PATHWAYS TO CARBON NEUTRALITY IN CALIFORNIA

# Decarbonizing the Transportation Sector

January 2023

Stanford
Center for Carbon Storage
Carbon Removal Initiative

# About

## About the Stanford Center for Carbon Storage

Carbon Capture, Utilization, and Storage is a key technology for achieving net-zero greenhouse gas emissions. The Stanford Center for Carbon Storage (SCCS) uses a multidisciplinary approach to address critical questions related to flow physics, monitoring, geochemistry, geomechanics and simulation of the transport and fate of $CO_2$ stored in partially- to fully depleted oil & gas fields and saline reservoirs. SCCS is an affiliates program associated with the Stanford University School of Earth, Energy and Environmental Sciences.

## About the Stanford Carbon Removal Initiative

The Stanford Carbon Removal Initiative (SCRI) seeks to create science-based opportunities and solutions for gigaton-scale negative emissions and atmospheric carbon removal. The initiative helps to enable removal of atmospheric greenhouse gasses at scale by generating and integrating knowledge, creating scalable solutions, informing policies for technology deployment and governance, and demonstrating approaches and solutions with industry collaborators. All of this is done with a focus on social acceptance and equity, as well as environmental, economic, and social costs. SCRI is an affiliates program associated with the Precourt Institute for Energy and the Woods Institute for the Environment.

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# Acronyms

| | |
|---|---|
| AFV | Alternative fuel vehicles |
| BAAQMD | Bay Area Air Quality Management District |
| BAU | Business as usual |
| BEV | Battery electric vehicle |
| CalCAP | California Capital Access Program |
| CALeVIP | California Electric Vehicle Infrastructure Project |
| CAFE | Corporate average fuel economy |
| CARB | California Air Resources Board |
| CEC | California Energy Commission |
| CNDA | California New Car Dealers Association |
| CVRP | California Vehicle Rebate Program |
| DAC | Disadvantaged communities |
| DGE | Diesel gallon equivalent |
| EMFAC | Emission factors database from CARB |
| ETW | Equivalent test weight |
| EV | Electric vehicle |
| EVSE | Electric vehicle supply equipment |
| FCEV | Fuel cell electric vehicle |
| GGE | Gasoline gallon equivalent |
| GHG | Greenhouse gas |
| GWR | Gross vehicle weight rating |
| HDV | Heavy duty vehicle |
| HVIP | Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project |
| ICE | Internal combustion engine |
| IOU | Investor-owned utility |
| LDA/P | Light duty passenger car |
| LDT | Light duty truck |
| LDT1 | Light duty truck 1 |
| LDT2 | Light duty truck 2 |
| LDT3/MDV | Light medium duty vehicle |
| LHD1 | Light heavy duty vehicle 1 |
| LHD2 | Light heavy duty vehicle 2 |
| T6 | Medium heavy duty vehicle |
| T6 OOS | Medium heavy duty out of state vehicle |
| T7 | Heavy heavy duty vehicle |
| T7 OOS | Heavy heavy duty out of state vehicle |
| T7 Port | Heavy heavy duty port vehicle |
| MH | Motorhome |
| MC | Motorcoach |
| MSRP | Manufacturer’s suggested retail price |
| Mt | Millions of metric tonnes |
| LDV | Light duty vehicle |
| LDT | Light duty truck |
| LCFS | Low Carbon Fuel Standard |
| MSS | Mobile Source Strategy |

| | |
|---|---|
| OOS | Out of state |
| PHEV | Plug-in hybrid electric vehicle |
| SIP | State Implementation Plan |
| VMT | Vehicle miles travelled |
| ZEV | Zero emission vehicle |

## Key Findings

- California needs to reduce emissions from the transportation sector, as transportation is the single largest contributing sector to the state's greenhouse gas emissions.
- Sales of new light duty vehicles (LDVs) and light duty trucks (LDTs) may need to be 100% ZEVs starting immediately to meet full decarbonization of the ICE fleet by 2045.
- As an alternative to requiring sales of new LDVs to be ZEV by 2035, if California were to start retiring all vehicles that are 11 years or older in 2023 and thereafter, the state could achieve a decarbonization of the fleet by 2045.
- A simplified total cost of ownership (TCO) analysis shows that the current trajectory of reducing battery costs and economies of scale will be sufficient to achieve cost parity between ICE and electric vehicles (EVs).
- Light heavy-duty trucks (LHD1 and LHD2) make up 59% of the heavy-duty vehicle (HDV) fleet and account for 26% of HDV $CO_2e$ emissions, whereas heavy-heavy duty vehicles (T7, T7 OOS, T7 Port) make up 13% of the vehicle fleet and are responsible for 52% of HDV $CO_2e$ emissions. T7 vehicles registered out of state or jointly registered in California and another state that drive within California make up only 5% of the heavy-duty vehicle fleet and are responsible for 34% of heavy duty $CO_2e$ emissions driven within the state. Thus, there is a need for a concerted effort between the state of California and other states to achieve a deep decarbonization of the HDV fleet.
- Rapid growth in hydrogen demand is expected in some zero-emission scenarios. Total hydrogen demand will be between 1.5 and 4 Mt per year for the mixed and high hydrogen scenarios (HDV) and about 4 Mt per year (LDV) by 2045 for scenarios with high use of hydrogen in transportation.
- Rapid growth in electricity demand is expected in all zero-emission scenarios. Total electricity demand could range from 55 to 90 TWh per year in mixed and high electrification scenarios for heavy duty vehicles (HDVs). A decarbonized and highly electrified LDV and LDT fleet by 2045 would require about 90 TWh per year. Emissions arising from increased electricity sector infrastructure are not included in this analysis.
- The key conclusion from this work is that policy interventions will be needed to accelerate retirement of the existing vehicle stock and spur sales of ZEVs if decarbonization by 2045 is to be achieved.

# Introduction

To mitigate the negative consequences associated with climate change, the world will need to drastically reduce emissions of greenhouse gases (GHGs). Energy systems will need to be deeply decarbonized. Reducing emissions from transportation is of key importance since transportation is the single largest contributing sector to California GHG emissions. In 2019, tailpipe (i.e., *direct*) emissions of all vehicles (including on-road, off-road, shipping, and aviation) accounted for almost 40% of total statewide emissions at 170 $MtCO_2$ [1]. This value increases even further when accounting for emissions from extracting, refining, and moving transportation fuels [1].

The California Air Resources Board (CARB) has found that about 70% of the direct emissions from the transportation sector are attributable to light duty vehicles (LDVs) [1]. Heavy-duty vehicles (HDVs) account for 20% [1]. Furthermore, LDVs constitute 28% of total state level GHG emissions, and HDVs represent about 8% of total state level GHG emissions [1]. Aviation, shipping, and rail account for 1%, 0.9%, and 0.4% respectively. Thus, the focus of this report is on road transportation.

The shares of emissions from different sectors and from transportation sub-sectors, as estimated by the California Air Resources Board (CARB) for year 2019, are shown in Figure 1 [1].

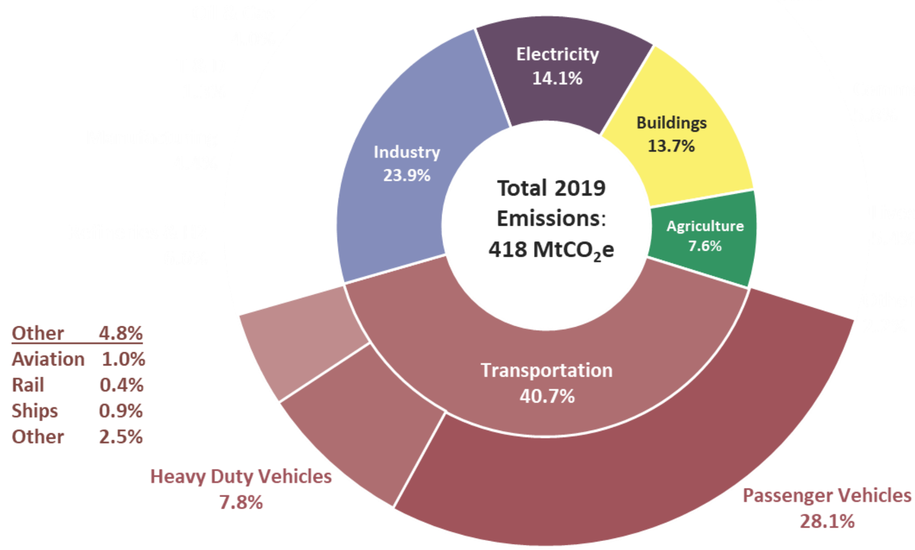



*Figure 1: GHG emissions sector and sub-sector category. Data in figure from CARB [1].*

## Current Policies and Programs That Shape the Transportation Sector GHG Emissions in California

California has implemented ambitious policies to reduce its GHG emissions. Most recently, Executive Order B-55-18 established a goal of achieving economy wide carbon neutrality by 2045. This extends existing statewide emissions reductions targets, such as SB 32 (the California Global Warming Solutions Act of 2016), which requires the reduction in GHG emissions to 40% below the 1990 levels by 2030 [1][2].

There are federal policies and programs that will affect emissions from the transportation sector in California, namely the GHG emissions standards [3]. CAFE standards and carbon emissions standards, promulgated by National Highway Traffic Safety Administration (NHTSA) and by the Environmental Protection Agency (EPA), mandate that the sales-weighted average fuel efficiency and carbon emission intensity (miles per gallon and $CO_2$ emissions per mile) of all LDVs sold by each manufacturer in a particular year must meet a specific target [4],[5].

Other policies and programs that come into play in some states, including California, are the ZEV Program, which mandates alternative fuel vehicle (AFV) sales, and the Low Carbon Fuel Standard (LCFS), which is designed to encourage use of cleaner lower carbon transportation fuels in California [6].

In the transportation sector, California's Advanced Clean Cars II regulation requires 100% of new passenger car and light-duty truck sales to be zero-emission by 2035 [7]. Similarly, CARB's Advanced Clean Truck Program [8] requires all new medium- and HDVs sold in California to be ZEVs by 2045. Beginning in 2024, manufacturers seeking CARB certification for vehicles must achieve mandated annual sales percentages for medium- and heavy-duty ZEVs sold in California. Other relevant policies include:

- SB 375, which focuses on community strategies that align transportation demand, housing, and land-use policies.
- SB-1274 (Charge Ahead California Initiative), which creates a fleet modernization program for the retirement of high polluting vehicles and ensures vehicle replacement or compensation for vehicles retired [9]. Specifically in the Bay Area, the Bay Area Air Quality Management District (BAAQMD) grants up to $9,500 to income-eligible residents to replace a vehicle eligible for retirement with an electric or fuel-cell vehicle [10].
- Electric Vehicle Supply Equipment (EVSE) Loan and Rebate Programs, which is part of the California Capital Access Program (CalCAP), provides loans for the design, development, purchase, and installation of EVSE at small business locations in California. Other projects, largely funded by the California Energy Commission (CEC) and the California Electric Vehicle Infrastructure Project (CALeVIP), include incentive projects in all major counties to set up charging stations (EVSE) inside and outside disadvantaged communities (DACs).
- SB-44 California Environmental Quality Act's Environmental Leadership Transit Projects, also known as the "Ditching Dirty Diesel" bill, which has the main goal of reducing emissions and improving air quality in areas with high use of heavy- and medium- duty vehicles [11].
- The Clean Vehicle Rebate Program (CVRP), which offers rebates for the purchase or lease of qualified vehicles. CARB determines funding amounts for the CVRP, which has been expanded to be effective through 2023. It provides rebates of up to $4,500 for fuel cell electric vehicles (FCEVs), $2,000 for EVs and $1,000 for plug-in hybrid electric vehicle (PHEVs), and $750 for zero emission motorcycles [12].

- CARB's 2020 Mobil Source Strategy (MSS), which further informs the State Implementation Plan (SIP) and 2022 Climate Change Scoping Plan, was developed to plan for scenarios to meet criteria air pollutant, GHGs, and toxic air pollutant reduction goals. While MSS differs from scenarios and fleet turnover models presented in this study, MSS is relied upon to fill in gaps of assumptions where data is not openly available [13].
- The fleet of LDVs and their emissions is also shaped by policies in the electricity sector. For example, Investor-Owned Utilities (IOUs) and municipal utilities in California have incentive mechanisms for EV adoption through rebates on setting up charging stations, time-of-use retail rates, and rebates for pre-owned EV lease or purchase [14].

## Characterizing the Current Stock and New Sales

### Light Duty Vehicles and Light Duty Trucks

For the purposes of this study, LDVs and LDTs are defined as having a gross vehicle weight rating (GWR) less than 8,500 lbs, as defined by EPA [15]. Jointly, LDVs and LDTs include passenger cars (LDA/P), light duty trucks (LDT1 and LDT2), and light medium duty vehicles (LDT3). CARB has estimated that LDVs, as defined in this report, are responsible for 28% of total state GHG emissions [1] and for slightly more than 70% of transportation related GHG emissions [1].

The composition of the 2019 stock of LDVs and LDTs in California in terms of vehicle categories, weight, number of vehicles, sales, and total VMT (see below) is used as a starting point for this analysis. This information was then used to estimate the composition of the future stock of vehicles in California under different scenarios.

Estimates for the stock, emissions, vehicle miles driven and fuel consumption by vehicle category, fuel type, and age are from CARB's EMFAC [16]. Sales are back calculated from EMFAC's reporting on the total stock of vehicles through 2046. Passenger cars make up most of the current stock, miles driven, emissions, and fuel consumption of all LDVs.

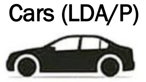
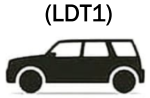
| Vehicle class | Fuel type | Fleet ($10^3$ vehicles) | Total VMT ($10^6$ miles/year) | $CO_2$ emissions ($10^6$ tons $CO_2$) | Fuel consumption ($10^6$ GGE) | Sales ($10^3$ vehicles) |
|---|---|---|---|---|---|---|
| **Passenger Cars (LDA/P)**  | Gasoline | 13,806 | 178,199 | 62 | 6,577 | 759 |
| | Diesel | 62 | 684 | 0 | 17 | 9 |
| | Electric Vehicles | 298 | 3,485 | 0 | 0 | 66 |
| | Plug-in Hybrid | 200 | 3,178 | 1 | 60 | 32 |
| | **Total** | **14,366** | **185,546** | **63** | **6,654** | **867*** |
| **Light Duty Trucks 1 (LDT1)**  < 6000 lbs, ETW ≤3750 lbs | Gasoline | 1,540 | 17,025 | 7 | 750 | 195 |
| | Diesel | 1 | 6 | 0 | 0 | 0.01 |
| | Electric Vehicles | 2 | 17 | 0 | 0 | 2.5 |
| | Plug-in Hybrid | 0 | 0 | 0 | 0 | 2 |
| | **Total** | **1,543** | **17,048** | **7** | **750** | **200*** |
| **Light Duty Trucks 2 (LDT2)**  <6000 lbs, ETW: 3751 - 5750 lbs | Gasoline | 5,806 | 74,623 | 33 | 3502 | 613 |
| | Diesel | 17 | 241 | 0 | 8 | 6 |
| | Electric Vehicles | 1 | 9 | 0 | 0 | 7 |
| | Plug-in Hybrid | 7 | 122 | 0 | 2 | 6 |
| | **Total** | **5,831** | **74,995** | **33** | **3,512** | **632** |
| **Medium Duty Vehicles (LDT3)**  6000-8500 lbs | Gasoline | 4,248 | 51,367 | 28 | 2,919 | 368 |
| | Diesel | 64 | 903 | 0 | 39 | 13 |
| | Electric Vehicles | 0 | 1 | 0 | 0 | 3 |
| | Plug-in Hybrid | 12 | 192 | 0 | 4 | 8 |
| | **Total** | **4,325** | **52,463** | **28** | **2,963** | **392** |

*Table 1: Vehicle stock, VMT, and $CO_2$ emissions for LDVs in California in 2019 by vehicle class and by fuel type. Sources [17] and [13] for sales, and [18] for all other fields. Notes: ETW = equivalent test weight; lbs = pounds; Gross vehicle weight rating is defined as maximum operating weight/mass of a vehicle as specified by the manufacturer; Equivalent test weight is defined as the weight, within an inertia weight class, which is used for dynamometer testing of a vehicle. Hydrogen = fuel cell vehicle. * = Computed by the authors as the sum of sales of vehicles of that category for all fuels listed in Table 1.* The values for *fuel cell* and *natural gas vehicles* are not included *as their portion of the fleet and sales is very small or zero. Figures were rounded to the units shown in the first row, so some values that appear as zero correspond do have small positive values. GGE = gasoline gallon equivalent.*

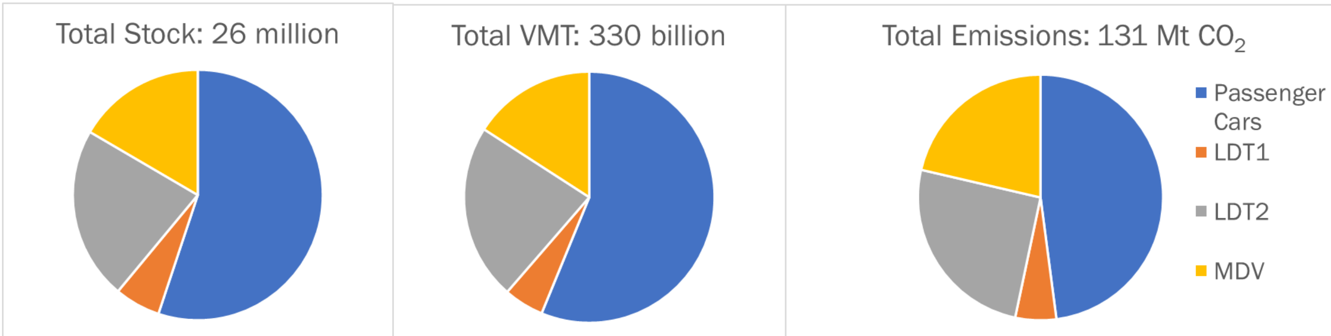



*Figure 2: Summary of number of vehicles, miles travelled and $CO_2e$ emissions for the 2019 California fleet of LDVs used in this analysis. Data from [16].*

## Heavy Duty Vehicles

HDVs are defined as vehicles greater than 8,500 lbs. As of 2019, the California heavy-duty fleet consists of just over 2 million vehicles. Of these, 59% are “light heavy duty” (vehicles up to 14,000 lbs: LHD1; LHD2), 16% are “medium heavy duty” (vehicles up to 30,000 lbs: T6; T6 OOS [out of state]), and 14% are “heavy heavy-duty” (vehicles weighing more than 30,000 lbs: T7; T7 OOS; T7 Port). The remaining 11% include other heavy-duty vehicles such as buses, motorcoaches, and motorhomes.

The characterization of the existing HDV fleet in this report is based on vehicle stock, fuel consumption, and VMT figures from CARB’s EMFAC [16].

$CO_2e$ emissions for each vehicle type, fuel type and model year are calculated as follows:

$$Total\ CO2e\ Emissions\ (MMT\ CO2e) = \sum_{i,j,k} \frac{VMT_{i,j,k}(miles)}{Fuel\ economy_{i,j,k}(miles/DGE)} \times Carbon\ intensity\ of\ fuel_i(CO2e/DGE)$$

Where,

$$i: fuel\ type = \{gasoline, diesel, hydrogen, electricity\}$$
$$j: vehicle\ type = \{LHD1, LHD2, T6, T6\ OOS, T7, T7\ OOS, T7\ Port, Buses, MC, MH\}$$
$$k: model\ year = \{1974{:}\ 2019\}$$

CARB’s EMFAC Fleet Database was used as the basis for the fleet model shown in the next section of this report. CARB’s Emissions Inventory contains 49 different vehicle classifications in the heavy-duty sector. For simplicity, these were aggregated into ten categories, shown in Table 2 along with key characteristics of each category. Vehicle stock and VMT is from is from CARB’s EMFAC Fleet Database [16].

New vehicle sales are estimated as the number of one-year old vehicles in 2019 in the Fleet Database, as recommended by CARB staff. Fuel economy for each vehicle type, fuel type and model year is calculated as the total VMT divided by the total fuel consumption.

$CO_2e$ emissions are estimated as shown in the equation above. As fuel economy and VMT differ for vehicles of different ages, categories, and fuel types, the emissions for each subset of the 2019 fleet are calculated separately and summed to get the fleetwide $CO_2e$ emissions in 2019. $CO_2$, $CH_4$, and $N_2O$ are included in this analysis, as they are included in the CARB GHG Inventory. While some vehicle categories use a small amount of renewable diesel and other biofuels, this analysis does not distinguish between biofuels and fossil fuels as the data source does not differentiate between the two. Estimates of $CO_2e$ emissions using this approach are then compared to the $CO_2e$ emissions reported in CARB's GHG Inventory [1]. CARB reports 32.5 Mt $CO_2e$ in 2019 in the heavy-duty transportation sector, while this analysis estimates emissions of 40.1 Mt $CO_2e$. However, CARB reports an additional 8.6 Mt $CO_2e$ of biogenic emissions in the sector, for a total of 41.1 Mt $CO_2e$. This is about 2% higher than calculated in this analysis. $CH_4$ and $N_2O$ emissions from biofuels are included in CARB's emissions estimate, while $CO_2$ emissions from biofuels are considered biogenic.

As shown in Figure 3, while light heavy-duty trucks (LHD1 and LHD2) make up 59% of the vehicle fleet, they account for 43% of the fleetwide VMT, and only 26% of fleetwide $CO_2$ emissions. Heavy-heavy duty vehicles (T7, T7 OOS, T7 Port) make up 13% of the vehicle fleet but are responsible for 52% of fleetwide $CO_2e$ emissions. Included in that total are T7 vehicles registered out of state or jointly registered in California and another state (T7 OOS) that drive within California. These vehicles are included in EMFAC [16] and were included in the fleet model since they are responsible for a large fraction of emissions in the state. Though they make up only 5% of the heavy-duty vehicle fleet, T7 OOS trucks are responsible for 34% of heavy duty $CO_2e$ emissions driven within the state. Emissions from T6 OOS and T7 OOS account for only for the portion of emissions from miles driven within the state, and do not include emissions associated with the miles driven out of state. VMT estimates from EMFAC represent VMT driven within state boundaries, but we note that EMFAC uses in-state diesel fuel consumption to estimate VMT, and some of this fueling may be for VMT driven out of state (and similarly, a small amount of refueling occurs out of state for miles driven within California).

Figure 4 shows the number of vehicles by fuel type in each of the categories in this analysis. Diesel is the most common fuel type, especially for heavier (T7) vehicle types. The light heavy-duty subsector along with motorhomes have a significant number of gasoline vehicles. There are a relatively small number of natural gas buses as well as natural gas T7 trucks.

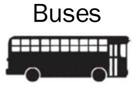
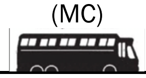
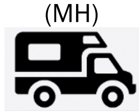
| | Classification | 2019 stock (in $10^3$) | Annual VMT per vehicle ($10^3$miles) | Fuel Efficiency (miles/DGE) | 2019 new vehicle sales stock (in $10^3$) |
|---|---|---|---|---|---|
| LHD1  | Light Heavy Duty Trucks (8,500 – 10,000 lbs) | 973 | 22.9 | 17.1 | 49 |
| LHD2  | Light Heavy Duty Trucks (10,000 – 14,000 lbs) | 220 | 21.7 | 14.6 | 12 |
| T6  | Medium Heavy Duty Trucks (14,000 – 30,000 lbs) | 336 | 18.3 | 8.5 | 16 |
| T6 OOS  | Out of State Medium Heavy Duty Trucks (14,000 – 30,000 lbs) | 1 | 59.3 | 9.1 | 93 |
| T7  | Heavy Heavy Duty Trucks (>30,000 lbs) | 157 | 31.2 | 5.7 | 8 |
| T7 OOS  | Out of State Heavy Heavy Duty Trucks (>30,000 lbs) | 107 | 92.7 | 5.7 | 8 |
| T7 Port  | Heavy Heavy Duty Trucks in Ports (>30,000 lbs) | 18 | 37.3 | 5.7 | 0.2 |
| Buses  | Other | 69 | 15.7 | 4.1 | 3 |
| Motorcoaches (MC)  | Other | 2 | 45.9 | 5.0 | 0.2 |
| Motorhomes (MH)  | Other | 149 | 5.9 | 9.7 | 5 |

*Table 2: Estimates of vehicle stock, VMT, and fuel economy for heavy-duty vehicles in California in 2019 by vehicle class. Source: [16] Notes: DGE = Diesel Gallon Equivalent*

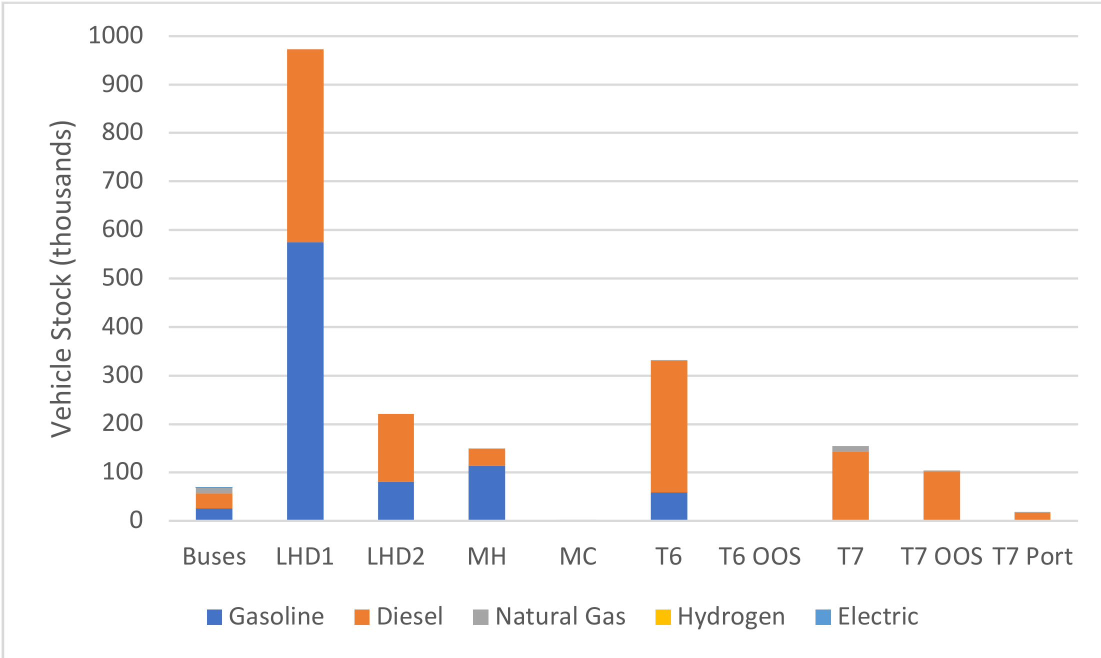



*Figure 3: HDV stock by fuel and vehicle type.*

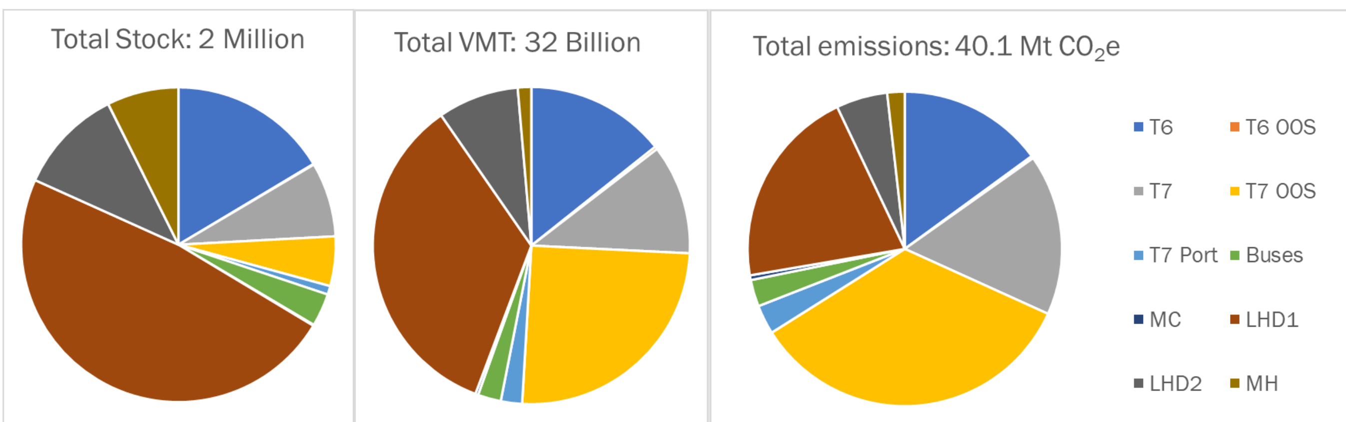



*Figure 4: Summary of number of vehicles, miles travelled and $CO_2$e emissions for the 2019 California fleet of HDVs. used in this analysis.*

# Scenarios for Deep Decarbonization Pathways

Most direct greenhouse gas emissions from on-road vehicles that are within the scope of this report are $CO_2$. For LDVs and LDTs this analysis focuses on scenarios that replace ICE gasoline vehicles since these are the largest contributor to GHG emissions.[2] Thus, only $CO_2$ emissions are considered for LDVs and LDTs. In the context of heavy duty, emissions from other GHGs are included as well. Emissions of $CH_4$ and $N_2O$ are converted to $CO_2$ equivalents ($CO_2e$) using 100-yr global warming potentials (GWPs) of 25 and 298 respectively, which represent the amount of $CO_2$ that would result in an equivalent degree of warming over 100 years.

## Light Duty Vehicles and Light Duty Trucks

### *Model, Data and Assumptions*

In this section, several scenarios are simulated for the future fleet of on road vehicles. The first step was to develop a stock and flow model that characterizes the number of vehicles of different types between now and 2045 under a business-as-usual scenario (BAU).

It is assumed that the natural rate adoption of ZEVs and other alternative vehicles is exogenous to the model and follows the trends seen in recent years. Thus, the number of ZEV and AFVs that are naturally adopted is the same across scenarios. Some of the scenarios considered in this report are defined to force additional ZEV or AVF vehicle adoption.

The stock in each year is modeled as follows:

$$stock_{c,y+1} = \sum_{type\,=\,1}^{type\,=\,n} \sum_{age\,=\,1}^{age\,=\,n} \left[p_{c,type,a} \times stock_{c,y,type,a}\right] + sales_{c,y,type}$$

Where *stock* represents the number of vehicles of a class *c*; *class* is either passenger cars, LDT1, LDT2, or LDT3; *y + 1* refers to the beginning of the year the stock is being simulated for, and *y* represents the preceding year; *type* represents either gasoline, diesel, natural gas, hydrogen, hybrid electric vehicles, or battery electric vehicles.

*p* is the probability of a vehicle of age *a* to survive to the next year. This "survival function", is calculated from EMFAC's vehicle stock forecasting [16]. Thus, $(1 - p_{c,y,type,a}) \times stock_{c,y,type,a}$ represents vehicles that are retired during year y. Vehicles in the fleet that are older than 30 years are ignored, as these vehicles very likely drive a small number of miles per year.

*sales* represent sales of new vehicles during year *y*. Sales can be further decomposed into sales due to demand growth or to replace retired vehicles (i.e., $(sales_{c,y,type} = (1 - p_{c,y,type,a}) \times stock_{c,y,type,a} + \ additional\ demand\ _{c,y,type}\,))$.

The 2019 vehicle stock, age distribution, vehicles miles travelled (VMT) as a function of age, $CO_2$ intensity ($gCO_2$/mile) as a function of age (all from EMFAC), and sales are used as the initial year in the model. Across all scenarios, it is assumed that decarbonization policies

[2] Scenarios involving use of low carbon intensity fuels to reduce emissions are not considered in this analysis, but they will be included in phase 3 of this study (Integrated Economy-Wide Model for Carbon Neutrality By 2045).

start in year 2023 or after. It is assumed that the average fuel efficiency and carbon intensity of new gasoline vehicles follows EMFAC's forecasts for model years 2020 to 2045. Only emissions of gasoline vehicles are considered in both the business-as-usual (BAU) and decarbonization scenarios.

| LDV Passenger Vehicles | | | | | |
|---|---|---|---|---|---|
| Vehicle age | Age distribution in 2020 | Real world MPG as a function of vehicle age in 2020 (miles per gallon) | Real world $CO_2e$ as a function of vehicle age in 2020 (in $gCO_2e$/mile) | VMT per vehicle as a function of vehicle age (thousand miles per vehicle per year) | Survival function as a function of vehicle age |
| 0 | 5% | 32 | 285 | 19 | 100% |
| 1 | 6% | 31 | 293 | 18 | 99% |
| 2 | 7% | 31 | 297 | 18 | 96% |
| 3 | 7% | 30 | 298 | 17 | 94% |
| 4 | 7% | 29 | 295 | 17 | 92% |
| 5 | 6% | 29 | 302 | 16 | 89% |
| 6 | 6% | 28 | 308 | 15 | 86% |
| 7 | 5% | 28 | 308 | 15 | 82% |
| 8 | 4% | 28 | 317 | 14 | 78% |
| 9 | 4% | 26 | 333 | 14 | 74% |
| 10 | 3% | 26 | 320 | 13 | 70% |
| 11 | 4% | 25 | 352 | 12 | 65% |
| 12 | 5% | 24 | 371 | 12 | 60% |
| 13 | 4% | 24 | 370 | 11 | 54% |
| 14 | 4% | 23 | 379 | 11 | 49% |
| 15 | 3% | 23 | 379 | 10 | 43% |
| 16 | 3% | 23 | 386 | 10 | 38% |
| 17 | 3% | 23 | 381 | 10 | 33% |
| 18 | 2% | 23 | 382 | 9 | 28% |
| 19 | 2% | 23 | 383 | 9 | 24% |
| 20 | 2% | 23 | 385 | 8 | 20% |
| 21 | 1% | 23 | 387 | 8 | 16% |
| 22 | 1% | 23 | 400 | 7 | 13% |
| 23 | 1% | 23 | 414 | 7 | 11% |
| 24 | 1% | 23 | 426 | 7 | 9% |
| 25 | 0% | 23 | 421 | 6 | 7% |
| 26 | 0% | 23 | 423 | 6 | 6% |
| 27 | 0% | 23 | 424 | 6 | 5% |
| 28 | 0% | 23 | 451 | 5 | 5% |
| 29 | 0% | 23 | 452 | 5 | 4% |
| >30 | 0% | 23 | 453 | 5 | 4% |

*Table 3: Assumptions on initial distribution of the fleet of passenger vehicles by age in 2020, Real world MPG as a function of vehicle age in 2020, Real world $CO_2$ as a function of vehicle age in 2020, VMT per vehicle as a function of vehicle age and probability of survival as function of vehicle age.*

| LDT1 | | | | | |
|---|---|---|---|---|---|
| Vehicle age | Age distribution in 2020 (%) | Real world MPG as a function of vehicle age in 2020 | Real world $CO_2$ as a function of vehicle age in 2020 (in $gCO_2$/mile) | VMT per vehicle as a function of vehicle age (thousand miles per vehicle per year) | Survival function as a function of vehicle age |
| 0 | 3 | 28 | 326 | 18.34 | 100% |
| 1 | 5 | 28 | 335 | 17.69 | 99% |
| 2 | 3 | 27 | 339 | 17.06 | 98% |
| 3 | 7 | 26 | 340 | 16.44 | 97% |
| 4 | 9 | 26 | 337 | 15.84 | 96% |
| 5 | 3 | 25 | 344 | 15.26 | 93% |
| 6 | 4 | 24 | 351 | 14.71 | 90% |
| 7 | 3 | 24 | 350 | 14.17 | 88% |
| 8 | 1 | 23 | 360 | 13.66 | 85% |
| 9 | 1 | 24 | 378 | 13.16 | 81% |
| 10 | 4 | 23 | 362 | 12.69 | 78% |
| 11 | 5 | 22 | 398 | 12.24 | 74% |
| 12 | 3 | 21 | 420 | 11.80 | 70% |
| 13 | 2 | 21 | 417 | 11.39 | 66% |
| 14 | 1 | 20 | 422 | 10.99 | 62% |
| 15 | 2 | 20 | 426 | 10.62 | 58% |
| 16 | 3 | 20 | 433 | 10.26 | 54% |
| 17 | 4 | 20 | 440 | 9.93 | 49% |
| 18 | 4 | 19 | 442 | 9.61 | 45% |
| 19 | 4 | 19 | 442 | 9.31 | 41% |
| 20 | 4 | 18 | 443 | 9.03 | 37% |
| 21 | 4 | 19 | 416 | 8.77 | 33% |
| 22.00 | 3 | 18 | 422 | 8.53 | 29% |
| 23.00 | 3 | 19 | 428 | 8.31 | 26% |
| 24.00 | 2 | 18 | 437 | 8.10 | 23% |
| 25.00 | 2 | 18 | 435 | 7.88 | 21% |
| 26.00 | 2 | 18 | 437 | 7.66 | 18% |
| 27.00 | 1 | 17 | 442 | 7.46 | 16% |
| 28.00 | 1 | 18 | 478 | 7.26 | 14% |
| 29.00 | 1 | 18 | 478 | 7.08 | 12% |
| >30 | 8 | 19 | 479 | 6.89 | 11% |

*Table 4: Assumptions regarding the distribution of the fleet of T1 vehicles by age in 2020, Real world MPG as a function of vehicle age in 2020, Real world $CO_2e$ as a function of vehicle age in 2020, VMT per vehicle as a function of vehicle age and probability of survival as function of vehicle age. Note: we assume the survival and the VMT per vehicle functions hold for each year from 2020 to 2045. MPG and $CO_2$ intensity assume here are that of SUVs.*

| LDT2 | | | | | |
|---|---|---|---|---|---|
| Vehicle age | Age distribution in 2020 (%) | Real world MPG as a function of vehicle age in 2020 | Real world $CO_2$ as a function of vehicle age in 2020 (in $gCO_2$/mile) | VMT per vehicle as a function of vehicle age (thousand miles per year) | Survival function as a function of vehicle age |
| 0 | 9 | 19 | 348 | 18 | 100% |
| 1 | 9 | 19 | 348 | 18 | 98% |
| 2 | 8 | 19 | 363 | 17 | 95% |
| 3 | 6 | 19 | 363 | 16 | 94% |
| 4 | 5 | 19 | 369 | 16 | 93% |
| 5 | 5 | 19 | 379 | 15 | 91% |
| 6 | 5 | 18 | 385 | 15 | 90% |
| 7 | 3 | 17 | 391 | 14 | 87% |
| 8 | 4 | 17 | 400 | 14 | 85% |
| 9 | 3 | 17 | 403 | 13 | 81% |
| 10 | 2 | 17 | 410 | 13 | 77% |
| 11 | 3 | 17 | 435 | 12 | 72% |
| 12 | 4 | 16 | 460 | 12 | 67% |
| 13 | 5 | 16 | 460 | 11 | 61% |
| 14 | 5 | 16 | 460 | 11 | 56% |
| 15 | 4 | 16 | 468 | 11 | 50% |
| 16 | 3 | 16 | 475 | 10 | 44% |
| 17 | 3 | 16 | 522 | 10 | 39% |
| 18 | 3 | 16 | 522 | 10 | 33% |
| 19 | 2 | 16 | 523 | 9 | 28% |
| 20 | 2 | 17 | 524 | 9 | 24% |
| 21 | 1 | 16 | 525 | 9 | 20% |
| 22 | 1 | 17 | 532 | 8 | 18% |
| 23 | 0 | 17 | 540 | 8 | 15% |
| 24 | 0 | 17 | 551 | 8 | 14% |
| 25 | 0 | 17 | 549 | 8 | 12% |
| 26 | 0 | 17 | 558 | 8 | 11% |
| 27 | 0 | 18 | 562 | 7 | 10% |
| 28 | 0 | 17 | 613 | 7 | 9% |
| 29 | 0 | 18 | 614 | 7 | 8% |
| >30 | 1 | 17 | 615 | 7 | 7% |

*Table 5: Assumptions regarding the distribution of T2 vehicles by age in 2020; real world MPG as a function of vehicle age in 2020 real world $CO_2e$ as a function of vehicle age in 2020, VMT per vehicle as a function of vehicle age and probability of survival as function of vehicle age. Note: we assume the survival and the VMT per vehicle functions hold for each year from 2020 to 2045. MPG and $CO_2$ intensity assume here are that of SUVs.*

| LDT3 | | | | | |
|---|---|---|---|---|---|
| Vehicle age | Age distribution in 2020 (%) | Real world MPG as a function of vehicle age in 2020 | Real world $CO_2$ as a function of vehicle age in 2020 (in $gCO_2$/mile) | VMT per vehicle as a function of vehicle age (thousand miles per year) | Survival function as a function of vehicle age |
| 0 | 4 | 24 | 421 | 18 | 100% |
| 1 | 6 | 23 | 420 | 17 | 99% |
| 2 | 7 | 23 | 438 | 17 | 96% |
| 3 | 7 | 22 | 437 | 16 | 95% |
| 4 | 6 | 22 | 445 | 16 | 93% |
| 5 | 5 | 22 | 457 | 15 | 90% |
| 6 | 5 | 22 | 465 | 15 | 88% |
| 7 | 4 | 21 | 472 | 14 | 85% |
| 8 | 3 | 20 | 483 | 13 | 82% |
| 9 | 3 | 20 | 486 | 13 | 78% |
| 10 | 3 | 20 | 495 | 13 | 74% |
| 11 | 2 | 19 | 526 | 12 | 70% |
| 12 | 4 | 18 | 556 | 12 | 66% |
| 13 | 5 | 18 | 556 | 11 | 61% |
| 14 | 4 | 17 | 551 | 11 | 57% |
| 15 | 5 | 17 | 567 | 10 | 52% |
| 16 | 5 | 16 | 575 | 10 | 47% |
| 17 | 5 | 16 | 587 | 10 | 42% |
| 18 | 4 | 16 | 590 | 9 | 38% |
| 19 | 4 | 16 | 591 | 9 | 34% |
| 20 | 3 | 16 | 591 | 9 | 30% |
| 21 | 2 | 16 | 532 | 8 | 26% |
| 22 | 1 | 16 | 531 | 8 | 23% |
| 23 | 1 | 16 | 531 | 8 | 19% |
| 24 | 1 | 16 | 531 | 8 | 17% |
| 25 | 1 | 16 | 555 | 8 | 14% |
| 26 | 1 | 16 | 569 | 7 | 12% |
| 27 | 0 | 16 | 569 | 7 | 11% |
| 28 | 0 | 16 | 655 | 7 | 10% |
| 29 | 0 | 17 | 655 | 7 | 9% |
| >30 | 1 | 16 | 656 | 6 | 8% |

*Table 6: Assumptions regarding the distribution of LDT3 vehicles by age in 2020; real world MPG as a function of vehicle age in 2020 real world $CO_2e$ as a function of vehicle age in 2020, VMT per vehicle as a function of vehicle age and probability of survival as function of vehicle age. Note: we assume the survival and the VMT per vehicle functions hold for each year from 2020 to 2045. MPG and $CO_2$ intensity assume here are that of Truck-SUVs.*

A business as usual (BAU) scenario is considered, as well as 2 simple scenarios with different policy designs as follows:

- In Policy 1, it is assumed that 100% of the sales of new vehicles will be ZEV starting in policy year *pol* and continuing for all following years until year 2045. Under this simulated policy, the stock of vehicles would continue to follow the BAU scenario until the policy kicks in. Scenarios are run for a policy start year ranging from 2023 to 2044.
- In Policy 2, the annual emissions of $CO_2$ avoided are simulated assuming that starting in 2023 all vehicles that reach a certain age are retired and replaced with ZEV vehicles.

### *Business As Usual (BAU)*

As shown in Figure 5, under the BAU scenario the fleet of passenger vehicles continues to be predominantly composed of gasoline vehicles. As shown in Figure 6, the $CO_2$ emissions decrease slightly over time in the BAU case, owing to a natural replacement of retired vehicles and new demand with less emissions-intensive gasoline passenger vehicles, ZEVs, and other AFVs.

Of course, the results from the simulated policies in the following sections will depend on the BAU assumptions. We leave as a future task the running of different BAU scenarios.

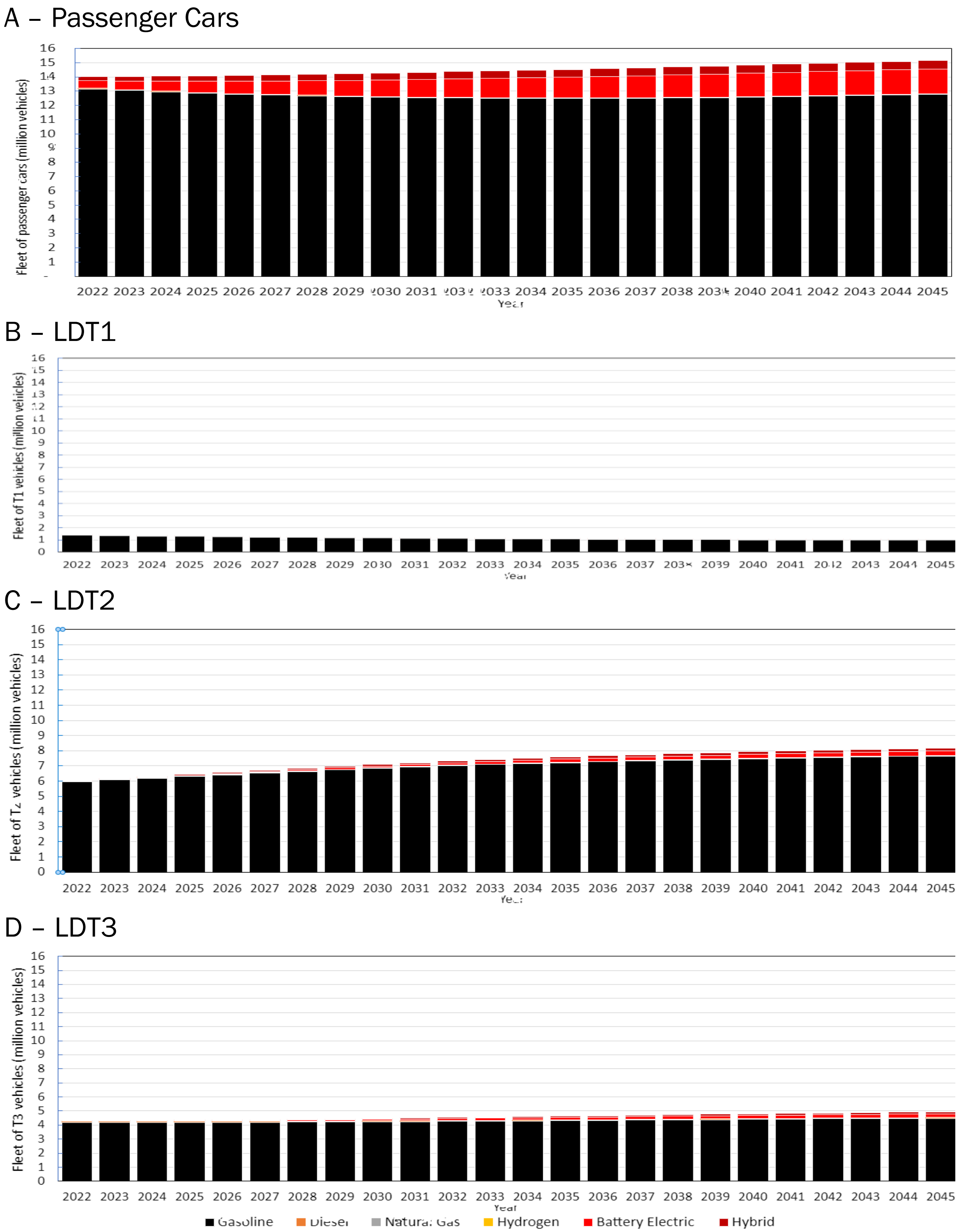
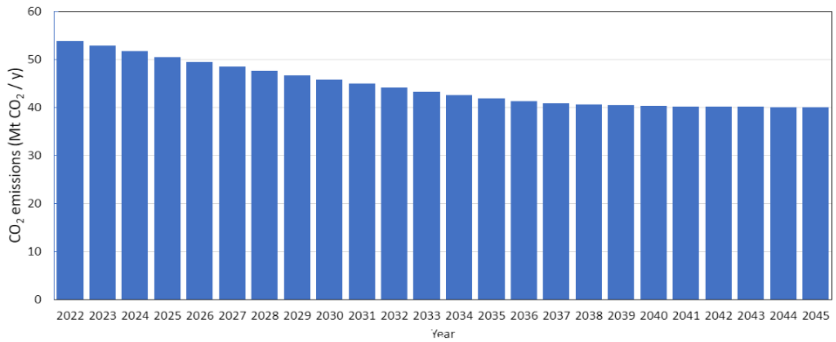
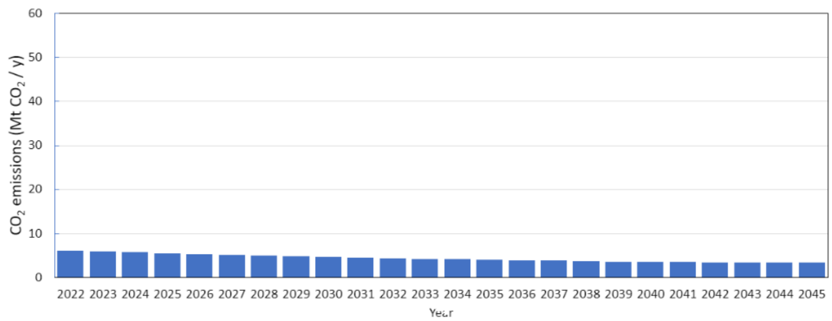



*Figure 5: Fleet composition of (A) passenger cars, (B) LDT1, (C) LDT2, and (D) LDT3 by vehicle type over time in the business-as-usual scenario.*

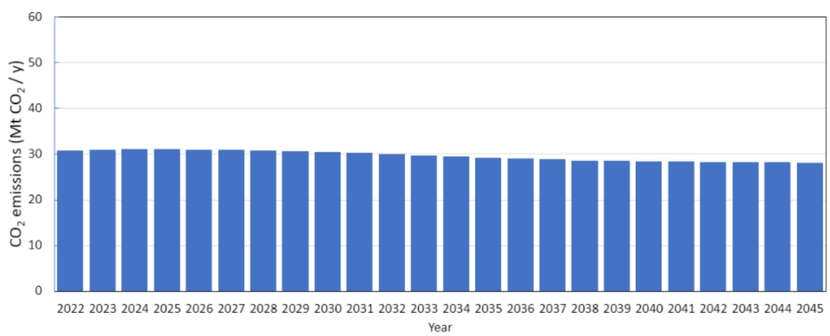
## A – Passenger Cars




## B – LDT1




## C – LDT2




## D – LDT3

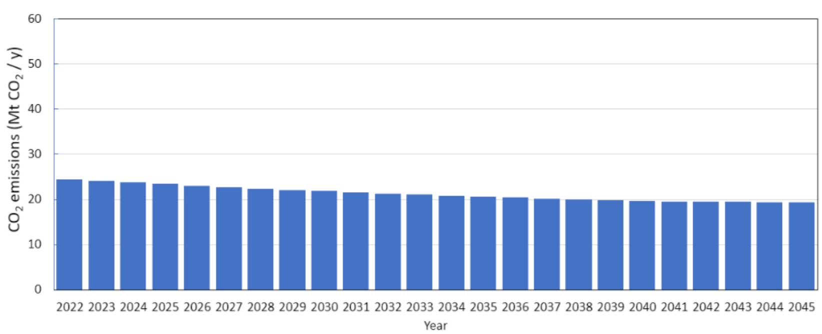



*Figure 6: $CO_2$ emissions per year (A) passenger cars, (B) LDT1, (C) LDT2, and (D) LDT3 by vehicle type over time under the business-as-usual scenario.*

### *Policy 1*

In policy 1, it is assumed that 100% of the sales of new vehicles would need to be ZEV starting in policy year *pol* and continuing for all following years until year 2045. Under this simulated policy, the stock of vehicles would continue to follow the business-as-usual scenario until the policy kicks in.

Scenarios are run for a policy start year ranging from 2023 to 2044. In Figure 7 the results for a policy onset of 2023, 2029, 2031, 2033, 2035, 2037, 2039, 2041, and 2043 are shown for illustration.

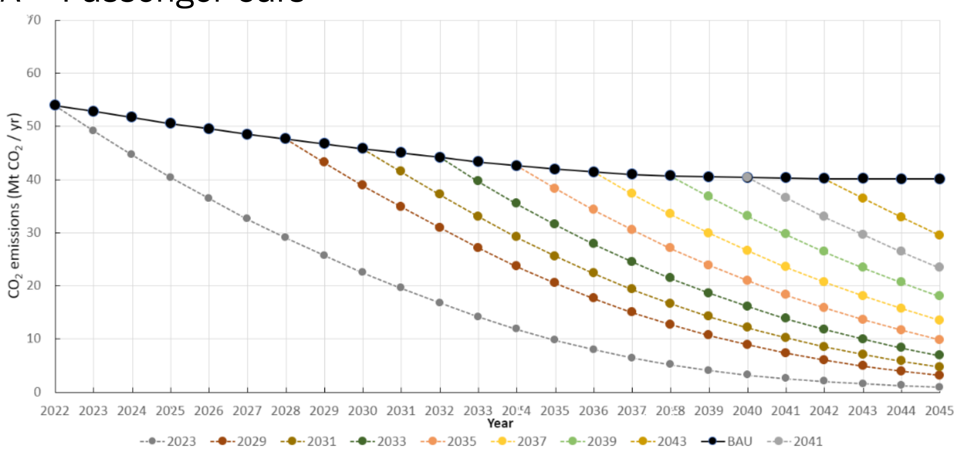
As shown in Figure 7A below, it is necessary to have all passenger car new vehicle sales be ZEV starting at the latest in 2023 and sustaining it for all years after that in order to achieve a fully decarbonized fleet of passenger vehicles by 2045. Delaying action until 2035 (and keeping on a BAU track until then) would not achieve a full decarbonization of the direct emissions of the passenger car fleet by 2045.

For LDT1, all sales would need to be ZEV by 2023 and sustained each year after that to achieve a near full decarbonization of the ICE gasoline emissions by 2045. For LDT2 and LDT3, the last year to achieve the policy goals is also 2023.

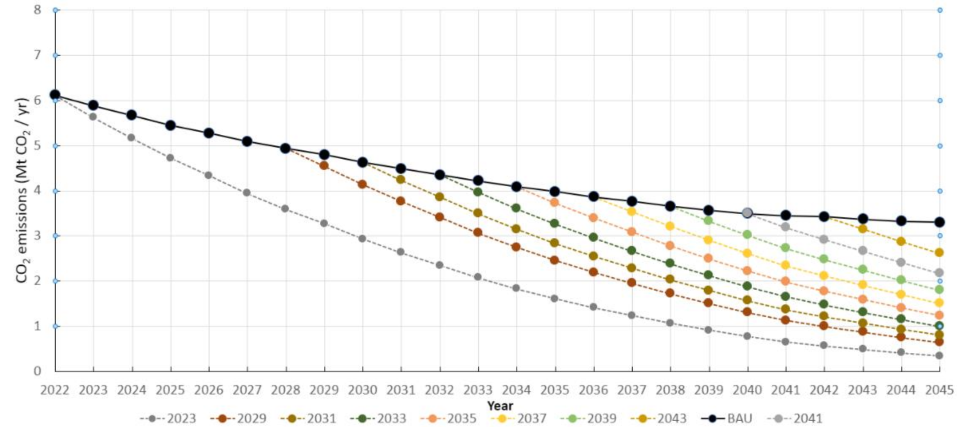
It is important to stress that these results are dependent on the assumptions about the future stock of vehicles under the BAU conditions, as well as other key assumptions regarding fuel efficiency, natural retirements, vehicles miles driven, etc.

While the specific first year for which 100% of the sales would be needed to be ZEV in order to meet a full decarbonization of the ICE gasoline fleet is uncertain, a key finding is that California may need to start having 100% of the sales being ZEV before 2035.

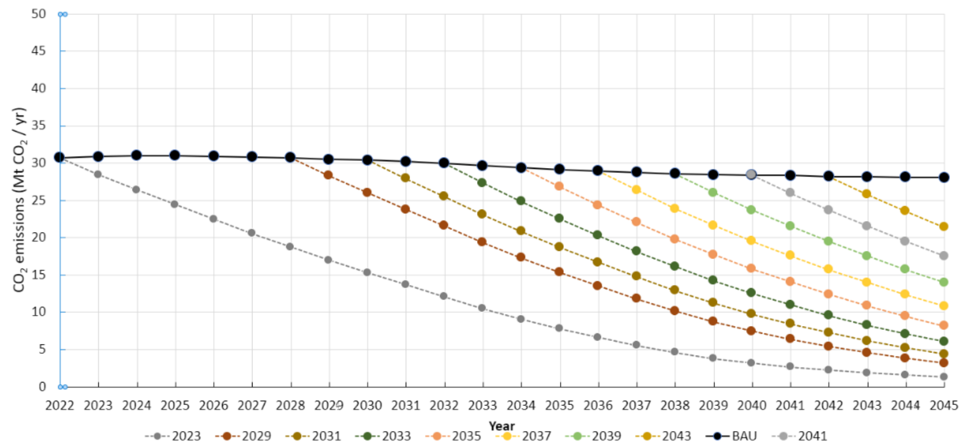
A – Passenger Cars



B – LDT1




C – LDT2




D – LDT3

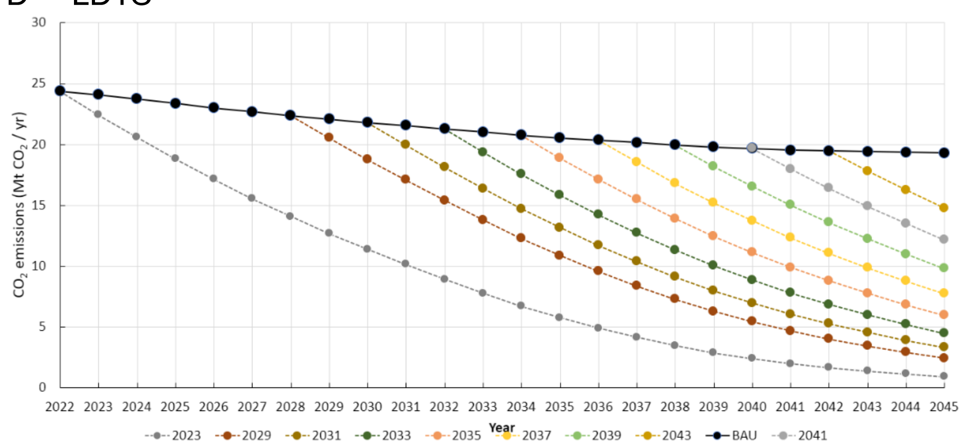



*Figure 7: Emissions of (A) passenger cars, (B) LDT1, (C) LDT2, and (D) LDT3 over time as a function of a policy onset year. The black markings correspond to BAU emissions. The other data series, from left to right, correspond to a policy onset year of 2023, 2029, 2031, 2033, 2035, 2037, 2039, 2041, and 2043. The policy simulated corresponds to 100% ZEV sales on and after the policy onset year. It is assumed that the BAU fleet is followed until the policy onset year.*

Figure 7 shows the cumulative $CO_2$ emissions that could be avoided between 2023 and 2045 as a function of the policy onset year.

For passenger cars, if ZEVs accounted for 100% of sales from 2023 onwards, it would be possible to reduce the cumulative tailpipe emissions between now and 2045 by 53% as compared to the BAU, with similar values holding for LDT1, LDT2 and LDT3.

Note that this assumes that the business-as-usual path is followed with a switch to 100% ZEVs in the policy onset year. To improve over this simplifying assumption, consider policy B, described below.

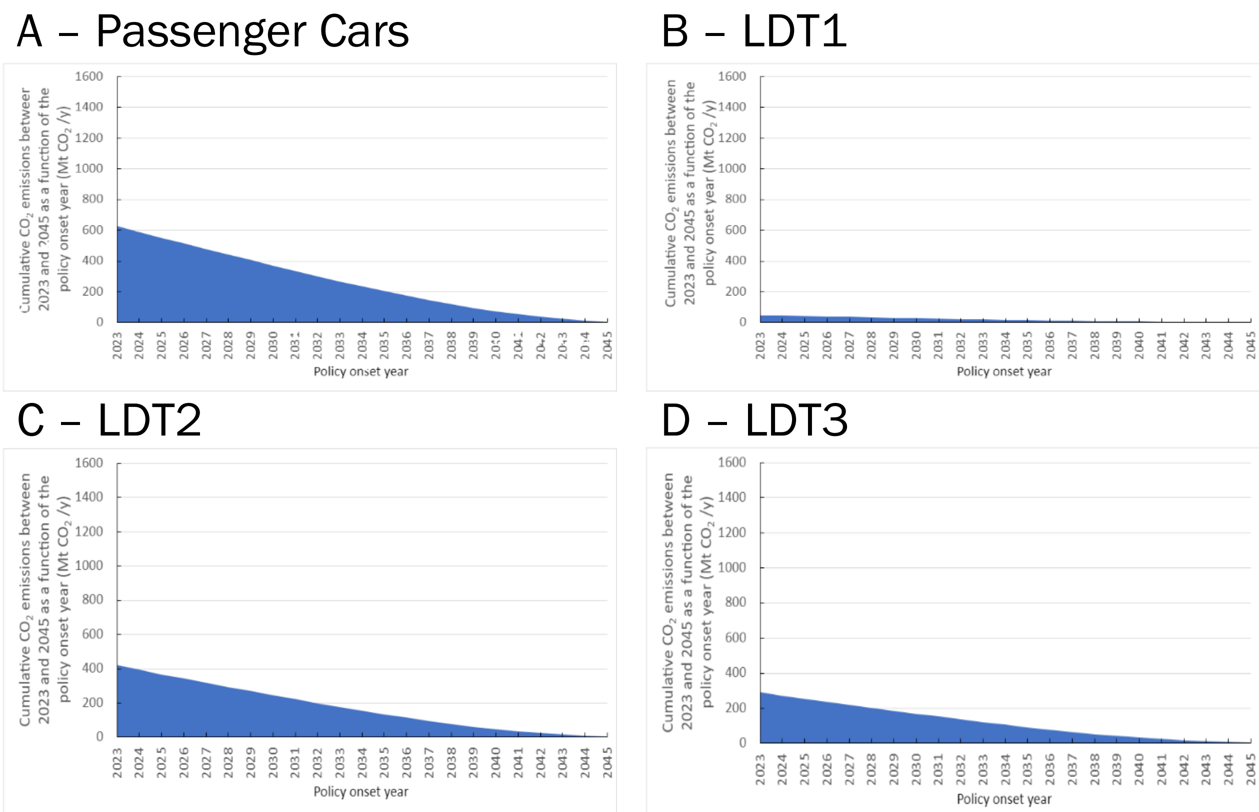


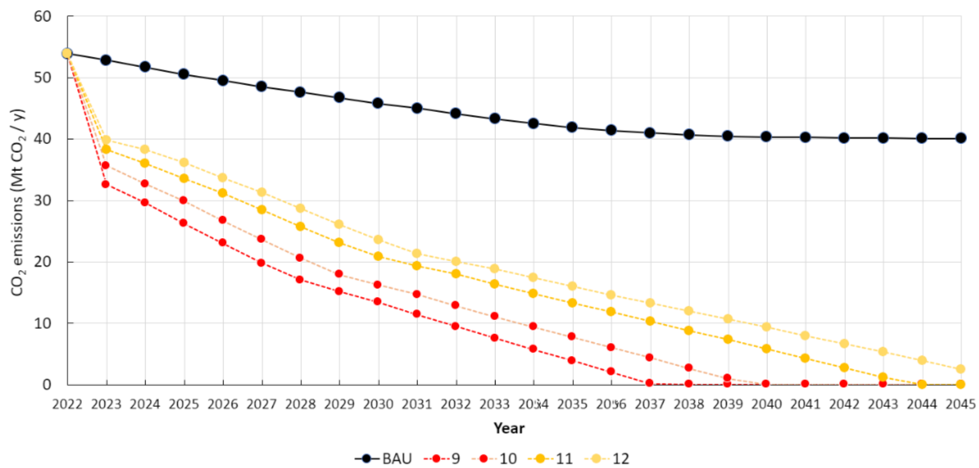

*Figure 7: Cumulative emissions reductions for (A) passenger cars, (B) LDT1, (C) LDT2, and (D) LDT3 between 2023 and 2045 as a function of the policy onset year.*

*Policy 2*

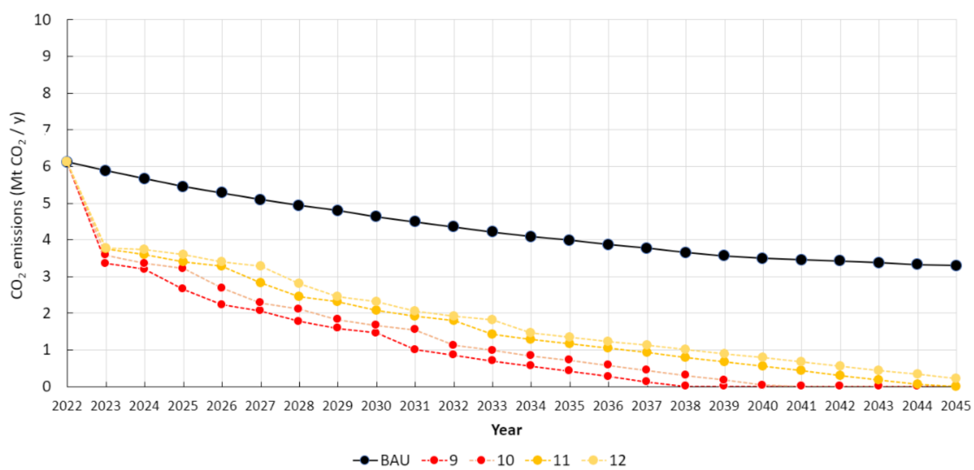
In policy 2, the annual emissions of $CO_2$ avoided are simulated assuming that in 2023 all vehicles of age *a* or older are retired and replaced with ZEV vehicles.  Emissions reductions for values of age *a* of 9, 10, 11, and 12 are illustrated below.

As shown in Figure 9, if starting in 2023 all LDVs and LDTs that are 9 years old or older are retired every year, California would likely be able to achieve a full decarbonization of passenger cars by 2045.

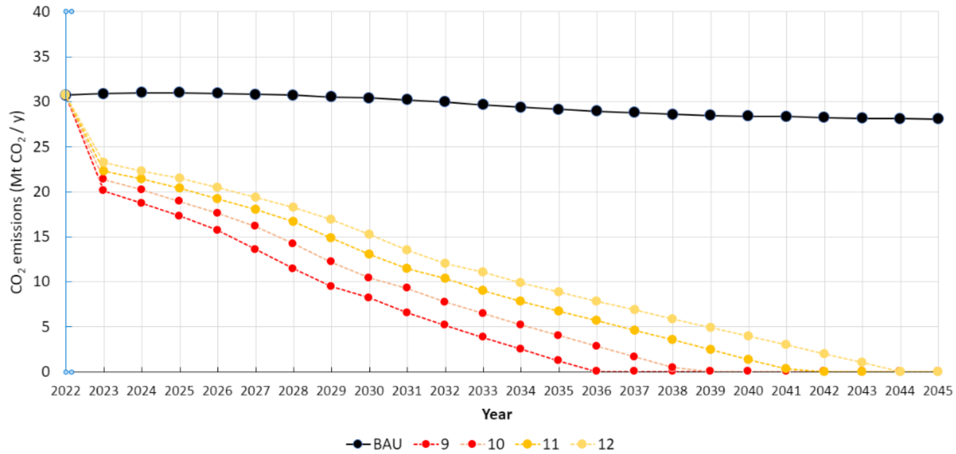
A – Passenger Cars




B – LDT1



C – LDT2




D – LDT3

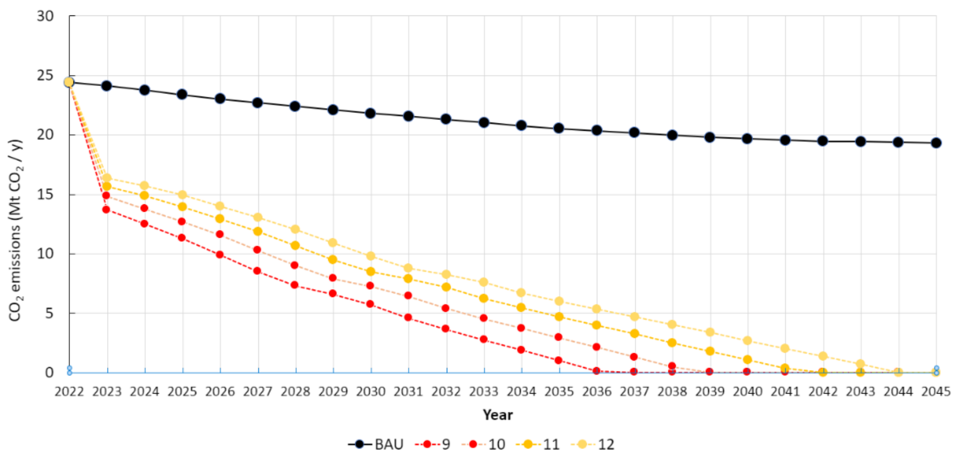



*Figure 9: Emissions of the fleet of (a) passenger cars, (b) LDT1, (c)LDT2, and (d) LDT3 over time for Policy 2. In Policy 2, starting in 2023, all vehicles of age a or older are retired (for ages 9, 10, 11 or 12). Vehicles retired are replaced with ZEVs.*

## Heavy Duty Vehicles

### *Model, data, and assumptions*

2019 is the base year for the model and the initial stock is taken from the EMFAC [16]. The initial stock is determined by summing the number of vehicles by vehicle type and fuel type in calendar year 2019. The vintage profile (distribution of stock across vehicle ages) is assumed to be the same across fuel types and is determined by calculating the percentage of vehicles of each age in 2019 based on the vehicle model year, as shown in Figure 10.

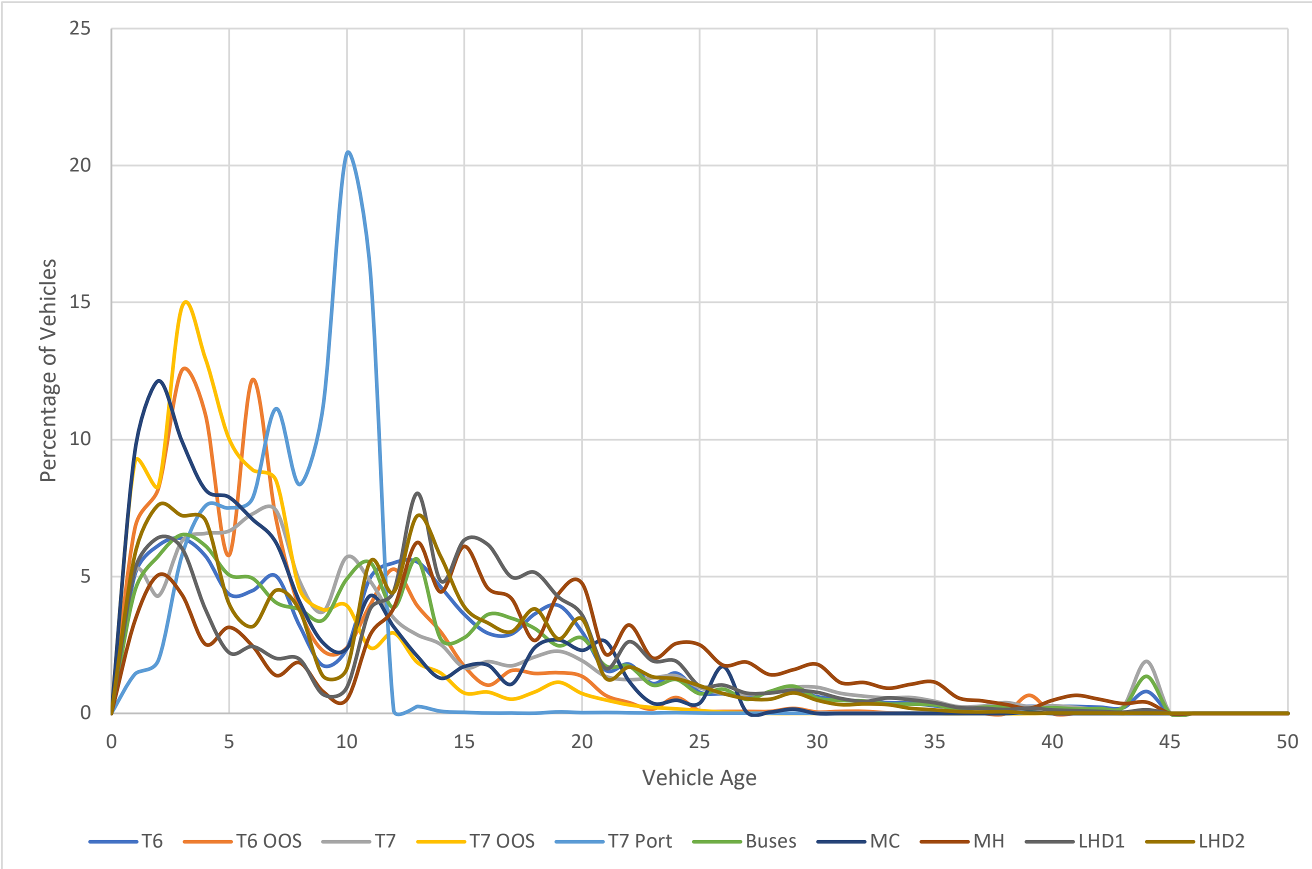



*Figure 10: Vintage profile of HDVs in 2019.*

Fuel economy of new vehicles is determined by dividing the total VMT by the total fuel consumption for each vehicle type and fuel in 2019. For model years less than or equal to 2019, the calculated fuel economy for the specific model year is used. For future model years, it is assumed that the fuel economy is equal to the fuel economy of new vehicles of that same type in 2019. For certain fuel and vehicle type combinations, there is no data for 2019. In nearly all cases, there is no data available for battery electric and hydrogen fuel cell vehicles. To estimate fuel economies for these vehicles, fuel economy ratios are taken from Lee et al [20] and Lieu et al [21] and multiplied by the diesel fuel economy. For buses, the BEV and FCEV efficiencies are taken from AC Transit's 5X5 study [22]. For vehicle types missing data for diesel, gasoline, or natural gas fuel economy, assumed efficiencies are the same as for the vehicle type with the closest fuel economy in fuel types for which data exists.

This study did not have direct data for vehicle sales, and instead uses the number of one-year old vehicles in 2019 as a proxy for new vehicle sales. Year-one vehicles are used instead of year-zero vehicles as the EMFAC data is based on DMV data which is collected in October, which would exclude some vehicles. This number does not account for vehicles which are initially sold in another state and then subsequently sold or registered in California. This exchange of vehicles is accounted for by adjusting the survival profiles rather than altering the sales estimates. For all scenarios (described below), it is assumed that the total number of sales each year grows by rates that match the growth of one-year old vehicle stock in EMFAC's Fleet Database. Sales growth rates vary by vehicle type, and the distribution of sales among the different fuel types is defined for each scenario.

Survival profiles (Figure 11) are used to determine the number of vehicle retirements in each year. Survival profiles are estimated for each vehicle category by fitting historical vehicle age data from 2000 to 2019 from EMFAC's Fleet Database. For many vehicle categories, new vehicles enter the fleet from out of state. Without data that specifies retirements or sales directly, it is impossible to distinguish between the two when attributing net changes to the fleet. To address this issue, an effective survival profile is calculated rather than a true survival profile assuming that the survival rate does not decrease until the age at which retirements exceed sales.

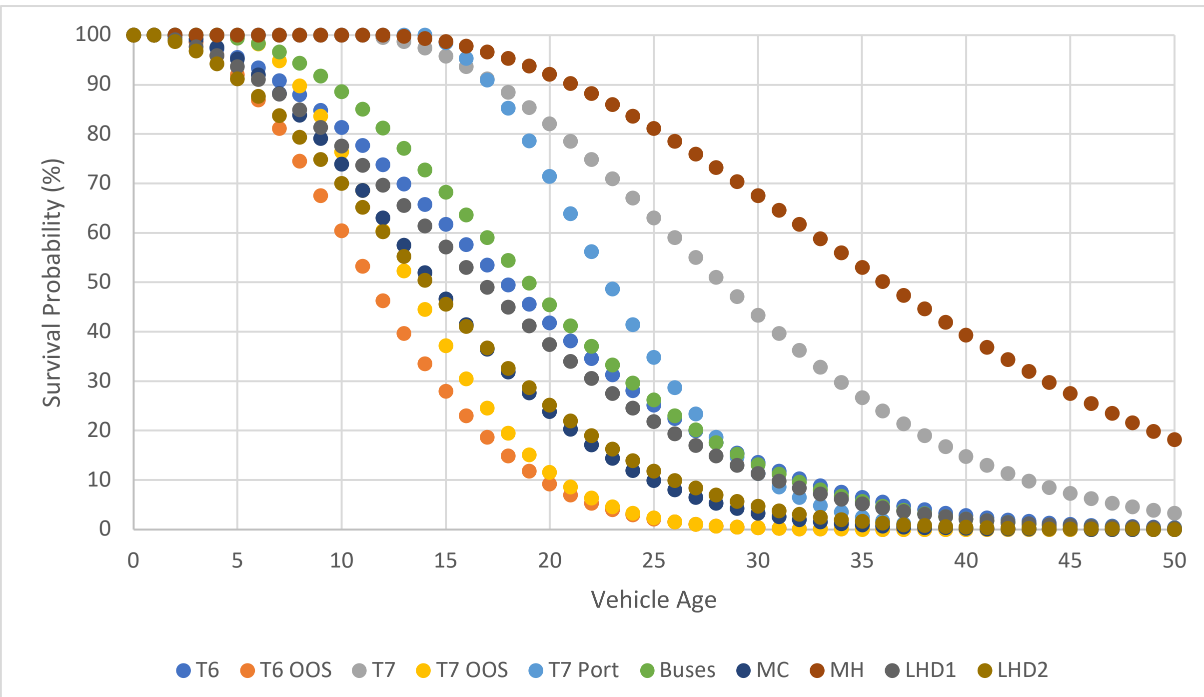



*Figure 11: Survival profiles of HDVs.*

In general, older vehicles are not driven as much as newer vehicles. For each vehicle category, the VMT degradation profile (Figure 12) is determined based on historical data from 2000 to 2019. For most categories, an exponential fit is used. For categories where there is no clear pattern (T6 OOS, T7 Port, and MC), a constant VMT at all ages is used. For LHD1 and LHD2 a logarithmic degradation is assumed.

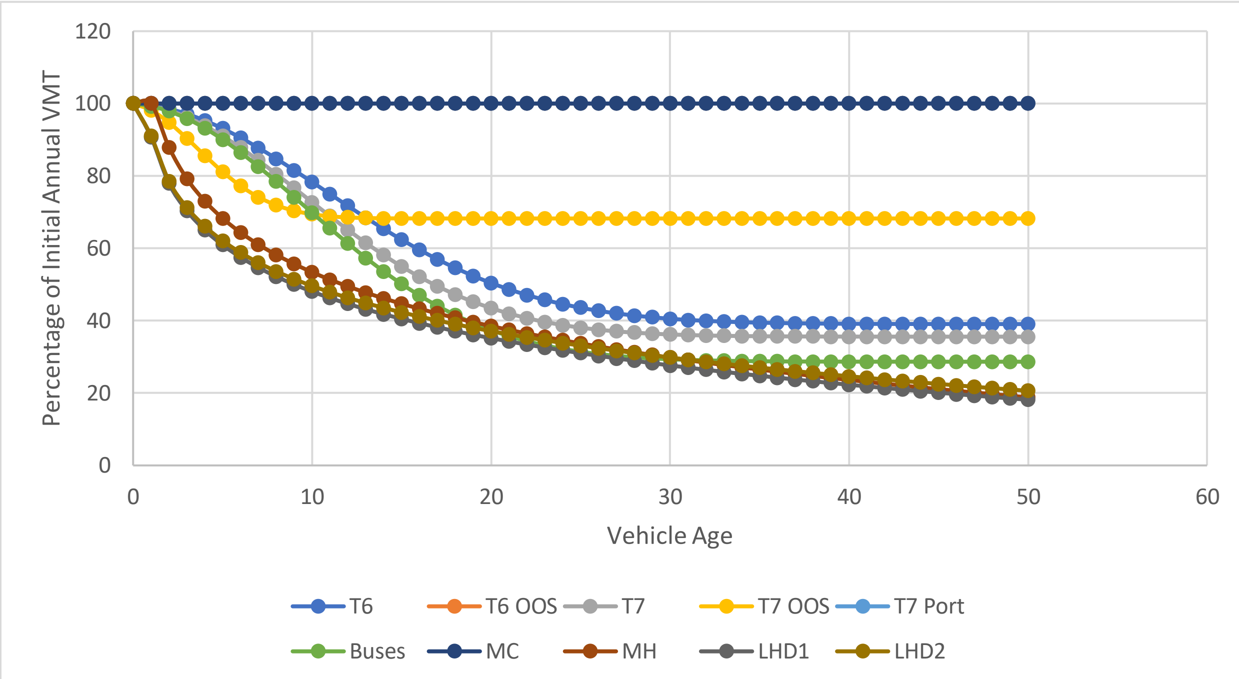



*Figure 12: VMT decrease as a function of vehicle age for Heavy-Duty Vehicles.*

Four scenarios are considered: one business as usual (BAU) scenario, and three illustrative decarbonization scenarios. In each of the decarbonization scenarios, sales and retirements of each vehicle type are adjusted to reach zero carbon emissions by 2045. This equates to the entire vehicle stock being ZEVs by 2045. In each decarbonization scenario, the total vehicle stock for each vehicle type is assumed to remain the same as in the BAU scenario, but the sales percentage of ZEVs is adjusted to reach 100% by 2045.

Adjusting sales alone is not sufficient to reach zero ICE vehicles, as older ICE vehicles will remain on the road even after sales are entirely ZEVs. To account for this, early retirement of older ICE vehicles is forced in the model. In the heavy-duty decarbonization scenarios, a ban of ICE vehicles greater than fifteen years old is implemented starting in 2035, and a ban of all ICE vehicles is implemented in 2045. Rather than assuming that all vehicles meeting this criterion will be retired at once, a five-year phase-in period in which a fraction of vehicles that will be impacted by the ban are retired each year is assumed. To make up for the large number of early retirements, each vehicle that is retired early is replaced by a new ZEV vehicle. If replacing all vehicles that are retired early would result in an increase in vehicle stock compared to the BAU case, all sales are reduced proportionately such that the stock remains the same. Three decarbonization scenarios are considered: high electrification; high hydrogen; and a scenario of mixed hydrogen and electrification. These scenarios are not intended to represent the best solution and should not be taken as recommendations, but rather they demonstrate the impact of different approaches that could be taken to reach zero emissions by 2045.

### *Business as Usual*

The BAU scenario is based on EMFAC's fleet projections through 2050. The annual sales growth rate is estimated by calculating the percent change in the number of one-year old vehicles in each year of EMFAC's projections. Retirements are calculated based on the survival profiles discussed above. As shown in Figure 13, the BAU scenario includes significant growth in EV sales but does not include sales of hydrogen FCEVs. The percentage of diesel and gasoline sales decrease, but do not go to zero.

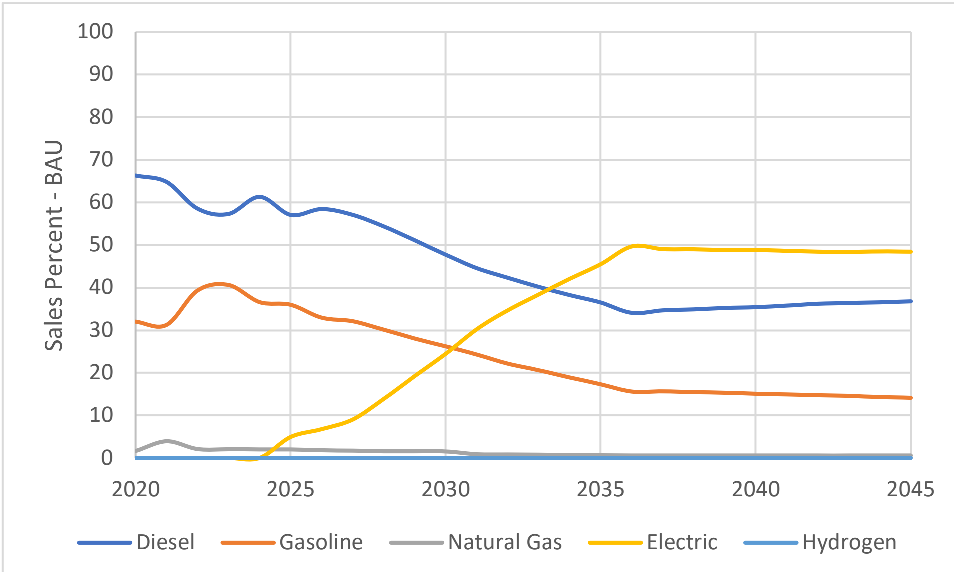
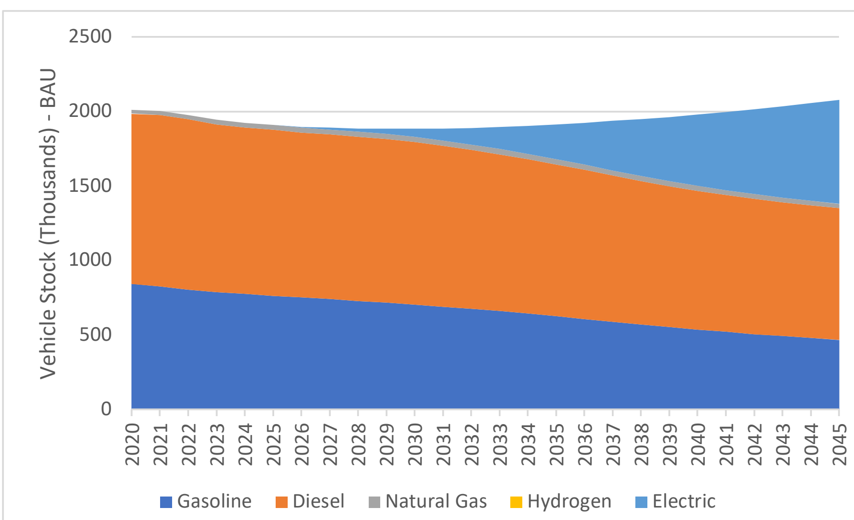
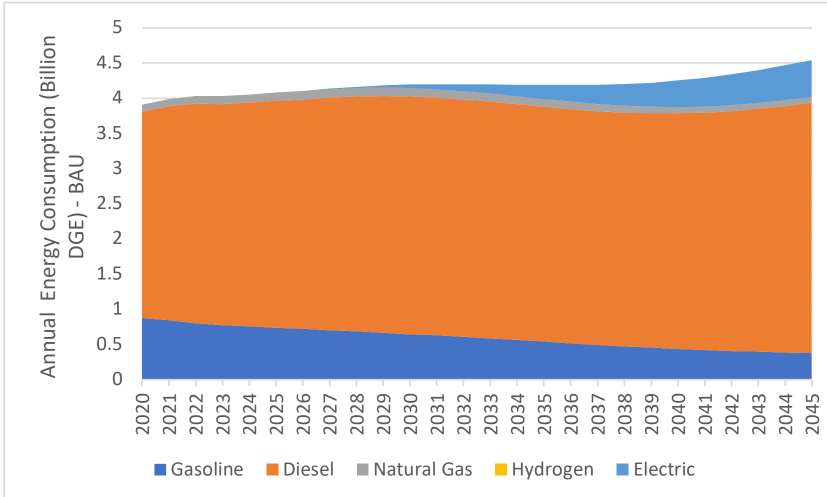



*Figure 13: Sales percentage of HDVs in the BAU scenario.*

The total vehicle stock increases slightly by 2045 (Figure 14), reaching about 2.07 million vehicles (from 2.05 million today). The initial decrease in total stock reflects a predicted decrease in overall vehicle sales in 2020 and 2021 due to the COVID-19 pandemic.





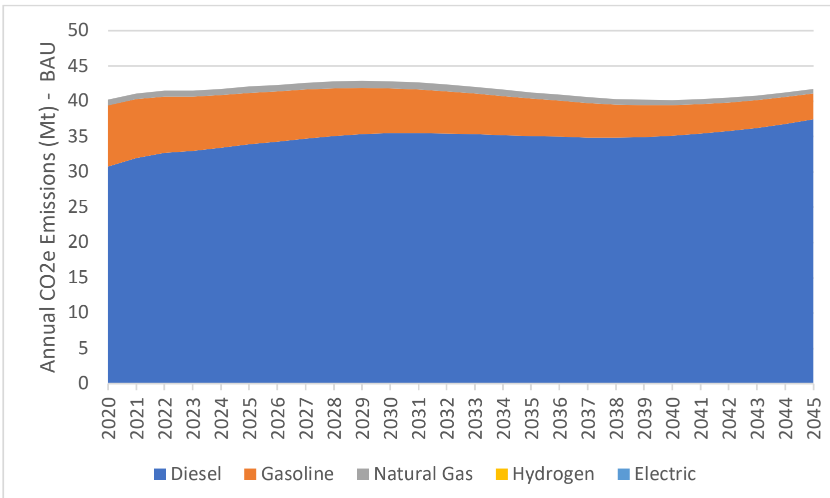




*Figure 14: BAU HDV fleet evolution, fuel consumption, and $CO_2$ emissions.*

In the BAU scenario (Figure 15), by 2045 only 34% of heavy-duty vehicles are ZEVs, with 1.4 million heavy duty ICE vehicles still on the road. This results in 41.8 Mt $CO_2$e in 2045. The slight increase in emissions compared to the 2019 baseline emissions is caused by both the increase in the total number of vehicles and the increase in the number of heavier, lower fuel-efficiency vehicles relative to smaller higher-efficiency vehicles.

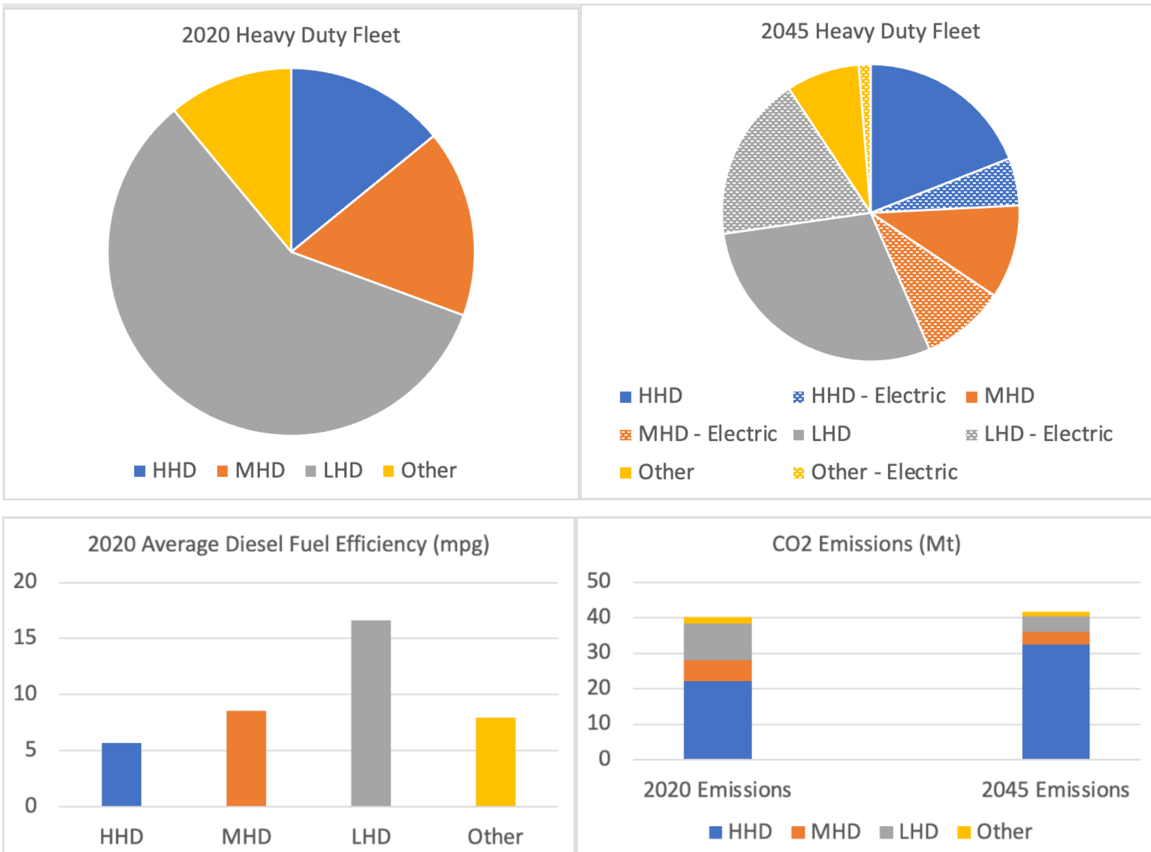



*Figure 15: Fleet Composition, fuel efficiency, and $CO_2$ emissions of the HDV fleet in the BAU scenario.*

In 2019, heavy-heavy duty vehicles make up only 14% of the heavy-duty fleet, while our projections suggest that in 2045 they make up 24% of the fleet. Conversely, light heavy-duty vehicles make up 59% of the fleet in 2019, and only 47% of the fleet in 2045. Diesel fuel efficiency of heavy-heavy duty vehicles is around 5.7 miles/DGE, while fuel efficiency for the light heavy-duty vehicles is much higher (ranging from 14.6 - 17.1 miles/DGE). In the BAU scenario, there is more electrification of the light heavy-duty fleet than of the heavy-heavy duty fleet.

54% of the electric vehicles projected in 2045 are light-heavy duty vehicles (LHD1 and LHD2), while only 15% are heavy-heavy duty vehicles. This demonstrates that electrifying the "low hanging fruit" will not be sufficient to reduce emissions.

In the BAU scenario, the electrification of light-heavy duty vehicles is not enough to offset the increase in the proportion of heavy-heavy duty vehicles. One important caveat to this discussion is that improvements in fuel economy in either ICE vehicles or BEV or FCEV vehicles has not been considered. By 2045, the efficiency of heavy-duty ICE vehicles will likely have improved, and this effect may be reduced. However, even with significant improvements to fuel economy, there would still be substantial carbon emissions in 2045 under the BAU assumptions.

### *High Electrification Scenario*

In the high electrification scenario, it is assumed that 100% of new ZEV sales are BEVs. In this scenario nearly all categories of heavy-duty vehicles reach 100% BEV sales by 2040, except for long-haul trucks (T6 OOS and T7 OOS), which do not reach 100% until 2045. The model allows these categories to reach 100% later because of the difficulties associated with electrifying long-haul trucks, namely battery range and weight. The proportion of sales in each year is shown in Figure 16.

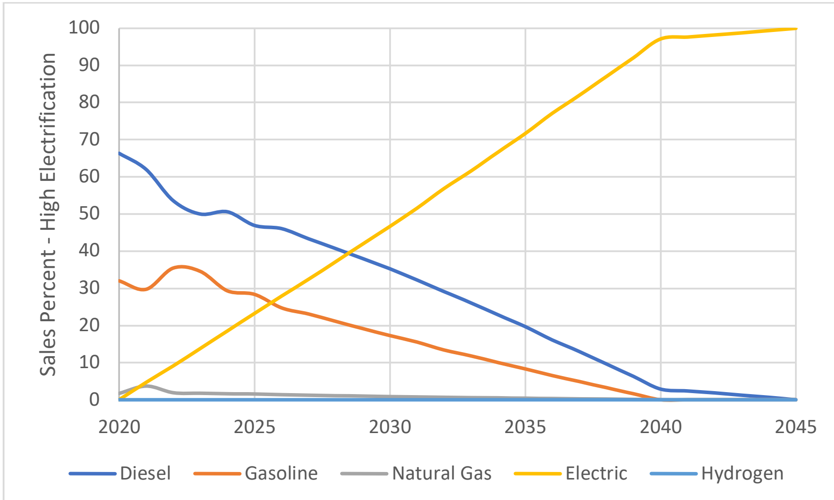



*Figure 16: Sales Percentage of Heavy-Duty Vehicles in the High Electrification Scenario.*

The resulting vehicle stock is shown in Figure 17. The stock of BEV vehicles increases slowly until 2030, when the rate of increase speeds up. This scenario clearly represents a large increase in the penetration of electric HDVs. As there are currently very few electric HDVs, this would be a challenge for the industry to achieve.

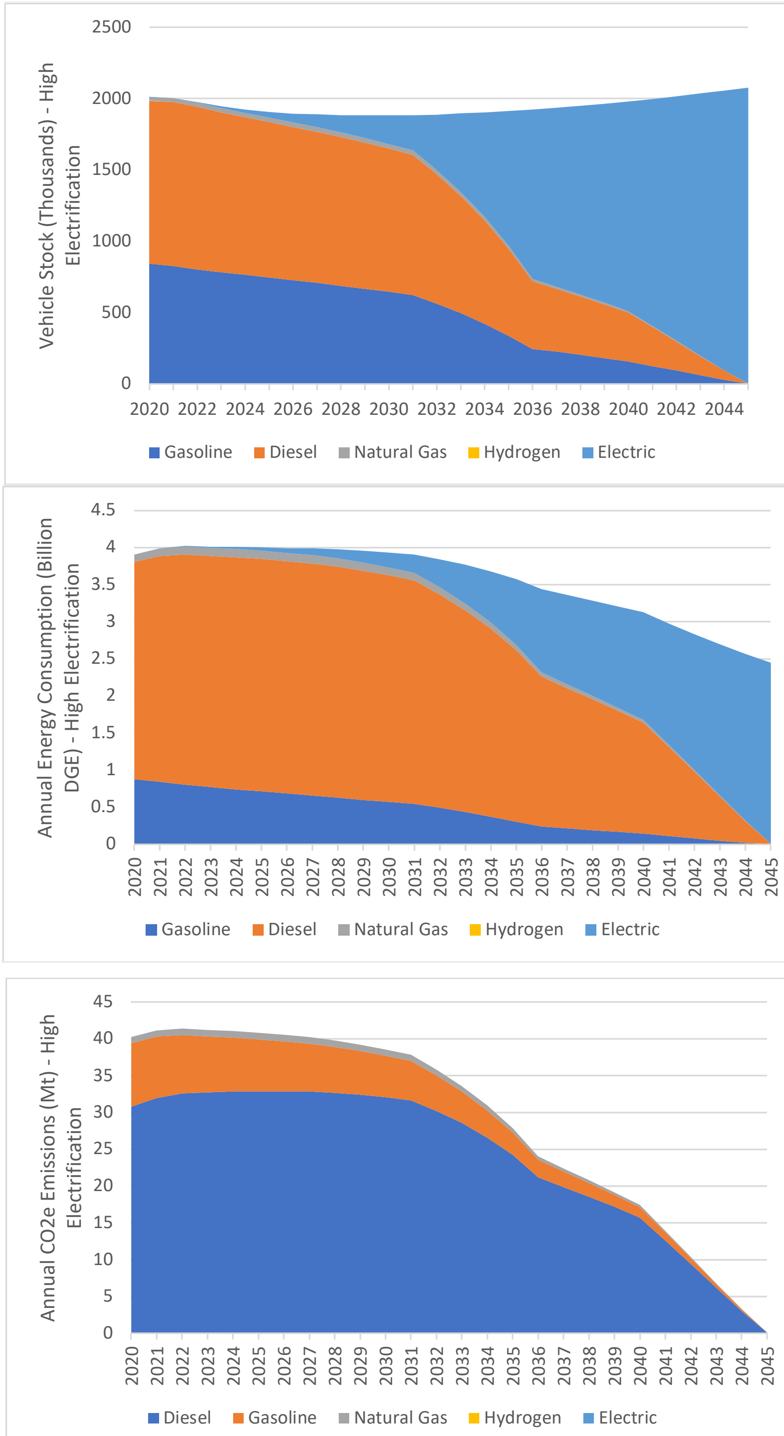



*Figure 17: HDV fleet evolution, fuel consumption, and $CO_2$ emissions in the high electrification scenario.*

Switching to electric vehicles results in a significant decrease in the total on-vehicle energy consumption in the heavy-duty transportation sector, as shown in Figure 18. This is due to BEVs being significantly more efficient than their ICE counterparts. However, this will require a significant increase in the amount of electricity that the power sector will have to provide (discussed further in following sections).

## *High Hydrogen Scenario*

The high hydrogen scenario is identical to the high electrification scenario, but with ZEV sales being 100% FCEVs instead of BEVs. The proportion of sales in each year is shown in Figure 18. As in the High Electrification scenario, the sales percentages of diesel and gasoline decrease and are replaced by hydrogen.

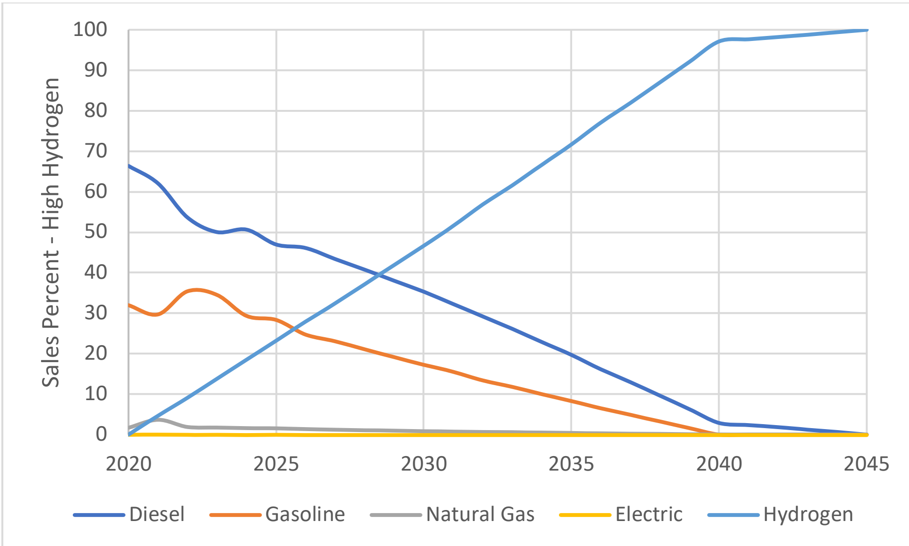
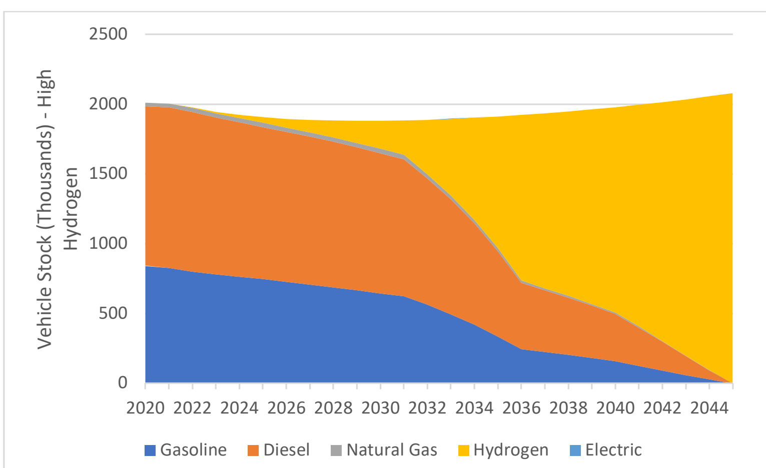



*Figure 8: Sales percentage of HDVs in the high hydrogen scenario.*

The resulting vehicle stock is shown in Figure19. Again, this is similar to the high electrification scenario, but with hydrogen making up the ZEV component. This scenario would likely be an even greater challenge for the industry, as hydrogen fuel cell vehicles are currently rare in the heavy-duty fleet, and not available for many specific types of vehicles.



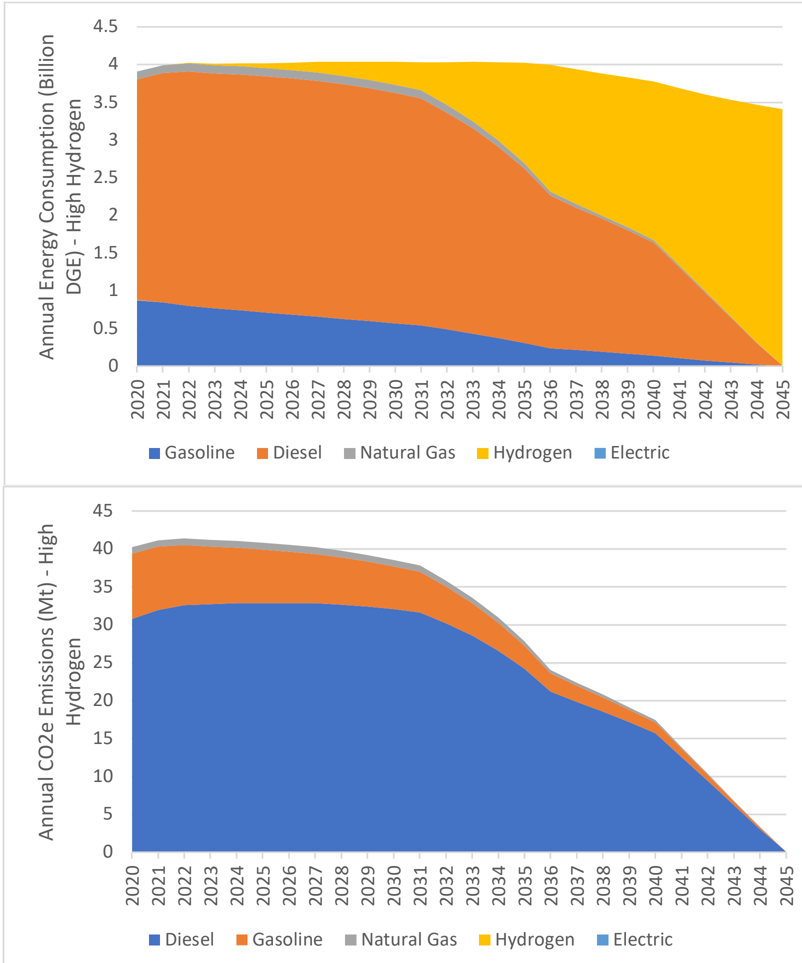



*Figure 19: HDV fleet evolution, fuel consumption, and $CO_2$ emissions in the high hydrogen scenario.*

The total on-vehicle energy consumption, shown in Figure 20, is lower than in the BAU scenario, but higher than in the High Electrification scenario. This is due to FCEVs being more efficient than ICE vehicles, but less efficient than BEVs.

### *Mixed Scenario*

The final decarbonization scenario is a mix of hydrogen and electric vehicles. The trajectory of ZEV sales in total remains the same as in the other two decarbonization scenarios, as do the phased early retirements. Figure 20 shows the split between FCEVs and BEVs for each vehicle type.

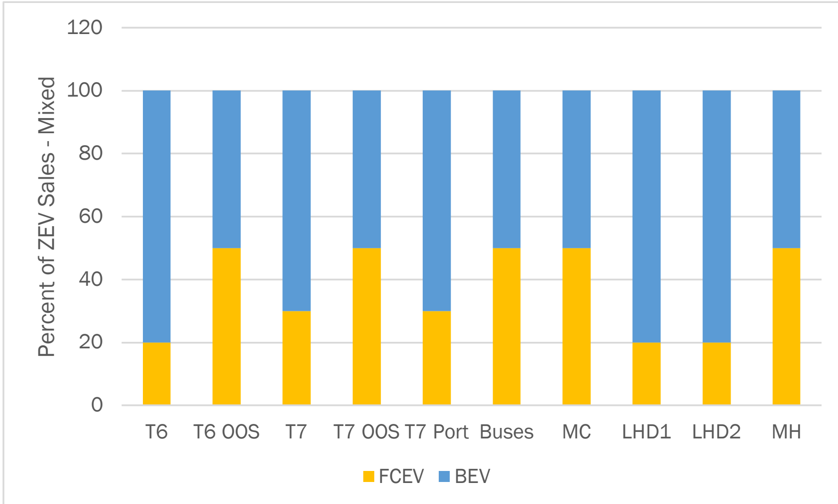



*Figure 20: Heavy Duty ZEV sales percentage in the mixed scenario.*

For all categories, at least half of ZEV sales are BEVs. For vehicle types that require longer ranges or that carry heavier loads, a higher fraction of FCEVs is assumed. For smaller vehicles, a higher percentage of BEVs is assumed. Figure 21 shows the overall distribution of sales.

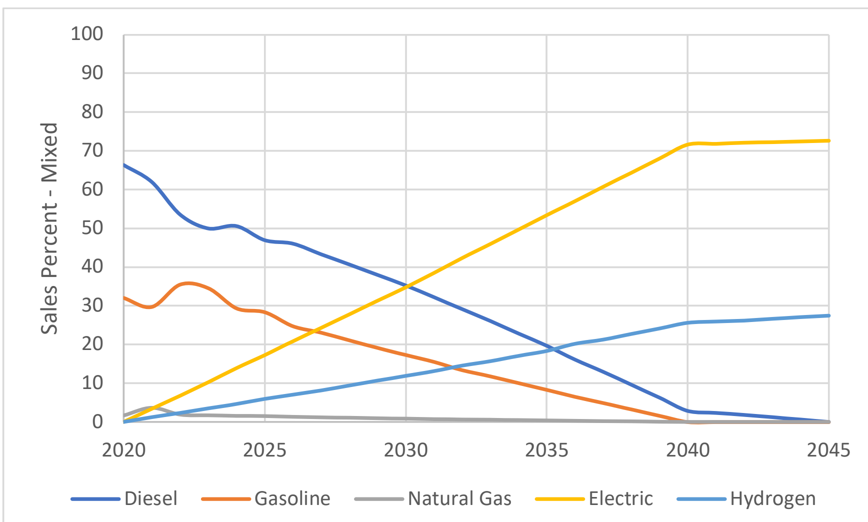



*Figure 21: Sales percentage of HDVs in the mixed scenario.*

The resulting vehicle stock is shown in Figure 22. BEVs still make up the majority of vehicles by 2045, but meeting some of the demand with FCEVs reduces the jump in BEVs compared to current levels. Even so, this scenario is likely to be challenging, as it would require significant increases in both ZEV and FCEV production, vast buildout of charging and refueling infrastructure, and generous incentives.

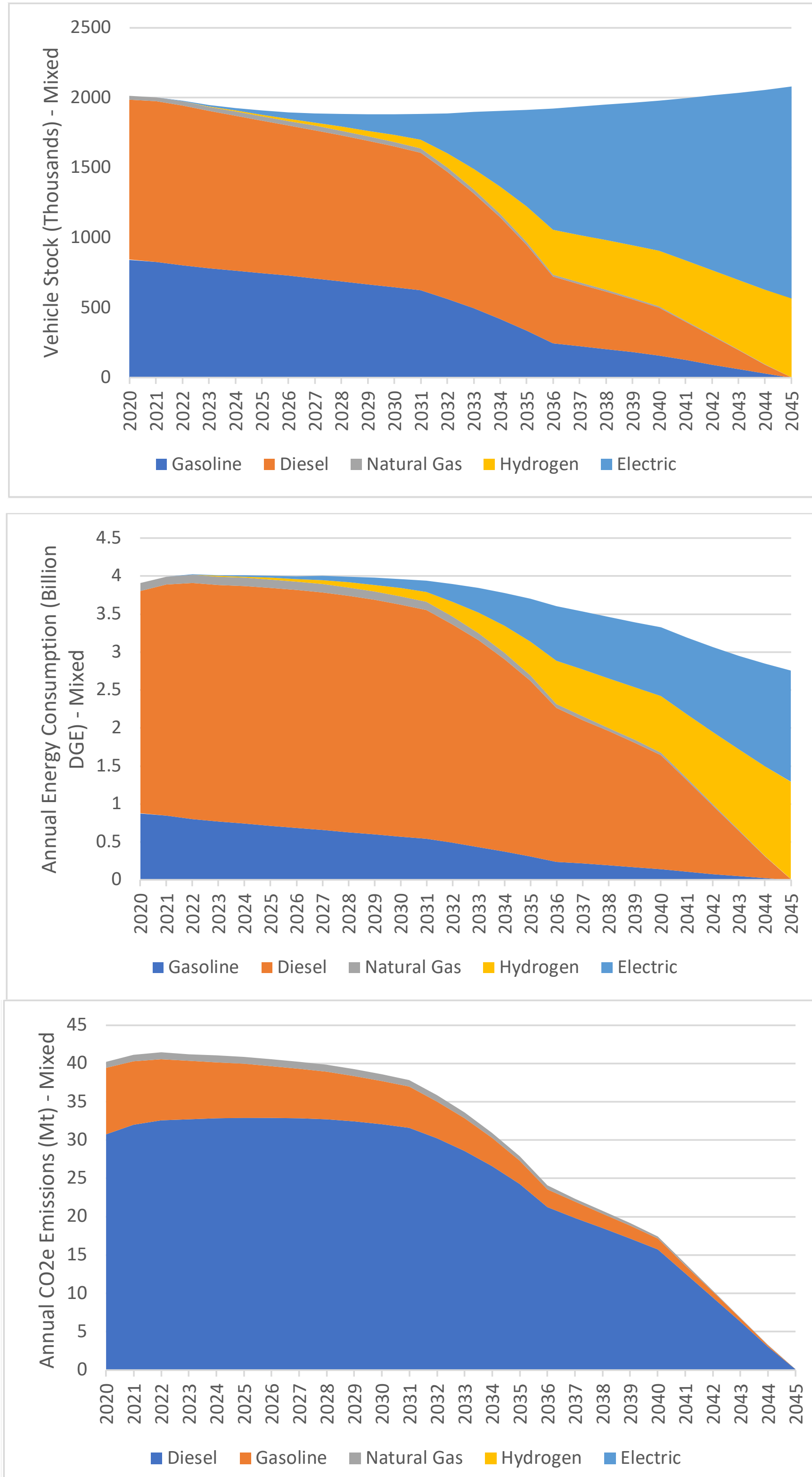



*Figure 22: HDV fleet evolution, fuel consumption, and $CO_2$ emissions in the mixed scenario.*

The total on-vehicle energy required in this scenario is lower than the total energy in the high hydrogen and BAU scenarios, but higher than the total energy in the high electrification scenario.

### *Scenario Comparison*

In each of the decarbonization scenarios, a significant increase in hydrogen or electricity production would be required to meet the heavy-duty transportation demand. Figure 23 shows the amount of electricity required in each scenario, and Figure 24 shows the amount of hydrogen required.

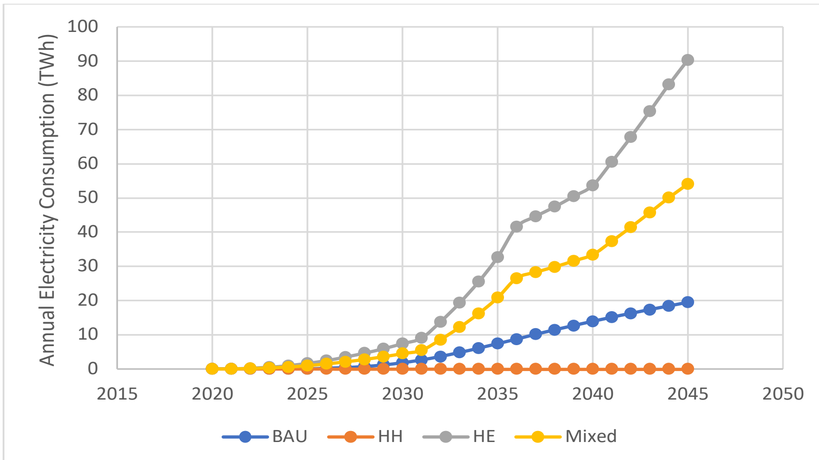



*Figure 23: Electricity consumption in each scenario.*

In the high electrification scenario, about 90 TWh of electricity will be required annually by 2045. In the mixed scenario, this is reduced to about 55 TWh of electricity per year. Both of these are significantly more than the electricity required in the BAU scenario (20 TWh). All of these would have a significant impact on California's electricity demand. Current annual electricity consumption in California is approximately 250 TWh [23]. The high electrification scenario for HDV only would add an additional 36% of demand, while the BAU scenario would add an additional 8%.

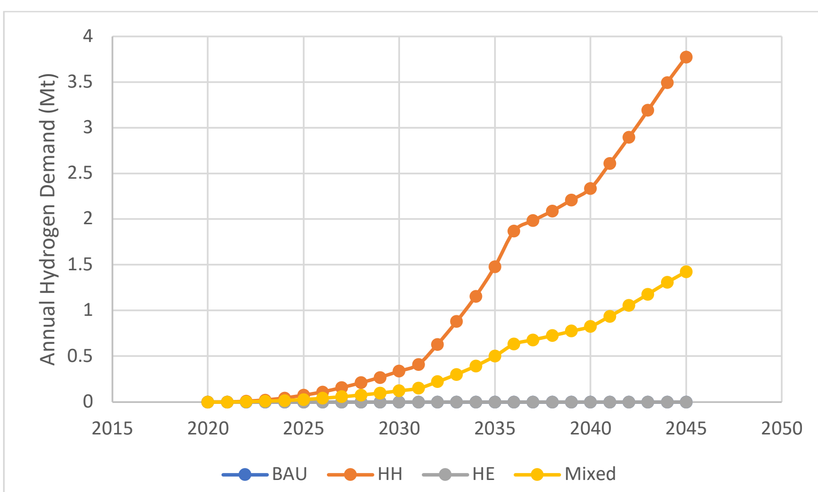



*Figure 24: Heavy-duty hydrogen demand in each scenario.*

In the high hydrogen scenario, nearly 4 Mt of hydrogen would be required. In comparison, in the mixed scenario, only about 1.5 Mt would be required. The hydrogen required in the high hydrogen scenario would exceed current state production, which is about 2 Mt [24].

This suggests that this scenario is unlikely to be achievable unless there is a significant increase in hydrogen production capacity. Even the mixed scenario represents a significant hydrogen demand.

Figure 25 shows the Annual $CO_2$ emissions in the 4 scenarios. Each of the decarbonization scenarios (high electrification, high hydrogen, mixed) results in the same amount of tailpipe $CO_2$ emissions as they have the same number of ZEVs. However, this does not take into account upstream emissions. Emissions from FCEVs will depend on the method used to produce the hydrogen. Emissions from BEVs will depend on the emissions intensity of the electric grid. Given the current emissions intensity of the grid, it is likely that upstream electricity emissions would be small compared to the tailpipe emissions for HDVs.

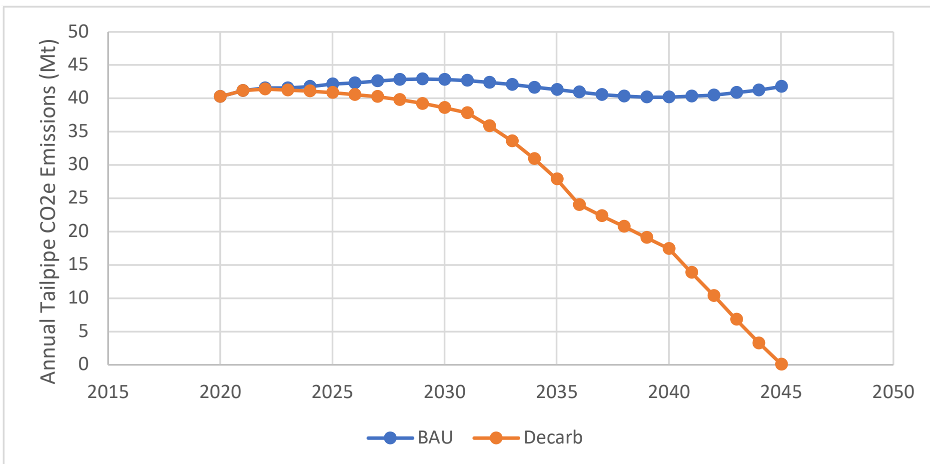



*Figure 25: HDV annual $CO_2e$ emissions in BAU and three decarbonization scenarios. The three scenarios (high electrification, high hydrogen, and mixed) all have the same tailpipe emission because they have the same number of ZEVS. Emissions associated with electricity generation or hydrogen manufacture are not included here.*

Figure 26 shows the cumulative tailpipe $CO_2$ emissions in each scenario. Once again, the emissions of the decarbonization scenarios are all the same. Cumulative emissions in the BAU scenario reach approximately 1100 Mt $CO_2$, while the decarbonization scenarios level out at approximately 750 Mt.

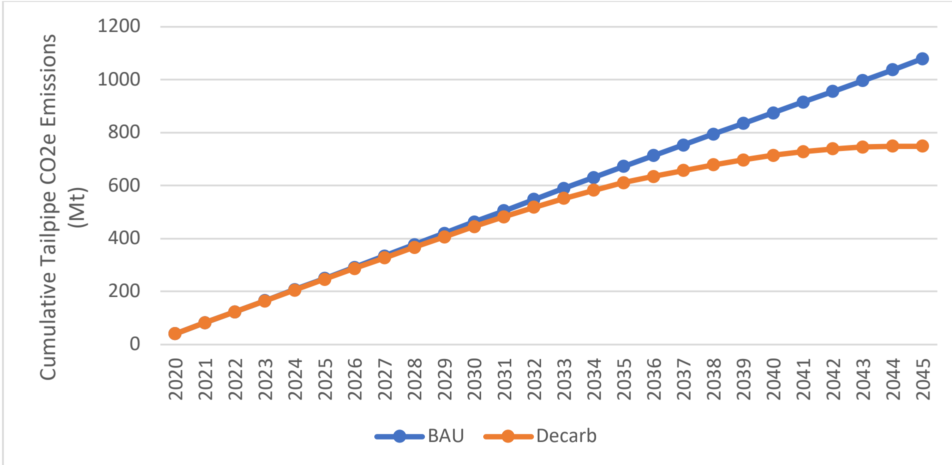



*Figure 26: HDV cumulative $CO_2e$ emissions in BAU and decarbonization scenarios.*

## Total Cost of Ownership

To assess the current and future costs of ZEVs, a total cost of ownership (TCO) analysis was performed for a variety of vehicle types. For both LDVs and HDVs, the total cost consists of three components: capital cost, fuel cost, and maintenance costs, all in present value terms.

Details of each analysis are described in the following sections. The Present Value (PV) of the costs of each vehicle were computed to compare vehicles using the following equation:

$$NPV = Capital\ Costs + \sum_{n=0}^{N} \frac{Operational\ and\ Maintainence\ Costs}{(1+i)^n}$$

Where price of the vehicle paid upfront constitute capital costs (inclusive of battery and vehicle manufacturing), operational costs are annual costs of fueling the vehicle, and maintenance costs are annual costs of maintaining and repairing the vehicle. $N$ is the total lifetime of analysis and $i$ is the discount rate.

### Light Duty Vehicles and Light Duty Trucks

Light duty electric vehicles reached 6.5% of the sales in 2020. However, that is a long way to 100% LDV electric vehicle sales by 2035, which is the goal set out in the Governor's Executive Order.

According to studies of EV adoption, range anxiety and higher costs of ownership are the two main reasons behind the low uptake of electric vehicles in United States[25] [26] [27] [28].

A simple total of cost of ownership tool was developed that incorporates three main sources of costs for LDVs – production costs (mainly battery and vehicle manufacturing costs), fuel costs (electricity and gasoline costs), and maintenance and repair costs. The results are presented for year 2020. Qualitative trends that may emerge in the future are discussed. The effect of changing vehicle miles traveled, discount rate, lifetime (operational life of the vehicle), battery cost, as well as fuel prices for electricity and gasoline are explored.

Costs of insurance, dealers profit, resale value, and subsidies that may be available to alternative fuel vehicles are not included.

### *Capital costs*

Capital costs are fixed, one-time costs incurred on the purchase and registration of the vehicle. While capital cost can have a lot of other costs baked in – manufacturing the vehicle, dealer profit, and in the future, setting up a charging infrastructure at residences – this model only considers manufacturing costs with Manufacturer's Suggested Retail Price (MSRP) as a proxy.

For battery electric vehicles, the battery cost and vehicle manufacturing cost are considered separately. Costs for ICE vehicles are modeled without any subcomponents. The motivation for this breakdown analysis is to explore the effect of battery cost improvements on comparative TCO across vehicles.

According to a report and raw data published by Mack Institute of Innovation Management at University of Pennsylvania [29], the industry-wide average cost of battery packs in 2020 was US $144 per kWh. Of course, in practice there is a wide range associated with the different batteries, but that value is used as a proxy in this simple analysis.

Battery costs are subtracted from MSRP of existing BEV models to approximate other manufacturing vehicle costs.

A sensitivity analysis on costs per kWh of battery as well as battery costs as percentage of total MSRP was performed to test the impact on TCO.

### *Fuel costs*

Fuel costs are computed using the equation below, where *i* is the discount rate, and *n* is the year:

$$Fuel\ costs(i) = \frac{fuel\ price * \frac{VMT}{fuel\ economy}}{(1+i)^n}$$

Variable costs include the cost of re-fueling the vehicles. For BEVs, energy consumption per mile was calculated using the vehicle's battery capacity (kWh) and range (miles); For ICE vehicles, the publicly released combined fuel economy numbers from U.S Department of Energy, Office of Energy Efficiency and Renewable Energy [30] was assumed. Adding total miles per year yields the fuel consumption for a year. Current values of gasoline and electricity are from EIA's annual retail gasoline price for California [31] and EIA's California State Energy Profile [32].

PG&E residential electricity rates (using the average values for California [33]) are assumed. Assumptions for current fuel costs are outlined in Table 7.

### *Maintenance costs*

Maintenance and repair costs differ between ICE and BEV vehicles. A new study by the Office of Energy Efficiency and Renewable Energy by the Department of Energy [34] shows that LDV BEVs have 40% lower scheduled maintenance costs compared to ICE vehicles, and

35% lower than hybrid gasoline vehicles. This is due to BEVs not having costs associated with engine oil, timing belt, oxygen sensor, spark plugs, etc. An ICE vehicle has scheduled maintenance costs of $0.101 per mile, while hybrid gasoline vehicle and BEV have maintenance costs of $0.094 per mile and $0.061 per mile [34]. Maintenance and repair costs usually increase with the age of the vehicle, but for this analysis they are assumed to be constant.

| | Unit | 2020 |
|---|---|---|
| Battery Cost | $/kWh | 144 |
| Electricity price (residential) | $/kWh | 0.24 |
| Electricity price (commercial) | $/kWh | 0.143 |
| Gasoline price | $/gallon | 4 |
| Maintenance & Repair Costs (ICE) | $/mile | 0.064 |
| Maintenance & Repair Costs (BEV) | $/mile | 0.04288 |

*Table 6: Assumptions used in the results below regarding capital (battery cost), operational (electricity price, gasoline price) and maintenance cost and repair costs for 2020.*

### *Results*

In the results shown below in Figure 27, the discount rate, lifetime, and annual miles are held at 7%, 10 years, and 12,000 miles per year for all years. According to this simple analysis and under this set of assumptions (battery costs at $144/kWh, electricity rate of 24 cents/kWh and gasoline price of $4 /gallon) in 2020 the Toyota Corolla and the Toyota RAV4 SUV would be slightly cheaper to buy and operate than the least cost BEV (the Nissan Leaf). The Tesla Model 3 (long range all wheel drive) has the highest cost in present value terms. Higher gasoline prices, such as the ones we are currently seeing, would make the Leaf the least expensive option to purchase and use.

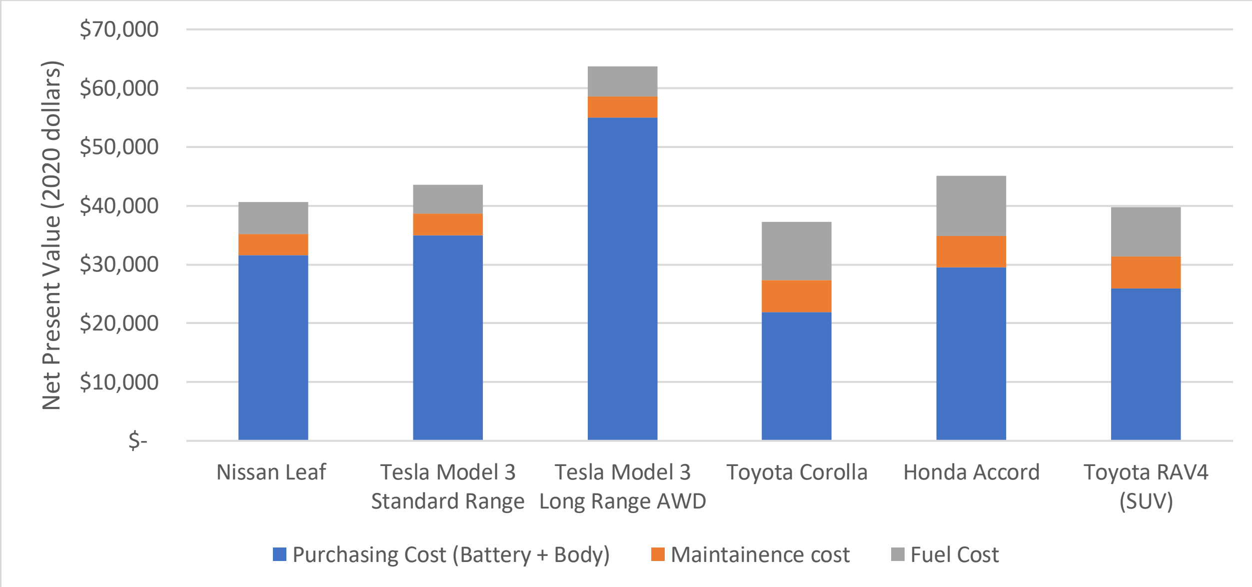



*Figure 27: Present Value for year 2020 for BEV and ICE vehicles, using a lifetime of 10 years and a discount rate of 7%. Electricity price is assumed to be 24 cents/kWh and gasoline price is assumed to be $4/gallon. Assumed lifetime is 10 years and vehicles run 12,000 miles a year.*

### *Limitations*

This TCO analysis doesn't include other components of costs such as insurance, profits of various agents, resale value, taxes and subsidies. In this analysis, manufacturing costs are based on a simplistic analysis between battery and rest of the vehicle manufacturing. A full tear down analysis which incorporates more accurate subcomponents and learning rates was outside the scope of the analysis. Costs of replacing batteries are not included.

## Heavy Duty Vehicles

Three primary components are considered in the heavy duty TCO analysis: vehicle purchase cost, fuel cost, and maintenance cost. For a selection of vehicle types, the total annualized cost based on a representative vehicle is calculated. Vehicle prices and maintenance costs are from the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) TCO Calculator [35]. TCO is compared between diesel, battery electric, and hydrogen fuel cell vehicles.

### *Capital costs*

Each of the vehicle categories spans a range of vehicle weights and use cases. For each category a representative vehicle is selected and the vehicle purchase price is from the HVIP TCO Calculator [35]. Table 7 shows the capital cost assumptions for each vehicle type. For T6 and T7 vehicles, the same capital cost is assumed for both in-state and out-of-state vehicles, as well as for drayage vehicles. While it is likely that in practice the cost of these vehicles would have some variation, there is not sufficient data to distinguish between them. For buses, cost data from AC Transit's 5x5 Zero Emission Bus Study [22] is used. Cost data is unavailable for FCEV light heavy-duty vehicles, so the analysis is limited to diesel and BEVs for those categories.

| | LHD1 | LHD2 | T6 and T6 OOS | T7, T7 OOS and T7 Port | Buses |
|---|---|---|---|---|---|
| **Diesel** | $35k | $50K | $55K | $107k | $488k |
| **BEV** | $55k | $120k | $189k | $300k | $938k |
| **FCEV** | - | - | $250k | $375k | $1,156k |

*Table 7: Heavy Duty Vehicle Capital Costs in $2020 for year 2020.*

### *Fuel costs*

The fuel costs (diesel, electricity, and hydrogen) are impacted by three components: fuel price, VMT, and fuel economy, according to the following equation, where *i* is the discount rate, and *n* is the year.

$$Fuel\ costs(n) = \frac{fuel\ price * \frac{VMT}{fuel\ economy}}{(1+i)^n}$$

Fuel prices used in the analysis are shown in Table 8.

| Fuel | Price | Source |
|---|---|---|
| Diesel | $4.60/gal | Assumed CA price [24] |
| Electricity | $0.143/kWh | Average commercial rate [25] |
| Hydrogen | $6.00/kg | Optimistic estimate |

*Table 8: Fuel prices used for HDV TCO analysis.*

For each vehicle category the annual fuel costs are calculated based on VMT in each year and the fuel price. VMT is assumed to decrease in each year as the vehicle ages (as described in the fleet characterization section), and as a result the total fuel costs decrease as well.

Unlike VMT, fuel economy is assumed to remain constant over the lifetime of the vehicle. Fuel economy of new vehicles as specified in the fleet characterization section are used in the TCO analysis.

### *Maintenance costs*

Maintenance costs are the third component considered in the analysis. Like the capital costs, these costs are taken from the HVIP TCO Calculator [30] for each vehicle type, except for buses which are taken from the AC Transit study [12]. As with fuel costs, maintenance costs depend on VMT, and as such decrease in each year. Table 9 shows the maintenance costs per mile for each vehicle type.

| | LHD1 | LHD2 | T6 | T6 OOS | T7 | T7 OOS | T7 Port | Buses |
|---|---|---|---|---|---|---|---|---|
| Diesel | 0.18 | 0.199 | 0.299 | 0.299 | 0.443 | 0.443 | 0.443 | 0.54 |
| BEV | 0.097 | 0.104 | 0.157 | 0.157 | 0.233 | 0.233 | 0.233 | 0.9 |
| FCEV | - | - | 0.121 | 0.121 | 0.180 | 0.180 | 0.180 | 0.56 |

*Table 9: Maintenance costs for HDVs in $2020/mile.*

### *Results*

The present value for the cost of owning and operating these vehicles is shown in Figures 29 to 30. A discount rate of 5% is used for all vehicle categories. For each vehicle category, the average lifetime is based on the survival profiles described in the fleet characterization section which varies from 14 years to 28 years.

Light heavy duty BEVs are less expensive than diesel vehicles under this set of assumptions as shown in Figure28. This is due to the reduced fuel and maintenance costs in the BEVs. Currently, there are no available fuel cell vehicles. For many of the vehicle categories considered in this analysis, diesel vehicles are still the least expensive technology. This is due to the large difference in capital costs. The reduced maintenance and fuel costs are not sufficient to make up the difference. For vehicle categories with particularly high VMTs (namely, the out of state vehicles), BEVs are cost-competitive with diesel vehicles, but fuel cell vehicles remain too expensive. Reducing the price of hydrogen would reduce this disparity, but capital cost remains a large barrier to cost parity.

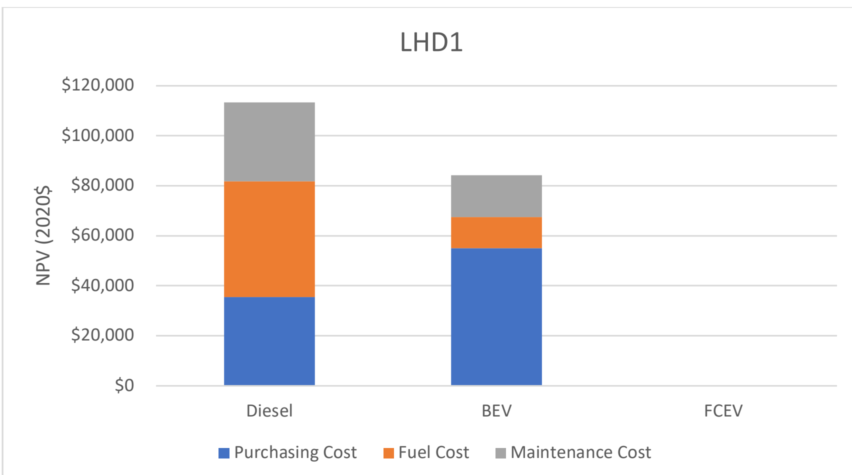



*Figure 28: Light-Heavy Duty TCO in 2020.*

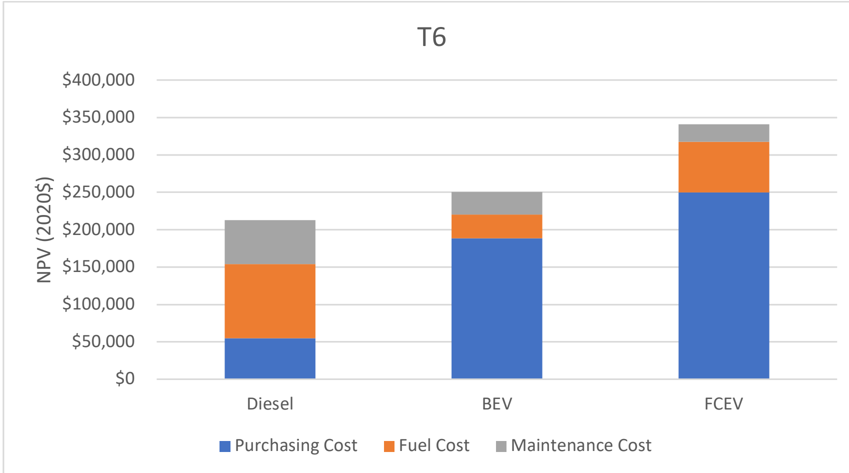



*Figure 29: Medium-Heavy Duty TCO in 2020.*

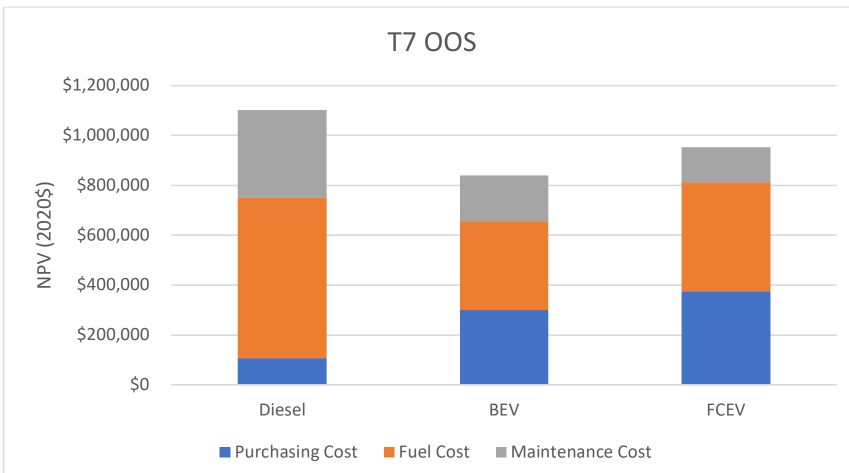



*Figure 30: Out of State Heavy-Heavy Duty TCO in 2020.*

### *Limitations*

Taxes, depreciation, insurance, and incentives are not included in these analyses. Incentives for battery electric or fuel cell vehicles have the potential to significantly decrease the capital cost of these vehicles. However, incentives are not guaranteed, and are therefore excluded here. Additionally, this analysis does not consider the range and battery size of the vehicle. The analysis shows that vehicles travelling longer distances (such as out-of-state trucks) are closer to cost-parity to diesel and battery models. However, this effect may be reduced if these vehicles require longer ranges and corresponding larger batteries to meet their needs. Further analysis of range requirements would be necessary to better understand this dynamic.

## Distributional Effects in LDV

In Figure 31, the percentage of BEVs in the 2019 vehicle fleet is shown by census tract block group vs. block group median income. The subset of block groups that are included in the EMFAC Fleet Database [18] and demographic data from the American Community Survey [36] are used in this analysis. Unsurprisingly, the BEV adoption is higher in census tracks that have higher median income. To successfully decarbonize the light duty vehicle fleet, access to EVs in medium and low-income communities is needed. High upfront vehicle cost, relying on the second-hand vehicles, lack of charging infrastructure in multi-family housing or for street parking, and high electricity rates are among some of the factors limiting adoption by these groups.

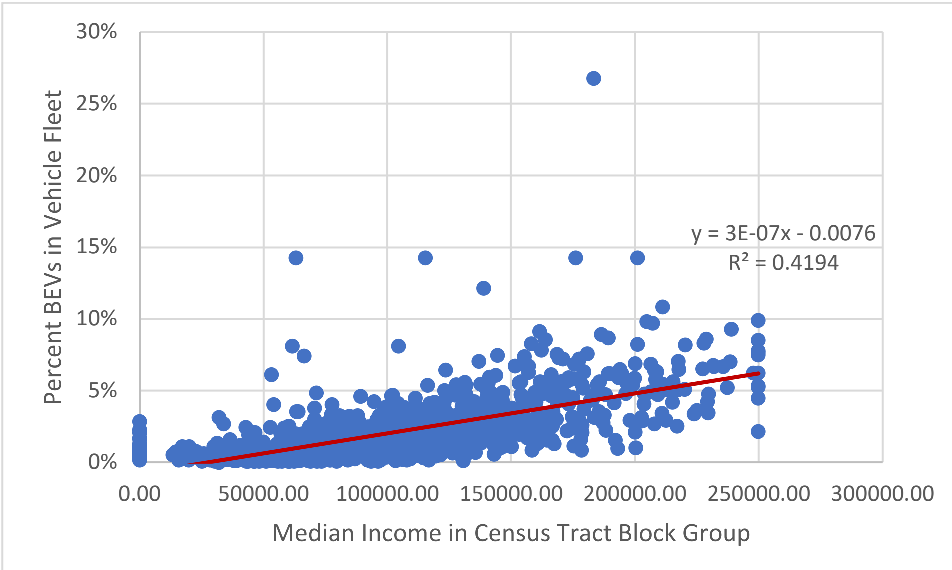



*Figure 31: Light duty BEV percentage by median income in CA Census Tract Block Groups.*

As described in the Fleet Turnover section, each of the decarbonization scenarios considered in this analysis requires early retirement of vehicles to reach zero emissions by 2045. This has the potential to disproportionately impact low-income communities and communities of color. An analysis of the average age of vehicles in EMFAC's Fleet Database compared to the median income of census tract block groups where the vehicles are located shows a negative correlation between mean vehicle age and median income (Figure 32). This suggests that block groups with lower incomes tend to have older vehicles registered within them. This dataset contains only a limited number of block groups, but other studies [37] suggest the trend holds outside of this particular dataset. This is likely to have racial justice implications as well, as median income and race are correlated. To ensure that these communities are not disproportionately burdened by early retirement requirements, additional policies and incentive programs will likely be needed.

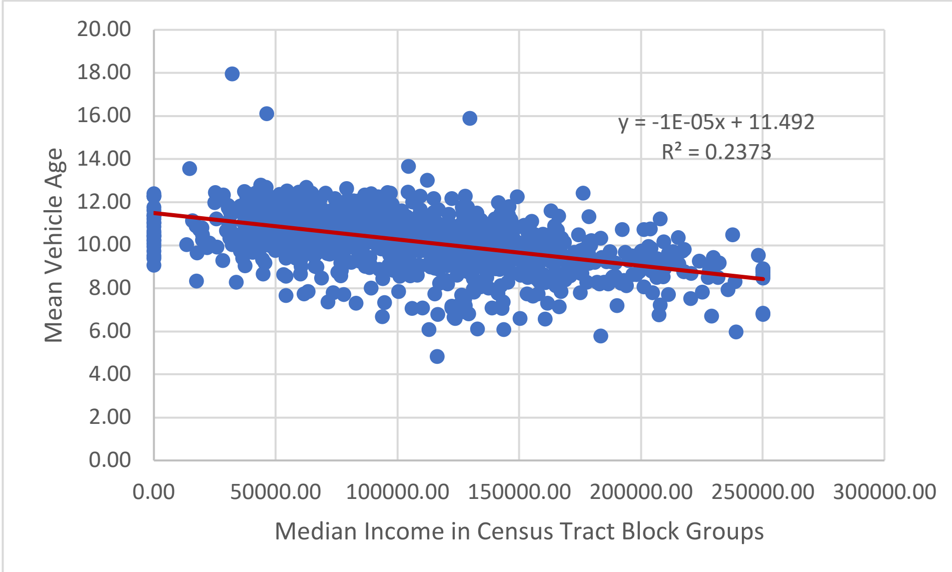



*Figure 32: Light duty mean vehicle age by median income of CA Census Tract Block Groups.*

Incentives are one way in which policy makers have attempted to improve access to EVs. While individual demographic data for participants in rebate programs is generally not available, geographic data provides insight into which communities are receiving rebates. Publicly available data from the CVRP program [12] was used to determine the number of rebates awarded in each census tract in 2019, and compared to demographic data from the American Community Survey [36]. Figure 34 shows the number of rebates per capita received in each census tract vs. the median income. This figure suggests that higher income households are receiving more rebates. Other studies have similarly found that this program has higher rebate use in DACs than in non-DACs [38], though they have also demonstrated that another program, the EFMP program [39], which targets equity more directly, has been more successful in providing rebates to DACs. Given the rapid transition to EVs that will be required to reach zero carbon emissions by 2045, it is likely that additional rebates or other incentives will be required. It will be necessary to ensure that these programs are well designed to be accessible to the low-income communities that will need the most help in the transition.

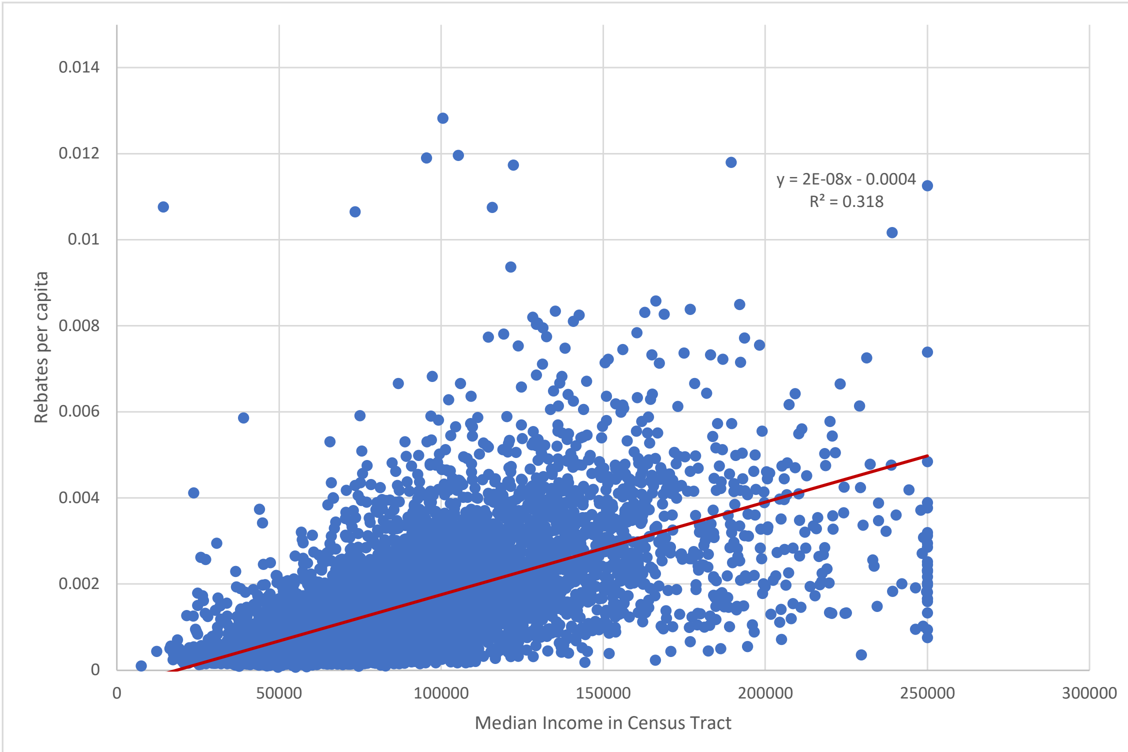



*Figure 33: Light Duty BEV Rebates per capita vs. Median Income in CA Census Tracts.*

## Vehicles and Premature Mortality from Air Pollution

Another aspect of distributional effects is exposure to air pollution from conventional and electric vehicles. Multiple studies have demonstrated that emissions from the transportation sector disproportionately impact low-income communities and communities of color. The Union of Concerned Scientists found that in California, African American and Latino communities are exposed to 19 and 15 percent higher PM2.5 concentrations from vehicle emissions than the state average [40], respectively. Chambliss et al. (2021), similarly found that local disparities in air pollution levels lead to systematically higher pollutant exposure for Black and Hispanic/Latino residents [41]. Houston et al (2014) Assessed disparities in exposure to vehicle emissions in the Long Beach Port Complex, and found that in this area Blacks and Asian/Pacific Islander residents experienced the highest exposure levels [42].

Replacing ICE vehicles with BEVs and FCEVs will inherently reduce tailpipe emissions and may provide co-benefits by decreasing premature mortality if the electricity or other energy that is used to fuel these vehicles has lower emissions of air pollutants. There are many different pathways to achieving zero carbon emissions, and the air quality and health impacts of each should be quantified as those pathways are assessed. Further assessment of the impacts of different pathways to carbon neutrality on air quality is needed to ensure that communities who have historically, and who currently bear the burden of poor air quality are not further burdened, and instead are the first to see the benefits of the transition.

## Additional Considerations

The following aspects were not considered in this report, but may warrant further careful attention:

> **Infrastructure:** Transitioning to a transport system that relies on hydrogen and electric vehicles will require refueling stations for hydrogen vehicles, charging stations for electric vehicles, and other related infrastructure. This report did not quantify new infrastructure needs, analysis of which is left for future work.
>
> **Automation:** Automation of the trucking fleet could improve efficiency and reduce fuel consumption and emissions quickly before ICE vehicles are fully phased out of the fleet [43], but there is a great deal of uncertainty regarding the potential for automation and its consequences.
>
> **Carbon Leakage:** California can pursue the existing and other policies to reduce the number of ICE vehicles within the state, but there is the possibility that people will simply purchase ICE vehicles in another state, or drive ICE vehicles within California that are registered in other states.

While simple framework has been laid out for an initial analysis of potential pathways and scenarios for decarbonization of on road vehicles, decarbonizing the transportation sector will be challenging, and will require consideration of the aspects included in this report as well as input from stakeholders and policy makers.

### Policy Observations

Two types of policies that would potentially help achieve zero emissions in the transportation sector are ZEV sales mandates and early retirement requirements for ICE vehicles. This analysis does not recommend a specific schedule for such policies, as these should be nuanced and require further study, but it will be essential both to rapidly increase the number of ZEV sales and to remove the ICE vehicles currently on the road.

Comparatively higher costs of electric vehicles as well as range anxiety are the main concerns impacting EV adoption. A simplified total cost of ownership analysis shows that the current trajectory of reducing battery costs and economies of scale will be sufficient to achieve cost parity between ICE and EVs. However, neither the current fertile resale market for vehicles nor the costs of future battery replacement are considered in this analysis, both of which could nullify the net costs. Ameliorating range anxiety would require not just a larger battery but also reducing battery weight [44], as higher weight reduces vehicle range for a given battery size. A network of DC fast charging stations at workplaces and multi-unit dwellings, and public charging infrastructure is needed to ease the transition for consumers.

This analysis assumes that vehicle miles traveled for light-duty vehicles remain constant over the years as per capita VMT in California has saturated. Reducing VMT through public transit and creating walkable and bikeable cities would also be helpful in reducing the total stock of vehicles required [45].

A key conclusion of this analysis, which differs from other similar work [46] [13], is the need for accelerated retirement in both light- and heavy- duty vehicles to reach zero ICE vehicles by 2045. Fleet modernization programs such as monetary incentives to replace or remove ICE vehicles will likely be necessary.

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