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HD ADOPT: Heavy-Duty Vehicle Choice Model Documentation

Alicia Birky, Lauren Sittler, Arthur Yip, Fan Yang, and Katerina Polemis

National Renewable Energy Laboratory

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List of Acronyms

ADOPT	Automotive Deployment Options Projection Tool
AEO	Annual Energy Outlook
BEV	Battery electric vehicle
CAFE	Corporate Average Fuel Economy
CNG	Compressed natural gas
CO_2	Carbon dioxide
EIA	Energy Information Administration
EU	European Union
EU-4	European Union subset (United Kingdom, Belgium, Germany, Netherlands)
FASTSim	Future Automotive Systems Technology Simulator
FCEV	Fuel cell vehicle
GHG	Greenhouse gas
HD	Heavy-duty
HDV	Heavy-duty vehicle
HHDDT	Heavy Heavy-Duty Diesel Truck drive cycle
ICE	Internal combustion engine
LD	Light-duty
LDV	Light-duty vehicle
U.S.	United States
VECTO	Vehicle Energy Consumption calculation TOol
VIUS	Vehicle Inventory and Use Survey
VMT	Vehicle miles of travel

Abstract

HD ADOPT is a logit consumer vehicle choice and stock model that analyzes the Class 8 tractor market. The model projects future technology shares, fuel consumption, and carbon dioxide (CO_2) emissions under input assumptions of technology progress, energy prices, and policies. ADOPT is distinguished from other vehicle choice models through inclusion of non-linear and heterogenous consumer preferences and characterization of the full range of market options rather than use of composite vehicles. In addition, ADOPT has integrated vehicle simulation capabilities that enable performance assessment and optimization of endogenous technology evolution. Optionally, the model is able to adjust this evolution to achieve compliance with fuel economy and greenhouse gas (GHG) emission regulations. Primary results include projection of technology shares and future in-use fleet energy demand, petroleum consumption, and CO_2 emissions. This enables analysis and comparison of future scenarios of technology improvements, economic conditions, and national policies. Recent new features for the heavy-duty (HD) modeling also enable examination of different onboard hydrogen fuel storage technologies from the lens of consumer preferences for vehicle cost and range. This report documents current ADOPT capabilities and methodologies.

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1 Introduction

The Automotive Deployment Options Projection Tool (ADOPT) is a consumer vehicle choice and stock model that was originally developed for the light-duty (LD) market. The heavy-duty (HD) ADOPT model is built on the LD framework and shares a core code base. Methodologies were adapted to reflect commercial vehicle markets and consumers while using the available data to the greatest extent possible, focusing first on the Class 8 tractor market to capture the largest contributor to commercial vehicle fuel consumption. This framework can be further adapted in the future to capture the remainder of the commercial vehicle market. As with LD modeling, ADOPT projects future technology shares, fuel consumption, and CO_2 emissions under assumptions of technology progress, energy prices, and policies.

This report provides an overview of the modeling approach but focuses primarily on documenting the ADOPT features and algorithms unique to the HD market and other new features. For greater detail on the general model methodology, the reader is referred to prior documentation (Brooker, Gonder and Lopp, et al. 2015). This report also provides documentation on data sources and analysis used to instantiate the model for the United States (U.S.) and European Union (EU) tractor markets, with the latter including the United Kingdom, Belgium, Germany and the Netherlands and referred to in this document as EU-4.

2 Approach

2.1 Overview

ADOPT is a logit consumer choice model that uses techniques from the multinomial logit method and the mixed logit method. Key ADOPT features that distinguish it from other vehicle choice models include consumer preferences that vary nonlinearly across the range of each vehicle attribute; characterization of consumer heterogeneity; and characterization of the full range of market options rather than use of composite vehicles. ADOPT represents the majority of existing vehicle makes and models and introduces new options and powertrains based on the market success of existing options. To estimate the performance of these new options, ADOPT is integrated with NREL's vehicle simulation tool, the Future Automotive Systems Technology Simulator (FASTSim) (Brooker, Gonder and Wang, et al. 2015). The model includes capabilities to optionally enforce compliance with fuel economy and GHG emission regulations through adjustments to product offerings and pricing. ADOPT also includes a vehicle stock turnover model to project future in-use fleet energy demand, petroleum consumption, and CO_2 emissions. The general modeling flow is shown in Figure 1.

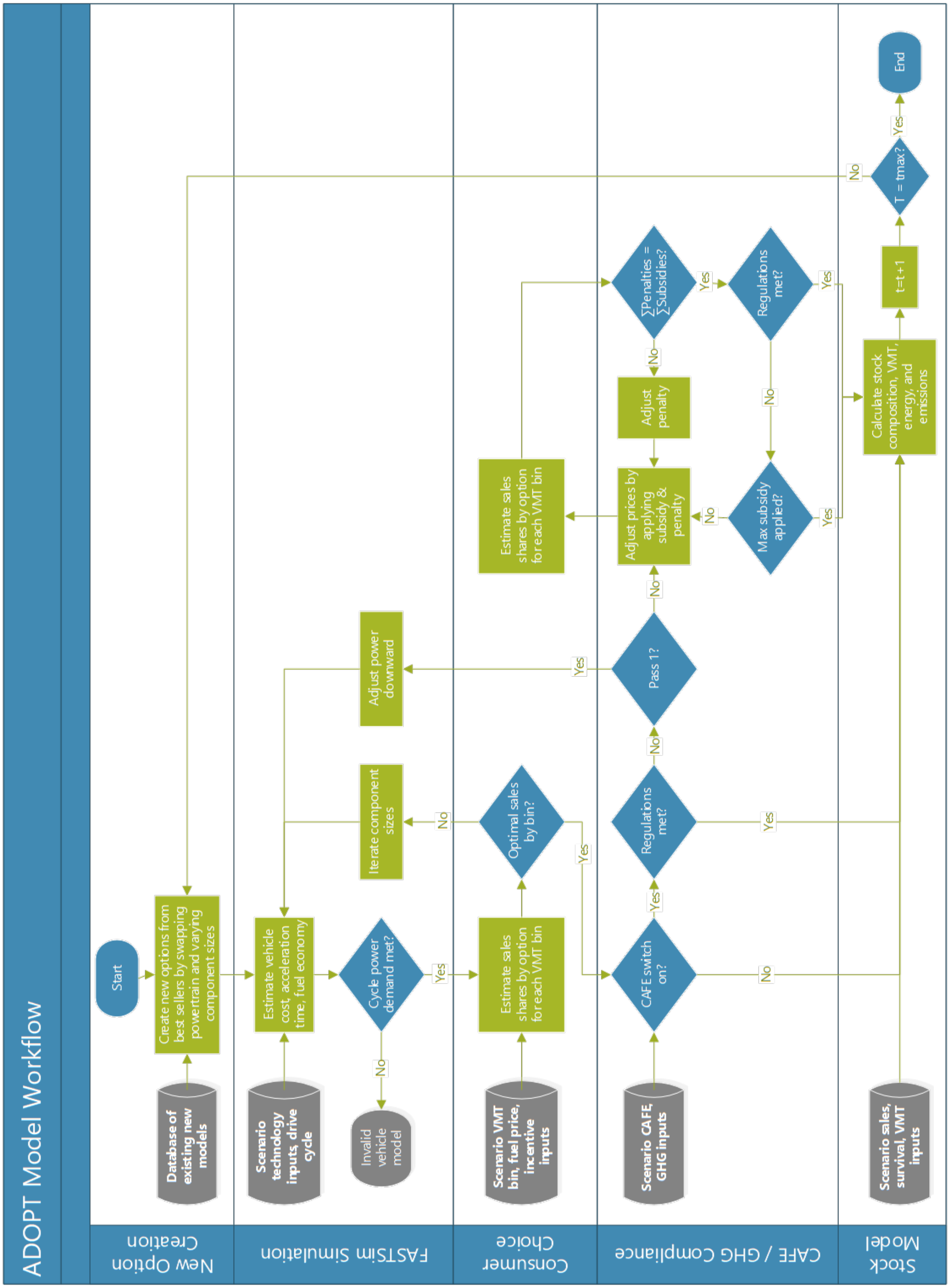


Figure 1: ADOPT model flow

Consumers consider many vehicle attributes and features when making purchase decisions (Brooker, Gonder and Lopp, et al. 2015). However, costs and functionality figure more prominently in purchase decisions for the HD market. Because of the wide range of use cases for commercial vehicles, operating costs can vary significantly and can dominate lifetime costs for customers with high annual vehicle miles of travel (VMT). High VMT also correlates with high vehicle range requirements, which are critical to achieving the vehicle's daily "mission" and generating revenue. To reflect these market differences, ADOPT replaces the LD consumer differentiation by income with differentiation of HD consumers by their annual VMT. Attribute preferences reflect increasing sensitivity to fuel cost and vehicle range with higher VMT. Similar to LDVs, HDV VMT falls as the vehicle ages, with trucks either transitioned within a fleet to operations closer to home base or sold from a long-haul fleet to a local or regional fleet. While ADOPT does not capture used vehicle market dynamics, new vehicle VMT distribution is used to characterize consumers and estimate technology market shares.

Much like LDVs, HDVs are subject to fuel consumption and GHG emission regulations that apply at the sales fleet level. As a result, the CAFE compliance module developed for LDVs can be used for HDVs. Additional modifications to the modeling framework for HDVs include a new algorithm for the range penalty and the addition of new hydrogen powertrain types. These modifications are detailed in Sections 2.5, 2.2.2, and 2.2.3.

2.2 Unique Features for HD

2.2.1 Consumer Classification

ADOPT differentiates HD consumers by their annual VMT to capture increasing sensitivity to fuel cost and vehicle range with higher VMT. The Vehicle Inventory and Use Survey (VIUS) provides the most comprehensive understanding of U.S. national commercial vehicle operations. While early versions of the HD ADOPT model used the 2002 VIUS survey, the latest version was able to take advantage of the 2021 survey released in late 2023 (U.S. Department of Transportation, Bureau of Transportation Statistics and U.S. Department of Commerce, U.S. Census Bureau; 2023). To capture the new vehicle market, the VIUS 2021 data were filtered to remove vehicles not in use (zero mileage) and extract only trucks zero to five years of age (model years 2016 and later). As described in Section 2.4.1, heavy truck VMT falls as vehicles age. Using new vehicle VMT rather than average VMT provides a better cost proposition in the adoption decision, with fuel cost savings from these technologies more rapidly offsetting higher purchase price. This characterization also provides a more accurate representation of new vehicle operating requirements, e.g. daily range, in the adoption decision. The VIUS 2021 new vehicle distribution by VMT, shown in Figure 2, is used to project future sales. For stock modeling, sales in prior years use the 2002 VIUS results through 2002 and interpolate between 2002 and 2021, reflecting market evolution between these two data years.

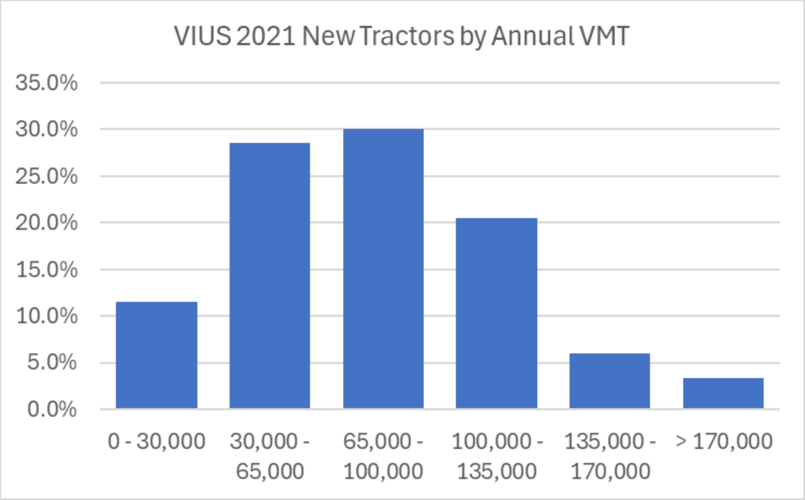


Figure 2: VIUS 2021 U.S. New Tractor VMT Distribution

For the EU-4 market, annual VMT distribution was taken from ICCT (2021), the original source a representative fleet documented by Wentzel (2020).

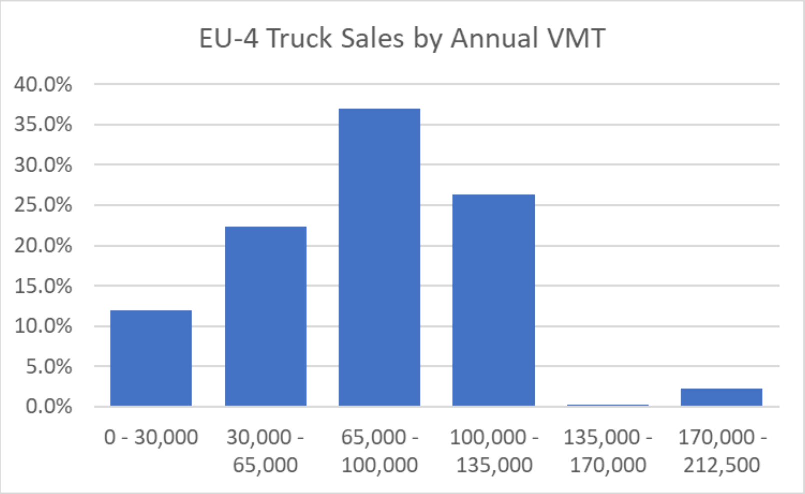


Figure 3. EU-4 Tractor VMT Distribution

2.2.2 *Range Penalty*

The total range penalty is calculated over a vehicle's lifetime and includes two terms: a "constant" term that values each refueling stop at a fixed cost and a variable term that depends on the fueling or charging rate and the time required to refill the tank or battery—the fueling dwell time. This approach assumes that operators value both the inconvenience of making a stop and the time required to refuel. The per-stop cost can also be used to capture the time required to deviate from the route to find a fueling location as well as maneuvering and possible queuing time. The hourly penalty can reflect either labor rates, assuming a driver must be paid for refueling time, or penalties assessed for late deliveries.

$$range\ penalty = Lifetime\ stopCost + \ Lifetime\ dwellTime\ Cost \tag{1}$$

To calculate the range penalty for each customer and vehicle option, ADOPT first estimates the number of annual refueling stops based on the customer's yearly mileage divided by the vehicle's range. The customer's mileage is estimated as the approximate midpoint of the VMT "bin" (see Section 2.2.1) assuming a bin width of 30,000 miles.

$$\frac{Refills}{Year} = \frac{\max(0,\ VMTbin_{max} - 15000)}{(vehicle's\ range)} \tag{2}$$

The total cost of refueling stops per year is then calculated as the number of refills per year multiplied by the cost per stop.

$$\frac{\$\ Stop\ Cost}{Year} = \frac{Refills}{Year} * stopCost \tag{3}$$

The dwell time costs depend on the storage capacity of the vehicle tank or battery, the fill or charge rate, and the hourly dwell rate cost in \$/hr:

$$\frac{\$\ Dwell\ Cost}{Year} = \frac{Refills}{Year} * \frac{Tank\ Size\ in\ kWh}{Fill\ Rate\ in\ kW} * dwellRate\left(\frac{\$}{hr}\right) \tag{4}$$

The general equation for the total range penalty, calculated over the vehicle life is then:

$$Life\ range\ penalty = \left(\frac{\$\ Stop\ Costs}{year} + \frac{Refills}{year} * \frac{Tank\ Size\ in\ kWh}{Fill\ Rate\ in\ kW} * \frac{\$\ Dwell\ Rate}{hr}\right) * Life\ Yrs \tag{5}$$

Range penalties are calculated for all powertrain types. However, the battery electric vehicles (BEVs) are assumed to be capable of refueling overnight without incurring an hourly penalty. This basically assumes that each vehicle can be charged unattended wherever it would normally be parked, such as at a depot or overnight truck stop. Assuming 250 operating days per year, the BEV-specific range penalty is then:

$$BEV\ range\ penalty = \frac{\$\ Stop\ Costs}{year} * LifeYrs +$$

$$\max\left(0, \frac{Refills}{year} - 250\right) * \frac{BEV\ kWh}{BEV\ charge\ rate} * \frac{\$\ Dwell\ Rate}{hr} * LifeYrs \tag{6}$$

For HD vehicles, the lifetime used for consumer decision-making is 12 years. Consistent with financial accounting practices, the range penalty is treated as a future cost and discounted using an input interest rate. This estimated range penalty is then valued differently within each consumer bin according to specified consumer preferences (see Section 2.3.3). Scenario input values that impact the range penalty are described in Section 3.2 and include the valuation of both the stop cost and dwell time as well as the fill rates for each powertrain.

2.2.3 Fuel Economy Valuation

Commercial vehicle purchase decisions are highly influenced by expected operating costs. Therefore, ADOPT values HD fuel economy by evaluating lifetime fuel purchases using fuel economy obtained from FASTSim simulation, assumed annual VMT, and fuel prices. As with range, the HD lifetime for purchase decisions is 12 years and future costs are discounted using the input interest rate. This estimated cost is then valued according to the preferences within each consumer VMT bin.

2.2.4 Powertrain Types

New powertrain types were added to model the market for hydrogen-powered vehicles in more detail, including:

- H_2 internal combustion engine (ICE)
- H_2-diesel dual-fuel ICE (convFutureVeh)
- Fuel cell vehicles (FCEVs) with different hydrogen storage options
    - Gaseous 350 bar
    - Gaseous 700 bar
    - Liquid
    - Cryo-cooled liquid

Each FCEV technology has an associated tank volume limitation that can change over time to reflect advances in technology and vehicle design (see Section 2.5). While these powertrain options could be used in a LD model run, the user would need to develop appropriate input assumptions for these vehicles, which would be complicated by the wide range of body types and associated packaging/integration issues. Note that the two H_2 ICE variants use a different set of input assumptions and only one storage technology can be modeled for these powertrains for a given scenario.

2.2.5 Fleet Data Sources

ADOPT requires data characterizing the HD vehicle fleet, including new vehicle model options, historical sales, historical fuel economy, and survival rates that replicate the age composition of the in-use stock of vehicles. Data sets were developed for the U.S. and EU-4 tractor markets using both public and private data sources as described in Table 1. The vehicle options database requires detailed information on vehicle configurations, which were obtained from registration data sets licensed from Experian and IHS Markit. The tractor market comprises almost entirely diesel ICE with a small number of compressed natural gas (CNG). Since CNG is not the focus of currently funded ADOPT research, these vehicles were excluded from the vehicle database. The U.S. market is characterized by a total of 124 options, while the EU-4 market includes 204 options.

Additional information on the age composition of the U.S. fleet was obtained from the Energy Information Administration's National Energy Modeling System (EIA NEMS) inputs for the Annual Energy Outlook 2023 (AEO 2023), which were based on analysis of multiple years of IHS registration data (EIA 2023). Similar information on the EU-4 fleet was obtained from Eurostat (Eurostat 2022).

While the ADOPT framework estimates sales shares by make-model and powertrain, the model does not estimate absolute sales volume and this projection is an exogenous input. Projected total sales demand for the U.S. was estimated from AEO 2023 Reference Case heavy (Class 7 and 8) sales (EIA 2023). Since the AEO reported sales include vocational (non-tractor) vehicles, VIUS 2021 data for the three most recent model years were used to determine the fraction of Class 7 and 8 vehicles that are tractors. Tractor sales were then estimated assuming that tractors account for 78% of diesel and 38% of CNG AEO heavy sales. The small number of AEO 2023 projected FCEV heavy sales were also assumed to be tractors.

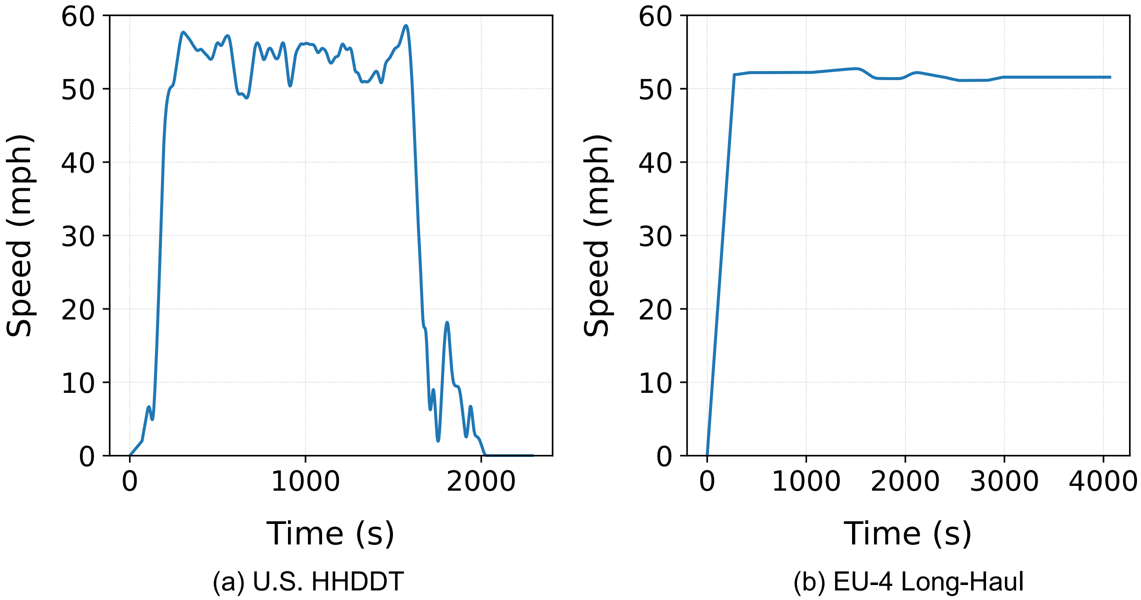
Projected total sales demand for heavy-duty tractors in the Belgium, Netherlands, Germany, and United Kingdom was estimated based on historical sales, stock, and survival statistics, derived from IHS-Markit (IHS-Markit 2022) and Eurostat (Eurostat 2022) vehicle stock data, assuming truck stock growth at the same rate of forecasted increases in vehicle kilometers of travel (demand for freight movement) from the EU Reference Scenario 2016 (European Commission 2016).

Table 1. Vehicle Data Sources

	U.S.	**EU-4**
Coverage	National	United Kingdom, Germany, Netherlands, Belgium
New vehicle options	Experian 2023 registrations, MY 2021-2022	IHS Markit, 2020 registrations, MY 2019-2020
Survival	EIA NEMS inputs for AEO 2023	Eurostat road tractor stock of vehicles (Eurostat 2022)
Historical sales	Backcast to MY 1989 using survival function and Experian 2022 registration by MY	IHS Markit (IHS-Markit 2022) and Eurostat (Eurostat 2022), MY 2000-2019
Historical fuel economy	EIA NEMS inputs for AEO 2023	Published analysis (ICCT 2018b), (Krause, et al. 2020)
Sales projection	EIA AEO 2023 Reference Case	IHS Markit (IHS-Markit 2022), Eurostat (Eurostat 2022), EU Reference Scenario 2016 (European Commission 2016)

2.2.6 Drive Cycle

To assess the fuel economy and range of vehicle configurations, FASTSim requires a drive cycle which is characterized by vehicle speed versus time. For the U.S. market, HD ADOPT uses the cruise mode of the Heavy Heavy-Duty Diesel Truck (HHDDT) schedule, a chassis dynamometer test developed by the California Air Resources Board and shown in Figure 4(a). For EU-4 analysis, the long-haul mission profile was extracted from the Vehicle Energy Consumption calculation TOol (VECTO) developed by the European Commission (European Commission n.d.). This schedule was converted from speed versus distance to speed versus time and smoothed to prevent harsh acceleration that caused trace misses for current market engine sizes, resulting in the cycle shown in Figure 4(b).



(a) U.S. HHDDT

(b) EU-4 Long-Haul

Figure 4: HD ADOPT Drive Cycles

2.3 New Vehicle Options

2.3.1 Introduction of New Options

ADOPT introduces new model options using several algorithms. First, to initiate model options for a powertrain that does not already exist in the input vehicle data set, a single new option is added for the specified introduction year. ADOPT then uses a seeding S-function to estimate the number of additional model options with that powertrain introduced over subsequent years. This function ensures that new options are retained for several years even if they find relatively low sales volumes. For LDVs, this function is parameterized to match historical trends in the number of available hybrid, battery electric, and flex fuel vehicle models (Brooker, Gonder and Lopp, et al. 2015). The HD tractor market consists almost entirely of diesel ICE with some CNG engines. Due to the lack of historical data on the introduction and success of alternative powertrains, the HD curve has been parameterized based on tractor sales, the number of current options, and the number of manufacturers (currently five in the U.S.: Daimler, Freightliner, PACCAR, Tesla, and Volvo). For reference, LD annual sales in 2024 are projected to reach 15.9 million,[1] while tractor sales are highly cyclic due to economic conditions but have averaged under 200,000 per year over the last 10 years (EIA 2023). The seeding function, shown in Figure 5, is in effect for ten years, provides plausible introduction rates, and can be updated in the future as data on real-word options become available.

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[1] https://www.spglobal.com/mobility/en/research-analysis/november-2024-us-auto-sales.html, accessed December 9, 2024.

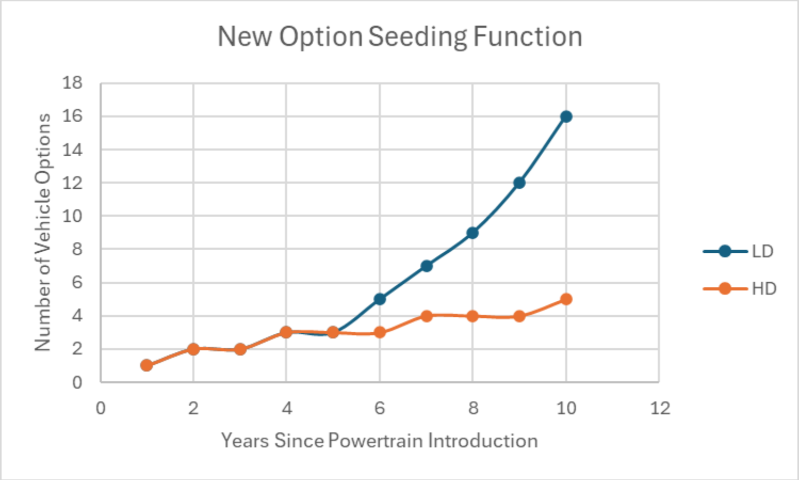


Figure 5. New Vehicle Option Seeding Function

For new option seeding, ADOPT creates variations in new model options by copying the best-selling conventional vehicles and replacing the existing powertrains with the newly introduced one. The powertrain component sizes, such as fuel cells, batteries, and motors, are modified and evaluated to find configurations that maximize sales (see Section 2.3.2).

Following the seeding function, two algorithms can trigger additional new options based on market success. The first trigger introduces variations of existing options if sales exceed specified levels for a given vehicle price as documented in Brooker et al (2015). This curve was developed to match historical option creation trends in the early market for LD hybrid electric vehicles. Since there is no comparable data for HD, the first trigger sales threshold has been set very high such that it is not in effect for HD modeling. The second trigger applies to new vehicle powertrains and introduces variations of existing options that become the best-seller within a VMT bin, presenting proliferation of successful vehicle configurations. In general, one new option is added per VMT bin per year.

Finally, ADOPT “scraps” options that perform poorly to maintain a constant number of total available options equal to the number of make-model options in the input vehicle database. While new options are generally retained for 10 years and the seeding function acts as a minimum number of options for a newly introduced powertrain, these options may be removed sooner if all older options have higher sales.

2.3.2 Vehicle Simulation and Optimization

While many consumer choice models use exogenously specified vehicle configurations and attributes, ADOPT endogenously creates and evaluates configurations with a variety of component sizes, such as fuel cell and motor power, battery capacity, and fuel tank volume. ADOPT’s optimization algorithm varies component sizes within input constraints and seeks a configuration that maximizes sales within a given VMT bin. Each vehicle configuration is first simulated using FASTSim and must be able to meet the drive cycle trace to be considered. The simulated vehicle attributes, such as acceleration time and fuel economy, are then passed to the consumer adoption algorithm to estimate sales as described below. This approach allows ADOPT to endogenously create a variety of vehicle options according to market preferences.

ADOPT uses a variation of the standard multinomial logit consumer choice method as described in Brooker et al (2015). The attribute coefficients used in the logit method are non-linear and vary across consumers as characterized by annual VMT, where in the LD version they vary with consumer income.

2.3.3 Logit Choice Basics

While commercial vehicle purchase decisions are primarily cost-based, market realities show that not all purchases appear to follow least-cost principles. Rather than make strict cost comparisons which would indicate a single winning choice for each consumer characterization, consumer choice models use a logit formulation. The logit model estimates the probability of purchase based on the consumer utility derived from purchasing option i. This utility is determined by the set of n vehicle attributes $X_i \in (X_{i,1}, X_{1,n})$ for that option and consumer preferences (β) for those attributes:

$$U_i = \sum_{w=1}^{n} \beta_w * X_{i,w} \tag{7}$$

Note that utility derived from an attribute can be either positive or negative. As an example, acceleration can provide positive utility while fuel costs represent negative utility or cost. For powertrain option i, the market share is the probability of purchase, P_i, based on that option's utility, U_i, relative to the total utility from all possible options j ∈ (1, N).

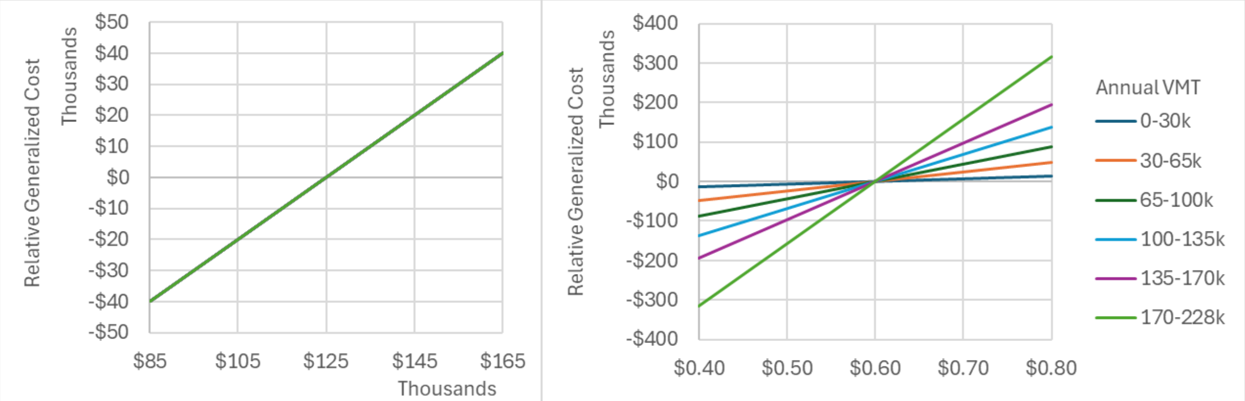
$$P_i = \frac{e^{U_i}}{\sum_{j=1}^{N} e^{U_j}} \tag{8}$$

Because of this mathematical formulation, options with low utility relative to other options may still have some probability of purchase and find small market shares.

2.3.4 Preferences

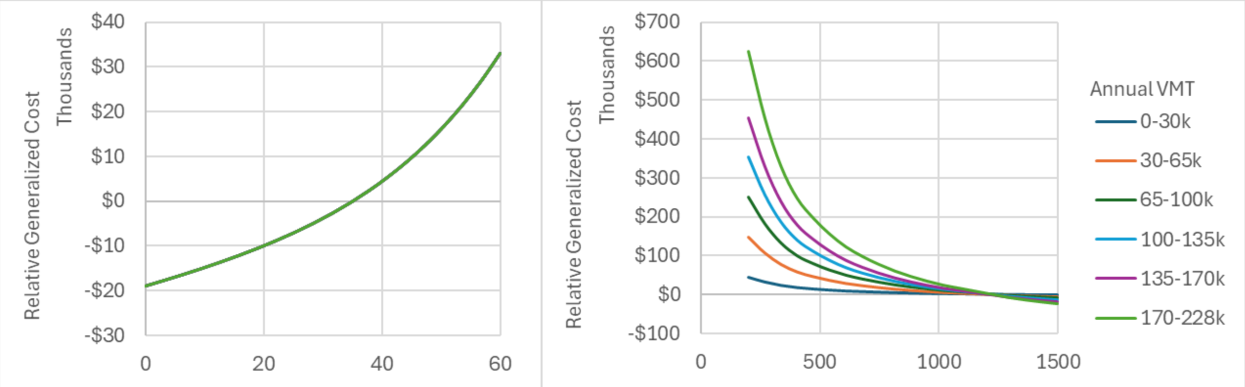
ADOPT expresses consumer preferences through generalized costs which measure the negative utility derived from various option attributes. Higher generalized cost can be thought of as a relative penalty associated with lower probability of purchase. HD ADOPT includes consumer preferences for vehicle price, acceleration time, range, and fuel cost per mile as illustrated in Figure 6. These coefficients are the same for the U.S. and EU-4 versions of the model. As previously discussed, the global tractor market is almost entirely composed of diesel ICE powertrains with relatively homogenous attributes, which prevents identification of regionally specific preferences. In the future, data on market uptake of alternative powertrains may be used to better differentiate these markets.

HD ADOPT preferences for vehicle price and acceleration time are constant across the consumer VMT bins, while preferences for vehicle range and fuel cost per mile are a function of annual VMT, reflecting sensitivity to daily operational needs and future lifetime costs. Consumers with higher VMT and therefore higher daily mileage and operational expenses assign a higher penalty to low-range vehicles and high fuel cost per mile. Another unique feature of ADOPT is the nonlinearity of preferences, which for HD occurs in the coefficients for acceleration time and range. These curves characterize increasing marginal cost (or disutility) as acceleration time increases and vehicle range decreases.



(a) Vehicle Price

(b) Fuel Cost ($/mi)



(c) Accel Time (sec, 0-60 mph)

(d) Range (miles)

Note: Consumer valuation of (a) vehicle price and (c) acceleration time are the same across VMT bins

Figure 6: Consumer Valuation of Vehicle Attributes

As described in prior documentation, ADOPT further approximates variations in consumer tastes by applying a normal distribution around each attribute curve (Brooker, Gonder and Lopp, et al. 2015). Sampling these distributions creates different combinations of the various coefficient values to produce a wide variety of consumer preferences. Relative to a standard logit model, this distribution of preferences improves substitution patterns as new vehicle models are added and reduces the tendency to violate the decision theory assumption of independence of irrelevant alternatives.

2.3.5 Sales/Production Limits

ADOPT limits the increase in sales of new options with user inputs for the maximum penetration power function coefficients. This function ensures realistic initial adoption and can be conceptualized as reflecting both limits in scaling production and knowledge diffusion among consumers. As shown in Figure 7, this function has been parameterized to limit first-year sales of each new option to 1,000 vehicles for the EU-4 market and 4,000 for the U.S. market. This compares to total annual sales of around 60,000 vehicles in the EU-4 and 200,000 in the U.S.

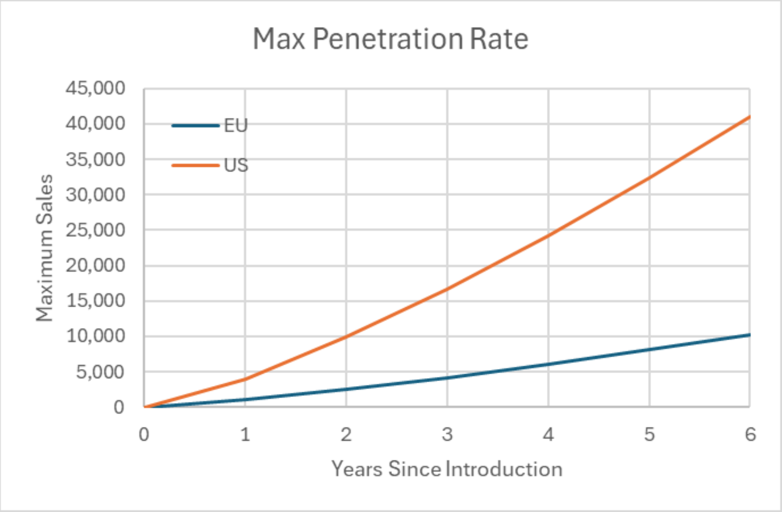


Figure 7. Maximum Penetration Rate

2.4 Stock Model

ADOPT's stock model projects fuel use and CO_2 emissions using input total sales and the future sales fleet composition resulting from consumer choices as described in Section 2.3.4. The stock model captures key usage details, including the observed decline in VMT and nonlinear cumulative survival as vehicles age. Capturing these features provides a more accurate projection than using lifetime average VMT, resulting in earlier and higher energy and emissions benefits with adoption of higher-efficiency solutions.

2.4.1 VMT by Age

U.S. tractor VMT as a function of vehicle age, shown in Figure 8, was obtained from analysis of the 2021 VIUS Public Use File (U.S. Department of Transportation, Bureau of Transportation Statistics and U.S. Department of Commerce, U.S. Census Bureau; 2023) after removing vehicles not in use (zero mileage for 2021). The EU-4 tractor VMT as a function of age, shown in Figure 9, is taken from the TRACCS Long Haul Adjusted schedule (ICCT 2018a). The Transport data collection supporting the quantitative Analysis of measures relating to transport and Climate Change (TRACCS) project was funded by the European Commission in 2012-2013.

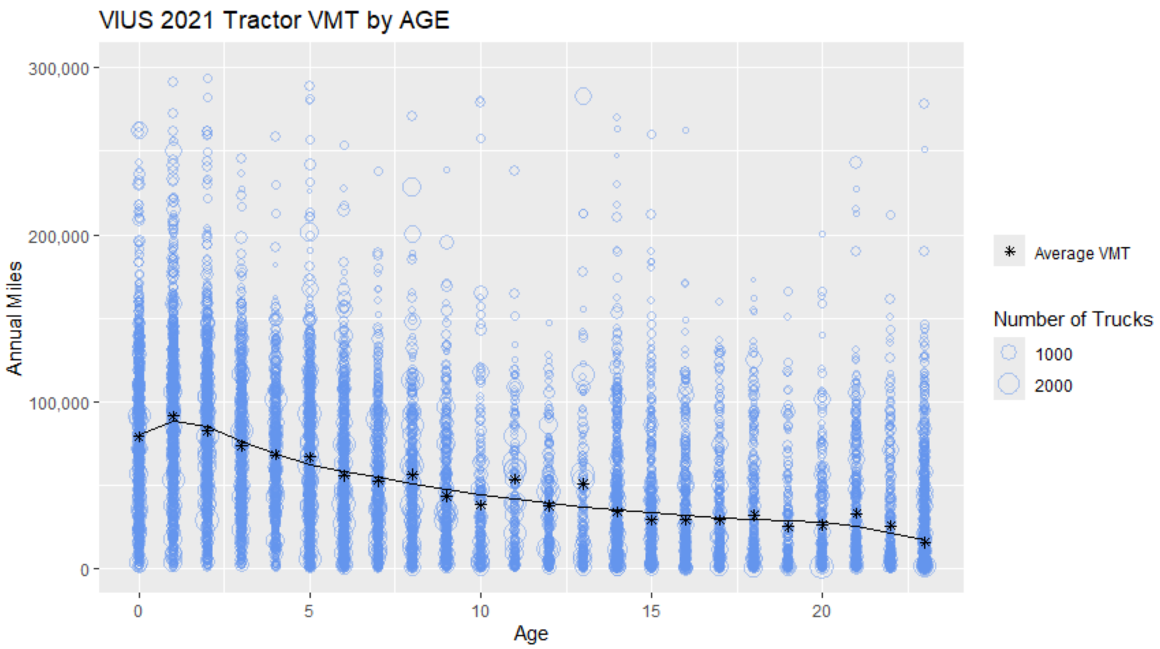


Figure 8. U.S. Tractor Annual Mileage vs. Age, 2021 VIUS

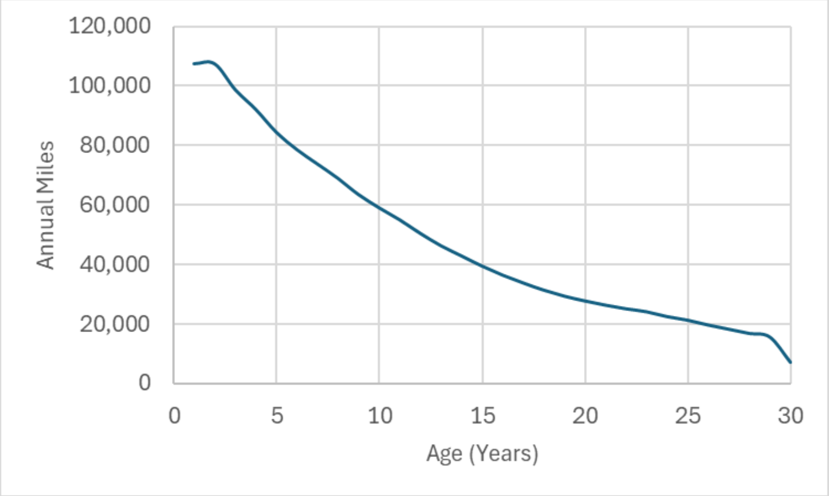


Figure 9: EU Tractor Annual Mileage vs. Age

2.4.2 Survival Rates

The ADOPT cumulative survival function is specified using a median age and coefficients that define the shape of the curve before and after this age. For the U.S., this curve was parameterized using historical data extracted from the NEMS model input for AEO 2023 as listed in Table 1. This data includes annual registrations by weight class and vehicle type (tractor vs. vocational) for 2012, 2014, 2016, 2018, 2019, 2020, and 2021 (EIA 2023). However, registration data inherently includes vehicles not in use which tend to be the oldest. Since the usage defined in Section 2.4.1 excludes these trucks, using all registered vehicles would overestimate annual fleet VMT. In addition, ADOPT estimates vehicle stock through age 30 such that any remaining vehicles are scrapped in year 31, resulting in a sudden reduction in total stock if a survival function reflecting actual registrations is used. Therefore, the survival curve was adjusted to phase older vehicles out of the fleet more gradually. The original and final (modified) cumulative survival function is illustrated in Figure 10 and the resulting comparison of estimated to actual vehicle stock by age is illustrated in Figure 11.

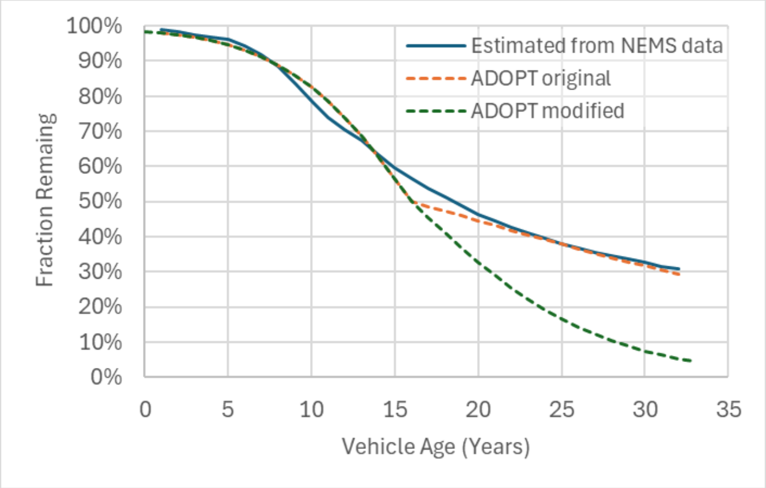


Figure 10. Cumulative Survival Function for U.S. Stock Projection

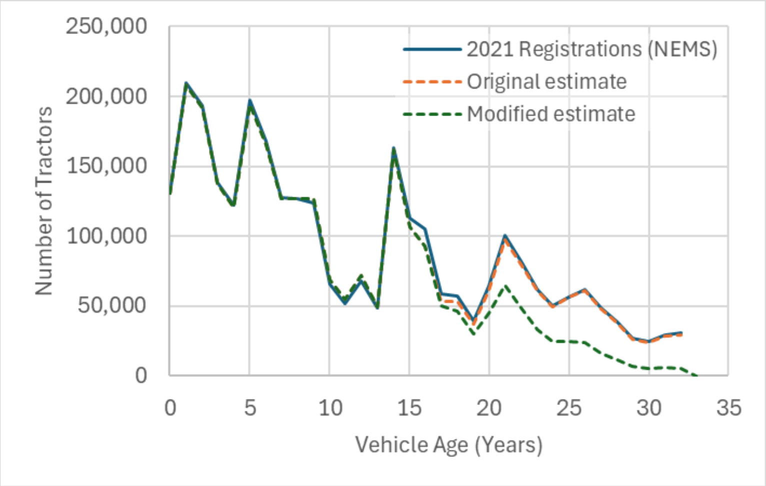


Figure 11. U.S. Stock Estimated Using Survival Function vs. Registration Data

The survival curve used for the EU, shown in Figure 12 was derived from analysis of the Eurostat road tractor stock of vehicles as listed in Table 1 (Eurostat 2022).

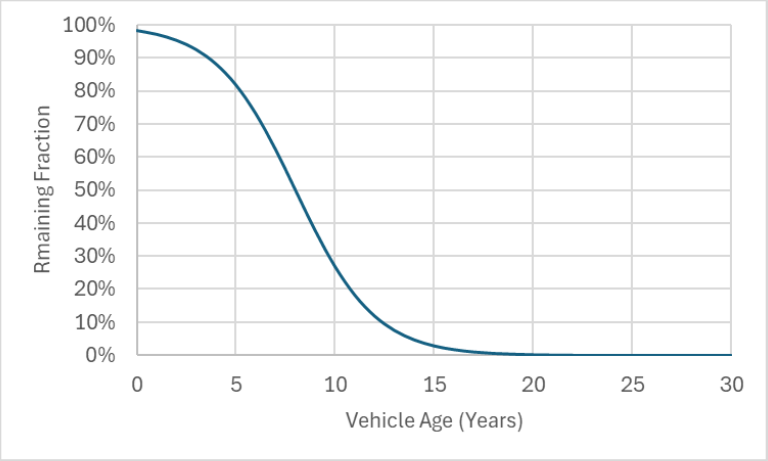


Figure 12: Cumulative Survival Curve for EU Stock Projection

2.5 Policy Modeling

ADOPT includes several features for accounting for existing and possible future policy. First, the user may input vehicle price incentives that change over time. This incentive reduces the price of the vehicle and is assumed to be realized in full by the consumer. Second, the impact of HD fuel consumption and GHG standards can be estimated by employing the optional LD Corporate Average Fuel Economy (CAFE) feature. When not selected, ADOPT bypasses this algorithm.

Although CAFE applies to individual manufacturers and includes provisions for credit banking and trading, ADOPT approximates this outcome by applying the specified fuel economy regulation at the entire sales fleet level. After market shares are initially estimated, ADOPT uses two approaches to enforce CAFE compliance. First, if the average sales fleet fuel economy falls short, ADOPT sacrifices consumer preference for faster acceleration time by reducing fuel converter engine power. If the sales fleet still does not comply with CAFE standards, ADOPT then applies vehicle price incentives and penalties, simulating manufacturer pricing strategy. Incentives (price reductions) are applied to vehicles that exceed CAFE in proportion to the amount they exceed it. Similarly, price penalties (increases) are applied to vehicles that fall short of CAFE proportional to the shortfall. The model iterates to find incentive and penalty rates that offset each other, resulting in a revenue neutral solution.

This formulation is easily adapted to simulate fuel consumption and emission standards applicable to U.S. and EU-4 HD vehicle sales. In June of 2024, the Phase 3 Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles established fleet level standards in terms of grams CO_2 equivalent per ton-mile.[2] The emission rates for tractors can be converted into fuel economy standards assuming complete combustion of diesel and average payloads as assumed in EPA's Phase 3 Regulatory Impact Analysis (U.S. EPA 2024). EPA's emission factors can then be input on the GHG Rule Rate category inputs (see Section 3.1). In this case, EPA assumes tailpipe

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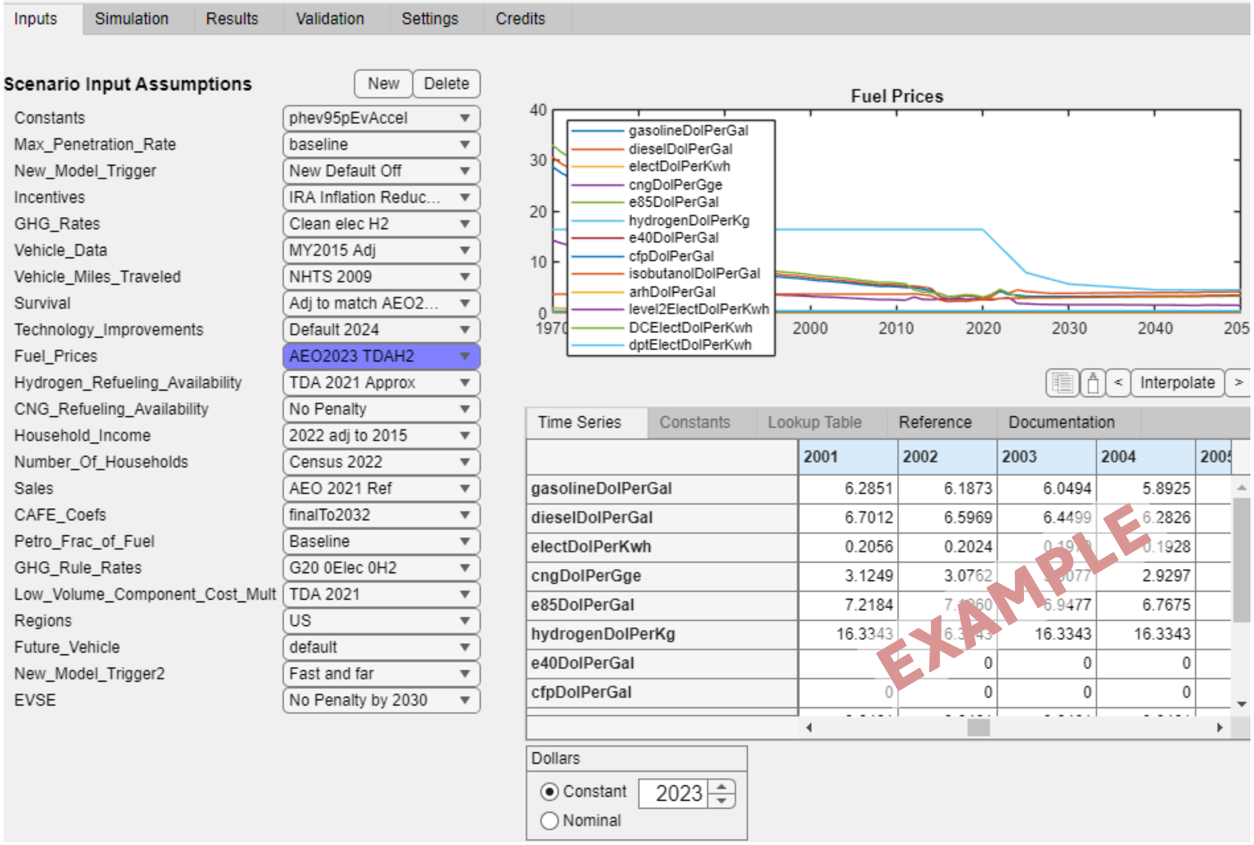
[2] The National Highway Traffic Safety Administration (NHTSA) is expected release harmonized fuel consumption standards, but as of this writing, has not done so.

emissions only, assigning a value of zero to battery electric, fuel cell, and hydrogen combustion engines.

3 Scenario Inputs

ADOPT scenarios are defined by a large set of user input assumptions covering fuel prices and emission factors, component technology performance and projections, and model parameters. The model provides a user interface, shown in Figure 13, for defining scenarios across the many categories of inputs by selecting prior inputs, importing data tables, or manually adjusting values. This interface also provides graphical visualizations of the inputs. Key inputs, particularly those that are unique to HDV, are described below.



Scenario Input Assumptions

Constants	phev95pEvAccel
Max_Penetration_Rate	baseline
New_Model_Trigger	New Default Off
Incentives	IRA Inflation Reduc...
GHG_Rates	Clean elec H2
Vehicle_Data	MY2015 Adj
Vehicle_Miles_Traveled	NHTS 2009
Survival	Adj to match AEO2...
Technology_Improvements	Default 2024
Fuel_Prices	AEO2023 TDAH2
Hydrogen_Refueling_Availability	TDA 2021 Approx
CNG_Refueling_Availability	No Penalty
Household_Income	2022 adj to 2015
Number_Of_Households	Census 2022
Sales	AEO 2021 Ref
CAFE_Coefs	finalTo2032
Petro_Frac_of_Fuel	Baseline
GHG_Rule_Rates	G20 0Elec 0H2
Low_Volume_Component_Cost_Mult	TDA 2021
Regions	US
Future_Vehicle	default
New_Model_Trigger2	Fast and far
EVSE	No Penalty by 2030

	2001	2002	2003	2004
gasolineDolPerGal	6.2851	6.1873	6.0494	5.8925
dieselDolPerGal	6.7012	6.5969	6.4499	6.2826
electDolPerKwh	0.2056	0.2024	[illegible]	0.1928
cngDolPerGge	3.1249	3.0762	[illegible]	2.9297
e85DolPerGal	7.2184	[illegible]	6.9477	6.7675
hydrogenDolPerKg	16.3343	[illegible]	16.3343	16.3343
e40DolPerGal	[illegible]	0	0	0
cfpDolPerGal	0	0	0	0

Dollars
● Constant 2023
○ Nominal

Figure 13: Scenario Input Interface

3.1 Fuel Specifications

Future fuel prices are a critical input assumption for technology adoption and influence ADOPT's consumer decisions through lifetime fuel expenditures. The primary source for future U.S. fuel prices is the AEO (EIA 2023), which serves as the official U.S. government's national energy projection. For the EU-4, prices may be taken from assumptions used by or projections provided by the European Commission, the International Energy Agency, and other sources.

GHG emission rates can also be specified in two categories. First, the GHG Rates category can be used to assess outcomes and compare scenarios; well-to-wheel values may be used if desired.

Second, the GHG Rule Rates category can be used to assess conformity with regulations or enforce compliance if the CAFE option is switched on (see Section 2.5). This second category of inputs should align with the values used by the regulatory agency.

3.2 Range Variables

The range penalty for HD ADOPT described in Section 2.2.2 requires input assumptions for the following variables:

- Fill rates for fuel tanks and batteries, assuming a constant rate
    - Diesel is specified in gallons per minute and converted to kW using a heating value of 37.66 kWh/gal
    - Hydrogen is specified in kg per minute and converted to kW using a heating value of 33.33 kWh/kg
    - Battery charge rates are specified in kW
- Cost per stop in $
- Cost per hour in $/hr

The tank or battery size of the vehicle is endogenously created by ADOPT and cannot be changed by the user. However, the user must specify the maximum allowable hydrogen tank volume as described in Section 3.4.1. The fuel tank size of the existing options is specified in the vehicle database, though this data includes only diesel vehicles. Since the vehicle registration data did not include details on fuel tanks, we assume that all current diesel options include two 150-gallon tanks.

3.3 Hydrogen Boil-Off

ADOPT includes input assumptions for loss of liquid hydrogen due to boil-off. This assumption applies only to the liquid hydrogen FCEV option and is specified as a constant fraction representing the net loss. For example, a fraction of 0.10 scales the fuel consumed by 1.10 and also reduces the vehicle range correspondingly. Boil-off therefore impacts sales of liquid hydrogen FCEVs by increasing fuel costs and increasing the number and duration of fueling events.

3.4 Future Vehicle Component Specifications

ADOPT includes a robust set of input assumptions for modeling technology improvements over time. These inputs inform the vehicle price and performance, with FASTSim estimating changes in component mass and efficiency on fuel economy and vehicle range. In general, these inputs are shared with the LD model. However, where the LD model currently allows for endogenous evolution of glider mass and aerodynamics through associated cost curves, these features have not been implemented for modeling the HD market. Key assumptions are listed below and further details on several are provided in the following subsections.

- Internal combustion engine efficiencies
- Fuel cell efficiency
- Motor efficiency
- Battery cost and energy density

- Motor cost and power density
- Hydrogen tank cost and energy density
- Hydrogen tank low volume multiplier
- Fuel cell low volume multiplier
- Maximum H_2 tank volume available

Note that all component costs are specified as price to consumer and should include any retail markups.

3.4.1 Fuel Storage Maximums

Current concepts and demonstration tractors using hydrogen in either a fuel cell or ICE powertrain typically stack multiple tanks behind the cab, as shown in Figure 14, and may also use the existing diesel tank locations. Stacking the tanks to the height of the cab can alter the vehicle dynamics. As a result, ADOPT assumes that early designs may not use the full available packaging volume, but later designs could increase utilization as the technology evolves. Therefore, inputs for maximum tank volume can be specified such that they change over time. The ADOPT optimization routine then uses these as upper limits for the tank size of endogenously created hydrogen-fueled options. Note that the mass and cost of the tanks are determined by additional assumptions for technology progress.

The design space for BEV batteries is established within the code and ranges from 100 to 1500 kWh. As with FCEVs, battery mass and cost are determined by technology progress assumptions. For diesel vehicles, new options may include one or two tanks, each consisting of 150 gallons.

Photo by Andrew Kotz, NREL

Figure 14: Typical Hydrogen Tank Location on Tractors

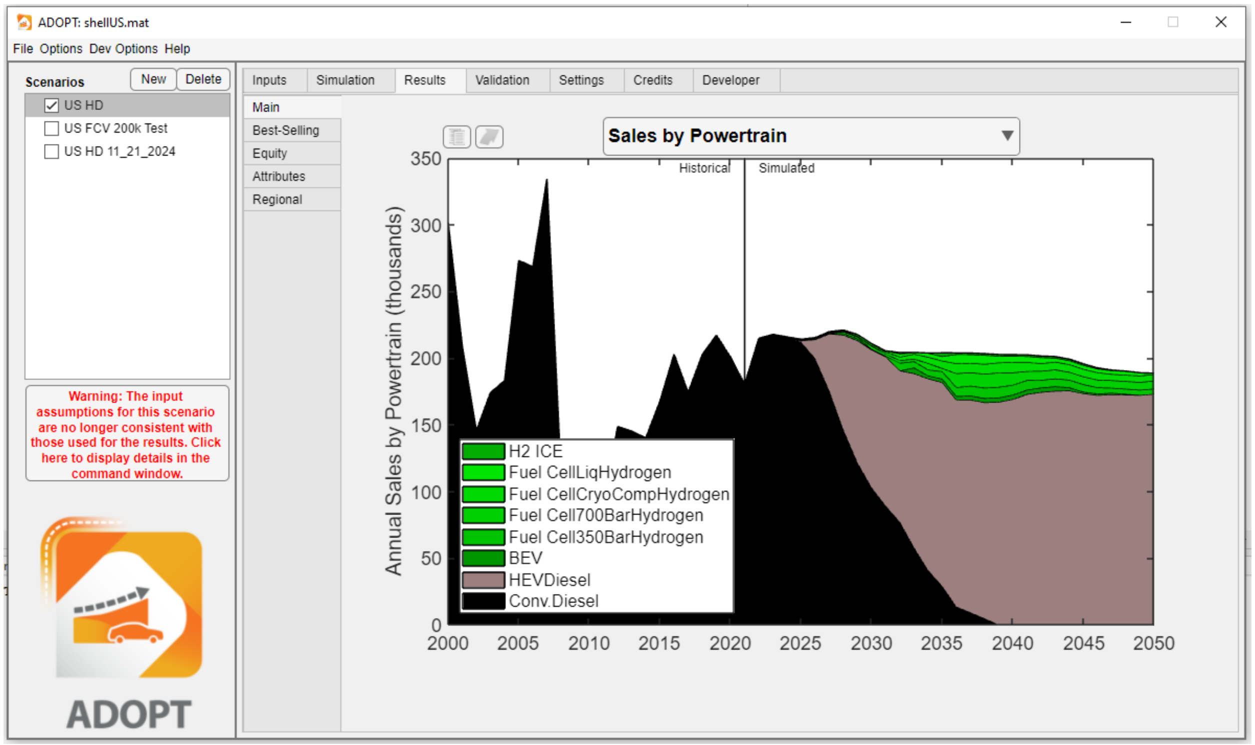
3.4.2 Low Volume Multipliers

ADOPT allows an additional adjustment to the cost of both hydrogen tanks and fuel cell stacks based on endogenously determined sales volumes. This allows the user to input high-volume component-level cost assumptions that include economies of scale that would not be realized at lower production levels. ADOPT currently estimates the sales volumes for both tanks and stacks as the sum of sales across all fuel cell powertrains. This effectively assumes that there are synergies in supply chains and/or production processes across the different fuel storage types listed in Section 2.2.3. Note that the storage tanks for the two hydrogen ICE powertrains currently benefit from these multipliers, with costs falling with increases in FCEV sales. However, the converse is not true and increasing sales of the two H_2 ICE powertrains do not reduce the cost of tanks for either these vehicles or FCEVs.

In the future, this algorithm will be adjusted to account for ICE sales and possibly to estimate multipliers for the tank types separately. However, it should be noted that tank and stack costs would likely be influenced by sales in other weight classes, including LD, as well as global markets. While prices can fall with increasing sales volumes across these other markets, prices can also increase due to supply chain issues such as market competition for limited parts and materials.

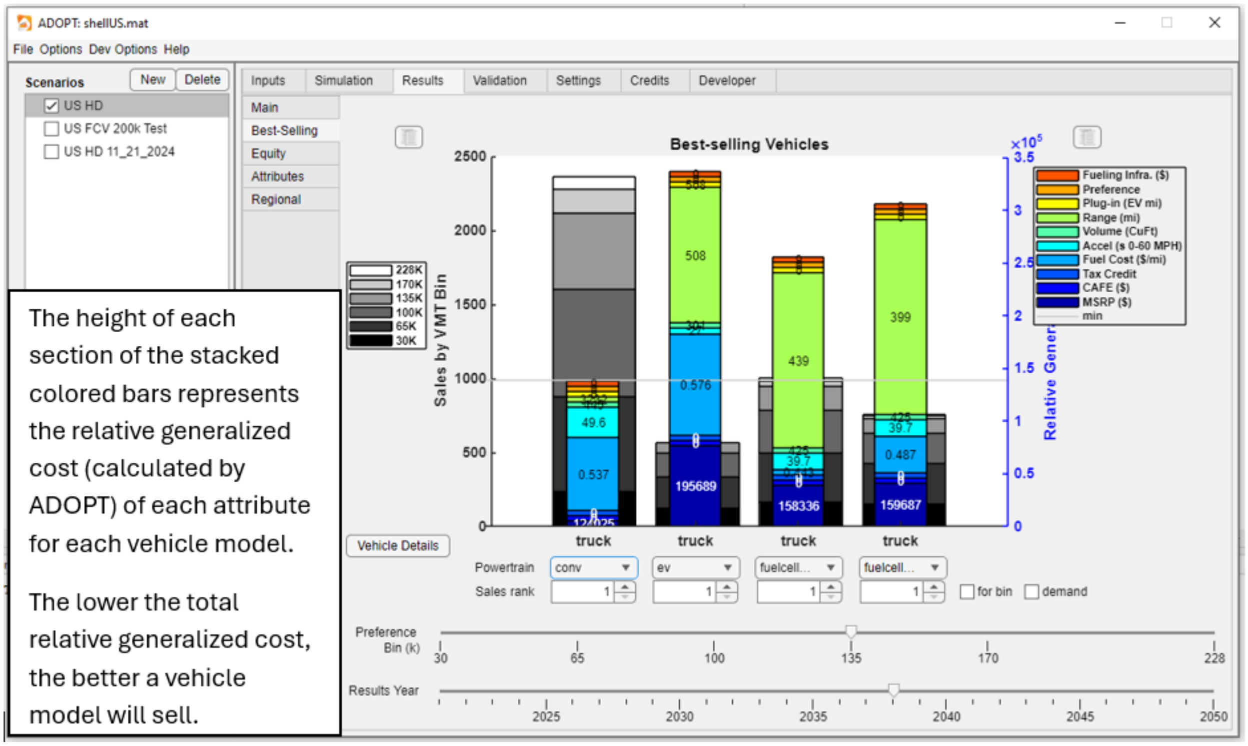
4 Model Results

ADOPT provides estimated projections through 2050 for sales by powertrain, vehicle stock composition, fuel consumption, and GHG emissions, as illustrated in Figure 15. In addition, the model interface provides detailed results to assist in analysis of market dynamics and the role of consumer preferences in the uptake of new technologies. The primary visualization for this purpose is the "best-selling" chart shown in Figure 16, which provides results for individual options within a selected VMT bin. This chart shows the sales for selected options through the gray-shaded bars, the contribution of each vehicle attribute to that option's generalized cost through the height of the colored stacked bar, and finally, the actual attribute value (e.g. range in miles), provided as a label on the chart. This chart clearly shows the inverse relationship between generalized cost and market share, with higher sales associated with lower total generalized cost. ADOPT also provides the option to export the data behind the results visualizations for external analysis with other tools such as Excel.



Warning: The input assumptions for this scenario are no longer consistent with those used for the results. Click here to display details in the command window.

Figure 15: ADOPT Model Results Sales by Powertrain



The height of each section of the stacked colored bars represents the relative generalized cost (calculated by ADOPT) of each attribute for each vehicle model.

The lower the total relative generalized cost, the better a vehicle model will sell.

Figure 16: ADOPT Model Results Best-Selling Chart

5 Summary

ADOPT is a logit consumer vehicle choice and stock model that includes capabilities to analyze LD and Class 8 tractor markets. The model projects future technology shares, fuel consumption, and CO_2 emissions under input assumptions of technology progress, energy prices, and policies. ADOPT is distinguished from other vehicle choice models through inclusion of non-linear and heterogenous consumer preferences and characterization of the full range of market options rather than use of composite vehicles. In addition, ADOPT has integrated vehicle simulation capabilities that enable performance assessment and optimization of endogenous technology evolution. Optionally, the model is able to adjust this evolution to enforce compliance with fuel economy and emissions regulations. Primary results include projection of technology shares and future in-use fleet energy demand, petroleum consumption, and CO_2 emissions. This enables analysis and comparison of future scenarios of technology improvements, economic conditions, and national policies. Recent new features for the HD modeling also enable examination of different onboard hydrogen fuel storage technologies from the lens of consumer preferences for vehicle cost and range.

While this report documents current ADOPT capabilities, several limitations described below suggest areas for future development.

HD ADOPT allows users to include future energy prices and consumer valuation of refueling time but currently does not explicitly include quantification of fueling infrastructure extent or availability. Therefore, results should be interpreted as representing a future where sufficient fueling becomes available where needed as new technologies diffuse.

The current tractor market comprises almost exclusively diesel ICE powertrains. HD consumer preference coefficients were developed using the demand for tractors, primarily distinguished by their engine power, coefficient of drag, and price. Because commercial vehicle consumers are highly driven by operating costs, a cost-based approach has been used to characterize vehicle range which does not vary much for diesel tractors. Emerging tractor options such as BEVs and FCEVs will have a greater range in vehicle attributes and future sales of these options will enable refinement of choice coefficients based on revealed consumer preferences.

Similarly, while ADOPT uses a 12-year lifetime for consumer decision, the current diesel tractor first ownership period is typically five to six years for long-haul and longer for shorter-haul use. Tractors are then sold into shorter distance and lower annual VMT use cases. By using the useful tractor life rather than first ownership period, ADOPT implicitly assumes that the second owner will value attributes similarly to the first owner. This also implies an assumption of equivalent depreciation rates across powertrains. In effect, if the first owner pays a premium for an alternative powertrain or other attribute, they will recoup the depreciated value of this premium at resale. Ownership periods, resale values, and used market dynamics for new technologies may be different from current market offerings, depending on the value of non-cost-related attributes as well as the repair and replacement costs for motors, batteries, and fuel cells relative to ICE components. When data on HD alternative powertrain ownership periods and resale values becomes available, future improvements to ADOPT could explicitly address these dynamics.

The HD code in ADOPT was developed considering specifics of the Class 8 tractor market. While the model could be instantiated with input data for other commercial vehicle markets, the code would need to be modified to accurately characterize operations and market dynamics for these segments.

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