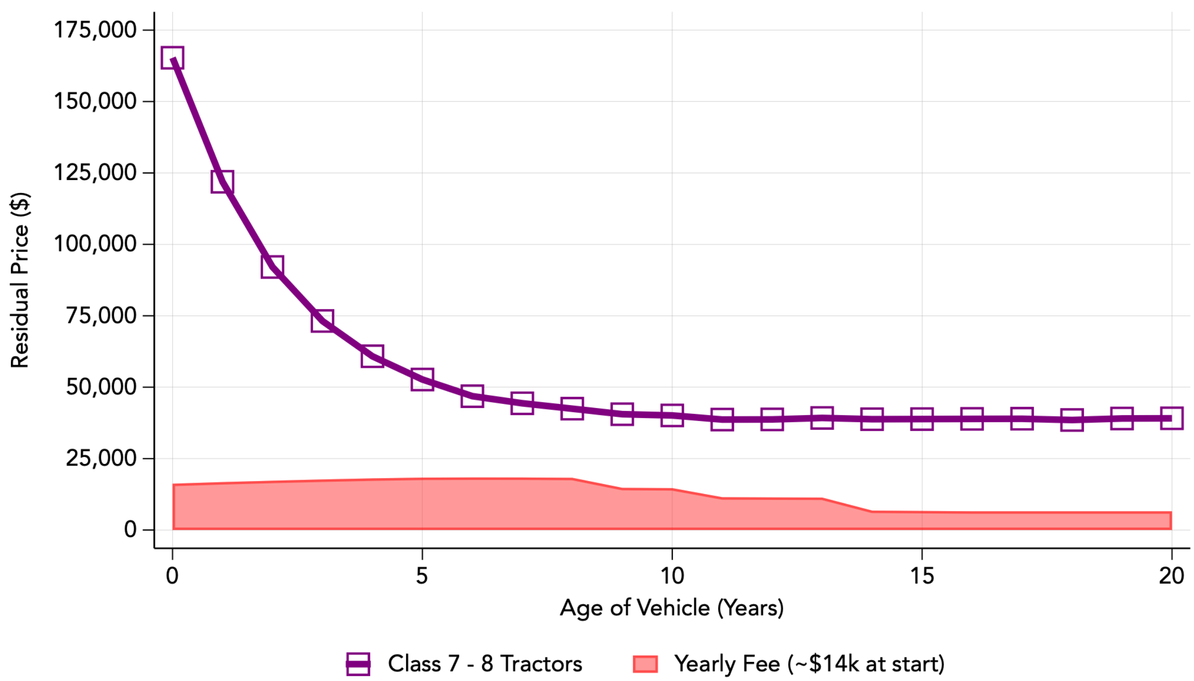
[13]Note that if they planned to sell the vehicle within California, the used asset price should capitalize the fees in the same way.

Figure 21: Comparing PDV Damages to Vehicle Price, by Truck Group



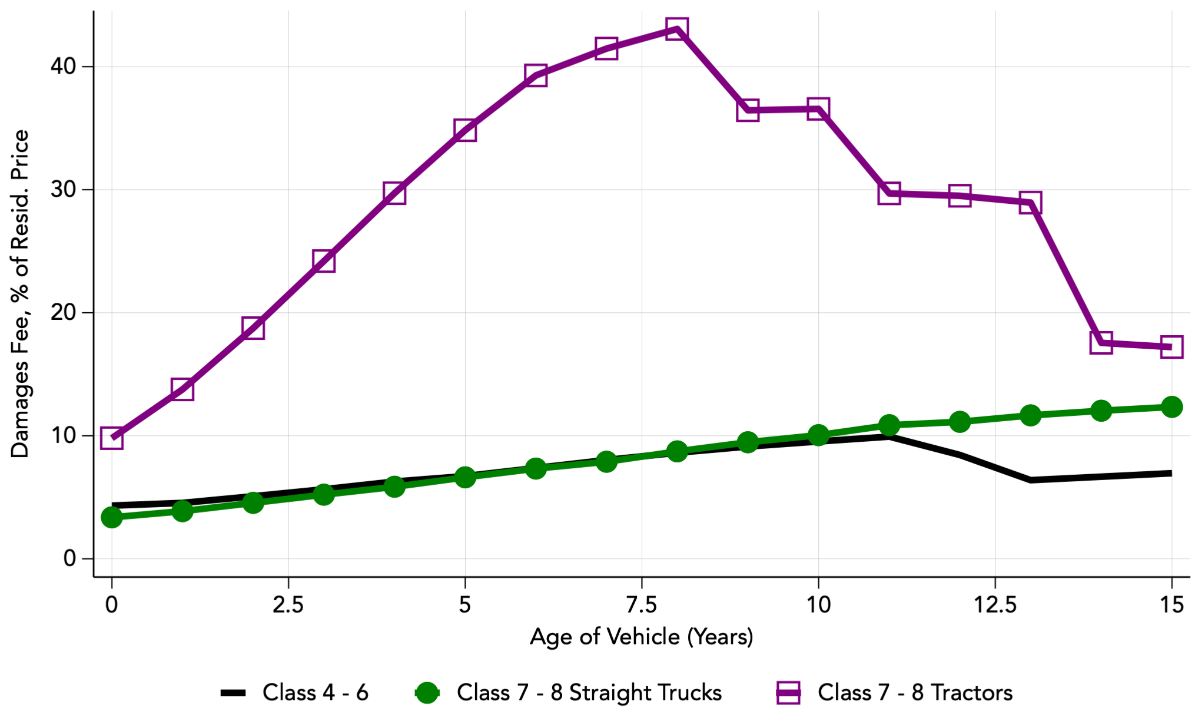
Note: The figure above uses damages calculated for new MY2030 Class 4 through 7 Instate trucks and new MY2030 Class 8 Tractors. Vehicle prices are derived from CARB's Total Cost of Ownership document, showing prices for a new MY2030 Class 5 Walk-in Van and a new MY2030 Diesel Sleeper Cab Tractor.

Figure 22: Residual Vehicle Price as Compared to Damages Fee (Low)



Note: This figure was produced using approximate values determined by digitizing Figure 15 in CARB's Draft Advanced Clean Fleets Total Cost of Ownership Discussion Document (California Air Resources Board, 2021). Residual values represent a vehicle's value when the initial purchaser is selling the vehicle to another party.

Figure 23: Damages Fee (Low) as a Percent of Residual Vehicle Price



Note: This figure was produced using approximate values determined by digitizing Figure 15 in CARB's Draft Advanced Clean Fleets Total Cost of Ownership Discussion Document (California Air Resources Board, 2021). Residual values represent a vehicle's value when the initial purchaser is selling the vehicle to another party.

8.3 Quantitative Estimates of Elasticities and Fee Impact

To estimate plausible ranges of the effect of a set of fees on the share of diesel truck miles, we have developed a method that focuses on using measures of substitution in demand across vehicle ages and between fossil-fuel trucks and ZETs. We calibrate our model to estimates of elasticities (the ease with which one type of truck miles is substituted for another) drawn from the literature. We note that this literature is sparse. We experiment with alternative values of the elasticities in order to assess sensitivity, but it remains the case that the underlying parameter estimates are highly uncertain because of a lack of prior research.

Using our model, we consider various fee structures and examine the overall impact on shares. Our demand setting allows analysis of distortionary cost, considering the loss in surplus faced by truck owners when they switch from their current truck (we assumed that is the preferred one in the absence of new fees and subsidies) to one that is incentivized by the new structure. In most cases we will consider a set of fees and subsidies such that no revenue is raised, and no money is spent by truck owners, on aggregate. This means the cost of policy can be summarized with just the surplus measures. For policy that transfers revenue on net to or from the government, the cost of policy to truck owners would be shifted up or down accordingly. Our analysis does not account for any increase in the cost of shipping that might be passed on to consumers. This effectively assumes that the trucking industry bears the burden of the policy entirely.

8.3.1 Methodology

In our analysis, the total number of miles driven is held fixed for each truck category (e.g. "Class 8"). This effectively assumes that the regulation does not change the total amount of transportation services that occurs in the state, nor does it cause a shift between truck classes. This offers the first set of restrictions to help us establish an elasticity matrix to work with for the estimates: within a truck class, reductions in truck miles in one type (e.g., older diesel) of truck are offset exactly by increases in another (e.g., new ZET). This accords well with a setting with aggregate inelasticity in demand for truck miles, or similarly, a setting where subsidies and fees balance out such that the typical cost of freight and other services from trucks (and therefore the overall usage of trucks) is relatively unaffected by the policy.

Policy therefore shifts the composition of trucks being used within a class, not the overall number of truck miles in the state. This simplification reflects the fact that total demand for truck miles in California may be mostly driven by macroeconomic conditions, infrastructure, and policy changes beyond the scope of what we consider here. A fuller model could potentially account for mode shifts and consider the scale of the trucking industry overall.

To build the simplest possible model of ages and fuel types that can deliver core policy insights we consider two ages (0-4 and 5-25-year-old trucks) and two fuel types (diesel versus electricity) summing to four vehicles altogether, within a given truck category (e.g., Class 8). The matrix describing substitution patterns in each category is then 4 x 4, for 16 parameters altogether. The challenge is to populate this matrix with reasonable values.

Standard economic theory requires that substitution matrices be symmetric in the demand derivatives, which reduces the number of free parameters from 16 to 10. Our assumption that VMT is held constant within a category provides another 4 restrictions, leaving 6 free parameters to create a full demand system.

Unfortunately, there is very little research on elasticities across different types and ages of trucks. The approach we take here draws two key elasticities from the limited literature and connects these to the remaining 4 by imposing an intuitive set of patterns on the substitution matrix. We believe this approach can yield qualitative insights about the plausible range of effects of taxes of a given size. At the same time, we note that because so little is known about the underlying demand system from prior research that a full analysis would need to explore a much broader range of possibilities.

The first of the two key elasticities we need to model is the substitutability between new ZETs and new diesel trucks. For this parameter we follow the Slowik et al. (2023) analysis of subsidies under the Inflation Reduction Act of 2023. This particular substitution parameter is also key to their analysis since it determines how many extra new ZETs will be sold given a particular—$40,000 in many cases they consider—lifetime subsidy for each truck. To determine this parameter they rely, in turn, on substitution parameters in the GCAM model (Bond-Lamberty et al. (2022)). We convert the logit share exponent in that model (-8) to an elasticity using baseline shares from EMFAC projections; the logit share model implies an elasticity that is a function of the baseline stock of ZETs. At the state-wide ZET share in 2030 in the EMFAC projection the equivalent elasticity is -4.2 for class 4-7 trucks (that is, for a 1% subsidy the sales of new class 4-7 ZETs would rise 4.2%) and -6.0 for class 8 trucks (a 1% subsidy increases sales 6%). When the baseline ZET share is higher, as it is in 2037 in EMFAC, the logit share model implies lower elasticities: -2.5 and -4.6 for the two class categories.

The second key elasticity needed to model policy impact in this setting is the substitutability between new and used trucks. Among other things new trucks (age 0-4 in our aggregate analysis) are more reliable and interface with more modern systems. This makes them different from, and so less than perfectly substitutable for, older trucks. For this parameter we draw on the literature studying light-duty vehicles, where new and used cars are again quite different in the eyes of many consumers. In that setting, -1 is a central value used for the elasticity of demand for new (relative to used) vehicles (Jacobsen et al. (2021)) and we employ it here. This elasticity says that if the average new vehicle becomes 1% more expensive then sales fall by 1% and the demand shifts into older vehicles. Note that this is much less elastic than the substitution between new diesel and new ZET trucks. The elasticity of -1 suggests that something about each type of business or task is well-suited to *either* a newer or older truck; with this calibration it is relatively hard for price changes to overcome that barrier and cause a switch in age.

Imposing these 2 elasticities leaves 4 more restrictions needed to identify a unique substitution matrix. We do not have strong priors on these values individually, so choose the rest of the matrix such that it gets as close as possible (measured via least squares) to satisfying all of the following intuitive conditions:

1. All cross-price elasticities are positive. That is, any given age and fuel-type vehicle is a substitute for the others.

2. For any given vehicle, cross-price elasticities when only one dimension is changed are twice as large as when both dimensions are changed. For example, if substituting away from an old diesel, the elasticities to a new diesel (same fuel type) or an old electric (same age) are twice as large as the elasticity to a new electric. This amounts to 8 equations, over-identifying the matrix and allowing us to make the least squares fit.

After constructing the matrix of demand elasticities the analysis of impacts is relatively straightforward in the central, linear, version of our analysis: any system of fees and subsidies corresponds to a set of price changes relative to the status quo. Matrix multiplication of the demand derivatives and price changes leads to a new set of demands. We also consider a non-linear version of the demand model with curvature in demand (as prices get high demand approaches zero ever more slowly, never actually reaching zero) based on the Almost Ideal Demand System in Deaton and Muellbauer (1980); for the fees we examine the effects are similar to the linear system and so we mostly rely on the simpler model. Some differences appear depending on overall revenue constraints and are discussed below.

Our focus on demand, and how it responds to fees, reflects a "partial equilibrium" in the sense that cost changes created by the annual fee policy feed directly through to demand without being influenced by the supply side of the truck market. This assumption may be most reasonable in a world where a much larger used truck market exists outside California, as we believe is the case. Changes in truck demand in California are then easily absorbed elsewhere in the country such that the capital values of trucks remain approximately constant. If instead the California market were closed we would expect both a demand and supply response.[14] A full equilibrium model

[14] As an example consider a fee levied on 10 year old trucks in a world where the California truck market is closed off from the rest of the country. If there is no way for these trucks to leave California then their value might drop sharply but most of them would continue to be operated: a cheaper price to buy a 10-year old truck (a supply adjustment) would compensate for the fee.

would be more important in that case, such that the supply side could absorb some of the fees and mute the price signal passed through to demand. The simple partial equilibrium we propose here seems like the most practical starting point.

Another key caveat to the analysis here is that it ignores the age structure of the fleet: clearly, there is a dependency over time in the sense that greater sales of ZETs now allow more switching to used ZETs later. Asset values in the truck market will adjust to reflect the long-lived nature of the capital, influencing both sales and retention rates. A dynamic analysis, considering changes and expectations over time, would be needed to explore this and a range of other similar effects.

Finally, getting from changes in the number of miles driven, as modeled here, to changes in registrations, the quantity most directly tracked in EMFAC, involves applying typical annual mileage patterns. Because newer trucks typically produce more miles per year (due to greater reliability and higher capital values) our calculation implies that one newer truck may be replacing somewhat more than one older truck. A more complex model could allow the number of miles conditional on age to change as substitution occurs.

8.3.2 Data for baseline no-change case

We focus our attention on a projection of the part of the truck market not subject to ACF regulation in 2030, according to guidance from CARB staff. We take the "no change" projection of truck counts, annual mileage, and emissions from CARB's EMFAC model from 2021. Note that these projections already take into account planned federal policy changes that will reduce emissions rates (such as EPA Phase 3 emission limits). EMFAC does not assume the imposition of any regulation finalized after March 2021, which includes the federal Clean Trucks Plan, and the Heavy-Duty Inspection and Maintenance Program. Both of these regulations aim to reduce heavy-duty NO_x emissions significantly. On the other hand, the Heavy-Duty Omnibus Rule which reduces NO_x emissions is incorporated into the model. EMFAC's baseline assumptions also include the Advanced Clean Trucks ruling.

8.4 Impact of Fee and Subsidy Systems

We group trucks into the general categories Class 4 through 7 and Class 8 and begin with 2030 projections of the non-ACF regulated fleet from the 2021 EMFAC model. Elasticities are specified as above.[15] Table 4 shows VMT and damages for 2030, in non-ACF fleets, in the absence of a policy change. Using the low estimate of damages there is about $2.1 billion in annual pollution damages from trucks in non-ACF fleets. At high estimates of damages this rises to $5.1 billion.

[15]We use the baseline state-wide ZET share (including both ACF and non-ACF fleets) to derive the substitution elasticity from the logit share parameter. This approach reflects the general penetration of ZET trucks into the

Table 4: 2030 Non-ACF Fleet and Damages, No Policy Change

	Diesel VMT (million miles)	*ZET VMT (million miles)*	*Damage, low (million USD)*	*Damage, high (million USD)*
Class 4-7	2,053	0	377	938
Class 8	4,655	0	1,695	4,140
All	6,708	0	2,072	5,077

We consider 4 possible fee and subsidy systems in Table 5 below. The first scenario in Table 5 is a revenue-neutral system of fees and subsidies chosen so that diesel miles fall by 6.3%. This level of stringency is chosen to match a command-and-control scenario, CARB Scenario B, considered below.[16] The VMT changes for the Class 4-7 group and the Class 8 group are targeted separately in order to match the CARB Scenario for both. The second scenario is chosen to produce a 16% reduction in diesel miles. This is calibrated to match a more aggressive CARB plan, which we refer to as CARB Scenario A. The last two scenarios correspond to fees calibrated to pollution damages assuming the low or high damage estimates, respectively.

We first discuss the most modest policy, associated with CARB Scenario B. At the elasticities we compute above, the fee needed for the 6.3% change works out to 0.7 cents per mile on diesel VMT combined with a subsidy of 10.7 cents a mile for ZETs.[17] If pollution damages are at the lower level we estimate above, then this policy saves $130 million in damages in 2030. If damages are at the higher level per ton of pollution, then the policy saves $318 million in damages. We measure policy cost (in the fourth column) as the change in surplus under the demand curves for each vehicle type. Since the policy is revenue neutral, no money is transferred between the government and truck fleets in aggregate, so the only costs are the "distortionary" costs borne by firms that move from their most-preferred truck type into another as a result of the financial incentive. Following the standard economic framework, a firm that just barely preferred a diesel before the system of fees and subsidies bears almost no distortionary cost from their switch to

state-wide new truck marketplace serving both ACF and non-ACF fleets.

[16]In that scenario diesel vehicle counts fall 5.5%, but when we convert to VMT the change is somewhat larger. The exact share of ZET VMT depends on how miles are re-weighted in the conversion process; here we hold total VMT in the non-ACF fleet, and also the ratio of VMT between newer and older trucks, fixed. Since the ZETs are newer than the diesels they replace they accumulate a somewhat larger fraction of miles. The opposite is true for CARB Scenario A, where newer diesels are also getting retired and re-weighted VMT changes end up somewhat smaller than the changes in vehicle counts.

[17]At low ZET penetration rates, a revenue-neutral policy will feature a relatively low fee combined with a relatively generous subsidy. The key incentive comes from the difference between the two, which tilts operator decisions towards ZETs.

a ZET in response to the system (since they were almost indifferent to start with). Firms that are farther from indifferent before the policy is put into place bear more cost from making the switch: there is a triangle of distortionary cost the farther the system is moved from its original state. Total distortionary cost after this system of fees and subsidies is $33 million.

The second scenario in Table 5 repeats the analysis, but now for a much more ambitious target of 16% of miles moved to ZETs. To maintain revenue-neutrality the ZET subsidy does not increase as much as the diesel fee (the subsidy is now paid to 16% of miles instead of 6.3%, so more revenue is required). The reduced pollution damages scale up proportionally with the scale up in ZETs. The distortionary costs scale up much more than proportionally, rising approximately in the square of the change in ZET share. This is because truck use cases that were much farther from being indifferent between diesel and ZET result in more distortionary cost when the switch is made. This is a standard prediction of economic theory which is encoded into our model—with a market based instrument, the marginal cost of inducing behavior change rises in quantity.

The third scenario in Table 5 sets the fee and subsidy structure such that the difference between the fee and the subsidy exactly equals the low estimate of damages. This is the economically efficient solution because pollution is now fully priced. In this case the difference between the fee and subsidy is 32.7 cents, which is equal to the pollution damages of the average diesel truck. Note that a system that provides zero subsidy to ZETs and a 32.7 cent fee on diesel miles would produce the same pollution gain in our framework: because the total number of truck miles in California is fixed in the model, the change in truck types is a function only of the relative price change. To the extent a fee-only system would encourage firms to switch to rail freight or improve the efficiency with which trucks provide their services (these effects are outside the present model) a fee-only system would encourage more of these improvements than a combination of fees and subsidies.

When comparing the second and third scenarios in the table (CARB Scenario A and fees equal to low damage estimates) the overall reduction in diesel VMT is about the same (16% and 17.5%), but the third scenario leads to more reductions in Class 8 relative to Classes 4-7. Two competing effects enter in the third scenario when setting fees equal to damages: first, damages are much higher for Class 8 vehicles and so the fees are much higher. At the same time, the elasticity to ZETs is lower for Class 8. The effects partly offset, with the greater damages being the more important factor and leading to much sharper shifts toward Class 8 ZETs in the fee case.

Finally, the fourth scenario uses the high estimate of pollution damages to set the difference between fee and subsidy. This is a very strong policy, which means that the projected effects are much farther from the starting point and therefore also more uncertain.

Using the model to consider a continuum of possible fees, between the individual scenarios above, we can summarize the fraction of diesel vehicles converted to ZET as a function of the fee

Table 5: 2030 Non-ACF Fleet, Changes with Fees and Subsidies

	% change in VMT		Damage reduction estimate		Market surplus cost ($million)	Average fee/mile	
	Diesel	ZET	Low ($million)	High ($million)		Diesel (cents)	ZET (cents)
Diesel VMT is reduced 6.3%							
Class 4-7	-5.7%	–	22	54	10	0.7	-11.4
Class 8	-6.5%	–	108	264	23	0.7	-10.4
All	-6.3%	–	130	318	33	0.7	-10.7
Diesel VMT is reduced 16%							
Class 4-7	-22.8%	–	87	216	157	11.0	-37.0
Class 8	-13.0%	–	214	525	92	2.9	-19.3
All	-16.0%	–	301	740	250	5.2	-27.0
Fee differences equal to low damage estimate							
Class 4-7	-8.7%	–	33	82	23	1.6	-16.7
Class 8	-21.4%	–	353	863	250	7.9	-28.8
All	-17.5%	–	386	946	273	5.8	-26.9
Fee differences equal to high damage estimate							
Class 4-7	-21.8%	–	82	204	141	10.0	-35.6
Class 8	-52.8%	–	863	2114	1509	48.7	-43.4
All	-43.3%	–	946	2319	1650	32.4	-42.2

level. This is shown in Figures 24 and 25. The rate of switching between diesel and ZET depends on the elasticities as discussed above, and on the overall strength of the incentive as measured by the difference between fees and subsidies. The vertical axis in the figures displays this as a function of the low estimate of damages. A value of 1.0 on the vertical axis represents an average difference between diesel and ZET fees of 32.7 cents per mile. The dashed vertical lines show VMT conversion from diesel to ZET for the first two policies in Table 5.

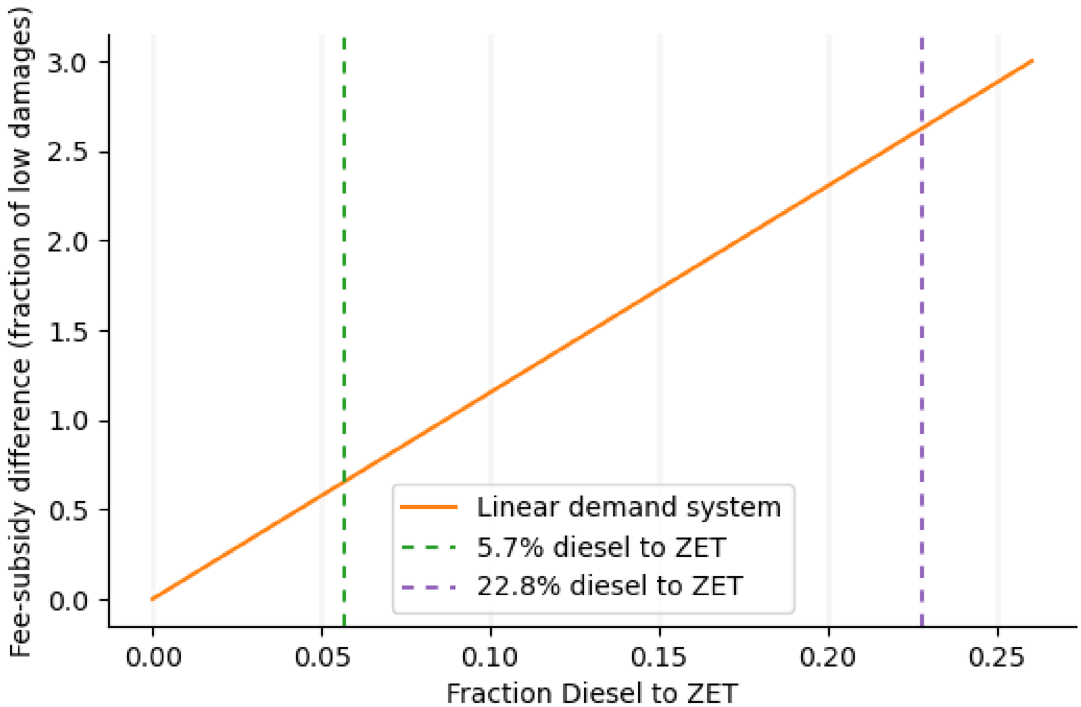


Figure 24: Class 4-7 Fraction ZET in 2030 as Function of Fee Differences

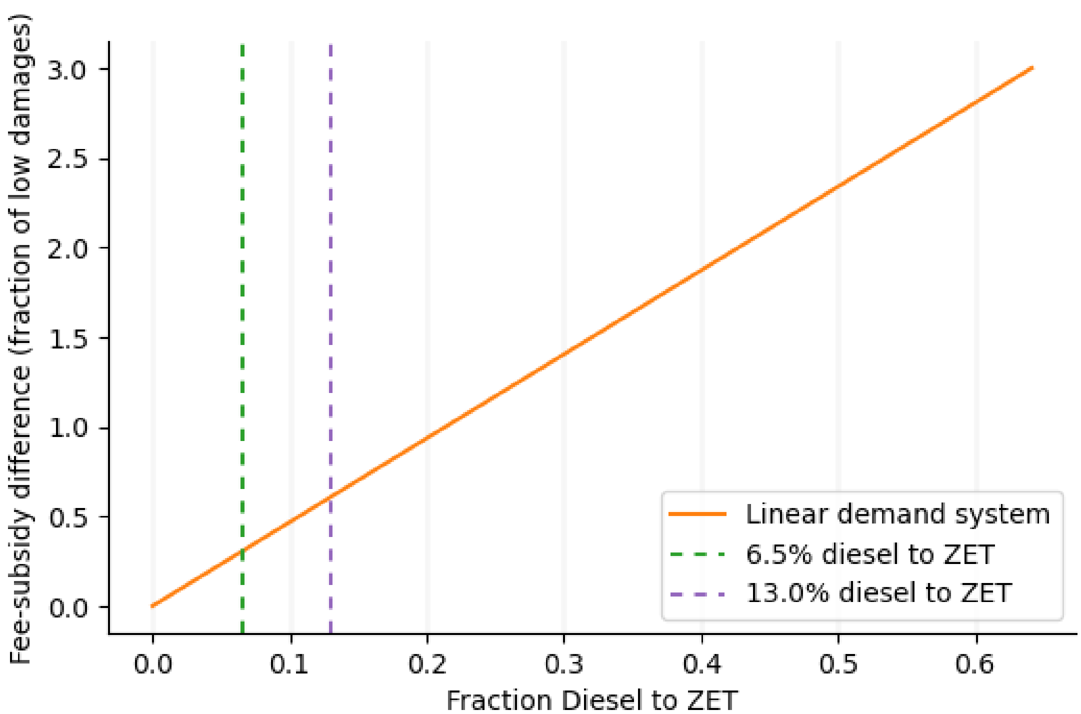


Figure 25: Class 8 Fraction ZET in 2030 as Function of Fee Differences

8.4.1 Alternative Elasticities

The degree of flexibility firms have to choose alternative vehicles is critical to the analysis and so we consider a range of other possible elasticities here.

The elasticity of -1 for new to used substitution, in the analysis above, is particularly conservative in the sense that it allows relatively little movement of VMT away from older diesels in favor of new ZETs; most of the flexibility in the system comes instead in movements of VMT from new diesels to new ZETs. We therefore consider cases with a doubling of this elasticity, from -1 to -2.

Next, we observe that the central calibration in Slowik et al. (2023) (a logit share exponent of -8 that governs the ease of transition to ZETs) implies a very elastic shift to ZETs in the presence of fees or subsidies. This is realistic if much of existing demand for new diesel trucks is already close to the margin, so that only a small nudge is needed to shift that demand to ZET. However, it may also be informative to look at more pessimistic cases, where a bigger wedge exists between diesel and ZET demand. We therefore also follow the Slowik et al. (2023) analysis in considering a smaller (closer to zero) logit exponent of -6 to explore a case where substitution to ZETs is somewhat more difficult.

Table 6: Fraction of Diesel VMT that switches to ZET Under Alternative Elasticities

New-Used Elasticity	New ZET logit share parameter	Fees using low damage estimate			Fees using high damage estimate		
		Class 4-7	Class 8	All	Class 4-7	Class 8	All
2030							
-1	-6	0.07	0.16	0.14	0.17	0.40	0.34
-1	-8	0.09	0.21	0.18	0.22	0.53	0.44
-2	-6	0.09	0.17	0.15	0.22	0.43	0.37
-2	-8	0.10	0.23	0.19	0.26	0.55	0.47
2037							
-1	-6	0.11	0.20	0.17	0.27	0.48	0.42
-1	-8	0.10	0.23	0.19	0.26	0.56	0.47
-2	-6	0.23	0.30	0.28	0.58	0.73	0.69
-2	-8	0.22	0.33	0.30	0.55	0.81	0.73

Notes: The elasticity case used for values presented elsewhere in this section corresponds to a new-used elasticity of -1 and a logit share parameter of -8. Values in columns 3-8 are expressed as fractions of diesel VMT switching to ZET.

The shifts from diesel to ZET introduced over four combinations of these elasticities appear in Table 6. The results in the last six columns show the fraction of diesel VMT that is projected to switch to ZET mileage under alternative assumptions of the underlying demand parameters, for the low and high damage scenarios from Table 5. Results are shown for both 2030 and 2037.

Three key factors drive differences between the estimates for 2030 and 2037:

- As new ZETs make up a larger share of the market the elasticity to ZETs falls (this is an implication of the logit share model we draw on following Slowik et al. (2023)).
- The baseline for calibration (which includes ZETs statewide) now has many more old ZETs in the age 5-25 category. This creates the possibility of switches from used diesel to used ZET that weren't possible in 2030.
- The fees are smaller on both new and old diesels since newer vintages pollute less.

The smaller fees and lower elasticity of new ZETs push in the direction of smaller effects of the policy in 2037 than in 2030. The availability of used ZETs pushes in the direction of greater effects of the policy in 2037. In cases where demand for used vehicles is less elastic (-1 in the first column of the table) the various effects counterbalance each other almost exactly and fees produce roughly the same changes in 2037 as 2030. In cases where the demand for used vehicles is more elastic (-2) the added availability of used ZETs in 2037 dominates and we see much larger changes in 2037 than 2030.

8.5 Impact of Minimal Command and Control Policy

The prior calculations are all for alternative scenarios that use fees, a market based mechanism that has certain efficiency advantages. For comparison, we also estimate the pollution effects and costs of three command and control regulatory scenarios that we refer to as "minimal" options. They are minimal in the sense that the only change being mandated is that diesel vehicles may not be operated past a certain point in their life, trimming the very oldest diesels from the fleet. The useful life limits we consider here are assumed to follow SB1, which protects trucks from retirement mandates until they are (1) 13 years of age or older and have 800,000 or more miles, or (2) 18 years of age or older.

We consider various possibilities for where the miles formerly put on these oldest diesel trucks will go. The rules being considered in this section are minimal since they do not consider any restrictions on truck sales: that is, there is no sense in which a retired diesel must be replaced with a new ZET or even a new vehicle of any type. A national diesel truck market is assumed to supply as many used trucks to California as desired, and in this analysis, operators are free to use that market to fill a gap created by the retirement of vehicles past their useful life, which creates

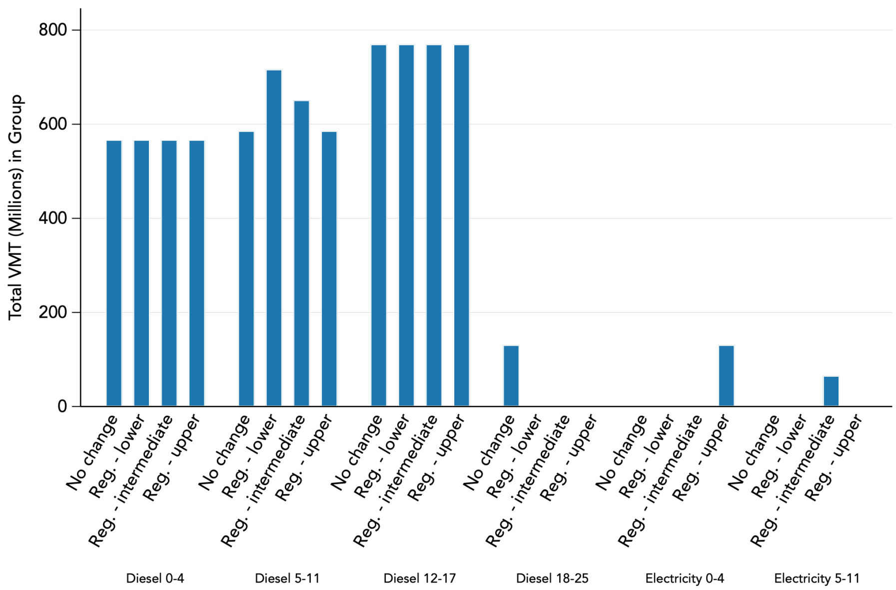


Figure 26: Re-allocation of VMT in Minimal Command-and-Control Example: Class 4-7 Trucks in 2030

what we called the used truck carousel above. In Section 9 below we utilize CARB analysis of alternative command-and-control policies that achieve greater substitution to ZETs.

In order to show the finer-scale changes expected with the minimal command and control policy, we subdivide the "used truck" category (age 5-25 in our cost analysis) into three categories: age 5-11, 12-17, and 18-25. This allows us to display the types of shifts that might occur if the oldest diesels are forced into retirement while middle-aged diesel trucks can still be imported from other states.

Figures 26 through 29 display three scenarios for where the miles currently projected to be driven past the end of useful life will end up. The figures show results for our two class groupings, Classes 4-7 and Class 8, and for years 2030 and 2037.

First, the "lower" estimate assumes that all miles lost in the non-ACF fleet are replaced by adding vehicles and miles in the 5 to 12-year-old diesel category. These trucks would presumably be purchased from the national market or from ACF-regulated fleets in California.

Second, the "intermediate" regulatory counterfactual assumes that lost miles are replaced by 5 to 12-year-old diesels *and* 5 to 12-year-old ZETs in the same ratio that these trucks exist in the California fleet broadly (ACF-regulated and unregulated). For example, if 100 miles are lost, and the current ratio of 5 to 12-year-old diesel to ZET VMT is 3:1, then 75 miles would be added to the 5 to 12-year-old diesel group, and 25 miles would be added to the 5 to 12-year-old ZET group. In 2030, very few 5 to 12-year-old ZETs exist, so the "lower" and "intermediate" scenarios have similar effects with most lost diesel miles replaced by more diesel miles emitted by slightly

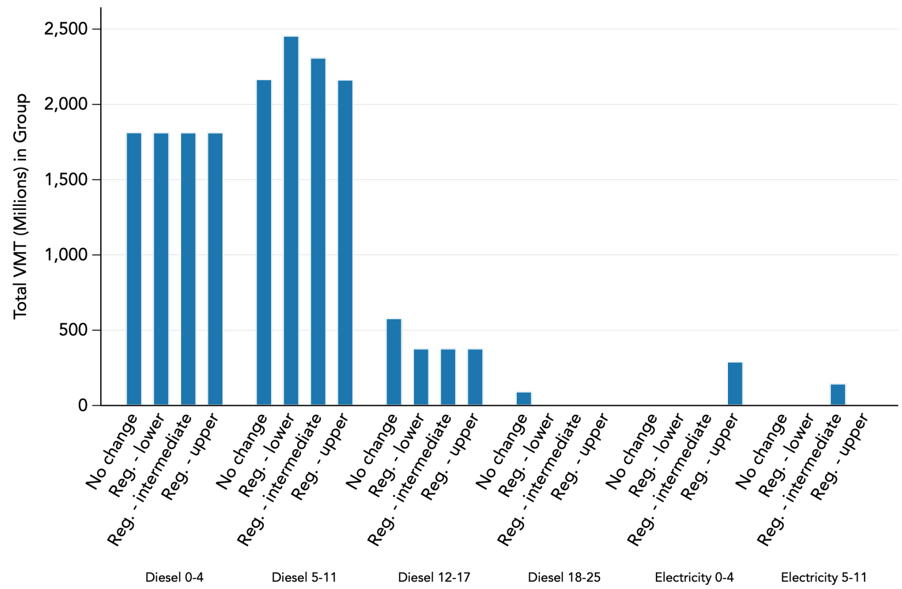


Figure 27: Re-allocation of VMT in Minimal Command-and-Control Example: Class 8 Trucks in 2030

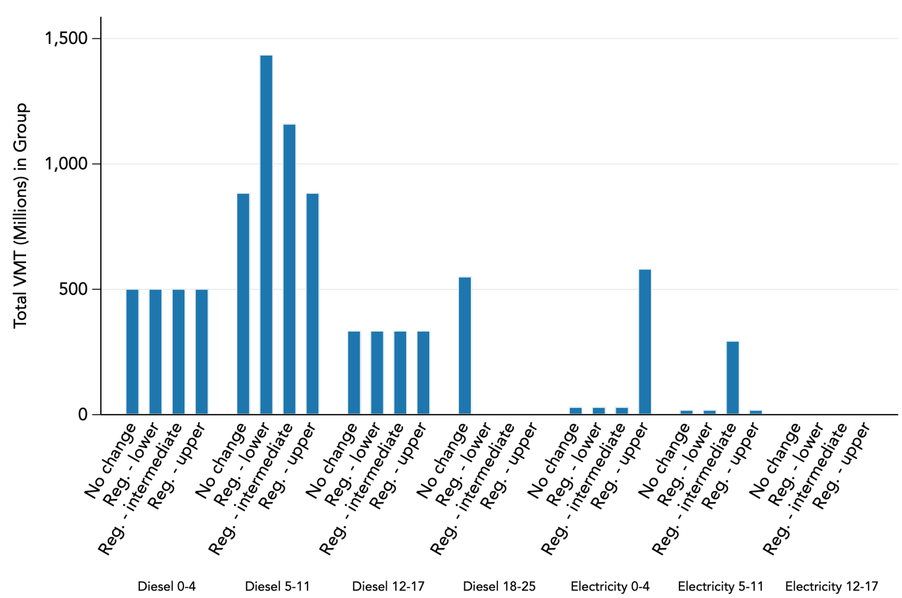


Figure 28: Re-allocation of VMT in Minimal Command-and-Control Example: Class 4-7 Trucks in 2037

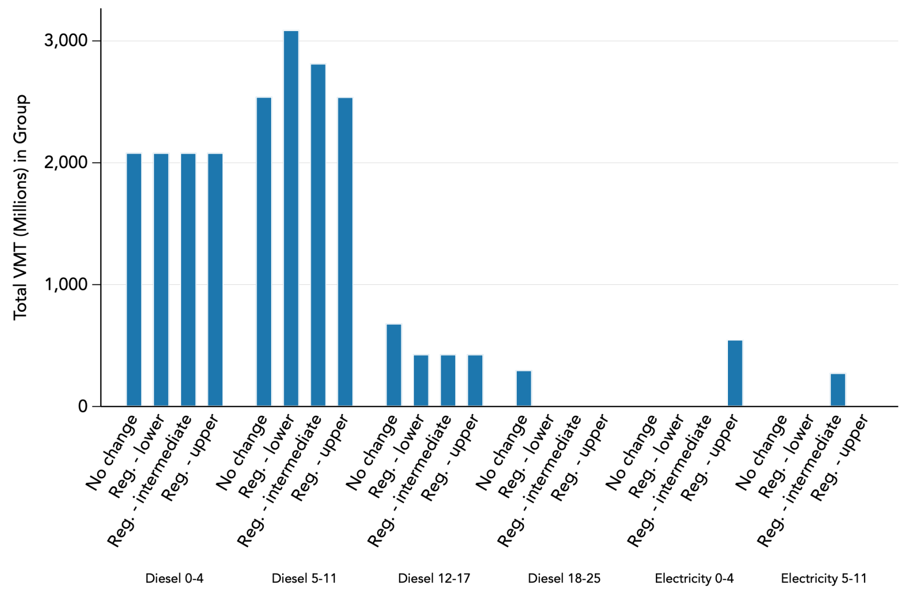


Figure 29: Re-allocation of VMT in Minimal Command-and-Control Example: Class 8 Trucks in 2037

younger trucks. As the fleet electrifies, the ratio becomes more favorable to ZETs as shown in Figures 28 and 29 showing the scenarios for 2037.

Finally, in the "upper" regulatory counterfactual, all lost VMT are replaced by VMT emitted by the young ZET group (0 to 4-year-old ZETs). This leads to the greatest ZET share possible while still in the minimal regulation world where other, middle-aged, diesels continue to be replaced with trucks coming from other states or the ACF-regulated fleet. This represents an upper bound on how much a policy that forces retirement at useful life could have, not a forecast of the actual effect. This magnitude of a response would only occur if policy somehow forced all retired diesel trucks to be replaced by new ZETs. We are not aware of a policy mechanism that would achieve that goal.

8.6 Summary of Fleet Composition Effects

The discussion above highlights individual policies; we now turn to a summary of all the policies we examine in the context of our four aggregate categories for truck VMT: new and old diesel vehicles, and new and old ZETs. Figures 30 and 31 shows how each of the policies moves this distribution in different ways. The two panels in each figure contrast the changes in 2030, when very few ZETs are available, and 2037 when many more ZETs are available. In 2037 there are larger numbers of used ZETs in the California market (coming from ACF-regulated fleets), allowing the possibility for new types of substitution in the non-ACF fleet.

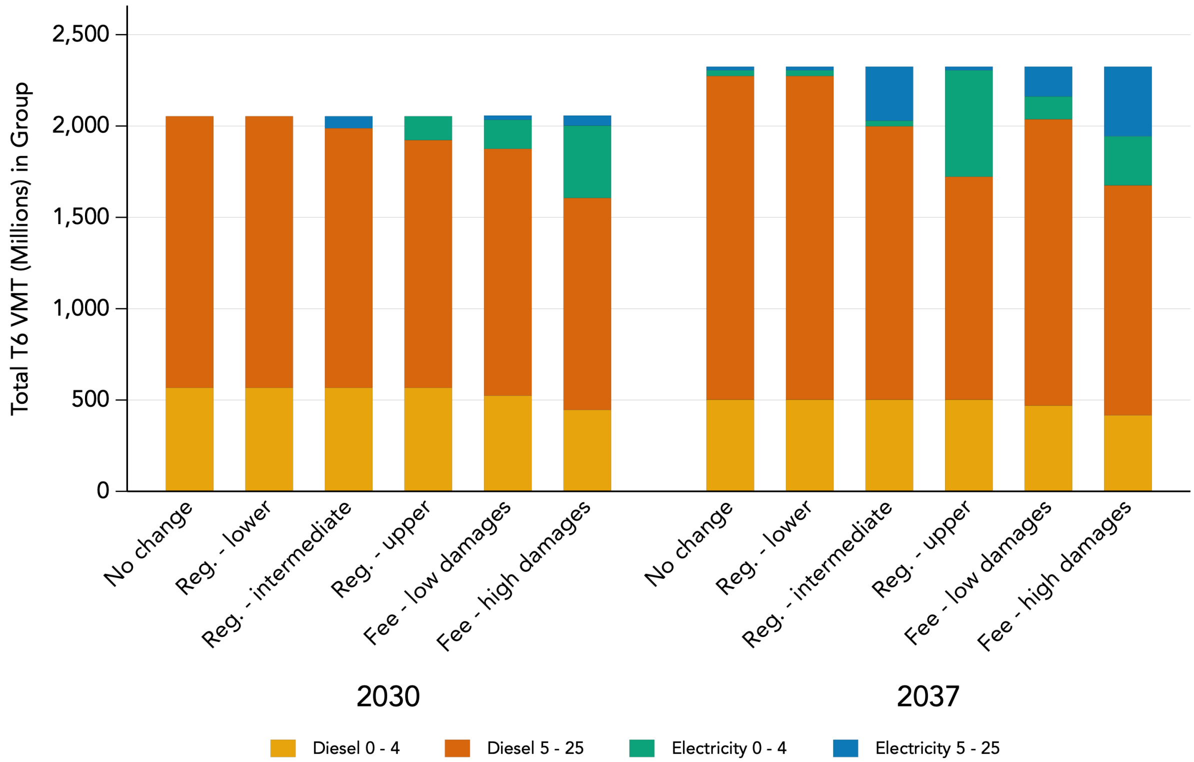


Figure 30: Re-allocation of VMT by Policy Type: Class 4-7

The first bar represents the no change baseline. The next three, labeled "Reg" are the minimal command-and-control cases with the three different assumptions about substitutions patterns. The last two bars are for fees, based on either low or high damage estimates.

The minimal command-and control cases produce relatively small changes in the distribution of VMT in 2030, coming directly from the fact that only a small fraction of miles are currently being driven past the end of useful life. Regulation around the useful life then has little effect if not paired with rules limiting the purchase of diesel vehicles much more broadly. In 2037 this minimal policy has a much larger effect, rivaling that of the fee-based rules. This is because the no-policy projections of 2037 from EMFAC indicate a large fraction of miles being driven on diesel trucks past the end of useful life; moving these miles to ZETs therefore has a much bigger impact. Recall, however, that the "Reg.-upper" scenario relates to a policy combination that we are not confident is feasible. It requires a policy mechanism that forces all retired vehicles to be replaced by new ZETs. It is difficult to imagine how policy would create this outcome, and we prefer to view this as an upper bound of effectiveness from regulation, rather than a forecast of a plausible effect size.

Several interesting patterns emerge in the fee-based policies. First, note that while the fees are

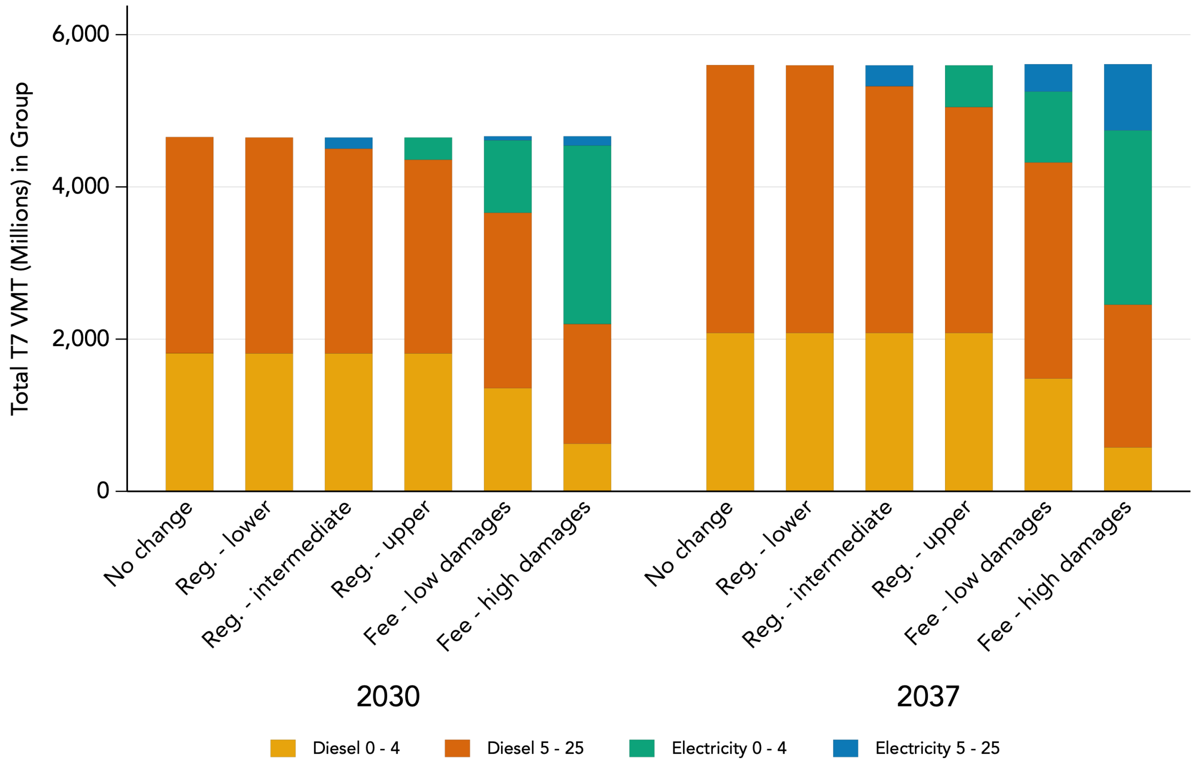


Figure 31: Re-allocation of VMT by Policy Type: Class 8

larger for older (relative to newer) diesel trucks, the fee impacts in 2030 are much more important for newer trucks. This traces directly to our elasticity assumptions: it is difficult to get companies to switch from older to newer trucks or vice versa, and so when there are almost no used ZETs available there aren't many options available for used diesels. New diesels, on the other hand, have excellent substitution possibilities (determined by the calibration of the logit share term) in new ZETs, and so this is the biggest impact of the fee system. In 2037 this changes: the elasticity in the new ZET market is falling as the state-wide share rises (capturing the idea that many of the firms and use cases that can switch easily have already done so) and at the same time used ZETs enter the market. The used-diesel to used-ZET substitution pathway therefore becomes much more important in 2037.

Another feature that emerges is that switches to ZETs as a result of fees linked to damages is as, or more, common for Class 8 vehicles as it is for the smaller Class 4-7 vehicles. Most directly, this is because damages are a larger fraction of overall cost per mile for Class 8, so policy set to the level of damages acts as a bigger incentive to switch away from diesel vehicles in this class. The fees we consider are roughly double for class 8 relative to classes 4-7. We also do not model technology constraints here except to the extent they are implicit in base quantities; if vehicle availability proves difficult then the effects of a fee system would likely concentrate within the diesel market instead, removing older diesels in favor of newer, cleaner ones.

Finally, Figures 32 and 33 map the VMT composition changes above into pollution damages. Reductions in damage come both from switches from older to newer diesels as well as from switches into ZETs.

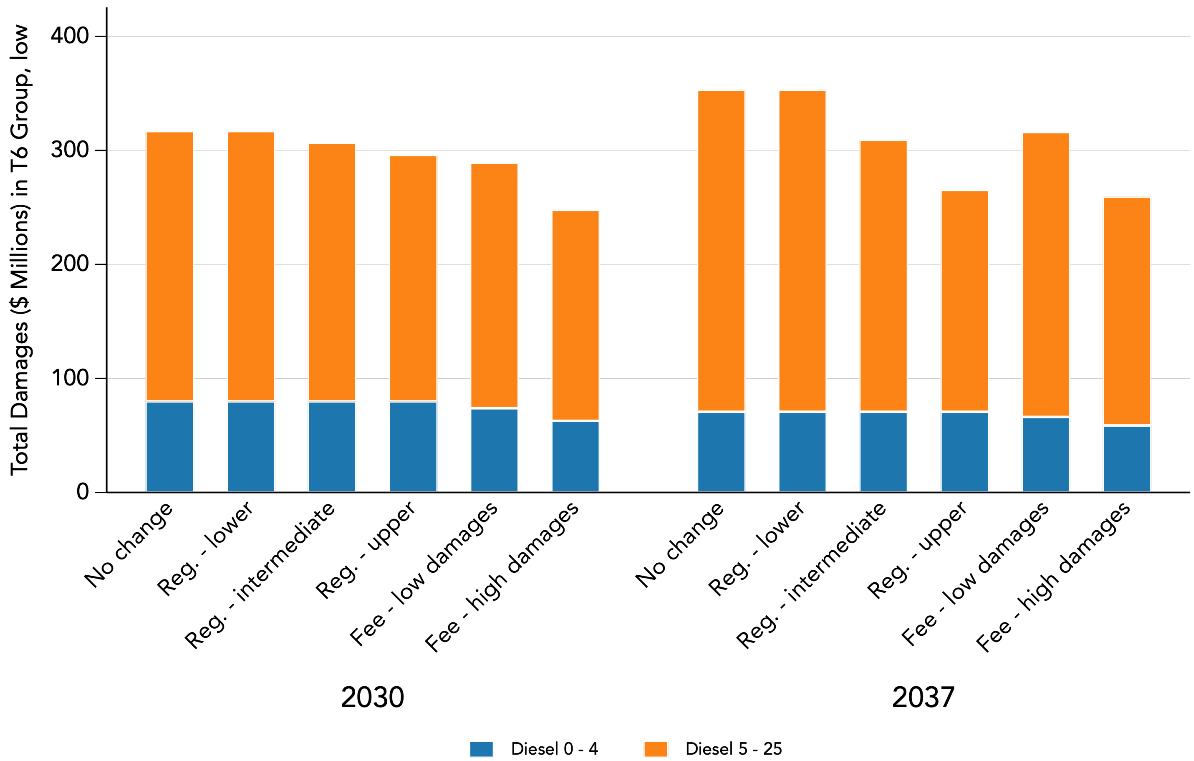


Figure 32: Comparing pollution damages among policy types: Class 4-7

9 Cost Comparisons Between Command and Control and Fee-Based Policy

As described in the qualitative analyses above, one of the key disadvantages of command-and-control regulation is the loss in economic efficiency resulting from heterogeneity among regulated firms. Where fee-based policies allow each firm to decide which truck type is most cost-effective, command-based policy can end up mandating costly switches on some truck owners while also missing some very "cheap" switches (owners who would need only a very small financial incentive to switch, but might not be required to switch under the command policy).

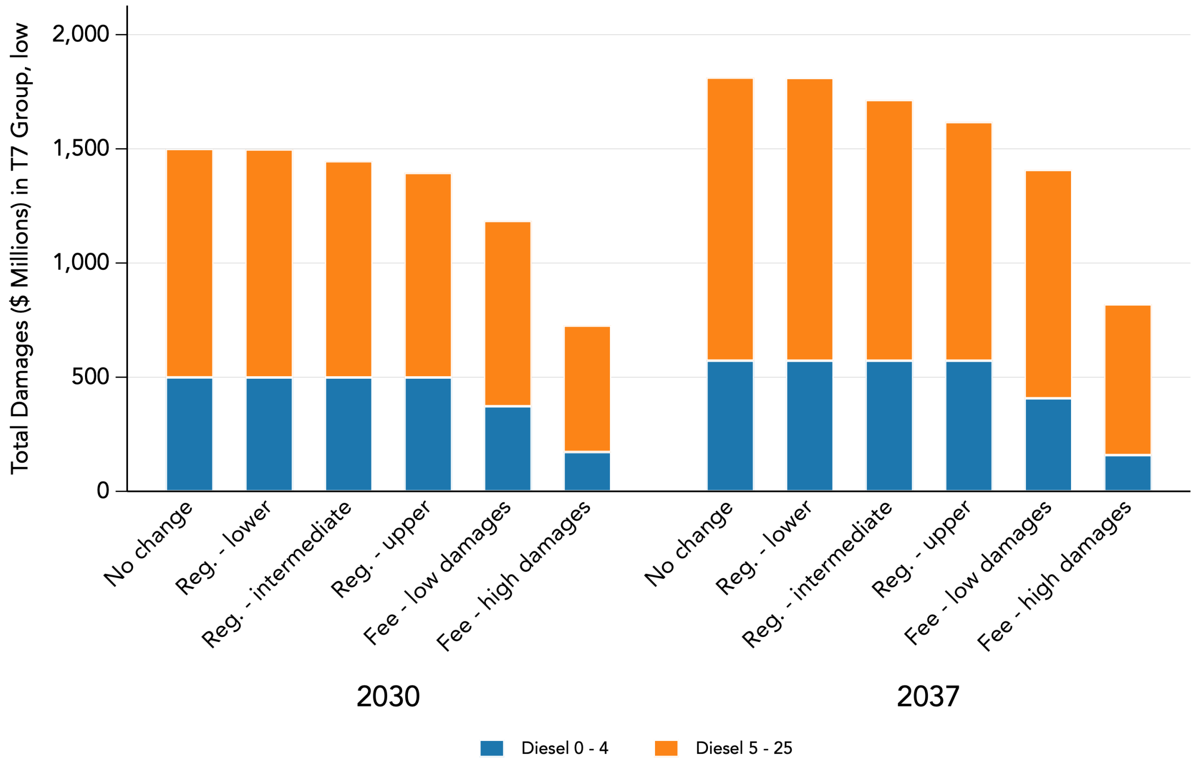


Figure 33: Comparing pollution damages among policy types: Class 8

Here we use a modified version of the quantitative model in Section 8.3 to consider distortionary costs under command-and-control rules. This analysis relies more heavily on functional forms and other assumptions but may be useful to provide an indication of the potential costs of command-and-control policies relative to fee-based systems.

9.1 Methodology

The distortionary cost of a fee-based system is equal to the surplus given up by all switchers up to the level of the fee. For example, if a particular firm values a used diesel by $100 more than a ZET alternative, but decides to give up the diesel in response to a $500 subsidy on ZETs, then there is an efficiency loss (in the market for trucks) in the amount of $100. This is the distortionary cost measured in the tables above. Note that the subsidy of $500 itself is just a transfer: the government spends $500 and the subsidy recipient gets $500; what we are concerned with in this analysis is the distortion of $100 reflecting the fact that the incentivized, and chosen, ZET is no longer quite as well matched to the firm's needs as the original diesel would have been.

Now consider a command-and-control policy. Suppose the firm above, that would have responded to the fee, happens to have a diesel that is not yet subject to the command regulation and so it doesn't switch to a ZET. Now consider a different company that prefers the diesel by $700 but is obligated to switch by the command-and-control policy. It would not do anything in response to a $500 subsidy offered on ZETs. But, since the diesel it has is subject to the command-and-control rules it must switch and incurs a distortionary cost of $700.

One approximation to the distortionary costs of a command-and-control system is to assign switches (e.g. from diesel to ZET) at random under the demand curve. In the context here, consider a group of firms with trucks of varying ages and suppose the ages are distributed approximately randomly, just depending on when the firm first needed a truck. Firms that happen to have a truck approaching a useful-life cutoff when the regulation goes into place, for example, will be immediately subject to the command-and-control rule and need to switch to a ZET. Some of the firms that will fall under this command-and control rule prefer the diesel by only a small amount, for example the $100 preference above. But others, also subject to the rule, might prefer the diesel by a large amount and so incur much larger distortionary costs. Converting a certain fraction of diesel VMT to ZET VMT approximately at random will then be much more costly than converting the same fraction to ZET using a subsidy where it is only the firms that were quite close to switching already that will be incentivized to switch.

With a linear demand system the assumption of random ages and therefore random compliance requirements technically amounts to calculating the following:

- For a fee-based system, distortionary costs are equal to the area of a triangle with height equal to the fee and base equal to the quantity reduction in diesel.
- For the command-and-control policy costs are equal to the area of a rectangle with width again equal to the quantity reduction in diesel. The height of the rectangle is equal to one-half the difference between the vertical intercept of the demand curve and the baseline cost of diesel VMT. This is a measure of the average economic surplus collected by diesel owners before the command policy is applied.

This method of achieving a cost comparison between command and control and market based mechanisms is grounded in economic theory, but it is only an approximation. The command and control policy will not literally randomly assign retirement across the fleet, and so the value of the vehicles forced to retire might be higher or lower than what we calibrate. Also, the exact values are sensitive to our assumption of a linear demand curve and of course to the slope of that curve that we have calibrated from the literature. Despite these caveats, however, we believe the cost comparisons do offer one way to understand the potential magnitude of the efficiency gains from market based policies.

9.2 Results

Table 7 first shows the pollution damage reductions and the approximation of distortionary costs associated with the three minimal command-based policies in Section 8 above. Costs here are sharply higher than with a fee-based policy. For example with the intermediate assumption on substitution, only 3% of diesel VMT moves to ZET. Distortionary costs, however are 10 times greater than for the first fee-based policy in Table 5, which moves 6.3% of miles to ZET. As policy goals get very small this ratio of costs will tend to infinity.[18] For large policy goals the costs come back together. In the limit, for a 100% ZET conversion, the fee-based policy and the command and control regulation have exactly the same distortionary cost. This is shown in Appendix D.

In the next two cases we consider alternative fleet compositions in 2030 supplied by CARB, corresponding to "Scenario B" and "Scenario A" that we discussed above. We calibrate the fees for Class 4-7 and Class 8 trucks in Table 5 such that the same number of VMT convert to ZET in those cases as in the last two panels of Table 7. For the 6.3% average conversion to ZET the command-and-control cost is approximately 14 times higher. For the 16.0% conversion to ZET the command-and-control policy is 6 times more costly.

There are a number of important caveats to estimates of costs for command-and-control policy to do with specific aspects of policy design. Suppose for example that truck buyers with very low VMT have especially high costs of switching to ZET. If the command-and-control rule exempted low-VMT trucks, then some of the high-cost switches would be avoided and the average mandated switcher would have a lower-than-average cost of switching. In general, correctly designed carve-outs and flexibilities in a command-and-control rule have the potential to move the emphasis of the rule toward lower-cost switchers.

On the other hand, it is also possible for costs to be higher than average; that is, the command-and-control rule could inadvertently end up targeting trucks that happen to be unusually far from charging stations or otherwise have high costs of switching, and so lead to cost outcomes that would be higher than those if selecting diesel trucks to switch to ZET at random. It is generally quite difficult to target only low-cost switchers with command and control regulation, especially in a market as heterogeneous as this one. Price incentives have the advantage of exclusively targeting those trucks that will be the lowest-cost switchers. Again, while our exact calculations hinge on parameter assumptions and rely on depicting command and control regulation as forc-

[18]To see why, consider a very small $10 subsidy offer that convinces just one truck-buyer in the whole state to switch to ZET. This buyer was presumably almost exactly indifferent between keeping their old diesel and buying a ZET, so that even this tiny subsidy offer was enough to convince them to stay at the dealership and make the purchase. Now consider a command and control regulation that picks a single diesel truck operator at random and makes them to switch to a ZET. Both policies get exactly one more ZET in California. But in expectation the command and control regulation will fall on the average diesel buyer in California, who may have a substantial preference for a diesel over a ZET. The command policy therefore creates a many-times larger distortion.

ing retirements of vehicles with an average value, the qualitative patterns about the efficiency differences across these policies are robust predictions of economic theory, and a wide range of results from other contexts have found that the efficiency gains from market based tools are large.

Table 7: 2030 Non-ACF Fleet, Changes with Command and Control Policy

	% change in VMT		Damage reduction estimate		Market
	Diesel	ZET	Low ($million)	High ($million)	surplus cost ($million)
Intermediate					
Class 4-7	-3.0%	–	12.2	30.2	100.8
Class 8	-2.9%	–	57.8	139.7	234.2
All	-3.0%	–	70.1	169.9	335.0
Upper					
Class 4-7	-6.2%	–	25.2	62.3	211.2
Class 8	-6.1%	–	118.8	287.1	398.4
All	-6.1%	–	144.1	349.5	609.6
CARB scenario B (in progress CARB regulations as limited by useful life)					
Class 4-7	-5.7%	–	19.6	49.4	166.2
Class 8	-6.5%	–	89.1	221.7	308.0
All	-6.3%	–	108.7	271.2	474.2
CARB scenario A (potential reductions with no useful life limits)					
Class 4-7	-22.8%	–	94.6	233.2	811.5
Class 8	-13.0%	–	240.2	582.8	798.8
All	-16.0%	–	334.8	815.9	1610.3

Notes: Costs are computed assuming that the policy falls on diesel trucks with the average willingness to pay for diesel relative to ZET under a linear demand curve.

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A Additional information on DMV data

In the data cleaning process for the DMV registration data, the following steps are taken:

1. Trucks (identified by anonymized Vehicle Identification Numbers, or VINs) linked to multiple model years are dropped. This step drops 1,334 VINs (0.2%).
2. Trucks linked to multiple BAR ranks are assigned the most current BAR rank (e.g., if a VIN is associated with T6 in calendar year 2018, but T7 in calendar year 2019, all years will be imputed to T7). This step corrects 3,678 observations (0.1%), where each observation is identified by calendar year and VIN.
3. Vehicle age[19] is forced to be the difference between calendar year and model year. This step corrects 2,237 (.08%) observations.
4. Small further restrictions are imposed for graph creation. Graph descriptions and footnotes provide more information. One common manipulation was to replace ages less than -1 with -1, which replaces only 13 values.

B Details and alternative assumptions for damage estimation

The marginal damage values used throughout this report are calculated using several key sources of data. This sections describes the datasets, assumptions, and methods used to make these calculations.

First, we retrieve data on the benefits of reducing PM2.5 and PM2.5 precursors from the US EPA's Benefits Mapping and Analysis Program (BenMAP).[20] These data includes estimates of the average avoided human health impacts and monetized benefits related to emissions of $PM_{2.5}$ and $PM_{2.5}$ precursors from 21 sectors by state or region. For the purpose of this report, we use the benefit per-ton (BPT) measures associated with the internal combustion engine sector. The data were prepared by EPA using the following three-step calculation procedure:

1. Predict annual average ambient pollutant concentrations resulting from VOC or NO_x from each emissions sector using source apportionment photochemical modeling

[19] The DMV stores vehicle age, which is different from engine age. Engine age is exactly one year older, and is used in policy such as the Truck and Bus Rule.

[20] The raw data can be retrieved directly from EPA here:https://www.epa.gov/benmap/estimating-benefit-ton-reducing-directly-emitted-pm25-pm25-precursors-and-ozone-precursors

2. Estimate the associated health impacts and the economic value of these impacts using the Environmental Benefits Mapping and Analysis Program-Community Edition (BenMAP-CE v1.5)

3. Divide the $PM_{2.5}$ related health impacts and their economic value by the level of associated precursor emissions. For example, primary $PM_{2.5}$ benefits are divided by direct $PM_{2.5}$ emissions, sulfate benefits are divided by SO_2 emissions, etc.

Health impacts and their economic value are estimated by EPA by modeling changes in population-level exposure and using a concentration-response relationship derived from the epidemiological literature. This allows EPA to estimate the number of PM2.5 related total deaths and illnesses during 2025, 2030, 2035, and 2040. For the purpose of this paper, we use their estimates for 2030. In estimating economic impacts, avoided premature deaths account for 98% of monetized PM and Ozone related benefits. EPA uses a Value of Statistical Life (VSL) equal to $6.3 million in 2000 USD. They adjust this value for inflation and and income growth.[21]

Second, we retrieve data on the benefits of reducing CO_2, CH_4, and N_2O from the US Government's Interagency Working Group (IWG) on the Social Cost of Greenhouse Gases (SC-GHG). The IWG released a Technical Support Document in 2021 outlining the social costs of Carbon, Methane, and Nitrous Oxide.

Finally, we retrieve data on the benefits of reducing Carbon Monoxide from Matthews and Lave (2000).

Table 8: Damage Values

	Damages ($1,000/Ton)		
Pollutant	Low	High	Source
NH_3	154.20	320.26	EPA BenMAP
NO_x	68.37	141.26	EPA BenMAP
$PM_{2.5}$	1,047.06	2,167.44	EPA BenMAP
SO_2	134.79	279.29	EPA BenMAP
CO_2	62	187	IWG SC-GHG
CH_4	2	5.2	IWG SC-GHG
N_2O	23	60	IWG SC-GHG
CO	.99	1.94	Matthews & Lave, 2000

[21]Detailed description of these data can be found here: https://www.epa.gov/system/files/documents/2021-10/source-apportionment-tsd-oct-2021_0.pdf

C Existing ZET Programs

This section outlines some existing programs that are in place to lower the cost of ZET adoption. These include a combination of funding for infrastructure, vehicles, operations costs, and fuel. Table 9 outlines some key components of each program.

C.1 National Programs

The Inflation Reduction Act of 2022 invests $369 billion in the American energy system by setting aside funding for modernization of industrial facilities, residential and commercial buildings, and the transportation, electric power, and agricultural sectors of the US economy. The Act invests $1 billion to be used in replacing class 6 and 7 dirty heavy-duty vehicles with zero emissions vehicles, installing zero-emissions vehicle infrastructure, workforce training, and other technical activities.[22] The money is set to be distributed by US EPA between 2022 and 2031 as part of the Clean Heavy-Duty Vehicle Program. Of the total funding, $400 million will be allocated to nonattainment areas.

C.2 California Programs

This section describes several existing ZET programs in California:

Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) This program has been allocated over $1.7 billion by the California Air Resources Board for FY22-23. This program provides vouchers for eligible refuse trucks and drayage trucks as well as public transit fleets and school busses. Purchasers can receive up to $240,000 towards a fuel cell electric truck or $120,000 toward a battery-electric truck. The includes reserved funding for specific vehicle types such as $157 million for class 8 drayage trucks.[23] As of July 2023, $250 million was still available in standard HVIP funding, and $147 million was still available in drayage truck specific funding.

The HVIP program adjusts vouchers based on characteristics of the buyer. For example, a BYD Motors 6F Battery Electric Truck has an incentive amount of $85,000 but this voucher is increased by 15% for public and private fleets with 10 or fewer medium- and heavy-duty vehicles. On the other hand, the voucher is reduced 20% or 50% for private fleets with 101-500 or over 500 medium- and heavy-duty vehicles, respectively.[24]

[22] https://www.energy.gov/sites/default/files/2022-08/8.18%20InflationReductionAct_Factsheet_Final.pdf and https://www.epa.gov/inflation-reduction-act/clean-heavy-duty-vehicle-program

[23] See https://californiahvip.org/about/ and https://californiahvip.org/funding/

[24] https://californiahvip.org/vehicles/byd-6f-cab-forward-truck/

Innovative Small e-Fleet Pilot (ISEF) This program includes a $33 million pilot program to fund HVIP approved vehicles for small trucking fleets and independent owner-operators. This funding can be put towards flexible leases, short term rentals, and truck-as-a-service (TAAS). ISEF eligible customers are able to recieve double the base HVIP voucher.[25] Eligible customers for the ISEF program include California companies and independent owner operators with 20 or fewer vehicles with a GVWR greater than 8,500 pounds and less than $15 million in annual revenue. Additionally privately owned trucking companies and non-profits are eligible. ISEF funding is intended to reduce the cost of new Clas 2b-8 ZETs to a monthly or per-mile cost equivalent to a diesel truck's operating cost. The ISEF voucher level is double the base voucher level of the HVIP program. For example, a Class 3 truck with a $45,000 HVIP voucher would receive $90,000 in under the ISEF program and this voucher can go towards purchase and operation expenses, including the costs of charging infrastructure, insurance, and fuel.

Carl Moyer Memorial Air Quality Standards Attainment Program The Carl Moyer program has encouraged voluntary adoption of clean trucks since 1998 and is implemented jointly by CARB and California's local air districts. As of 2021, the program had allocated about $757 thousand for drayage trucks, $103 million for heavy heavy-duty vehicles,$3 million for medium heavy-duty vehicles, $5 million for light heavy-duty vehicles, and $13 million had been allocated for solid waste/refuse collection vehicles. Additionally $7 million had been allocated to battery charging stations.[26]

Volkswagen Environmental Mitigation Trust The Volkswagen Mitigation Trust was established as part of the settlement between California and Volkswagen in the auto manufacturer's illegal use of defeat devices in diesel vehicles. California received $423 million to be used for projects aimed at reducing NOx emissions caused by VW's illegal actions. $90 million of this funding is available for replacement of Class 8 freight and port drayage trucks with zero-emissions vehicles. Eligible vehicles include engine model years from 1992 to 2012. The maximum incentive cap per vehicle is $200,000.[27] As of January 2023, $14.5 million had been used.

C.3 Out of State Programs

This section describes several programs in use to encourage ZETs outside of California.

[25] See https://californiahvip.org/wp-content/uploads/2023/06/FY22-23-HVIP-ISEF-IM-Appendix-F.pdf

[26] See https://ww2.arb.ca.gov/sites/default/files/2023-02/2021%20Carl%20Moyer%20Program%20Statistics%2002-24-2023.pdf

[27] See https://xappprod.aqmd.gov/vw/ and https://xappprod.aqmd.gov/vw/zero-emission.html

Hawaii – Diesel Replacement Rebate (DRR) Program Hawaii's DRR program provides rebates for zero-emissions replacements of Class 5-8 medium- and heavy-duty diesel vehicles. Replacement vehicles can be hydrogen or battery electric and the rebate can cover up to 45% of the cost of a battery electric vehicle charger. The program has $1,278,600 available between February 2023 and September 2024. The funding for the DRR program comes from Hawaii's own settlement with Volkswagen and the the Diesel Emissions Reduction Act (DERA).

Massachusetts – MOR-EV Trucks Program Massachusetts' MOR-EV Trucks Program is designed to encourage adoption of zero-emissions medium and heavy duty on-road vehicles by offering rebates for purchases and leases. Eligible vehicles must be operated in the state for at least 48 months after acquisition. Rebates are available for both public and private purchases. Incentives vary by vehicle class and decrease over time in three "Value Blocks" as more rebates are used. As of now, Class 2b and Class 3 vehicles are eligible for $7,500 or $15,000, respectively, until remaining Value Block 1 rebates run out. The rebate amounts will then drop to $6,375 and $12,750 in Value Block 2 and further in Value Block 3. Class 4-8 vehicles are also still eligible for value block 1 rebates which range from $30-$90 thousand.[28] Based on the available rebates and voucher amounts in each value block, total funding available is somewhere between $22 million and $38 million.

New Jersey – Zero-Emission Incentive Program New Jersey's Zero-Emissions Incentive Program includes a $90 million voucher pilot for medium- and heavy-duty vehicles. The funding for this initiative comes from proceeds from the Regional Greenhouse Gas Initiative (RGGI). Vouchers in this program range in value from $20-$175 thousand. As of May 2023, $6.35 million had been redeemed and $39 million in applications had been approved. The vouchers can be redeemed for Class 2b-8 vehicles that are operated in New Jersey at least 75% of the time.[29]

New York – Truck Voucher Incentive Program The New York Truck Voucher Incentive Program (NYTVIP) provides vouchers for the purchase or lease of Class 3-8 medium- and heavy-duty zero emissions battery electric or hydrogen fuel cell electric vehicles. The program has $18.4 million in funding for Class 3-8 trucks. Of this funding $8.4 is from the state's settlement with Volkswagen and the remainder is from the Congestion Mitigation and Air Quality Improvement Program (CMAQ).[30]

[28] https://mor-ev.org/mor-ev-trucks.
[29] See https://www.njeda.gov/njzip/
[30] See https://portal.nyserda.ny.gov/servlet/servlet.FileDownload?file=00P8z000002CEV6EAO

Table 9: Zero-Emission Truck Incentive Programs

Program/Policy Name	State	Type	Funding	Class	Webpage
Inflation Reduction Act	National	Vehicles Infrastructure Operations	$1 billion*		Link
HVIP	CA	Vehicles	Varies Annually $422 million in FY22-23	Class 2b-8 Trucks	Link
ISEF	CA	Vehicles Infrastructure Operations	Varies Annually $35 million in FY22-23	Class 2b-8 Trucks	Link
Carl Moyer Program	CA	Vehicles Infrastructure	About $60 million per year		Link
VW Mitigation Trust	CA	Vehicles	$90 million	Class 8 Trucks	Link
DRR Program	HI	Vehicles Infrastructure	Varies by Cycle $1.2 million for 2023-2024		Link
MOR-EV Trucks Program	MA	Vehicles	Between $22 and $38 million		Link
Zero-Emissions Incentive Program	NJ	Vehicles	$90 million	Class 2b-8 Trucks	Link
Truck Voucher Incentive Program	NY	Vehicles	$18.4 million	Class 3-8 Trucks	Link

* Some of this total funding may go towards busses in addition to trucks.

D Cost Comparison for Large-Scale Policies

As noted above the quantitative model is best suited to consider smaller changes using elasticities around baseline projections, though we can also consider large policies and provide a brief analysis here. Given how far away from the observed no-change allocation these policies are the results necessarily rely more heavily on assumptions.

Figures 34 and 35 consider the costs of fee-based or tradable systems (which equivalently act to incentivize the lowest-cost conversions from diesel to ZET) against a traditional command-and-control system. Costs for the command-and-control system are modeled as above, where we assume effectively random assignment into compliance; this would arise if for example compliance requirements are based mostly on truck age and truck age is in turn distributed randomly across a group of firms. In this world the command-and-control system is affecting the average truck, and so costs increase approximately linearly until all trucks are converted. The small deviations from linearity have to do with conversions of new versus used diesels. In contrast, fee-based systems (or tradable credits) have convex costs since, as the systems progress, they work their way from the cheapest to the most expensive conversions.

Figure 36 shows, for all truck classes combined, the ratio of costs under command-and-control to costs under a fee-based or tradable credit system. The command-and-control policy results in approximately double the cost to achieve a 45% conversion to ZET. At 65% conversion to ZET, the command-and-control system is 50% more costly than a comparable fee-based or tradable credit system.

Figure 34: Distortionary cost by policy type, Class 4-7 2030

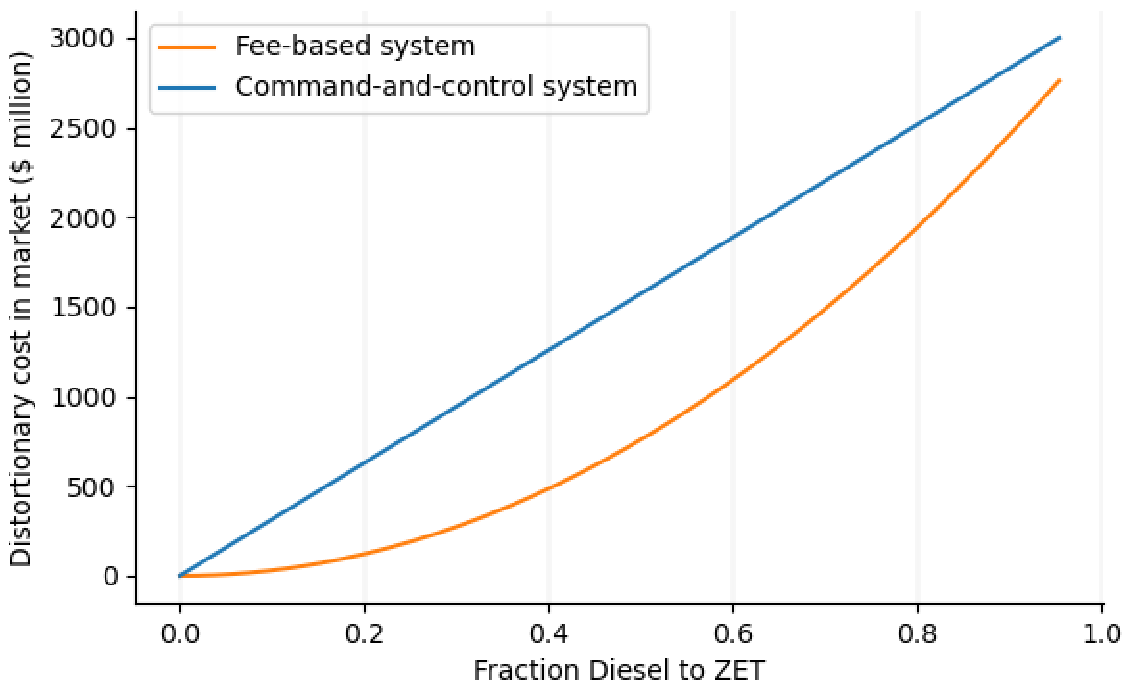


Figure 35: Distortionary cost by policy type, Class 8 2030

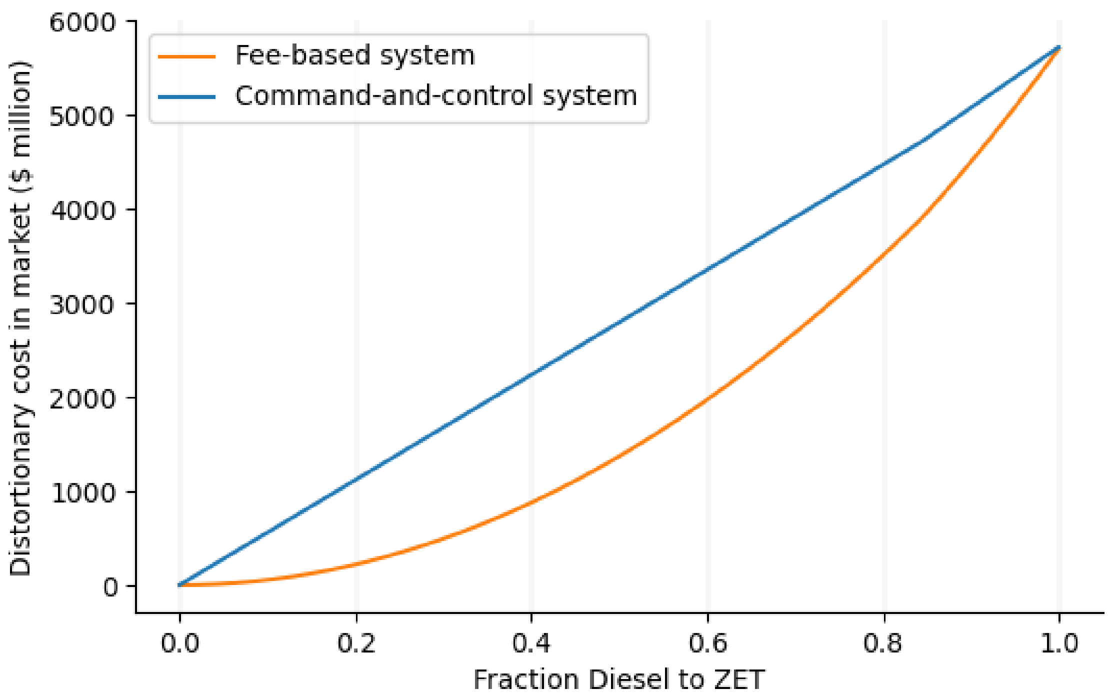
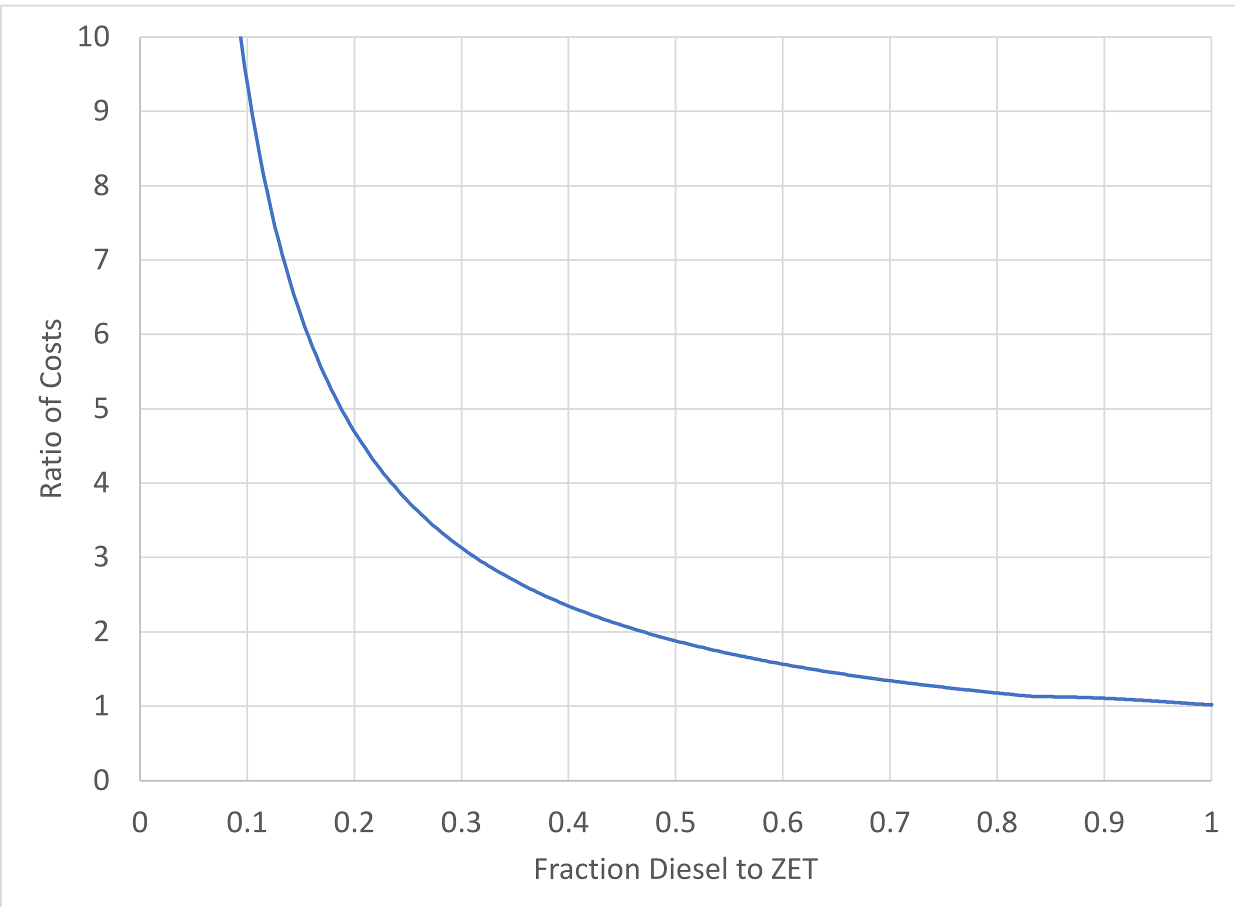


Figure 36: Ratio of Costs, 2030



E Vehicle Operating Cost Calculations

This section describes the data for the original per-mile costs for T6 and T7 trucks, before the addition of any new policy. We use itemized cost values provided by CARB as well as manually calculating capital costs associated with vehicle value depreciation. The following cost groupings comprise the total non-capital costs and are divided by total vehicle miles traveled to get costs per mile:

- Fuel Taxes
- Other Taxes & Fees
  - Sales tax on vehicle purchase
  - Federal excise tax
  - Registration fees
- Insurance Cost
- Depreciation Tax Credit
  - State
  - Federal
- Midlife & Maintenance Costs
  - Midlife Cost
  - HD I&M Cost
  - Maintenance Cost
  - Maintenance Facility Upgrade Cost
- EVSE & Infrastructure Costs
  - EVSE maintenance
  - Unamortized EVSE cost to manufacturer
  - Amortized EVSE cost to fleet
  - Unamortized infrastructure cost to manufacturer
  - Amortized infrastructure cost to fleet
- Fuel Costs

- Fuel Costs minus taxes
- Diesel Exhaust Fluid Consumption
- Low Cost Fuel Standard Revenue

The final cost we calculate is capital cost associated with vehicle depreciation. We calculate this as the loss in vehicle value during one year using the vehicle values provided in the CARB cost data. We then divide this capital cost by the annual mileage of the given vehicle age and category to get capital cost per mile. While this abstracts from loan interest that capital owners may be paying, it has the advantage of spreading depreciation out over each year rather than applying it only during times when vehicle payments are being made. Figure 37 provides the breakdown of these per-mile costs (and credits) for each category of truck. Finally, figure 38 shows the total per-mile cost after subtracting credits.

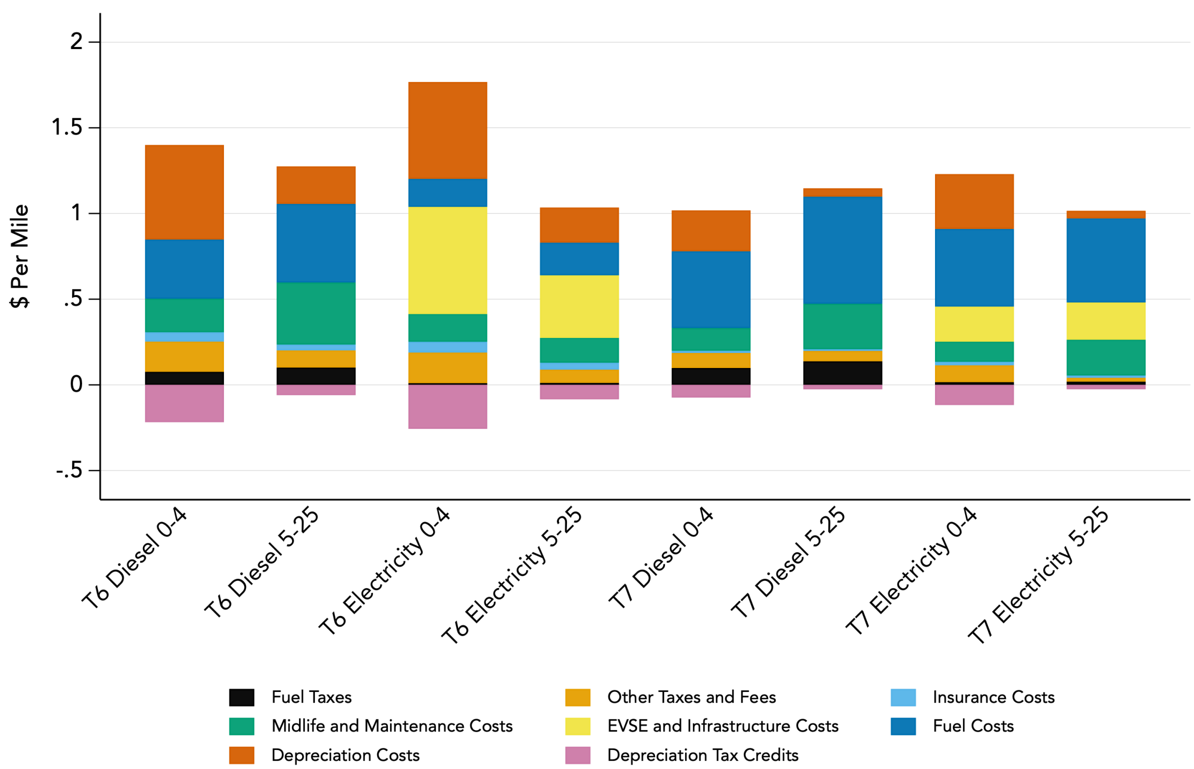


Figure 37: Per-mile cost breakdown by truck type and fuel

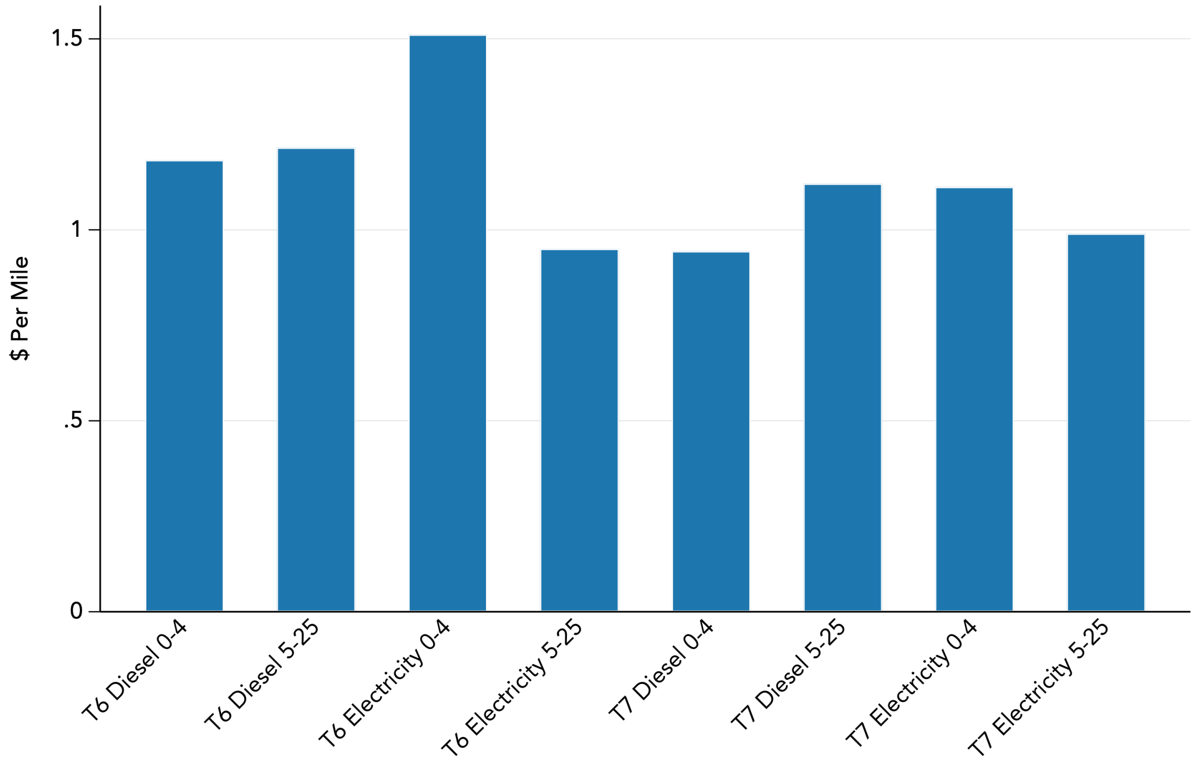


Figure 38: Total per-mile costs by truck type and fuel

F Fee Estimates Under Alternative Elasticities

Here we provide estimates of the fees necessary to reduce diesel VMT by 6.3% in 2030, as in the first three rows of Table 5, but under the alternative elasticities considered in Table 6. The second row of each panel corresponds to the baseline elasticities that we use in Table 5: new-used elasticity of -1 and new ZET logit share parameter of -8. Thus, the second row of each panel replicates results in Table 5.

The first row shows the effects of less flexibility between new diesel vehicles and new ZETs. In this case, with less flexible adjustments, greater fees and rebates are necessary to obtain the same targeted 6.3% reduction in diesel VMT.

To interpret each panel's fourth row, it is necessary to recall that there will be relatively few used ZETs available in 2030. Thus, if truck owners are more able to substitute between new and used vehicles (new-used elasticity is -2 rather than -1), lower fees and rebates will be required to induce an owner to use a new ZET instead of an older diesel vehicle. Finally, Row 3 presents estimates when both elasticities are changed.

There are reasons to consider even more combinations of values for these elasticities. For example, the base quantities of ZETs could be greater or smaller than the estimates we use; because elasticities describe relative changes, a difference in the base quantity is equivalent to a different elasticity. Alternatively, it could be the case that the owners of the non-ACF fleet are more able to substitute between new and used vehicles because these owners do not rely as heavily on the latest technologies. This would imply a larger (more negative) value for the new-used elasticity. It is also possible that the non-ACF fleet operates in locations or industries that make it harder to access charging facilities. This could rationalize a lower new ZET logit share elasticity. On the other hand, non-ACF vehicles may spend more time idle, making charging time less costly for these owners. Suffice to say that there are a range of possibilities and that these calculations could benefit from experience and data that estimates adoption responses in the real world. In the meantime, we recognize the uncertainty in these claculations and suggest this range of estimates as a useful scaling exercise to offer insights on the order of magnitude of potential required fees that could generate the target response.

Table 10: Fees Necessary to Reduce Diesel VMT 6.3% in 2030 Under Alternative Elasticities

			Average fee/mile	
New-Used Elasticity	New ZET logit share parameter	Market surplus cost ($million)	Diesel (cents)	ZET (cents)
Class 4-7				
-1	-6	12.8	0.9	-14.2
-1	-8	10.0	0.7	-11.4
-2	-6	12.7	0.7	-11.3
-2	-8	9.5	0.6	-9.4
Class 8				
-1	-6	29.6	1.0	-13.6
-1	-8	23.2	0.7	-10.4
-2	-6	29.9	0.9	-12.6
-2	-8	21.8	0.7	-9.8

G Compliance cost heterogeneity quantification

A critical concern for policymakers is whether a policy triggers compliance cost differences across operators. Market based instruments provide greater flexibility of compliance and, as a result, generally reduce the size of compliance differences across operators. This is why they increase efficiency.

A command and control system consistent with state targets will need to force retirement at the end of useful life while mandating only zero emission trucks be sold in the new market. This creates compliance cost heterogeneity due to timing.

Operators that have to retire a vehicle and replace it with a ZET in an earlier year face a higher capital cost than operators who need to take the same action at a later date. The reason for this difference is that the cost of ZETs is assumed to be declining over time. In addition, there is a time value of money difference when viewed from today's perspective.

This section makes an approximation of the heterogeneity in costs due to these timing differences alone by exploring the heterogeneity in ZET capital costs, the present value cost of purchasing a ZET in a given year. These costs represent cost heterogeneity created by a command and control system. In a market-based policy, such as a set of vehicle fees, the cost heterogeneity is capped at the vehicle fee amount because an operator can pay the fee instead. This allows operators who have an older truck today (and thus an earlier required replacement under a command and control system) to pay the fee for some number of years while waiting for prices to come down. This reduces compliance cost heterogeneity.

G.1 Price variation

The calculation in this section is based on variation that comes over time in the projected cost of adopting a ZET. The cost of ZETs is projected to decline as the market evolves.

CARB provided estimates of future costs of ZETs, with a different estimate for each combination of fleet grouping, calendar year, and vintage year. We take these costs as given and translate them into a price index for each fleet grouping in each year (e.g., T7 interstate, or CAIRP, trucks in 2035). Specifically, we match the vehicle categories used by CARB to those used by the California DMV. Then we use the market shares and prices projected in CARB for each category-age to calculate the weighted geometric mean, with market shares as weights. We use this simple price index, the Cobb-Douglas price index, to describe the average truck price faced by operators in each year of a potential ZET purchase. In figure 39, we present the price index for T7 CAIRP trucks as an example of how these price indices decrease over time.

These figures show that prices are expected to fall by roughly 50% over a decade starting from 2024. Because prices are declining significantly over time, operators who need to replace their vehicle sooner rather than later will face a higher cost. Under a command and control approach, the timing of when operators need to replace their vehicle is determined by the age of vehicles today. As a result, we can quantify the heterogeneity in cost of a command and control system that

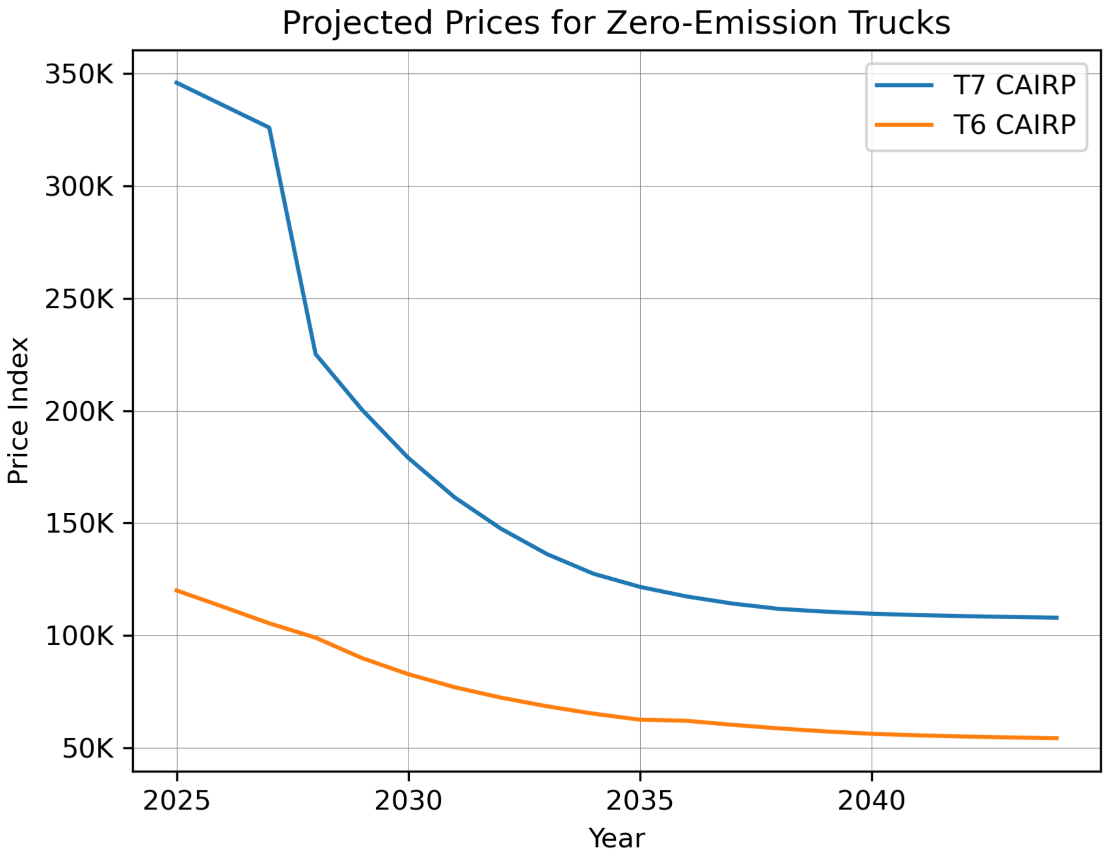


Figure 39: Illustration of how projected replacement costs decrease over time for sample class

forces retirement at the end of useful life by looking at today's fleet of vehicles from registration data and translating that into a cost of replacement, assuming retirement at the end of useful life.

We assume that all new trucks must be ZET starting in 2025, and that all T6s must be retired after 18 years and T7s must be retired after 13 years. This analysis is based on our registration data, which ends in 2019, so we assume that the age distribution in 2025 is the same as what is observed in 2019.

Under these assumptions, figure 40 shows the distribution of the year in which the estimated 2025 fleet would need to be retired. There is a mass at 2025, which represents vehicles that are already above their useful life threshold. A vehicle with one year before its useful life threshold would be replaced in 2026, and so on.

To translate this distribution of retirement year into a distribution of ZET capital costs faced by operators, we use the price index that represents the cost of replacing a truck in that year. To translate costs that occur in different years into common units from the point of view of 2025, we calculate the present discounted value using a 5% annual discount rate.

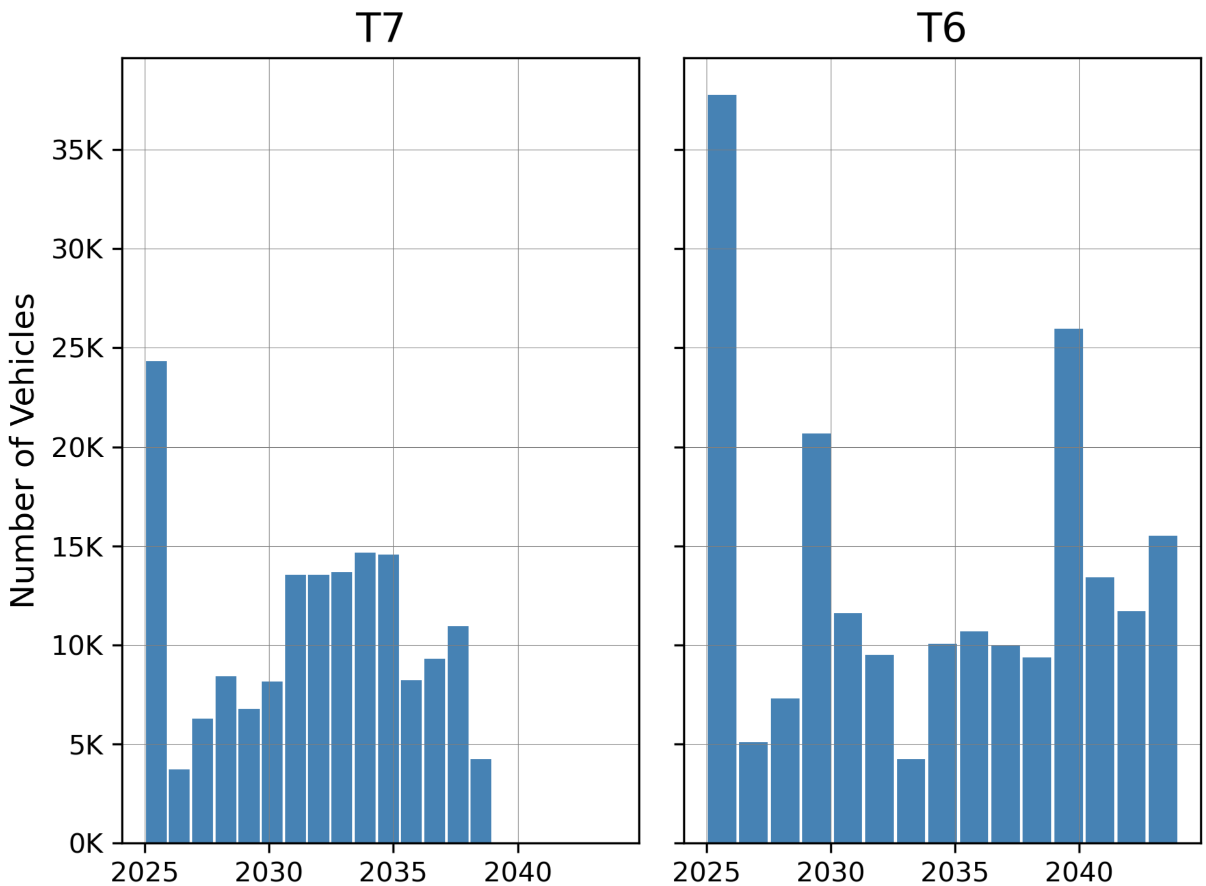


Figure 40: Variation in replacement year of the current fleet

The resulting values indicate the cost of a regulation imposed in 2025 on each truck in present value. Differences in this analysis are entirely driven by differences in vehicle category and the date of the vehicle's retirement, accounting for both cost declines and the time value of money, and thus are an underestimate of true compliance cost heterogeneity, which would also include variation in use value and idiosyncratic barriers to adoption.

Even without accounting for those types of cost heterogeneity, the data suggest large spreads in ZET capital costs per vehicle triggered by a policy that forces retirement at different ages as shown in figure 41. More flexible policy instruments, like the market-based mechanisms described throughout this report, can reduce cost heterogeneity. In particular, this means we could impose smaller burdens on operators who happen to own older vehicles today because they would have the option of, for example, paying an annual fee for several years while the truck market evolves, and in particular, while the used truck market matures.

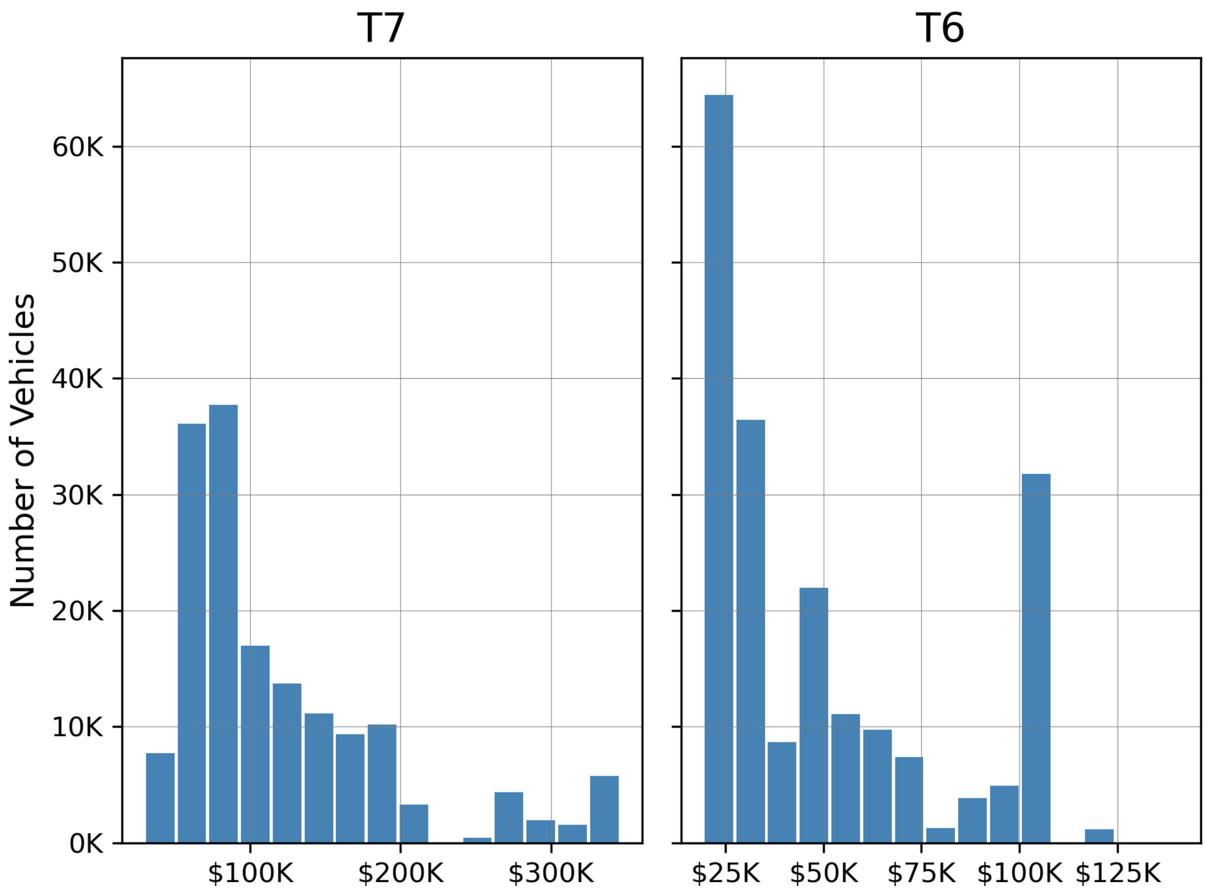


Figure 41: Variation in ZET capital costs in present value

Table 11: Summary Statistics of ZET Capital Costs (present value $)

	T6	T7
count	202,837	160,324
mean	50,702	118,793
std	30,677	73,609
min	19,316	29,612
10%	21,649	55,214
25%	24,559	66,752
50%	37,398	90,317
75%	65,464	145,947
90%	107,269	202,681
max	140,609	346,000

H Potential Approach to a Dynamic Model and the Needed Inputs

ARB currently relies on EMFAC for projecting changes in the fleet over time. EMFAC captures many important features of the market and provides a granular view of how the fleet will evolve over time. What we call here a "dynamic equilibrium model" would add capabilities not currently available in EMFAC. Such a model would enable improved analysis of several key features, most importantly the way in which policies or technological change would impact survival rates and the role of out of state imports.

A dynamic equilibrium model would take new ZET and new diesel truck prices as given, but it would solve for the price of used ZET and used diesel trucks of any given age as an equilibrium that requires supply to equal demand. This is important because these equilibrium prices would in turn be used to make survival (scrappage) rates and net imports or exports equilibrium objects.

At present, EMFAC uses the historical survival rates of vehicles, based on an analysis of the age distribution of trucks in recent years. This is an appealing approach because it is grounded in data. But, it has two key weaknesses. First is that these survival rates are then assumed to carry forward into the future, even when price shocks and policy interventions change the economic logic behind vehicle survival (scrap). When survival rates change in response to policy, this could create large differences from the current EMFAC approach. The dynamic equilibrium approach allows these price trajectories to respond to changing market conditions and policy.

Second is that it currently does not separately identify survival rates of the existing California fleet from importation of trucks from out of state. Future policy will likely need to address the importation of used diesel trucks from out of state, and thus separately quantifying retention of existing in-state trucks versus trade with other states is critical for driving some policy insights.

To the extent the rest of the US truck market is large, national used truck prices (important for imports and exports) will not be much changed by California policy and so could be taken as external inputs (most easily, held constant at a baseline). The the extent the rest of the US market is small it may be productive to model it together with California, allowing equilibrium in both markets to evolve together.

Modeling trade in this way could perhaps build on experience with the Truck and Bus Rule; data from that period could allow estimation of trade frictions between California and the rest of the US. What is needed to execute on this is price information about truck prices by vintage before and after the implementation of the rule. This would allow quantification of how a reduction in demand within California for a particular set of vintages affected equilibrium prices and flow between the California fleet and the rest of the US. This response could be used to model how changes in demand within California due to ZET policies in the future could affect flow back and forth to the US market.

H.1 Setup and Key Relationships

The number of road miles driven in zero emissions trucks (ZETs) versus conventionally fueled trucks (diesel) determines emissions and depends on the sales of new trucks and on the composition of used trucks. Similarly, the share of ZETs among new truck sales (a quantity that is sometimes a focus of reporting and regulation) depends on prices and conditions in both the new and used truck markets. Sales of ZETs also depends, somewhat more subtly, on the values of used trucks, and especially of used ZETs, in the future. For example, an investor will be less likely to purchase a fleet of new ZETs if they anticipate falling residual values for used ZETs in the future. One reason used truck values might be lower in the future is if there are significant cost reductions and quality improvements for new trucks, making used trucks relatively less desirable.

A dynamic model accounts for this, and the many other, ways in which new and used truck markets are linked together over time. It solves directly for the way in which prices of used trucks move as technology and regulation evolve. The output of the model would then include a time path used prices and the corresponding time path of new and used quantities. The time path of prices and quantities evolves in an economically consistent way such that owners make appropriate decisions in terms of new truck purchases, used truck imports, used truck exports, and truck scrap at each point in time.

A dynamic model in this setting likely needs to distinguish (at least) two types of truck, in addition to their ages. For example, depending on the structure of regulation we could imagine that used diesel truck prices will evolve very differently from used ZET prices. Import, export, and scrap of used ZETs would therefore also look very different from the import, export, and scrap of used diesel trucks.

Note that the rationale for using a dynamic model and accounting for a changing time path of prices in used markets exists even if a new truck type (ZET) arrives with instant full availability and at a fixed price. Even with instant ZET availability, we would still expect a dynamic evolution of ZET sales and a dynamic path of used truck values over time as the transition proceeds. It is not the case that new sales would simply adjust once and for all to the presence of the new truck type.

The need for a dynamic model becomes compounded in the (very likely) case that, in addition to the dynamics coming from ZET penetration into the used market over time, the prices, quality, or availability of new ZETs are changing through time. For example, it is likely that ZET prices will fall over time and that costs of ownership (for example related to charging convenience, driver training, availability of maintenance technicians, etc.) will also fall over time. The time path of these technological changes will combine with other dynamic forces in the used market.

Table 12 shows the structure of a basic dynamic model of the truck market.

Table 12: Dynamic Model Structure

Inputs

Starting conditions (stable point before the introduction of new technology or regulation)
–Scrap/export/import rates by age
–Truck values (prices) by age
–Typical sales

Path of new truck prices going forward
–New diesel price path
–New ZET price path

Path of changes (relative to the starting conditions) in regulatory constraints, fees, or subsidies
–New and used trucks

Solving the Model: Dynamic Equilibrium

Solve for matrix of truck values (by calendar year, used age, and ZET/diesel type) such that:
Quantity demanded = quantity supplied for each calendar year, age, and type

Parameters needed to solve:
–Elasticities between ages and types (demand)
–Trade elasticities by age (supply)
–Scrap elasticities by age (supply)

Outputs

Sales
–by year and type
Scrap
–by year, type, used age
Exports from or imports to California
–by year, type, used age

H.2 Inputs

Starting conditions in the truck market provide benchmark levels of sales, scrap, import/export, and truck values. It simplifies the model greatly to assume that the starting conditions are a stable point: in other words if we don't make changes in technology or add new regulatory interventions then the starting conditions for sales and scrap rates would also be our forecast of sales and scrap rates going forward. In this sense, the desired input here is an average of recent values taken over a recent period of years, for example the average retention or scrap rate of a given age truck.

The future prices of new diesel and new ZET trucks would also be inputs to a dynamic model of quantities. These values may well be the output of a different model (looking at engineering or historical patterns, for example) but for simplicity would be treated as an input here. To the extent we desire to separate maintenance, fuel, labor, or other costs associated with truck services the expected time path of these items would also be treated as an input. Feedbacks may be possible (for example learning by doing if there are a lot of ZET sales). Such feedbacks could potentially be modeled internally if desired, but for simplicity here we assume that they are estimated separately and treated as an input here.

Finally, the time path of new regulatory constraints, fees, or subsidies is given as input. For example if a portion of new sales are required to be ZET then this could be modeled as a shadow subsidy on ZETs and a shadow tax on diesel trucks.

The equilibrium can offer a range of insights into the effects of the regulatory constraints. For example with new ZET subsidies we would expect, in a few years, to have fewer used diesel trucks available in the market. This will impact used diesel values and choices in the used market. Further, if new ZET sales are encouraged via subsidies then we might expect used ZET values to be relatively low in the future (since new ZETs are available cheaply). This in turn would influence exports of used ZETs.

H.3 Dynamic equilibrium and parameters

The equilibrium concept here is straightforward: truck supply and demand are required to match for each age and type (diesel or ZET) in each year modeled. To measure how supply and demand move when used values evolve the model also needs a range of parameter inputs. Most likely, these parameters would be treated as fundamentals that don't change over time (though in principle a model could be based on time-varying parameters as well).

Demand parameters

Demand elasticities are the core parameters needed: when truck costs change how easily will a firm switch between a new versus used truck, or a ZET versus diesel truck? The parameters controlling responsiveness of demand could be measured just with respect to the capital cost, or could be converted from a broader elasticity with respect to total costs of operation, depending what is more easily interpreted or available.

The combination of these demand parameters (effectively adding up across all truck ages) determines overall market responsiveness: if they combine to zero, then increases in the average cost of trucking will not result in shifts to other freight modes. This is probably a good, basic, starting assumption. The model is flexible though: if the demand parameters are set so that they combine to something negative, then increases in all truck costs together would push some truck miles to other modes and this effect could be measured over time together with other changes.

Supply parameters

New truck supply in a parsimonious dynamic model would most simply be described as perfectly competitive or elastic (i.e. if firms would like to buy more new trucks at the price set out in the model inputs, then manufacturers are willing to make any number of them).

The remaining supply parameters needed to understand the evolution of truck quantities are the ones controlling used truck supply. First, the trade elasticity determines supply from other states. When used truck prices are very low (high) in California there is pressure to export (import) trucks to or from other parts of the U.S. How much the market can respond to this pressure is captured in the trade elasticity. At one extreme, with infinitely elastic trade, the dynamic equilibrium becomes much simpler because used truck prices never change. Instead, the quantity of used trucks moves perfectly flexibly as demand rises or falls in the California market. At the other extreme, with zero trade elasticity, is a case where large frictions prevent trade (this could for example be connected to regulation or high implicit transaction costs). In this extreme without trade, the price effects captured in a dynamic model become especially important: this is a world where used truck prices in California would be expected to move around the most in response to a ZET transition.

Finally, the last key elasticity that determines used truck supply is the scrap (inverse of retention) elasticity. If used trucks become more valuable we can expect owners to put more effort into maintenance and repair. The more effort is put in, the greater the supply of used trucks available. Note that in the perfectly free trade case mentioned above this scrap elasticity becomes unnecessary: prices of used trucks don't change, so maintenance and repair don't change, and retention rates by age remain constant over time at the values in the "initial conditions" above.

H.4 Outputs

The first key output of a dynamic model is the quantity of trucks demanded (and supplied, in equilibrium) for each truck age and type in each year.

The equilibrium price from the model, combined with the scrap elasticity, determines the retention rate at any given age and year. Retention (and last year's quantity) gives the supply of trucks of any given vintage coming from inside California. By definition, any other used trucks in the state, that haven't been supplied by retentions, are coming in from other states via trade. (Note that one could equally well use the used vehicle price and trade elasticity to calculate net trade; they will be the same if the model has correctly solved for a set of prices that equate overall supply and demand).

Note that in this setting the demand for new trucks is a function not only of the price of new trucks but also the residual values of used trucks (the prices being solved for within the dynamic model). The more slowly equilibrium residual values fall with age the more attractive a new truck will be. To see how this works consider an extreme case: suppose new ZET prices are made very low (e.g. via a subsidy) while at the same time used ZET values in the future will be quite strong (perhaps because of demand for used ZETs in states outside California, or for use in other fleets within California). This particular combination would lead to lots of demand for new ZETs since the depreciation costs associated with owning them would be very small. Perhaps over time used ZET prices would adjust (such that new and used values become more in sync), leading to greater depreciation costs and a scaling back in demand for new ZETs. This is the sort of pattern a dynamic model is well suited to study.

H.5 EMFAC groups, ACF classification, and aggregate demand

Because supply and demand elasticities likely differ across dimensions other than "diesel/ZET" one possibility is to run the model separately, with separate inputs, across different groups of trucks. For example different vocations, EMFAC groupings, ACF/not-ACF, could each have their own dynamic model.

One important detail to do with this involves trade across categories but within the state. If analyzing a single dynamic model for a particular class of trucks in the whole state then the trade elasticity has the interpretation of trade to and from other U.S. states (assuming international trade is small). If running a dynamic model with inputs calibrated to a smaller level, for example class 8 trucks in the "ACF CAIRP" group, then the trade elasticity would need to be larger in order to also allow purchases from, or sales to, other groups inside California, like "non-ACF CAIRP". A richer model could even consider adding equilibrium conditions across groups, such that a single used truck market and price feeds multiple groups. This would allow explicit modeling of effects like the movement of diesel trucks away from groups that have large ZET requirements early on and into groups with more delayed ZET requirements.

Aggregate demand: While the elasticities between ZET and diesel and new and used likely have the most relevance here, note that the combination of all the elasticity inputs also implies an aggregate demand elasticity (that is, if the average truck become more expensive, how much is aggregate demand for trucks reduced). One simple possibility is to set this value to zero for each subgroup or EMFAC/ACF classification. This way the model focuses on the transition between different types and ages of truck while abstracting from the potential for shifts between ACF and non-ACF services, or to rail or other modes.

H.6 Example

It may help clarify the setup and outputs of the model to provide an example with dimensions.

Consider a model for class 8 trucks. Suppose we are interested in 18 ages (new, 1 year old, 2 years old,..., 17 years old) and a transition to ZET over a period of 30 years. For simplicity (both of computation and input specification) it would likely be best to keep the types very aggregate and include only two: ZET and diesel. Breaking out sub-types (sleeper versus regular cab, different types of diesel, or etc.) could be approximated by applying proportions ex post, or done by using a separate model for each specific type, i.e. a different model with its own calibration for "class 8 sleeper cabs."

These dimensions mean there are 1080 truck quantities of interest: ZET/diesel, ages new-17, years 1-30; 2 x 18 x 30.

Main inputs

Starting conditions:
– 2 values for new truck quantities (less than 1 year old), equivalent to sales
– 34 values for used quantities (ZET/diesel, ages 1-17)
– 34 retention rates (taken from historical averages, or projections for ZET)
– 34 used truck values (either taken from historical averages or interpolated by depreciating starting at truck price when new and reaching zero after age 17)
–Typical export/import quantities are then already determined from the above (they are the residual when comparing typical quantities at different ages with the sequence of retention rates)

New-truck prices:
– 60 new-truck prices would be needed (ZET/diesel, years 1-30)

Regulation:
– There are many potential scenarios to model, but for a general example consider modeling a set of 1080 fees by type, age, and year. 540 of the fees might be set equal to zero for the ZETs, and varying positive values for the diesel ones. Or as another example, consider setting all values to zero except for 30 of them, with the 30 being used to represent a subsidy applied only to new ZETs (one subsidy for each of the 30 years). Or perhaps set some fees positive and some negative to model a regulatory constraint (i.e. a revenue-neutral pattern of shadow fees and shadow subsidies that lead to a particular number of ZETs).

Parameters

36 x 36 matrix of demand elasticities
Note that economic theory implies symmetry and a range of other restrictions; many of the elasticities in this matrix may be set equal to one another, interpolated, or otherwise restricted. An approach for constructing a full matrix of this type from a relatively small set of inputs appears in Jacobsen et al. (2021). The small set of inputs needed in this approach still capture things like overall flexibility between new and used trucks in a company's fleet. This key "new-used" substitution parameter could possibly be taken from the light duty literature. Another, better, approach may be to estimate using historical data for trucks: looking at fleet composition changes as the relative prices of new and used trucks move around (exogenously). To the extent firms make large changes to the age structure of their fleets when prices move this would indicate greater elasticity.

34 scrap elasticities
Jacobsen and van Benthem (2015) show these elasticities are relatively similar across ages in the light-duty sector, so perhaps just two (ZET/diesel) or even a single value could be used here in practice.

34 trade elasticities
As with the scrap elasticity a single value, or pattern, could be specified to simplify the input. Estimating these elasticities may be feasible using data from before and after other truck regulations in California took effect. These elasticities relate changes in used truck values within California to changes in net imports. Zero, and very large, values may also be interesting to try as a bounding exercise. Entering very large trade elasticities as input will lead to stable used truck prices over time.

Outputs

The primary outputs of the model would be the 1080 truck quantities and 1020 retention rates. From this, net imports or exports at each time step can be directly computed, as can quantities like the cumulative penetration of ZETs at any point (i.e. the sum of quantities over the 18 ages of ZET divided by the sum of all 36 quantities in a given year).

The demand system (assuming it was calibrated to a zero aggregate elasticity) will assure that the same number of truck miles are produced in each of the 30 years; retirements in each year would be exactly balanced by new purchases, imports, or some combination at each step. This ability to match retirements and inflows in a consistent way over time is one of the core strengths of a dynamic model.

The matrix of equilibrium prices that the model solves internally (1020 of them; the remaining 60 are new-vehicle prices that were already specified as inputs) may also provide an interesting view on the forces at work in the model. Rising prices over time for a particular age and type of truck are working to increase inflows via trade and repair/retention. Falling prices of certain ages or type of truck lead to export and scrap.