Transportation Sector Demand Module of the National Energy Modeling System: Model

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Update Information

This 25th edition of the *Transportation Sector Demand Module of the National Energy Modeling System: Model Documentation 2025* reflects changes made to various sections and submodules of the Transportation Sector Demand Module (TDM) during the past 2 years for the *Annual Energy Outlook 2025* (AEO2025). These changes include the following:

1. Fully regionalized light-duty vehicle (LDV) consumer powertrain choice model
2. Fully regionalized freight truck powertrain choice model, including four additional powertrains and significantly more component-level cost and performance detail as well as incorporation of operational costs (e.g. maintenance and repair).
3. Ability to enforce U.S. Environmental Protection Agency (EPA) tailpipe greenhouse gas emission (GHG) standards for both light- and heavy-duty vehicles
4. Ability to enforce California Advanced Clean Trucks regulation
5. Ability to enforce U.S. EPA Low-NOx regulation
6. More detailed representation of electric vehicle charging infrastructure

Introduction

The Transportation Demand Module (TDM) of the National Energy Modeling System (NEMS) is a computer-based energy demand module of the U.S. transportation sector. This report documents the objectives, analytical approach, and development of the NEMS TDM, and it catalogues and describes critical assumptions, computational methodology, parameter estimation techniques, and module source code.

This reference document provides a basic description of the NEMS TDM for analysts, users, and the public. It also facilitates continuity in model development that enables customers to undertake and analyze their own model enhancements, data updates, and parameter refinements.

Model summary

The NEMS TDM encompasses a series of semi-independent submodules and components that address different aspects of the transportation sector. This comprehensive module primarily provides projections of transportation energy demand by fuel type, including motor gasoline, distillate, jet fuel, and alternative fuels (such as electricity, compressed natural gas (CNG), and liquefied natural gas (LNG)). The current NEMS TDM projection period extends to the year 2050 and uses 1995 as the start year. Projections are generated through separate consideration of energy consumption within the various modes of transport: private and fleet light-duty vehicles (LDVs), aircraft, marine, rail, and truck freight. Other transportation demands such as mass transit, military, and recreational boating are also considered. This modular approach helps us effectively assess the impacts of policy initiatives, legislative requirements affecting individual modes of travel, and technological developments.

The module also projects selected intermediate values necessary to determine energy consumption. These elements include:

1. Estimates of passenger travel demand by light-duty vehicles, air, and mass transit

2. Estimates of the energy requirements to meet transportation demand
3. Projections of vehicle stock and the penetration of new technologies
4. Estimates of the demand for truck, rail, marine, and air freight transport that are linked to projections of industrial output, international trade, and energy supply

The NEMS TDM consists of four submodules that represent a variety of travel modes that are different in design and use but share the same purpose: to convey passengers and freight. The four submodules are Light-Duty Vehicle (LDV), Air Travel, Freight Transport (heavy truck, rail, and marine), and Miscellaneous Energy Demand (Figure 1). Each submodule is composed of one or more components, consistent with the methodological requirements of the sector and in proportion with the relative impact that sector has on overall transportation demand and energy use. A fifth (inactive) submodule exists in the TDM that can estimate certain air emissions from highway vehicles.

Scope and organization

Publication of this document is supported by Public Law 93-275, Federal Energy Administration Act of 1974, Section 57(B) (1) (as amended by Public Law 94-385, Energy Conservation and Production Act), which states in part:

...that adequate documentation for all statistical and forecast reports prepared...is made available to the public at the time of publication of such reports.

In particular, this report is designed to meet EIA’s model documentation standards established under these laws.

Model archival citation

This documentation refers to the NEMS TDM as archived for the *Annual Energy Outlook 2025* (AEO2025).

The latest open-source NEMS code and input files are available at https://github.com/EIAgov/NEMS.

Model contact

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Model Overview

The TDM has two objectives:

1. Generate projections of transportation energy demand at national and census division levels
2. Endogenously incorporate the effects of technological innovation, macroeconomic feedback, infrastructure constraints, and demand behavior in making the projections

The TDM is made up of submodules that are sequentially executed in a series of program calls (Figure 1). The TDM receives inputs from NEMS, principally in the form of fuel prices, aggregate vehicle sales, economic and demographic indicators, and estimates of defense spending.

The TDM can evaluate a range of market and policy issues, including:

- Fuel taxes and subsidies
- Fuel economy performance by market class
- Fuel economy standards for light-, medium-, and heavy-duty vehicles
- Vehicle pricing by market class
- Demand for vehicle performance within market classes
- Fleet vehicle sales by powertrain type
- Alternative fuel vehicle sales share
- Changes in vehicle miles traveled (VMT)
- Various other policies and developments related to transportation energy use and greenhouse gas emissions

The modeling techniques in the TDM vary by submodule. The Light-Duty Vehicle (LDV) Submodule uses econometric models to forecast passenger travel demand and new vehicle market share and uses engineering and optimization models for estimating fuel economy. The Air Travel Submodule uses econometrics to forecast passenger travel demand and aircraft efficiency using world regional population and world regional gross domestic product (GDP) inputs. The Freight Transportation Submodule uses output from selected industries to estimate travel demand and energy consumption in each of three primary freight modes: truck, rail, and marine. The Miscellaneous Energy Demand Submodule forecasts passenger travel and energy and oil demand from military, mass transit (including bus and rail), recreational boating, and lubricants.

LDVs are classified according to eight size classes for cars, eight size classes by body type and gross vehicle weight rating (GVWR) for light trucks, and those are divided by fleet and private use. Freight trucks are categorized by 19 regulatory classifications and are aggregated into medium-light, medium-heavy, and heavy-duty market classes and by fleet and non-fleet vehicles. Buses are subdivided into commuter, intercity, and school buses. The Air Travel Submodule contains wide- and narrow-body aircraft and regional jets for both commercial passenger aircraft and dedicated freighters. Rail transportation is made up of freight rail and three modes of personal rail travel: commuter, intercity, and transit. Shipping is divided into domestic and international. Outputs from the submodules are provided to an integrating module, which then sends the various transportation demands to the supply modules.

Brief description of submodules

Details of each submodule and their associated components are provided in subsequent sections, which include descriptions, mathematical representations, and graphical illustrations of the structure of each submodule.

Light-Duty Vehicle (LDV) Submodule

The first submodule executed is the LDV Submodule, which projects attributes and sales distributions of new cars and light trucks. The LDV Submodule provides estimates of new LDV fuel economy and market shares of alternative fuel vehicles (AFVs). The LDV Stock Component generates travel, fuel economy, and fuel consumption estimates of the entire stock of LDVs, including both those owned and operated by households as well as by fleets. Information from the LDV Stock Component is subsequently passed to the Miscellaneous Energy Demand Submodule.

Air Travel Submodule

The Air Travel Submodule receives domestic macroeconomic input from NEMS, and incorporates exogenously defined world regional population and world regional GDP projections. The Air Travel Submodule uses an econometric estimation method to project travel demand and a stock-vintaging component to estimate the size and other characteristics of the aircraft fleet required to meet that demand. The output of this submodule also includes estimates of the demand for jet fuel and aviation gasoline, which are passed to the Miscellaneous Energy Demand Submodule.

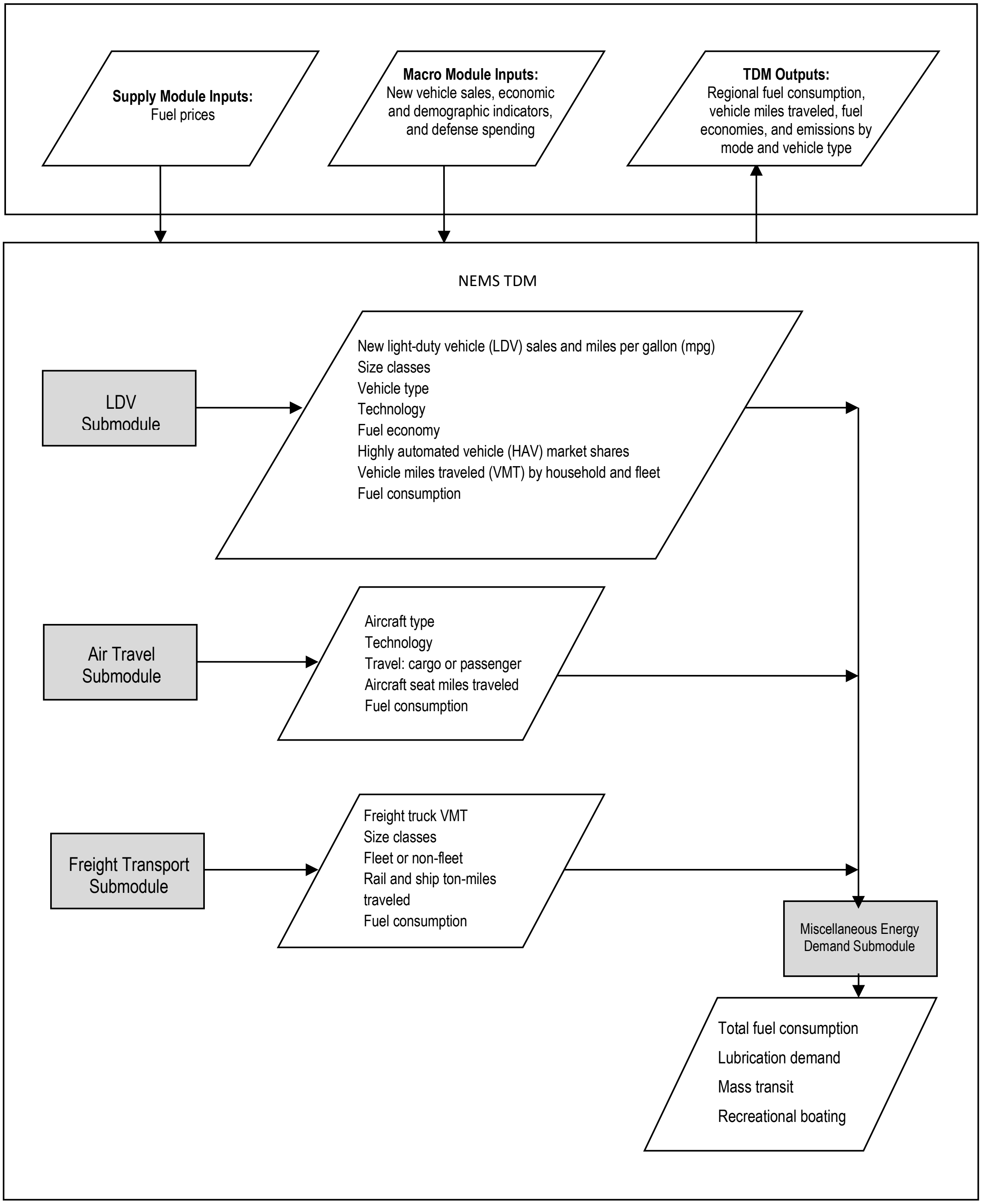
Freight Transportation Submodule

The Freight Transportation Submodule uses NEMS projections of fuel prices, trade indexes, and output related to selected industries to estimate travel demand and energy consumption in each of three primary freight modes: truck, rail, and marine. Travel and fuel demand estimates are subsequently passed to the Miscellaneous Energy Demand Submodule.

Miscellaneous Energy Demand Submodule

The Miscellaneous Energy Demand Submodule receives estimates of military expenditures from NEMS to generate projections for military fuel demand. Travel demand estimates from the LDV Stock Component and fuel efficiency estimates from the Freight Transportation Submodule are used to calculate regional fuel consumption by buses. Estimates of disposable personal income from NEMS are used to calculate the demand for fuel in recreational boating. Demand for lubricants used in transportation is estimated from aggregate demand for highway travel obtained from the LDV, Air Travel, Freight Transportation, and Miscellaneous Energy Demand Submodules. Passenger travel and energy demand are estimated for transit, commuter, and intercity rail.

Figure 1. Structure of the NEMS Transportation Sector Demand Module



Data source: U.S. Energy Information Administration
Note: Shaded boxes represent the module's main submodules.

Inputs and outputs of the module

The TDM sends information on regional fuel consumption to NEMS, where it is integrated with the results of the other demand, macroeconomic, and supply modules. To generate projections, the TDM receives a variety of exogenous inputs from other NEMS modules. The primary source of these inputs is the Macroeconomic Activity Module, which provides projections of economic variables, such as new vehicle sales and demographic indicators. Other inputs exogenous to the TDM, but endogenous to NEMS, include fuel price projections from the various supply modules.

The TDM produces projections of travel demand and associated energy demand, disaggregated by census division, vehicle and fuel type, and powertrain technology, as well as vehicle stocks and efficiency. Within NEMS, the TDM interacts with the Macroeconomic Activity Module and the various supply modules that provide the prices of transportation-related fuels at a given level of demand. For each projection year, NEMS performs several iterations to derive a set of fuel prices under which supply and demand converge. The reliance on economic and price inputs to each of the submodules in the TDM is detailed in the following sections.

Transportation Sector Demand Module (TDM) Structure

As described above, the NEMS TDM is made up of an array of separate submodules, each addressing different aspects of the transportation sector.

The general theoretical approach taken, assumptions considered, and methodology employed are discussed for each submodule and component. The key computations and equations are presented to provide a comprehensive overview of the TDM. The equations follow the logic of the FORTRAN source code to help understand the code and its structure.

Flowcharts are provided within the text or at the end of each section to illustrate the logic used in the submodules where necessary. These flowcharts are detailed, self-contained representations of the submodule or component. For clarity, origins and destinations of external information flows are not specified. A large number of data inputs exogenous to NEMS are supplied to the submodules within the TDM. These datasets remain unchanged throughout the projection and make up the assumptions about current and future conditions.

The TDM is structured so that the model representation captured in the variables and output of each submodule is appropriately dimensioned for subsequent steps. Because of the differing methodological approaches and data requirements, each section is presented individually. Several subroutine calls are made within each submodule and component. Appendix C maps the various subroutines and the order in which they are called.

Light-Duty Vehicle (LDV) Submodule

The LDV Submodule tracks the purchase and retirement of cars and light trucks, projects fuel efficiency, and estimates the consumption of transportation fuels based on projections of travel demand. The LDV Submodule requires the largest number of exogenous inputs and primarily consists of the following components (Figure 2):

1. LDV Sales Segmentation Component (subroutine *NEWLDV*)
2. Manufacturer Technology Choice Component (MTCC, subroutine *FEMCALC*)
3. Class and Group Share Component (subroutine *CGSHARE*)
4. Consumer Vehicle Choice Component (CVCC, subroutine *TLDV*)
5. Fuel Economy and Tailpipe GHG Standard Compliance Component (subroutines *CAFECALC, CAFETEST*)
6. LDV Fleet Component (subroutines *TFLTSTKS, FLTHAV, TFLTVMTS, TFLTMPGS*, and *TFLTCONS*)
7. LDV Stock Accounting Component (subroutine *TSMOD*)
8. Vehicle Miles Traveled Component (subroutine *TVMT*)

Components two through five are contained within the New Vehicle Fuel Economy Component (subroutine *TMPGNEW*). Each component performs calculations at a level of disaggregation that matches the nature of the mode of transport, the quality of the input data, and the level of detail required in the output. The projections are calculated for 11 vehicle manufacturers, including 5 car and 6 light truck groups. Cars and light trucks are each separated into size classes. Each size class represents an aggregation of vehicle models that are similar in size and functionality and that consumers believe offer similar attributes. The car classes are similar to the U.S. Environmental Protection Agency's (EPA) size classes and are based on passenger car interior volume. Truck classification is based on vehicle inertia weight class[1] by truck type (pickup, sport-utility vehicle, and van). This method leads to a total of 16 size classes, which are individually projected to 2050 for 11 manufacturer groups.

Changes in four factors affect the fuel economy of new vehicles:

1. Vehicle fuel economy, safety, and emission standards
2. Technology penetration
3. Level of acceleration performance achieved
4. Mix of vehicle size classes and vehicle powertrain types (for example, hybrid and electric) sold

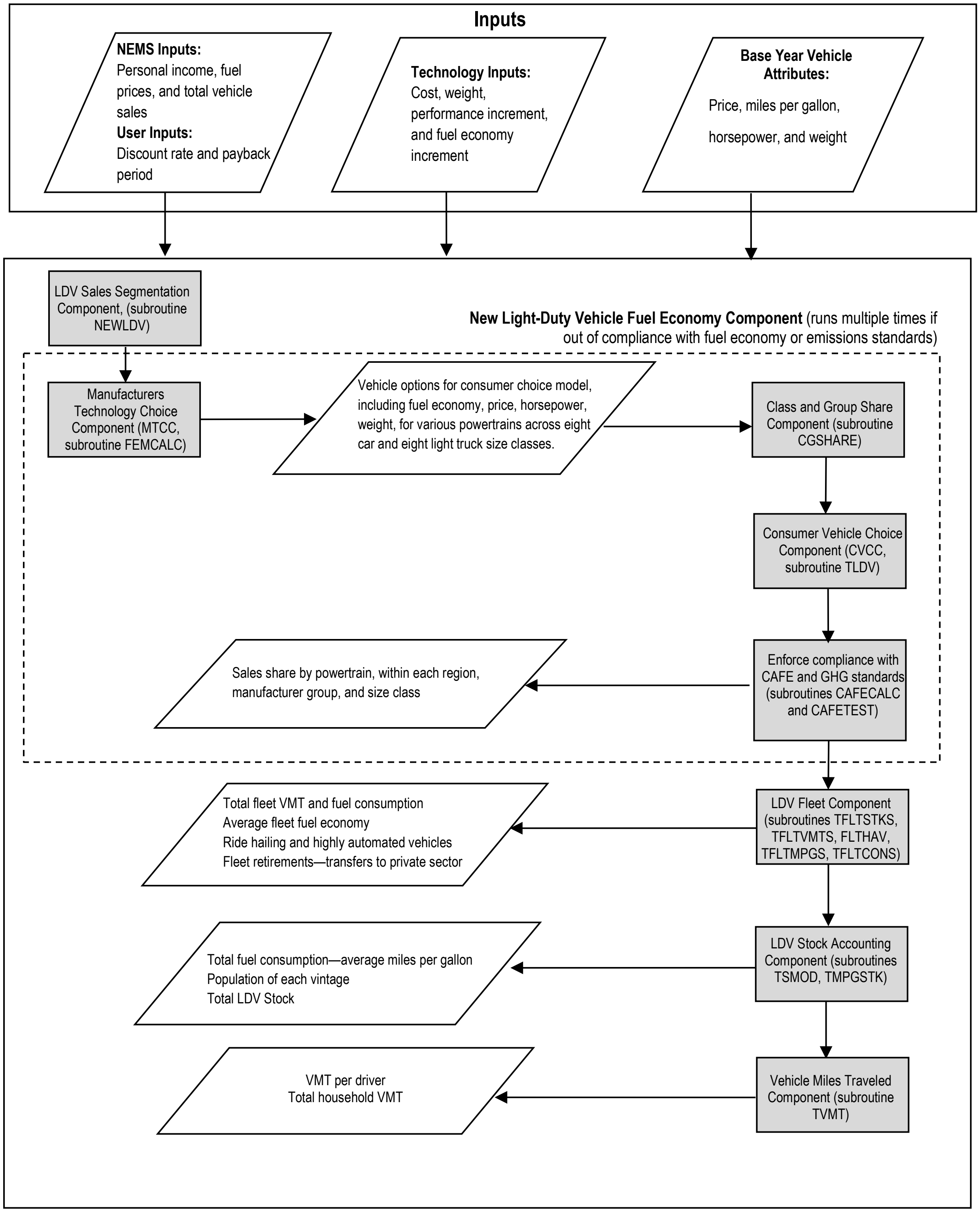
Technological improvements to each of these size classes are then projected based on the availability and cost-effectiveness of new technologies to improve fuel economy . The central assumptions involved in this technological projection are:

1. All manufacturers can obtain the same benefits from a given technology, provided they have adequate lead time (that is, no technology is proprietary to a given manufacturer in the long term).
2. Manufacturers will generally adopt technological improvements that are perceived as cost-effective to the consumer, even without any regulatory pressure. However, the term cost-effective needs to be interpreted from the manufacturer's perspective.

These projections also account for manufacturer lead time and tooling constraints that limit the rate of increase in the market penetration of new technologies. Based on the technological improvements adopted, a fuel economy projection is developed for each of the manufacturer groups, size classes, and powertrain types.

[1] *Vehicle inertia weight class* with respect to a motor vehicle is statutorily determined under 40 CFR § 86.129-94. According to 40 CFR § 86.082-2, the inertia weight class is the class (a group of test weights) into which a vehicle is grouped based on its loaded vehicle weight in accordance with the provisions of 40 CFR part 86.

Figure 2. Structure of the Light-Duty Vehicle Submodule of NEMS



Data source: U.S. Energy Information Administration

The fuel economy projection must be adjusted to account for changes in technology and changes in consumer preference for performance. The demand for increased acceleration performance for each size class is estimated based on an econometric equation that relates fuel prices and personal disposable income to demand for performance or horsepower, by size class. These relationships are used to project the change in horsepower, which is then used to project the change in fuel economy through an engineering relationship that links performance and fuel economy.

The change in the mix of size classes sold is projected as a function of fuel price, vehicle price, and personal disposable income. The sales mix by size class is used to calculate new fuel economy. For example, the Manufacturers Technology Choice Component (MTCC) uses econometric equations for the sales mix choice.[2] The submodule projects sales mix for the eight car and eight light-truck classes.

The LDV Submodule also allows us to specify fuel economy standards by year and apply those standards to each of 11 manufacturer groups, as well as the penalty (in dollars) per car, per mile-per-gallon below the standard. The standards are accounted for in the projection by incorporating the penalty into the technology cost-effectiveness calculation in the submodules. Finally, the submodule also accounts for select state-level regulations, such as California's Zero Emission Vehicle (ZEV) requirement, followed by 10 additional states that follow Section 177: (Connecticut, Colorado, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, and Vermont)[3].

LDV Sales Segmentation Component

The LDV Submodule first estimates the allocation of LDV sales between cars and light trucks to capture the changing purchase patterns of consumers in recent years in subroutine *NEWLDV*. This is based on total sales from the Macroeconomic Activity Module. Total sales of trucks are shared into the following gross vehicle weight rating (GVWR) categories:

1. Trucks less than 8,500 pounds, included in the LDV Submodule
2. Trucks from 8,500 to 10,000 pounds, modeled separately in the Class 2b Vehicle Component
3. Trucks over 10,000 pounds, included in the Freight Truck Component

Next, the submodule estimates the percentage of total light vehicles less than 8,500 pounds GVW that are cars and light trucks by region (*CarTrkSplit*) based on disposable income per capita (*INC00_D_16*), gasoline price (*PMGTR00_D_C_regn*), horsepower (*AHPCAR* and *AHPTruck*), curb weight (*AWTCAR* and *AWTTruck*), and fuel economy (*TRUEMPG_regn*).

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[2] Goldberg, U.S. Department of Commerce, Bureau of Economic Analysis, 1998.

[3] The ZEV mandate subroutine was inactive in all AEO2025 cases.

$$CARSHRT\_regn_{iregn,year} = e^{\left(\begin{array}{c} \beta_0(1-\rho)+(\rho\log(CarTrkSplit_{iregn,car,year-1}))+ \\ \beta_1\left[\log\left(INC00\_D\_16_{iregn,year}\right)-\rho\log\left(INC00\_D\_16_{iregn,year-1}\right)\right]+ \\ \beta_2\left[\log\left(PMGTR00\_D\_C\_regn_{iregn,year}\right)-\rho\log\left(PMGTR00\_D\_C\_regn_{iregn,year-1}\right)\right]+ \\ \beta_3\left[\log\left(AHPCAR_{iregn,year-1}\right)-\rho\log\left(AHPCAR_{iregn,year-2}\right)\right]+ \\ \beta_4\left[\log\left(AWTCAR_{iregn,year-1}\right)-\rho\log\left(AWTCAR_{iregn,year-2}\right)\right]+ \\ \beta_5\left[\log\left(TRUEMPG\_regn_{iregn,car,year-1}\right)-\rho\log\left(TRUEMPG\_regn_{iregn,car,year-2}\right)\right]+ \\ \beta_6\left[\log(DUMM_{year})-\rho\log(DUMM_{year-1})\right] \end{array}\right)} \quad (1)$$

$$TRKSHRT\_regn_{iregn,year} = e^{\left(\begin{array}{c} \beta_0(1-\rho)+(\rho\log(CarTrkSplit_{iregn,trk,year-1}))+ \\ \beta_1\left[\log\left(INC00\_D\_16_{iregn,year}\right)-\rho\log\left(INC00\_D\_16_{iregn,year-1}\right)\right]+ \\ \beta_2\left[\log\left(PMGTR00\_D\_C\_regn_{iregn,year}\right)-\rho\log\left(PMGTR00\_D\_C\_regn_{iregn,year-1}\right)\right]+ \\ \beta_3\left[\log\left(AHPTruck_{iregn,year-1}\right)-\rho\log\left(AHPTruck_{iregn,year-2}\right)\right]+ \\ \beta_4\left[\log\left(AWTTruck_{iregn,year-1}\right)-\rho\log\left(AWTTruck_{iregn,year-2}\right)\right]+ \\ \beta_5\left[\log\left(TRUEMPG\_regn_{iregn,trk,year-1}\right)-\rho\log\left(TRUEMPG\_regn_{iregn,trk,year-2}\right)\right]+ \\ \beta_6\left[\log(DUMM_{year})-\rho\log(DUMM_{year-1})\right] \end{array}\right)} \quad (2)$$

$$CarTrkSplit_{iregn,car,year} = \frac{CARSHRT\_regn_{iregn,year}}{CARSHRT\_regn_{iregn,year}+TRKSHRT\_regn_{iregn,year}},$$

$$CarTrkSplit_{iregn,truck,year} = 1 - CarTrkSplit_{iregn,car,year},$$

The distribution of LDV sales by census division (*regn_shr*) is then estimated based on the projected regional growth of licensed drivers in the United States. The submodule then calculates new car and light-truck (class 1 and 2a, less than 8,500 pounds GVWR) sales (*NEWLDVs*) as follows:

$$NEWLDVs_{iregn,ivtyp,year} = \left(MC\_SUVA_{year} + TEMPCLS12A_{year}\right) * CarTrkSplit_{iregn,ivtyp,year} * REGN\_SHR_{iregn,year} \quad (3)$$

where

MC_SUVA_{year} = Total car sales, from the Macroeconomic Activity Module; and

$TEMPCLAS12A_{Year}$ = Sales of class 1 and 2 light trucks.

NewLDVs is the primary output of this component, as it is used in the *Class and Group Share Component* to calculate total LDV sales across all dimensions of interest for the purposes of both determining regulatory compliance and estimating regional energy consumption by region, size class, manufacturer group, and powertrain.

New Vehicle Fuel Economy Component

The New Vehicle Fuel Economy Component (subroutine *TMPGNEW*) produces estimates of new light-duty vehicle fuel economy based on incremental technology adoption and enforcement of fuel economy and tailpipe emissions standards (Figure 3).

Because of the disparate characteristics of the various classes of LDVs, this component addresses the commercial viability of many separate technologies within each of 16 vehicle size classes, 11 manufacturer groups, and 16 powertrain types in the MTCC (subroutine *FEMCALC*). Baseline vehicle attributes that describe the fuel economy, weight, horsepower, and price in the last historical year (MY2023 for AEO2025) are read in and calibrated to National Highway Traffic Safety Administration (NHTSA) data (subroutine *CALIBNHTSA*).

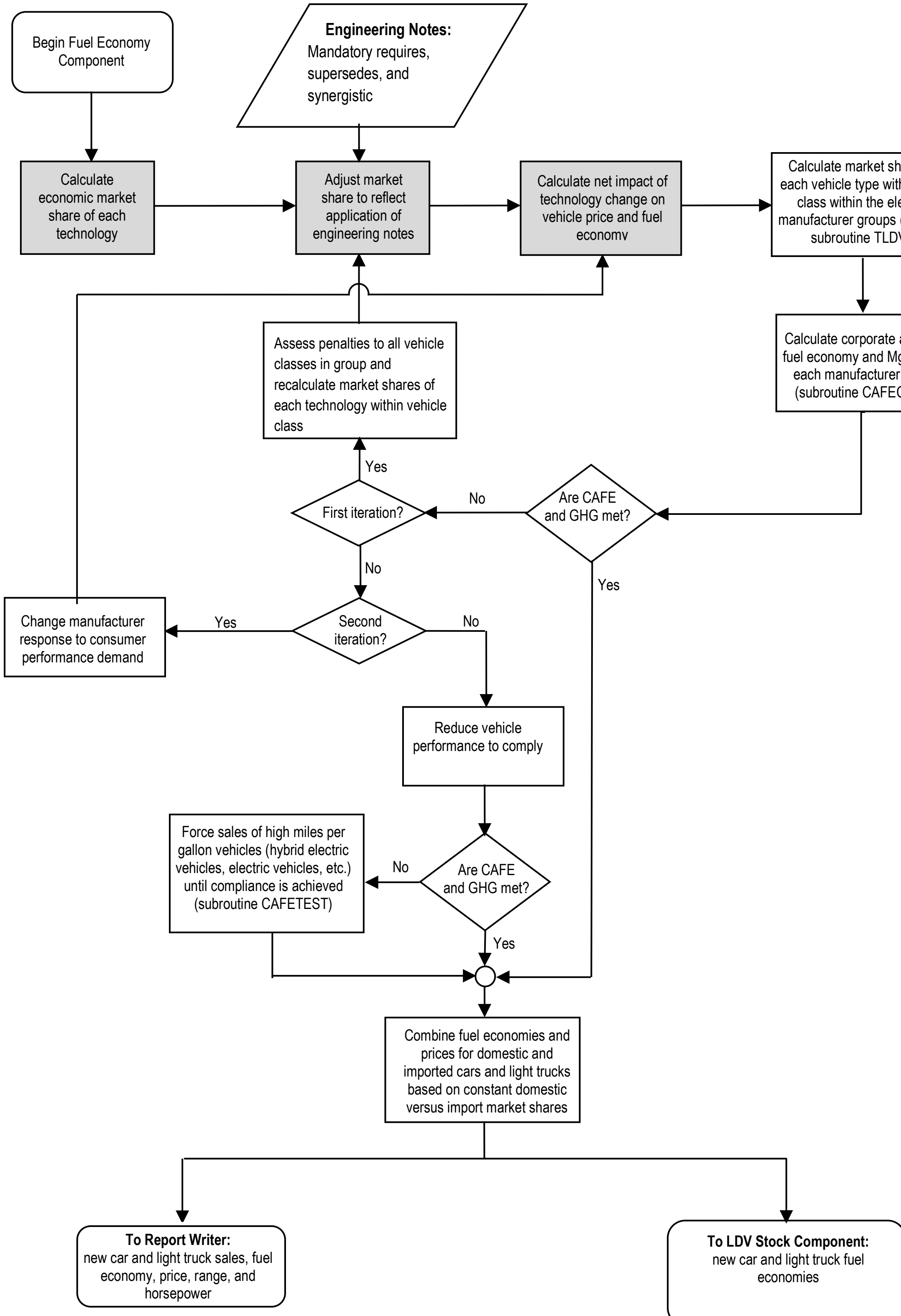
Each available technology is subjected to a cost-effectiveness test that balances its cost against the potential fuel savings and value of any performance increase. The result is used to generate an economic market share for the technology, constrained by engineering limitations and policy requirements. After all the technology market shares have been determined, the baseline attributes are updated to reflect the impact of the technology choices. Horsepower is adjusted to account for changes in vehicle weight, technology adoption, and consumer preference.

The CVCC then estimates the market penetration of the various powertrains produced, based on the attributes of those vehicles and the variation in consumer preference.

Once these steps have been taken for all vehicle size classes, fleet average fuel economy and fleet total CO_2 emissions ($MgCO_2$), for determining compliance with National Highway Traffic Safety Administration Corporate Average Fuel Economy (NHTSA CAFE) and Environmental Protection Agency (EPA) tailpipe greenhouse gas (GHG) light-duty vehicle standards respectively, are calculated for each of the 11 manufacturer groups (subroutine *CAFECALC*). When a group fails to meet the CAFE or GHG standard, and the maximum car/light-truck credit transfer allowance has been utilized, *FEMCALC* is run for a second time with the technology cost-effectiveness calculation modified to include the benefit of not having to pay the fine for failing to meet CAFE. After this second pass, if CAFE and GHG standards are still not met, a third pass is completed. The horsepower increases from previous passes are deactivated and converted to an equivalent fuel economy improvement. This process assumes manufacturers will minimize their costs by reducing performance to achieve compliance. If, after the third pass, either CAFE or GHG standards are not met, the model overrides consumer-derived alternative-fuel vehicle (AFV) sales from the CVCC until the market meets CAFE and GHG standards (subroutine *CAFETEST*). Determining which AFVs are used to override is based on cost-effectiveness to consumers, which, in turn, is based on incremental vehicle cost relative to fuel savings.

Compliance with LDV EPA tailpipe GHG regulations is enforced at the aggregate LDV market level as there are no limits on credit trading across manufacturers or car/light truck groups. Noncompliance in the aggregate market is addressed by applying the same iterative logic discussed above to those groups that are out of compliance with EPA tailpipe GHG regulations, in parallel with enforcement of CAFE compliance.

Figure 3. New Vehicle Fuel Economy Component of the Transportation Sector Demand Module, NEMS. Shaded boxes indicate steps that are completed in the MTCC, subroutine FEMCALC.



Data source: U.S. Energy Information Administration

Manufacturer Technology Choice Componenet (MTCC, subroutine *FEMCALC*)

Establish vehicle attributes

The MTCC is capable of building 16 distinct powertrain options within each manufacturer group and size class:

1. Conventional non-hybrid gasoline
2. Turbo direct-injection diesel
3. Flex-fuel ethanol
4. Plug-in hybrid electric 20- and 50-mile range gasoline vehicles (PHEV20, PHEV50)
5. Battery electric 100-, 200-, and 300-mile range vehicles (EV100, EV200, EV300)
6. Diesel/electric hybrid
7. Bi-fuel CNG/LNG and bi-fuel LPG (liquefied propane gas)
8. Dedicated CNG/LNG and LPG
9. Methanol fuel cell electric vehicle and hydrogen fuel cell electric vehicle (FCEV
10. Gasoline/electric hybrid

Vehicle attributes, including price, fuel economy, horsepower, tank size, trunk size, range, and weight, for vehicles that were offered by manufacturers in the last historical year (input files *trnfemx.xlsx* and *trnnhtsax.xlsx*) are the basis for projected attributes. Many alternative powertrains are only available in certain manufacturer groups and size classes.

For powertrains that are introduced in the projection, attributes must be developed based on historical data and other input assumptions. Attributes for diesel, flex-fuel ethanol, CNG, and LPG vehicles are derived based on exogenously determined incremental adjustments to the non-hybrid gasoline powertrain (subroutine *AFVADJ*). Price, weight, and fuel economy for hybrid electric, plug-in hybrid electric, battery electric, and fuel cell vehicles introduced during the projection period are derived endogenously using component price and weight estimates, along with relative fuel economy improvements versus conventional non-hybrid gasoline vehicles (subroutines *HEVCALC, PHEVCALC, EVCALC,* and *FCCALC*, as discussed later in this section).

Calculate technology market shares

The MTCC first determines the cost-effective market shares of technologies for each vehicle class and then calculates the resulting fuel economy, weight, horsepower, and price through the subroutine *FEMCALC*. For each projection period, this function is called up to three times. During the first pass, technology market shares are calculated for all vehicle size classes. In the second pass, the technology market shares are recalculated for manufacturer groups that fail to meet the CAFE and/or tailpipe GHG standard. During this pass, the cost-effectiveness calculation is adjusted to include the regulatory cost of failing to meet standards.[4] If a manufacturer group fails to meet the standards after the second pass, no further adjustments to technology market shares are made. In the third pass, the manufacturer groups focus solely on CAFE and tailpipe GHG compliance at the expense of increased performance.

For each vehicle class, *FEMCALC* follows these steps (Figure 4):

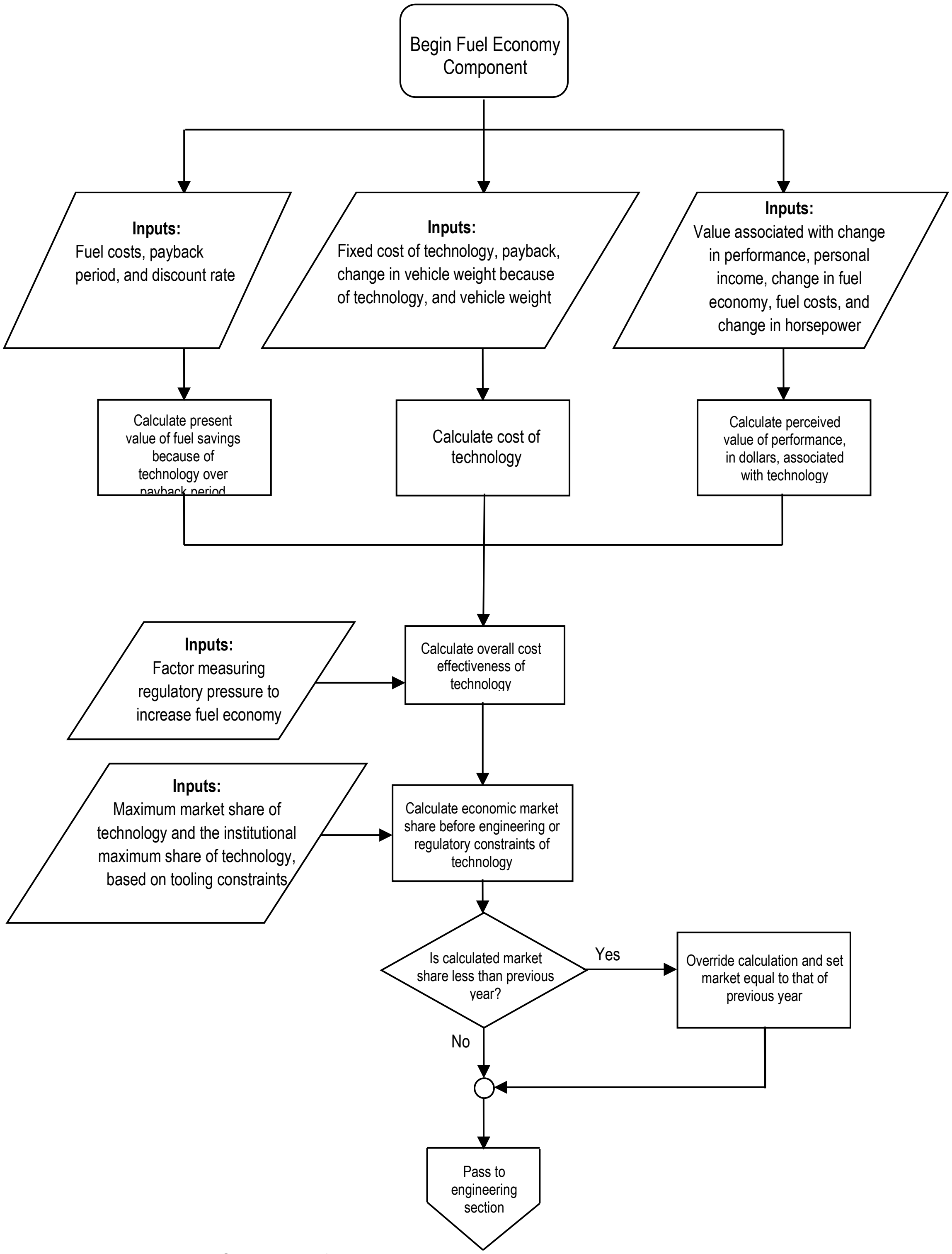
[4] See the variable REGCOST in Equation 15.

1. Calculate the economic market share for each technology.
2. Apply the engineering notes to control market penetration.
3. Adjust the economic market shares though application of the following three types of engineering notes: mandatory notes, supersedes notes, and requires notes.
4. Adjust the fuel economy impact by applying the synergy engineering notes.
5. Calculate the net impact of the change in technology market share on fuel economy, weight, and price.
6. Estimate battery electric vehicle (BEV), plug-in hybrid electric vehicle (PHEV), hybrid electric vehicle (HEV), and fuel cell electric vehicle (FCEV) characteristics.
7. Adjust horsepower based on the new fuel economy and weight.
8. Readjust fuel economy based on the new horsepower and price based on the change in horsepower.

Each step is described in more detail below. Note that all of the calculations in this section take place within loops by manufacturer group, size class, and powertrain type. In the interest of legibility, these dimensions are not shown in the subscripts, except to clarify the relationship.

The cost-effective market share calculation for each technology is based on the cost of the technology, the present value of the expected fuel savings, and the perceived value of performance.

Figure 4. Economic market share calculation of the Manufacturers Technology Choice Component of the Transportation Sector Demand Module, NEMS



Data source: U.S. Energy Information Administration

Fuel savings value

For each technology, the expected fuel savings associated with incremental fuel economy impacts is calculated. The decision to introduce a particular technology is made at least three years before actual introduction in the marketplace and is based on the expected fuel prices at the time of introduction rather than actual fuel prices.

Nominally, three-year lagged fuel costs and the annual rates of fuel price change are used to estimate expected dollar savings. However, because prices can spike and because manufacturing decisions are not based on one-year spikes, the three-year lagged costs and rates of price change used for this calculation are actually five-year moving average prices and are the difference between the three-year lagged five-year moving average price and the four-year lagged five-year moving average price. The expected present value of fuel savings depends on the expected price of fuel, payback period (the amount of time the purchaser is willing to wait to recover the initial investment), discount rate (the time value of money), and the distance driven over the period. This estimation involves the following three steps:

1. Calculate the linear fuel cost slope (*PSLOPE*) from the national average price of gasoline (*FUELCOST*), which is used to extrapolate the expected fuel cost over the desired payback period and constrain the value to be equal to or greater than zero

$$FIVEYR\_FUELCOST_1 = \frac{1}{5} * \sum_{i=Year-7}^{Year-3} FUELCOST_i \quad (4)$$

$$FIVEYR\_FUELCOST_2 = \frac{1}{5} * \sum_{i=Year-8}^{Year-4} FUELCOST_i \quad (5)$$

$$PSLOPE = MAX(0, FIVEYR\_FUELCOST_1 - FIVEYR\_FUELCOST_2) \quad (6)$$

2. Calculate the expected fuel price (*PRICE_EX*) in year *i* (where *i* goes from 1 to *PAYBACK*)

$$PRICE\_EX_{year=i} = PSLOPE * (i + 2) + FIVEYR\_FUELCOST_1 \quad (7)$$

3. For each technology, calculate the expected present value of fuel savings (*FUELSAVE*) over the payback period

$$FUELSAVE_{itc} = \sum_{i=1}^{PAYBACK} VMT_i * \left(\frac{1}{FE_{year-1}} - \left(\frac{1}{1 + DEL_{FE_{itc}} * FE_{year-1}} \right) \right) * PRICE\_EX_i * (1 + DISCOUNT)^{-i} \quad (8)$$

where

VMT_i = annual vehicle miles traveled;

itc = the ***i***ndex representing the ***t***echnology ***c***hoice under consideration;

i = index: 1, 2, … , PAYBACK; defined locally;

FE_{year-1} = fuel economy of previous year;

DEL_FE_{itc} = fractional change in fuel economy associated with technology *itc*;

PAYBACK = user-specified payback period; and

DISCOUNT = user-specified discount rate.

Technology cost

Technology costs may have absolute and weight-dependent components. An absolute component is a fixed dollar cost for installing a particular technology on a vehicle. Most technologies have only an absolute component. A weight-dependent component is associated with material substitution technologies, where a lightweight material replaces heavier material. This component is split between an absolute and relative weight-based cost. In this case, the technology cost is a function of the amount of material, which is, in turn, a function of the weight of the vehicle. The technology cost equation is a sum of these components:

$$TECHCOST_{itc,year,ildv} = DEL\_COSTABS_{itc} + DEL\_COSTWGT_{itc} * \left(ABS(DEL\_WGTABS_{itc}) + ABS(DEL\_WGTWGT_{itc}) * WEIGHT_{year-1,ifuel}\right) \quad (9)$$

where

$TECHCOST_{itc,year,ildv}$ = cost per vehicle of technology *itc*;

$DEL\_COSTABS_{itc}$ = absolute cost of technology *itc*;

$DEL\_COSTWGT_{itc}$ = weight-based change in cost ();

DEL_WGTABS_{itc} = fractional change in absolute weight associated with technology *itc*;

DEL_WGTWGT_{itc} = fractional change in relative weight associated with technology *itc*; and

$WEIGHT_{year-1,\ ifuel}$ = original vehicle weight for different fuel type vehicles.

Learning cost adjustment

The technology cost is adjusted to include the product of two individual cost multiplier adjustments (*LEARN_COST_MULTIPLIER*). The two cost multipliers represent two separate portions of the same learning cost curve. The first cost multiplier represents the flattened portion of the learning curve, where most of the effects of learning for that technology have already been gained. The second cost multiplier represents the steeper portion of the learning curve, where the effects of learning are greatest for those technologies. The first cost multiplier applies to most of the technologies, except for those that can gain no more learning. The second cost multiplier applies to technologies that can still gain significant cost reductions as a result of learning, including micro hybrid and mild hybrid technologies, and Level 2 rolling resistance tires.

$$TECHCOST_{itc} = TECHCOST_{itc} * \prod_{l=1}^{2} LEARN\_COST\_MULTIPLIER_{l} \qquad (10)$$

Performance value

Although a number of technological factors affect the perceived performance of a vehicle, in the interests of clarity and simplicity, the model uses a vehicle's horsepower-to-weight ratio as a proxy for the general category of performance. The perceived value of performance is a factor in the cost-effectiveness calculation. The value of performance for a given technology is positively correlated with both income and vehicle fuel economy and negatively correlated with gasoline prices.

$$VAL_{PERF\,itc,year} = VALUEPERF * PERF\_COEFF * \frac{INCOME_{year}}{INCOME_{year-1}} * (1 + DEL\_FE_{itc}) * \frac{FUELCOST_{year-1}}{FUELCOST_{year}} * DEL\_HP_{itc} \qquad (11)$$

where

$VAL\_PERF_{itc,year}$ = dollar value of performance of technology *itc*;

VALUEPERF = value associated with an incremental change in performance;

PERF_COEFF = parameter used to constrain vehicle performance;

DEL_HP_{itc} = fractional change in horsepower of technology *itc*;

$FUELCOST_{year}$ = actual price of gasoline for the given year; and

$INCOME_{year}$ = income per capita in 1990 dollars.

Economic market share

The market share of the considered technology, based on fuel savings or on performance, is determined by first evaluating the cost-effectiveness of technology *itc* as a function of the values described above

$$COSTEF\_FUEL_{itc} = \frac{FUELSAVE_{itc} - TECHCOST_{itc} + \left(REGCOST * FE_{year-1} * DEL\_FE_{itc}\right)}{TECHCOST_{itc}} \qquad (12)$$

$$COSTEF\_PERF_{itc} = \frac{VAL\_PERF_{itc} - TECHCOST_{itc}}{TECHCOST_{itc}} \qquad (13)$$

$$MKT\_FUEL_{itc} = \frac{1}{1 + e^{MKT\_1COEFF * COSTEF\_FUEL_{itc}}} \qquad (14)$$

$$MKT\_PERF_{itc} = \frac{1}{1 + e^{MKT\_2COEFF * COSTEF_{PERF\,itc}}} \qquad (15)$$

where

$COSTEF\_FUEL_{itc}$ = a unitless measure of cost effectiveness based on fuel savings of technology;

$COSTEF\_PERF_{itc}$ = a unitless measure of cost effectiveness based on performance of technology;

REGCOST[5] = factor representing regulatory pressure to increase fuel economy, in dollars per miles per gallon;

MKT_FUEL_{itc} = market share based on fuel savings;

MKT_PERF_{itc} = market share based on performance;

MKT_1COEFF = -4 if COSTEF_FUEL < 0, and -2 otherwise; and

MKT_2COEFF = -4 if COSTEF_PERF < 0, and -2 otherwise.

The two separate market shares are combined to determine the actual market share for the technology.

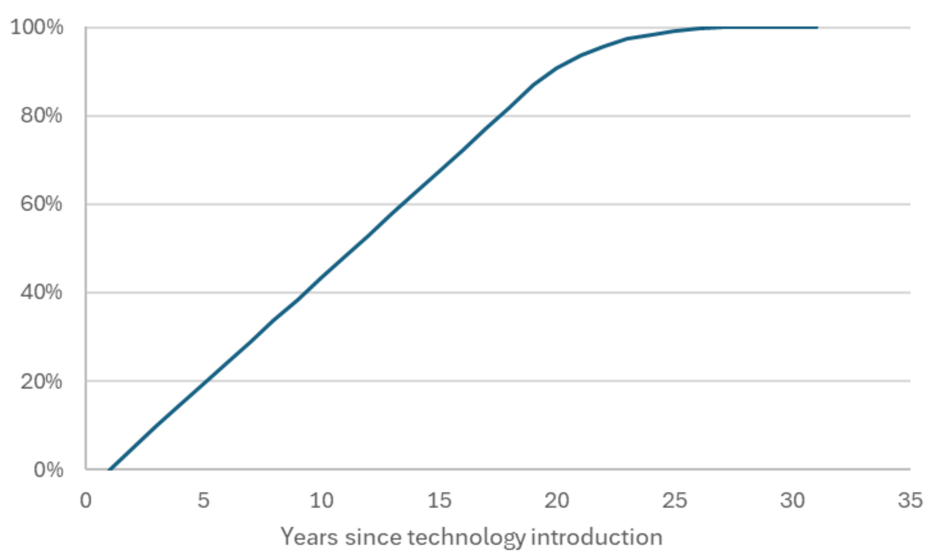
$$ACTUAL\_MKT_{itc,year} = PMAX_{itc,year} * MAX(MKT\_FUEL_{itc}, MKT\_PERF_{itc}) \qquad (16)$$

where

$ACTUAL\_MKT_{itc,year}$ = economic share consideration of engineering or regulatory constraints; and

$PMAX_{itc,year}$ = institutional maximum market share, modeling tooling constraints on the part of the manufacturers; set in a separate subroutine, *FUNCMAX* (see Figure 5).

Figure 5. Insitutional maximum market share set in FUNCMAX



Data source: U.S. Energy Information Administration

We use the variable name $ACTUAL\_MKT_{itc,year}$ for several different variables that may have different

[5] During pass 1, REGCOST has a value of 0. During passes 2 and 3, it is set to REG_COST, which is a user input. This penalty is discussed in the earlier section entitled Calculate Technology Market Shares.

values. The model adjusts the initial value to arrive at a final value.

If the manufacturer does not satisfy CAFE, production can be accelerated to reach 100% penetration in half the time and continue at that pace every year thereafter.

Market share overrides

Existing technologies are assumed to maintain their market shares unless forced out by later technologies. If the cost-effectiveness calculation yields an economic market share lower than that of the previous period, then the calculated value is overridden.

$$ACTUAL\_MKT_{itc,year} = MAX\left(MKT\_PEN_{itc,year}, ACTUAL\_MKT_{itc,year}\right) \tag{17}$$

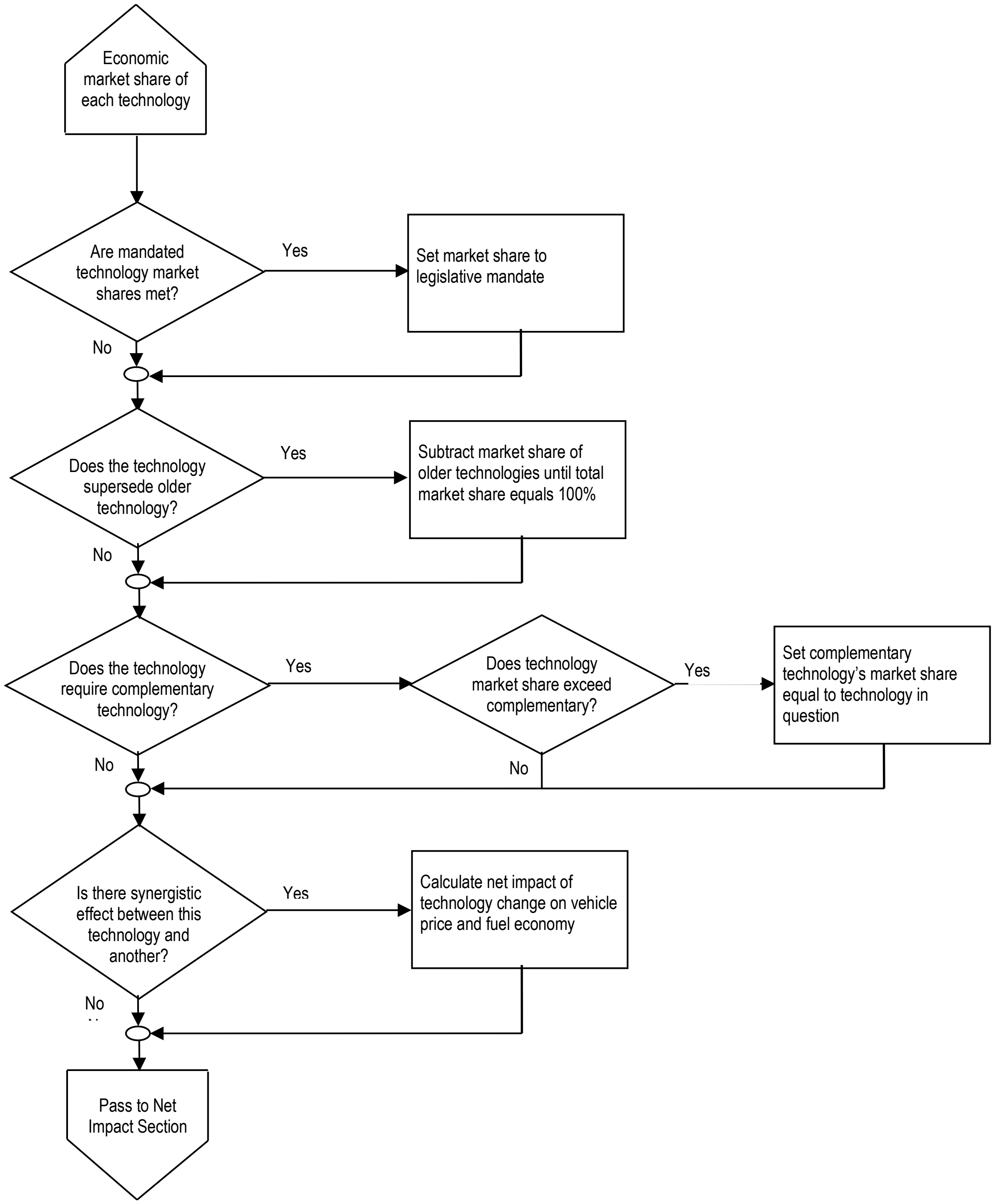
Finally, the economic market share is bounded by the maximum market share, *MKT_MAX* or 1.0, whichever is smaller.

$$ACTUAL\_MKT_{itc,year} = MIN\left(1, MKT\_MAX_{itc}, ACTUAL\_MKT_{itc,year}\right) \tag{18}$$

Apply the engineering notes

The engineering notes consist of a number of overrides to the economic cost-effectiveness calculations done in the previous step. Three types of notes (mandatory, supersedes, and requires) directly affect the technology market share results obtained above. The synergy note does not affect the market share and is applied after all other engineering notes have been applied (Figure 6).

Figure 6. Engineering notes for Manufacturers Technology Choice Component of the Transportation Sector Demand Module, NEMS



Data source: U.S. Energy Information Administration

Mandatory notes

Mandatory notes are usually associated with safety or emissions technologies that must be in place by a certain year, legislative or regulatory action. If the number of phase-in years is one or less, the full required market share, *MANDMKSH,* is adopted immediately.

$$ACTUAL\_MKT_{itc,year} = MAX\left(ACTUAL\_MKT_{itc,year}, MANDMKSH_{itc,year}\right) \quad (19)$$

If the number of phase-in years is greater than one, the model adds a proportional share of the total mandatory share, *MANDMKSH*, each year. Both the base and maximum market penetrations can vary by vehicle class, the actual market share logic must adopt annual shares in proportion to the allowable market share spread for each vehicle class, and the technology base year (BaseYear) and penetration (*MKT_PEN)* are defined by the base share for the class.

$$ACTUAL\_MKT_{itc,year} = MAX\left(ACTUAL\_MKT_{itc,year}, CLASSSHR_{year}\right) \quad (20)$$

where

$CLASSSHR_{year} = MKT\_PEN_{itc,BaseYear} + PHASESHR_{Year} * (MKT\_MAX_{itc} - MKT\_PEN_{itc,BaseYear})$; and

$PHASESHR_{year}$ = fraction of the total mandatory share in *year*.

The economic market share is bounded above by the maximum market share, *MKT_MAX*

$$ACTUAL\_MKT_{itc,year} = MIN\left(ACTUAL\_MKT_{itc,year}, MKT\_MAX_{itc}\right) \quad (21)$$

Supersedes notes (subroutine *NOTE_SUPER*)

Superseding technology notes define technologies that functionally overlap and, therefore, will not be present on the same vehicle. For example, if technology X is a more sophisticated version of technology Y, either, but not both, can appear on a particular vehicle. If that happens, the market share of technology X plus the market share of technology Y must not exceed the maximum allowable market share for the basic technology. Because technology cost effectiveness is determined on an individual technology basis, such situations are handled by so-called superseding technology code that adjusts cost-effective market shares for individual technologies under their functional overlaps. To correctly handle the relationship among more than two technologies, the superseding technology engineering notes that define the relationship and the adjustment of the cost-effective market shares under that relationship must be designed to treat all affected technologies concurrently.

Market shares are further adjusted so the sum does not exceed the maximum market penetration of the group. The model first calculates the aggregate market share, *TOT_MKT*, of all superseding technologies related to a single technology

$$TOT\_MKT_{itc,year} = \sum_{ino=1}^{num\_sup} ACTUAL\_MKT_{ino,year} \quad (22)$$

where

ino = index identifying the technologies in the superseding group related to technology *itc*; and

num_sup = number of technologies in the superseding group related to technology *itc*.

The model identifies the largest maximum market share for the group of technologies related to the technology of interest, *MAX_SHARE*

$$MAX\_SHARE = MAX\left(MKT\_MAX_1 \ldots, MKT\_MAX_{num\_sup}\right) \tag{23}$$

If the aggregate market share, *TOT_MKT*, is greater than the maximum share, *MAX_SHARE*, the model reduces the excess penetration of those technologies that are in the group of related technologies, as follows:

1. The model calculates the reduction in market share of a superseded technology, *DEL_MKT*, ensuring that the decrement does not exceed that technology's total share

$$DEL\_MKT_{itc} = TOT\_MKT_{itc,year} - MAX\_SHARE_{itc,year} \tag{24}$$

2. The model adjusts the market share of the superseded technology to reflect the decrement

$$ACTUAL\_MKT_{itc,year} = ACTUAL\_MKT_{itc,year} - DEL\_MKT_{itc} \tag{25}$$

3. The model adjusts total market share to reflect this decrement

$$TOT\_MKT_{itc,year} = MAX\_SHARE_{itc,year} \tag{26}$$

Required notes

These notes control the adoption of technologies that require additional technologies in the vehicle. This note is implemented as follows:

1. For a given technology, *itc*, defines a group of potential matching technologies, *req*, one of which must be present for *itc* to be present. Sum the market shares of the matching technologies (*req*), ensuring total market share is no more than 1.0. This value, *REQ_MKT*, indicates the maximum market share of technology *itc*.

$$REQ\_MKT_{year} = MIN(\sum\nolimits_{req} MKT\_PEN_{req,year}\,, 1.0) \tag{27}$$

2. Compare *REQ_MKT* to the market share of technology, *itc.*

$$ACTUAL\_MKT_{itc,year} = MIN(ACTUAL\_MKT_{itc,year}, REQ\_MKT_{year}) \tag{28}$$

The adjusted economic market share, *ACTUAL_MKT*, is assigned to the variable *MKT_PEN*, by market class and group, for use in the remainder of the calculations

$$MKT\_PEN_{itc,year} = ACTUAL\_MKT_{itc,year} \tag{29}$$

Synergistic notes

Synergistic technologies are those that, when installed simultaneously, interact to affect fuel economy. A vehicle with synergistic technologies will not experience the change in fuel economy predicted by adding the impact of each technology separately. Conceptually, such interactions could yield either greater or lower fuel economy; however, in all cases observed in the MTCC, the actual fuel economy is lower than expected. For example, Variable Valve Lift I is synergistic with 8-speed automatic transmissions. If both are present on a vehicle, then the actual fuel economy improvement is 0.7% lower than what would be expected if the improvements from the two technologies were simply added together with no regard for their interaction.

Synergy adjustments are made once all other engineering notes have been applied. Market share affected by synergy effects between two technologies is estimated as the probabilistic overlap between the market shares of the two technologies. Mathematically, this market share is expressed as the product of the market shares of the two technologies. The incremental market share overlap for a single year is equal to the cumulative estimated overlap (based on cumulative estimated market penetrations) for the current year minus the cumulative estimated overlap for the previous year. Note also that the input value of *SYNR_DEL*, the synergistic effect of related technologies on fuel economy, is negative, so that the estimated synergy loss (*SYNERGY_LOSS*) will also be negative and should be treated as an additive parameter.

$$SYNERGY\_LOSS_{itc} = \sum_{syn}\left(MKT\_PEN_{itc,year} * MKT\_PEN_{syn,year}\right) * SYNR\_DEL_{itc,syn} - \sum_{syn}\left(MKT\_PEN_{itc,year-1} * MKT\_PEN_{syn,year-1}\right) * SYNR\_DEL_{itc,syn} \quad (30)$$

Calculate net impact of technology change

The net impact of changes in technology market shares is first calculated for fuel economy, weight, and price. Horsepower depends on these results and must be subsequently calculated. For a given technology *itc*, the change in market share since the last period, *DELTA_MKT*, is calculated as follows

$$DELTA\_MKT_{itc} = MKT\_PEN_{itc,year} - MKT\_PEN_{itc,year-1}{}_{itc,Year} \quad (31)$$

DELTA_MKT is used to calculate the incremental changes in fuel economy, vehicle weight, and price as a result of implementing the considered technology.

Fuel economy

Current fuel economy for a vehicle class is calculated as the previously adjusted fuel economy plus the sum of incremental changes because of newly adopted technologies, *NUMTECH.*

$$FE_{Year} = FE_{Year} + FE_{Year-1} * \left(\sum_{itc=1}^{NUMTECH} DELTA\_MKT_{itc} * DEL\_FE_{itc} + SYNERGY\_LOSS_{itc}\right) \quad (32)$$

Vehicle weight

Current weight for a vehicle class is modified by incremental changes because of newly adopted technologies. As with the technology cost equation, the weight equation has both absolute and variable components. Most technologies add a fixed number of pounds to the weight of a vehicle. With material substitution technologies, the weight change depends on how much new material is used, which is a function of the original weight of the vehicle. The weight equation includes both absolute and weight-dependent terms in the summation expression. For any given technology *itc*, one term or the other will be zero.

$$WEIGHT_{year,ildv} = WEIGHT_{Year,ildv} + \sum_{itc=1}^{NUMTECH} DELTA\_MKT_{itc} * \left(DEL\_WGTABS_{itc} + WEIGHT_{Year,ildv} * DEL\_WGTWGT_{itc}\right) \quad (33)$$

Vehicle price

The current price for a vehicle class (*PRICE*) is calculated as the previous price plus the sum of incremental changes in the technology cost because of newly adopted technologies.

$$PRICE_{year} = PRICE_{year-1} + \sum_{itc=1}^{NUMTECH} DELTA\_MKT_{itc} * TECHCOST_{itc} \quad (34)$$

Estimate HEV, PHEV, BEV, and FCEV characteristics (subroutines *HEVCALC*, *PHEV20CALC*, *PHEV50CALC*, *EVCALC*, and *FCCALC*)

Vehicle attributes, including price, weight, fuel economy, and horsepower, are adjusted for the specific characteristics of hybrid electric, plug-in hybrid electric, battery electric, and fuel cell vehicles.

First, the price of the vehicle is adjusted to account for the endogenously calculated cost of components specific to the HEV, PHEV, BEV, or FCEV powertrain (*ElecSysIncCost*):

$$PRICE_{icl,igp,year,ildv} = PRICE_{icl,igp,year,ildv} + ElecSysIncCost_{icl,igp,year,ildv} \quad (35)$$

ElecSysIncCost includes battery, non-battery systems (e.g. electric motor, power electronics), and, in the case of FCEV vehicles, storage tank and fuel cell stack costs.

Battery costs (subroutine LIONCOSTCALC) and impacts (EVCALC, PHEVCALC, FCCALC, HEVCALC)

Battery electric vehicles (EV100, EV200, EV300), hybrid-electric vehicles, plug-in hybrid-electric vehicles (PHEV20 and PHEV50), and fuel-cell electric vehicles use battery technology as energy storage devices. The TDM considers nickel metal hydride (NiMH) and lithium-ion batteries for use in HEV applications and lithium ion batteries for use in PHEV20, PHEV50, FCEV, and BEV. NiMH battery costs measured in dollars per kilowatthour ($/kWh) are read in from *trnldv.xlsx*, and decline is estimated exogenously across the projection period. Lithium-ion battery costs ($/kWh) are calculated endogenously based on production learning and economies of scale, represented as a *learning rate* which couples production cost to cumulative battery production in kWh.

$$Li\_ion\_cost_{year} = pack\_a_{ildv} * \left(cumulative\_gwh_{year-1}\right)^{-pack\_b_{ildv}} + mat\_a_{ildv} * \left(cumulative\_gwh_{year-1}\right)^{-mat\_b_{ildv}} \quad (36)$$

where

$Li\_ion\_cost_{year}$ = cost of lithium ion battery ($/kWh);

pack_*a* = initial battery production cost, without materials cost ($/kWh);

$cumulative\_gwh_{year-1}$ = cumulative lithium ion battery production (gWh);

pack_*b* = cumulative production elasticity of production cost;

mat_a = initial battery materials cost; and

mat_b = cumulative production elasticity of materials cost.

The first component of the cost equation—including the coefficients with the prefix *pack*—estimates the battery pack production cost, and the second component—coefficients with the prefix *mat*—provides a cost floor so that the total pack cost does not drop below the cost of materials mining and processing.

The *b* variables – *pack_b* and *mat_b* – represent the learning rate (*LR*) assumptions as follows:

$$b = -\frac{\ln(1 - LR)}{\ln(2)} \tag{37}$$

Total battery cost per vehicle also relies on the size of the battery pack in kWh, *BatPackSize*, which is estimated based on the historical relationship between an equivalent gasoline vehicle weight (*weight*) and corresponding battery size for each of the electrified powertrains (*LIONkWh_perLb*)*:*

$$BatPackSize_{year,icl,igp,ildv} = weight_{icl,igp,year,ildv=1} * LIONkWh\_perLb_{icl,igp,ildv} \tag{38}$$

For PHEVs and HEVs, *LIONkWh_perLb* is reduced over time as depth of discharge improves and the usable portion of the battery pack approaches the nominal capacity. Depth of discharge improvements for BEVs increase range rather than reduce nominal battery pack size. For HEVs (subroutine *HEVCALC*), the TDM chooses between NiMH and Li-ion based on cost.

The final incremental cost, compared with a conventional gasoline powertrain, is calculated by adding non-battery system costs (*ElecNonBattCst*), depending on the powertrain and size class. Fuel cell vehicle non-battery costs are broken out by component, including the drivetrain cost per kW (*FuelCell_D_kW*), which is applied based on a constant 0.028 kW/pound requirement, and cost of the hydrogen storage tank (*TANKCOST*).

After estimating cost, each powertrain's weight is increased based on a pound per kWh input (*LION_LB_perkwh*) applied to the *BatPackSize* estimated above. For fully electric vehicles (EV100, EV200, EV300), the weight of internal combustion engine components—estimated to be 500 pounds—is subtracted from the final vehicle weight.

Next, the vehicle horsepower for BEV, HEV, PHEV20, PHEV50, and FCEV is calculated assuming they have the same horsepower per pound performance requirement as a gasoline vehicle.

Finally, the TDM estimates vehicle fuel economy based on electric vehicle range (EV100, EV200, EV300), share of miles driven that are electric (PHEV20, PHEV50), or a constant gallon-per-mile efficiency (FC).

For a vehicle introduced in the projection period (i.e., no historical vehicle attributes to pull from), EV range is calculated using its historical relationship to battery pack size (*BatPackSize*), modified by the improvement in EV depth of discharge (*EV_DOD*) since the endpoint of that historical data.

$$EV\_range_{icl,igp,ildv} = \left(BatPackSize_{year,icl,igp,ildv} * ev\_range\_m_{ildv} + ev\_range\_b_{ildv}\right) * \frac{EV\_DOD_{year}}{EV\_DOD_{base_{year}}} \tag{39}$$

where

$Ev\_range\_m_{ildv}$ = EV range equation coefficient (slope);

$Ev\_range\_b_{ildv}$ = EV range equation coefficient (constant); and

Fuel economy is then estimated using range (*EV_range*) and battery pack size (*BatPackSize*), adjusted by a multiplier derived from historical data representing the difference between bottom-up estimated EV fuel economy and final published tested fuel economy.

$$FE_{icl,igp,year,ildv} = \frac{EV\_range_{icl,igp,ildv}}{BatPackSize_{year,icl,igp,ildv} * EV\_DOD_{year}} * evmpg\_adj_{igp,icl,ildv} \tag{40}$$

The TDM estimates PHEV fuel economy using a harmonic average, weighted by the share of miles driven on gasoline and electricity. The electric share of miles—often called the *utility factor*—varies based on the PHEV range (PHEV20 and PHEV50). Fuel cell vehicle fuel economy is calculated based on a constant fuel efficiency input, *GALPERMILE*, which is set to 0.00625 for Methanol FC and 0.00570 for Hydrogen FC,.

$$FE_{icl,igp,year,FC} = \frac{1}{GALPERMILE_{FC} * \frac{WEIGHT_{icl,igp,year,Gasoline}}{1000}} \tag{41}$$

Impact of technology on horsepower

Calculating the net impact of changes in technology share on vehicle horsepower is a three-step process (Figure 7).

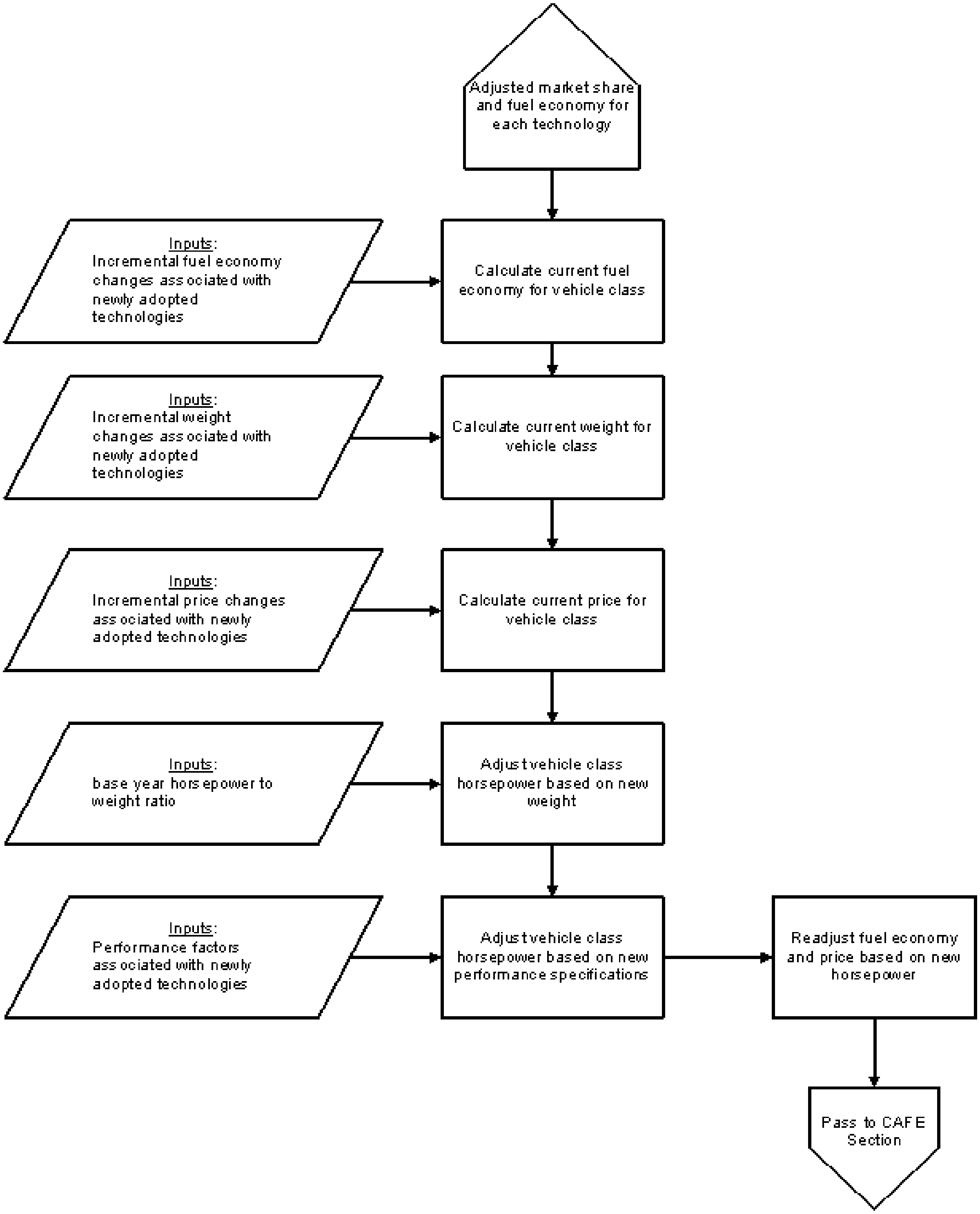
Unadjusted horsepower

First, horsepower is calculated based on weight, assuming no change in performance. This initial estimate simply maintains the horsepower-to-weight ratio observed in the base year. Assuming a constant horsepower/weight ratio for cars and light trucks

$$HP_{icl,igp,year,ildv} = WEIGHT_{year,ildv} * \frac{HP_{year-1,ildv}}{WEIGHT_{year-1,ildv}} \tag{42}$$

The horsepower adjustments for hybrid, electric, and fuel cell vehicles are described above.

Figure 7. Weight and horsepower calculation for Manufacturers Technology Choice Component of the Transportation Sector Demand Module, NEMS



Data source: U.S. Energy Information Administration

Adjust horsepower

The second step adjusts the total horsepower, *TTL_ADJHP*, which has two components. The first component is an adjustment associated with the various technologies adopted, *TECH_ADJHP*, and the second component adjusts for any changes as a result of additional consumer performance demand, *PERF_ADJHP*. Adjustments to horsepower are done for cars and light trucks at the market class and AFV technology level, with the exceptions noted above.

Technology adjustment

Calculate the annual horsepower adjustment because of technology introductions, *DEL_HP*, which is equal to the sum of incremental changes because of newly adopted technologies

$$TECH\_ADJHP_{year} = \sum_{itc=1}^{NUMTECH} (DELTA\_MKT_{itc} * DEL\_HP_{itc}) \tag{43}$$

Consumer preference performance adjustment

The next step is to calculate the annual horsepower adjustment and consumer preference for performance, *PERF_ADJHP.* The initial calculation is based on household income, vehicle price, fuel economy, and fuel cost

$$PERF\_ADJHP_{year} = \left(\frac{INCOME_{year}}{INCOME_{year-1}}\right)^{0.9} * \left(\frac{PRICE_{year-1}}{PRICE_{year}}\right)^{0.9} * \left(\frac{FE_{year}}{FE_{year-1}}\right)^{0.2} * \left(\frac{FUELCOST_{year-1}}{FUELCOST_{year}}\right)^{0.2} - 1 \tag{44}$$

The calculated consumer demand for horsepower is initially unconstrained as the projection begins, but is multiplicatively adjusted downward to decrease consumer performance demand as the projected horsepower-to-weight ratio approaches its constrained limit, *PERFCAP*. The model calculates the value of *PERF_COEFF*, the parameter used to constrain the incremental value of additional vehicle performance. This parameter decreases as performance increases so that the incremental value of additional performance declines. The demand that has accrued between 1990 and the base year (2022 for AEO2025), *DEMAND_USED*, must be accounted for through the input parameter *USEDCAP*

$$DEMAND\_USED = (PERFCAP - HP\_WGT_{BaseYear}) * \left(\frac{USEDCAP}{1 - USEDCAP}\right) \tag{45}$$

and

$$PERF\_COEF_{year} = 1 - \left(\frac{HP\_WGT_{year} - HP\_WGT_{BaseYear} + DEMAND\_USED}{PERFCAP - HP\_WGT_{BaseYear} + DEMAND\_USED}\right) \tag{46}$$

and

$$PERF\_ADJHP_{year} = PERF\_ADJHP_{year} * PERFFACT * PERF\_COEFF_{year} \tag{47}$$

where

$HP\_WGT_{BaseYear}$ = horsepower-to-weight ratio in the given year, in this case BaseYear;

$PERF\_COEFF_{year}$ = performance coefficient, between 0 and 1; and

PERFFACT = performance factor, exogenous input from trnldv.xlsx.

In addition, if CAFE standards are not achieved after the second CAFE compliance pass through FEMCALC, the additional consumer demand for performance is set to zero (or the minimum value required to maintain a sufficient horsepower-to-weight ratio) to allow manufacturers to focus on CAFE compliance rather than satisfy increased performance demands.

The total horsepower adjustment is now calculated

$$TTL\_ADJHP_{year} = TECH\_ADJHP_{year} + PERF\_ADJHP_{year} \quad (48)$$

Maximum Limit on Total Horsepower Adjustment

The total horsepower adjustment for a given projection year is constrained in several ways. First, the total adjustment in any one year is limited to 10%. If an adjustment greater than 10% is calculated by the econometric algorithms described above, the additional consumer demand portion is adjusted downward first since the impacts of this demand are not yet included in the fuel economy projections. If it is not possible to obtain the full level of downward adjustment—to less than a 10% increase from the previous year—from the additional consumer demand portion of the horsepower adjustment, the remainder is taken from the technology-based adjustment. The magnitude of any technology-based horsepower giveback, *HP_GIVEBACK*, is tracked and converted into equivalent fuel economy because the basic fuel economy projection already incorporates the full impact of technology-based horsepower adjustments. So, if total horsepower adjustment, *TTL_ADJHP*, is greater than 10%

$HP\_GIVEBACK_{year} = TTL\_ADJHP_{year} - 0.1,$

$$PERF\_ADJHP_{year} = PERF\_ADJHP_{year} - HP\_GIVEBACK_{year} \quad (49)$$

If the required horsepower giveback, *HP_GIVEBACK*, is smaller than the consumer demand for performance, *PERF_ADJHP*, the technology adjustment, *TECH_ADJHP*, is left unchanged. Otherwise, the technology adjustment is decreased by this performance adjustment

$$TECH\_ADJHP_{year} = TECH\_ADJHP_{year} - HP\_GIVEBACK_{year} \quad (50)$$

Now, calculate the modified total horsepower adjustment

$$TTL\_ADJHP_{year} = TECH\_ADJHP_{year} + PERF\_ADJHP_{year} \quad (51)$$

Maximum Limit on Horsepower-to-Weight Ratio

This adjustment imposes a maximum limit on the horsepower-to-weight ratio so that performance characteristics do not become unreasonable. If the horsepower-to-weight ratio is too high, first subtract any consumer preference for performance, *PERF_ADJHP*, because the fuel economy effect is not considered until later. If the horsepower-to-weight ratio needs to be lowered further, decrease any additional required horsepower demand from the technology-based part of the adjustment, *TECH_ADJHP*, and track this giveback because *HP_GIVEBACK* must be converted back into fuel economy equivalent.

Horsepower-to-weight ratio must ensure drivability

Finally, make sure the horsepower-to-weight ratio stays higher than what is required for drivability, *HP_WGT_MIN*, (either 90% of the base year value or 4% for two-seaters and 3.3% otherwise, whichever is lower). If an upward adjustment is required to satisfy this constraint, it is added to the additional consumer demand portion of the planned horsepower adjustment because the fuel economy impacts of this demand are not yet considered in the fuel economy projections. Additional demand does not need to be specially tracked because it is reflected in *PERF_ADJHP*, which is automatically converted to fuel economy equivalent in the algorithms that follow.

The next series of statements calculate the desired and resulting horsepower demand. The desired demand is the difference between the minimum horsepower adjustment, *MIN_ADJHP*, and the total horsepower adjustment. Adding the desired demand to the current horsepower adjustment produces the total horsepower adjustment

$$MIN\_ADJHP_{year} = (\frac{HP\_WGT\_MIN_{Baseyear} * WEIGHT_{year}}{HP_{year}} - 1)$$

$$PERF\_ADJHP_{year} = PERF\_ADJHP_{year} + MIN\_ADJHP_{year} - TTL\_ADJHP_{year}$$

$$TTL\_ADJHP_{year} = TECH\_ADJHP_{year} + PERF\_ADJHP_{year} \quad (52)$$

Final horsepower adjustment for CAFE compliance

If CAFE standards are not achieved after the second CAFE compliance pass through FEMCALC, the technology-based horsepower adjustment is constrained to the maximum of either zero or the level of adjustment required to maintain the minimum allowable horsepower-to-weight ratio. In other words, the third pass takes back the technology-driven horsepower demand, except when it is required to maintain the minimum horsepower-to-weight ratio. The magnitude of any technology-based horsepower giveback is tracked and converted into equivalent fuel economy. So, a third pass through FEMCALC allows manufacturers to focus solely on CAFE compliance at the expense of increased performance.

$$EXCESS\_ADJHP_{year} = MIN(TECH\_ADJHP_{year}, TTL\_ADJHP_{year} - MIN\_ADJHP_{year}),$$

$$TECH\_ADJHP_{year} = TECH\_ADJHP_{year} - EXCESS\_ADJHP_{year}$$

$$TTL\_ADJHP_{year} = TECH\_ADJHP_{year} + PERF\_ADJHP_{year} \quad (53)$$

The model first computes the horsepower give back

$$HP\_GIVEBACK_{year} = HP\_GIVEBACK_{year} + EXCESS\_ADJHP_{year} \quad (54)$$

The current year horsepower is then calculated as initial horsepower times the final horsepower adjustment

$$HP_{year,FuelType} = HP_{year,ifuel} * \left(1 + TTL\_ADJHP_{year}\right) \tag{55}$$

Readjust fuel economy and price

Once the horsepower adjustment has been determined, the final fuel economy, vehicle price, and vehicle range are calculated.

Fuel economy

Fuel economy is adjusted up or down according to the sum of consumer-driven horsepower adjustment and any horsepower giveback. Horsepower giveback is horsepower demand already considered in fuel economy estimates but not actually taken. Therefore, fuel economy estimates need to be adjusted upward for any giveback based on the relationship between fuel economy and horsepower. Technology-driven effects are already accounted for in the technology incremental fuel economy values. Note that the consumer and giveback estimates are aggregated into the consumer preference parameter for horsepower to facilitate the series of ensuing fuel economy and price algorithms, recognizing that giveback is *negative demand*

$$PERF\_ADJHP_{year} = PERF\_ADJHP_{year} - HP\_GIVEBACK_{year} \tag{56}$$

$$ADJFE_{year} = -0.22 * PER\_ADJHP_{year} - \left(0.56 * SIGN * PER\_ADJHP_{year}{}^{2}\right) \tag{57}$$

where

SIGN = -1, if PERF_ADJHP < 0, and 1 otherwise.

The final vehicle fuel economy is then determined as follows

$$FE_{Year} = FE_{Year} * \left(1 + ADJFE_{year}\right) \tag{58}$$

Vehicle price

Vehicle price is finally estimated

$$PRICE_{year} = PRICE_{year} + PERF\_ADJHP_{year} * VALUEPERF_{year} \tag{59}$$

Note that these calculations are final adjustments and the results do not feed back into the horsepower adjustment equation. The above equations result in an estimate of the market shares of the considered technologies within each class of vehicle. The effective range for each vehicle class is then calculated. The implication is that market penetration is affected and changes over time.

Vehicle range (subroutine FEMRANGE)

For most vehicles, range is a function of tank size and fuel economy. This range is based on *adjusted* fuel economy, accounting for degradation from 2-cycle *tested* fuel economy using a degradation factor estimated from historical data (*degfacgrp*), and size of the fuel tank (*TANKSIZE*).

$$RANGE_{year,ildv} = TANKSIZE * FE_{year,gasoline} * degfacgrp_{igp,icl,ildv,year} \tag{60}$$

The ranges for EVs, PHEVs, HEVs, and FCEVs are set by the respective vehicle attribute subroutines specific to those powertrains as discussed above: *EVCALC*, *PHEVCALC*, *HEVCALC*, and *FCCALC*.

Calculate size class market shares (subroutine CGSHARE)

This routine calculates vehicle size class market shares within each corporate average fuel economy group. Car market shares for each class are derived by calculating an increment from the previous year's value. The market share increment (or decrement) is determined by the following equation

$$DIFFLN_{year} = A*\ln(year-2018) + B*\ln\left(\frac{FUELCOST_{year}}{FUELCOST_{year-1}}\right) + C*\ln\left(\frac{INCOME_{year}-\$13{,}000}{INCOME_{year-1}-\$13{,}000}\right) + D*\ln\left(\frac{PRICE_{year,gasoline}}{PRICE_{year-1,gasoline}}\right) \quad (61)$$

where

$DIFFLN_{year}$ = log market share increment compared with the previous year; and

A, B, C, D = coefficients, elasticities, exogenously introduced from trnldv.xlsx.

The model then solves for the log-share ratio for each size class, *RATIO_LN*

$$RATIO\_LN = DIFFLN_{year} + \ln\left(\frac{CLASS\_SHARE_{iregn,icl,igp,nhtsalyr}}{1-CLASS\_SHARE_{iregn,icl,igp,nhtsalyr}}\right) \quad (62)$$

where

$CLASS\_SHARE_{iregn,icl,igp,nhtsalyr}$ = size class market share in year *nhtsalyr*; and

nhtsalyr = last year of National Highway Traffic Safety Administration historical data.

The model solves for the class market share

$$CLASS\_SHARE_{iregn,icl,igp,year} = \frac{e^{RATIO\_LN}}{1+e^{RATIO\_LN}} \quad (63)$$

The model normalizes so that shares total 100% within each CAFE group

$$CLASS\_SHARE_{iregn,icl,igp,year} = \frac{CLASS\_SHARE_{iregn,icl,igp,year}}{\sum_{icl=1}^{8} CLASS\_SHARE_{iregn,icl,igp,year}} \quad (64)$$

Consumer Vehicle Choice Component (CVCC, subroutine *TLDV*)

The CVCC is a projection tool designed to support the LDV Submodule in the TDM. The objective of the CVCC is to estimate the market penetration of various LDV powertrains through 2050, and it is useful for analyzing policies that might affect their penetration.

The CVCC uses attribute-based, discrete choice techniques and logit-type choice functions, which represent a demand function for vehicle sales in the United States. The demand function uses projections of the changes in vehicle and fuel attributes for the considered technologies to estimate the market share penetration for the various technologies.

The demand function is a logit discrete choice model represented as follows

$$\log\left(\frac{P_k}{1-P_k}\right) = \beta_1 + \beta_2 X_2 + \beta_3 X_3 + \cdots + \beta_k X_k + \varepsilon_k \tag{65}$$

where

P_k = probability of consumer choosing vehicle (k);

β_1 = constant term;

$\beta_{1\ldots,}$ β_k = coefficients of vehicle and fuel attributes; and

$X_i,\ldots X_k$ = vehicle and fuel attributes.

The basic structure of the projection component of the powertrain market share estimate is a three-dimensional matrix format. The matrix consists of *I* vehicle powertrain types, *K* attributes for each powertrain, and *T* year of projection. Each cell C_{ikt} in the *C* matrix contains a coefficient reflecting the value of attribute *k* of vehicle powertrain *i* for the given year *t*.

The calculation of market share penetration is expressed in the following equations

$$S_{it} = P_{it} = \sum_{n=1}^{N} \frac{P_{itn}}{N} \tag{66}$$

$$P_{itn} = \frac{e^{V_{itn}}}{\sum_{i=1}^{I} e^{V_{itn}}} \tag{67}$$

where

S_{it} = market share sales of vehicle type *i* in year *t*;

P_{it} = aggregate probability over population N of choosing type *i* in year *t*;

n = individual n from a population of size N;

P_{itn} = probability of individual n choosing type *i* in year t; and

V_{itn} = function of the K elements of the vector of attributes (X) and coefficients (β), generally linear in parameters, in other words,

$$V = ß_1X_1 + ß_2X_2 + . . . + ß_kX_k$$

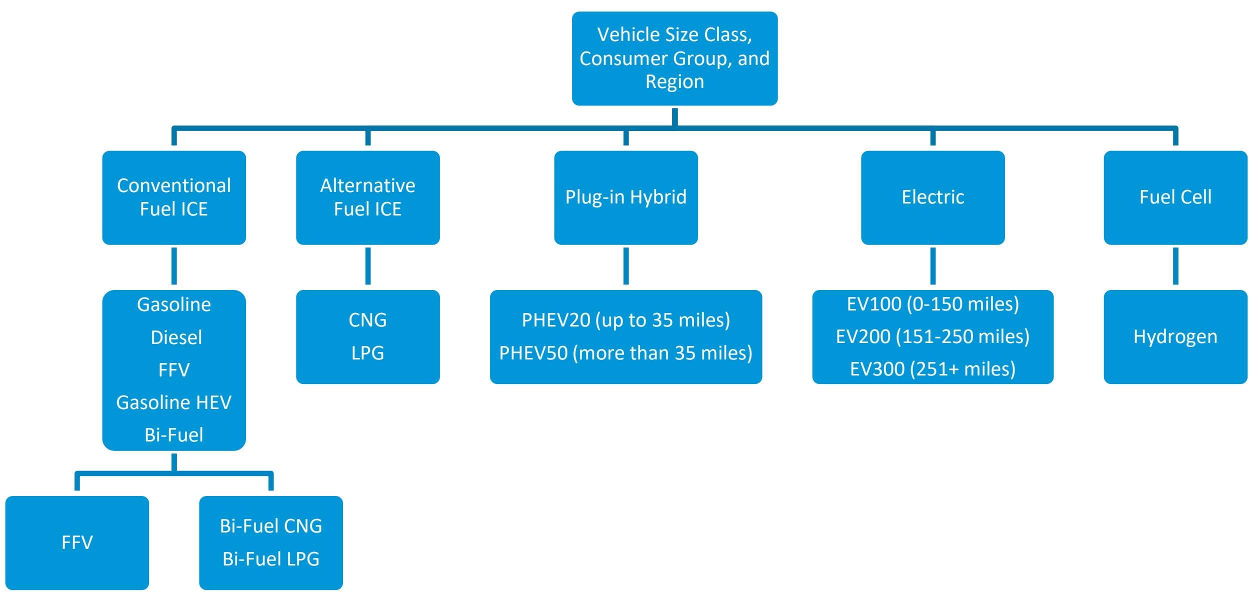
and V is specific to vehicle *i*, year t, and individual n.

This formulation assumes that the share of each powertrain is equivalent to the aggregate probability over the population choosing that powertrain, which is produced by summing the individual probability estimates. The individual probabilities are a function of the ratio of the *V*s (taken as an exponential). The market share of each vehicle type is ultimately determined by its attributes relative to the attributes of all competing vehicles.

The coefficients of the vehicle attributes in the CVCC are assumed to remain constant over time, which makes the calculation of the *C* matrix less cumbersome. However, the methodology can use either changing or constant coefficient values for the vehicle attributes. The *C* matrix is replicated for each year of the analysis and for each target group. A *V* value is produced for each of the vehicle technologies and each of the target regions, sizes, and scenarios.

The CVCC projects market shares for 16 powertrain technologies in three stages by using a bottom-up approach. Results from the lower stages are passed to the next higher stage in the sequence. The tree structure of the logit model is shown in Figure 8. In the first stage, the shares of vehicle sales are determined for five aggregate vehicle groups: conventional, dedicated alternative fuel, plug-in hybrid, electric, and fuel cell. The second stage of the logit model subdivides each of the five groups to estimate sales shares for the specific vehicle types within each group. The third stage of the CVCC estimates the proportion of the travel in which flex or bi-fuel vehicles are using the alternative or gasoline fuel.

Figure 8. Nesting structure for NEMS, Transportation Demand Module, Consumer Vehicle Choice Component



Source: U.S. Energy Information Administration

Note: EV=electric vehicles; ICE=internal combustion engine; CNG=compressed natural gas; LPG=liquid petroleum gas; FFV=flex-fuel vehicle; PHEV=plug-in hybrid electric vehicle; EV=electric vehicle; HEV=hybrid electric vehicle

Several vehicle attributes are weighted and evaluated in the utility function, including the following:

1. Vehicle price
2. Fuel cost or cost of driving per mile (fuel price divided by fuel efficiency)
3. Vehicle range
4. Fuel availability
5. Battery replacement cost
6. Performance (measured by the horsepower-to-weight ratio)
7. Home refueling capability
8. Maintenance costs
9. Luggage space
10. Make and model diversity or availability

The vehicle attributes are processed in subroutine *TATTRIB*. Vehicle purchase price, fuel cost, acceleration, maintenance, battery cost, and fuel availability are discussed in detail below.

The model first estimates the fuel cost per mile (*FLCOST*). For gasoline, diesel, flex-fuel, CNG, LPG, and non-plug-in hybrid vehicles, fuel costs are taken directly from endogenous calculations in other NEMS modules. PHEV fuel prices are a mileage-weighted average of the residential electricity price and gasoline price. BEV fuel prices are a weighted average of three different electricity prices: residential (*PELVHRS*), public level 2 charging (*PELP2CM*), and public DC fast charging (*PELPFCM*). The weights (*chg_dist*) depend on the endogenously estimated recharging infrastructure availability (*FAVL*); as more infrastructure is built out, the share of BEV charging that occurs at home declines. The share of charging that occurs at public level 2 and DC fast charge locations increases over time as a result.

$$chg\_dist_{iregn,home,year} = chg\_dist_{iregn,home,2023} - \frac{FAVL_{elec,iregn,year-1}}{1.4} \quad (68)$$

$$chg\_dist_{iregn,level2,year} = \frac{chg\_dist_{iregn,level2,2023}}{chg\_dist_{iregn,level2,2023} + chg\_dist_{iregn,dcfc,2023}} * \left(1 - chg\_dist_{iregn,home,year}\right) \quad (69)$$

$$chg\_dist_{iregn,dcfc,year} = 1 - chg\_dist_{iregn,home,year} - chg\_dist_{iregn,level2,year} \quad (70)$$

Fuel cost per mile is then the fuel price for a given powertrain (*FPRICE*) divided by the tested fuel economy from the MTCC (*femmpg*).

$$FLCOST_{igp,ildv,icl,iregn,year} = \frac{FPRICE_{ildv,iregn,year}}{femmpg_{igp,icl,year,ildv}} \quad (71)$$

The model then calculates the vehicle purchase price based on the output from the MTCC (*fempri*) and the application of relevant policy incentives (IRA Clean Vehicle Credit, *IRA_Credit*, and a weighted average state government credit, *state_cred*).

$$PSPR_{ivtyp,ildv,icl,year} = fempri_{ivtyp,ildv,icl,year} - ira\_credit_{ildv} - state\_cred_{iregn,year,ildv} \quad (72)$$

The model then calculates the horsepower-to-weight ratio and carries over other attributes that require no further pre-processing (luggage space, vehicle range, maintenance cost, home refueling). Home refueling is a binary variable: it is assigned a value of one for BEVs and zero for all other powertrains.

Fuel availability methodology (subroutine *TALT2*)

The fuel availability variable attempts to capture the dynamic associated with the increasing number of refueling stations. The premise is that the number of refueling stations is proportional to the number of vehicles. Therefore, as vehicle stocks accumulate over time, the number of refueling stations will increase as a function of a historical relationship between the number of refueling stations and vehicle stocks. Fuel availability is used in the logit-based CVCC as an input to determine the proportion of travel associated with the use of alternative fuels in a flex or bi-fuel vehicle. Fuel availability is also used in the utility function within the CVCC to allocate sales among various vehicle types or powertrain groups. The final fuel availability variable is configured as an index relative to the number of gasoline refueling stations.

Table 1. Powertrain type to highway fuel type

Powertrain type	Highway fuel type
Gasoline	Gasoline
Gasoline hybrid, gasoline plug-in hybrid electric	Gasoline/electricity
Flex-fuel ethanol	Ethanol/gasoline
Fuel cell methanol	Methanol
Bi-fuel and dedicated compressed/liquefied natural gas (CNG/LNG)	CNG/LNG/gasoline
Bi-fuel and dedicated liquefied propane gas (LPG)	LPG/gasoline
Dedicated electricity 100-, 200-, and 300-mile range	Electricity
Hydrogen fuel cell	Hydrogen

Data Source: U.S. Energy Information Administration

Standard methodology

For all fuels but electricity, the model starts by calculating the vehicle stocks by the highway fuel type to determine the number of refueling stations that might be using the fuel. It estimates the vehicle stock used to calculate how many refueling stations are needed

$$PREDSTK_{ifuel,year} = \sum_{ildv=1}^{16} \left[W_{ifuel,ildv} * LDVSTK_{ildv,year-1}\right] \tag{73}$$

where

$PREDSTK_{ifuel,year}$ = predicted vehicle stock used to calculate needed refueling stations;

$LDVSTK_{ildv,year-1}$ = vehicle stock, by powertrain type, 1 ... 16, using above mapping;

$W_{ifuel,ildv}$ = weight given to assumed proportion of vehicle stock that refuel with a given fuel (for example, 25% of flex-fuel vehicles are fueled with flex-fuel, 75% are fueled with conventional gasoline); and

ifuel = highway fuel type, 1...8.

Next, the model estimates the number of new refueling stations needed to meet the requirements of the vehicle stock

$$ALTSTAT_{ifuel,year} = ALTSTAT_{ifuel,year-1} + \frac{PREDSTK_{ifuel,year} - PREDSTK_{ifuel,year-1}}{STA\_RAT_{ifuel}} \quad (74)$$

where

$ALTSTAT_{ifuel,year}$ = total national level alternative fuel refueling stations based on historical ratio of vehicle stock per refueling station; and

STA_RAT_{ifuel} = ratio of refueling stations to vehicle stock based on history.

The total number of refueling stations is then allocated to the regions based on proportions of vehicle sales (*ldv_sales*) that use a given fuel

$$ALTSTA_{iregn,ifuel,year} = \frac{ldv\_sales_{iregn,ifuel,year}}{\sum_{iregn=1}^{9} ldv\_sales_{iregn,ifuel,year}} * ALTSTAT_{ifuel,n} \quad (75)$$

Fuel availability (*FAVAIL*) is estimated as an index relative to the number of gasoline refueling stations on a regional basis, where a value of 1 implies that fuel is as easily available and as accessible as gasoline.

$$FAVAIL_{ifuel,year,iregn} = \frac{ALTSTA_{iregn,ifuel,year}}{ALTSTA_{iregn,gasoline,year}} \quad (76)$$

Methodology for electricity

Availability of electric vehicle charging infrastructure is calculated based on exogenous estimates of charging station installations due to planned public and private sector investment through 2032. Fuel availability is calculated based on the available vehicle throughput; electric vehicle chargers dispense fuel at a lower rate than liquid refueling stations. First the regional gasoline vehicle refueling throughput, in vehicles per hour, is estimated based on the number of stations (*INITSTA*), pumps per station (*gas_stat*), and refuelings per pump per hour (assuming a refueling time of 10 minutes).

$$gas\_tput\_hr_{iregn} = INITSTA_{gasoline,year,iregn} * gas\_stat * 6 \quad (77)$$

Regional electric vehicle recharging throughput is then estimated based on the number of charging ports (PRT_CNT) by charging speed (ichrg) and the corresponding rate of charge for each charging speed (*PRT_RT*).

$$port\_time_{ichrg,iregn} = \frac{PRT\_CNT_{ichrg,year,iregn}}{PRT\_RT_{ichrg}} \quad (78)$$

$$port\_time\_tot_{iregn} = \sum_{ichrg=1}^{3} port\_time_{ichrg,iregn} \quad (79)$$

The fuel availability for BEVs is then calculated as a ratio of the charging infrastructure and gasoline refueling throughputs.

$$FAVAIL_{elec,year,iregn} = \frac{port\_time\_tot_{iregn}}{gas\_tput\_hr_{iregn}} \tag{80}$$

After 2032, the fuel availability grows proportional to the growth of light-duty BEV on-road stocks.

After completing fuel availability calculations for each fuel (*ifuel*), the subroutine populates regional fuel availability variable $FAVL_{ildv,iregn,year}$ by mapping highway fuels (*ifuel*) to vehicle powertrain types (*ildv*).

Light vehicle AFV market penetration (TALT2X) subroutine methodology

Operation of this component begins at the third level of the logit model and progresses to the first level because the values from the third and second levels are used as a part of the evaluation in the second and first levels. The component starts at level three because it is the value function for all vehicle technologies. At level two, the component calculates the share of technologies within each group, using the results of level three. Next, at level one, the component computes the value function and the share of each group using the previous two level results. Finally, the market share of each vehicle powertrain is calculated using the shares computed in level one and level two.

Throughout this section, subscripts indicate the manufacturer group (index *igp*), size class (index *icl*) and car versus light truck (index *ivtyp*) vehicle designations.

Level three

First, the CVCC calculates the share of fuel use between alternative fuel and gasoline use within the bi-fuel vehicles[6]

$$X31T2_{ivtyp,icl} = X31T1_{ivtyp,icl} * \frac{XR_{ivtyp,icl}}{XFC_{ivtyp,icl}},$$

$$BETAFA31T_{ivtyp,icl} = X31T1_{ivtyp,icl} * \frac{BETAFA231T_{ivtyp,icl}}{XFC_{ivtyp,icl}} \tag{81}$$

where

T = powertrain (5 = CNG/LNG bi-fuel, 6 = LPG bi-fuel);

$X31T2_{ivtyp,icl}$ = coefficient for vehicle range;

$X31T1_{ivtyp,icl}$ = coefficient for level 3 multi-fuel generalized cost by vehicle type and market class;

$XR_{ivtyp,icl}$ = coefficient for logit level 2 vehicle range;

$XFC_{ivtyp,icl}$ = coefficient for logit level 2 fuel cost;

$BETAFA31T_{ivtyp,icl}$ = coefficient for fuel availability linear element; and

[6] While the functionality to model CNG/LNG and LPG bi-fuel vehicles is retained in the codebase as described in this section, neither vehicle type is available on the market today and manufacturers do not have plans to offer such vehicles in the future. Therefore the sales shares are zero. The third level of the nested multinomial logit model is not used in AEO2025.

$BETAFA231T_{ivtyp,icl}$ = coefficient for fuel availability non-linear element.

Utility values (value of monetized and non-monetized attributes to consumers) are estimated for the general cost function. The values in the equations below vary across other dimensions but are shown with the key dimension for brevity.

$$UISUM_{fueltyp} = X31T1 * FLCOST_{fueltyp} + \frac{X31T2}{VRANG31T_{fueltyp}} + BETAFA31T * e^{BETAFA231T * FAVAL31T_{fueltyp}} \quad (82)$$

where

$UISUM_{fueltyp}$ = utility value function for vehicle attributes at multi-fuel level for vehicle type, powertrain type, market class, and region;

$VRANG31T_{fueltyp}$ = inverse of vehicle range in miles for powertrain T, by vehicle type and market class;

$FAVAL31T_{fueltyp}$ = fuel availability indexed relative to gasoline for powertrain T, by vehicle type and region; and

fueltyp = index representing each of the fuels that can be used in a multi-fuel vehicle (for example, gasoline and E85 for a flex-fuel vehicle).

Utility values are exponentiated (*ESUM*) and summed (*ETOT*)

$$ESUM_{fueltyp} = e^{UISUM_{fueltyp}},$$

$$ETOT = \sum_{fueltyp} ESUM_{fueltyp} \quad (83)$$

ETOT is sent to the general cost function to estimate third level market share values

$$GENCOST = \frac{\log(ETOT)}{X31T1} \quad (84)$$

where

GENCOST = general cost function or value from third level that is used as the value of fuel cost of driving at the second level of the logit.

Level two

The second level of the CVCC calculates the market shares among the AFV technologies within each of the five first level groups. The five groups are:

1. Conventional vehicles (gasoline, diesel, flex-fuel ethanol, gasoline hybrid electric, and bi-fuels CNG/LNG and LPG)

2. Dedicated AFVs (CNG/LNG and LPG fueled)
3. Plug-in hybrid electric vehicles (gasoline plug-in hybrid electric)
4. 100-, 200-, and 300-mile range electric vehicles
5. Fuel cell vehicles (hydrogen fueled)

Second-level logit model utility values for all vehicle types except the bi-fuel vehicles are calculated as follows.[7] These values are used to determine their shares within the five groups (*jg*) at the first level where: *jg*=2 for plug-in hybrid vehicles; *jg*=3 for dedicated alcohol and gaseous vehicles; *jg*= 4 for fuel cell vehicles; and *jg*=5 for electric vehicles.

$$UISUM_{jt} = nmlmco_{1,icl,igp} * PSPR_{ivtyp,ildv,icl,iregn,year} + nmlmco_{2,icl,igp} * FLCOST_{igp,ildv,icl,iregn,year} + nmlmco_{3,icl,igp} * \frac{1}{VRNG_{ivtyp,ildv,icl,iregn,year}} + nmlmco_{4,icl,igp} * BRCOST25_{ivtyp,ildv,icl,year} + nmlmco_{5,icl,igp} * ACCL_{ivtyp,ildv,icl,iregn,year} + nmlmco_{6,icl,igp} * HFUEL_{ivtyp,ildv,icl,iregn,year} + nmlmco_{7,icl,igp} * MAINT_{ivtyp,ildv,icl,iregn,year} + nmlmco_{8,icl,igp} * LUGG_{ivtyp,ildv,icl,iregn,year} + nmlmco_{11,icl,igp} * \log\left(MMAVAIL_{ivtyp,ildv,icl,iregn,year}\right) + X210_{ivtyp,ildv} + nmlmco_{9,icl,igp} * e^{nmlmco_{11,icl,igp} * FAvl_{ildv,iregn,year}} \tag{85}$$

where

$UISUM_{jt}$ = utility value for the powertrain type (*jt*) at the second level within one of the five groups (*jg*) at the first level;

$nmlmco_{1:11,icl,igp}$ = coefficients for vehicle attributes considered in the consumer powertrain choice;

$X210_{ivtyp,ildv,iregn}$ = represents the utility the consumer assigns to the vehicle not captured in the vehicle attributes of the model;

$PSPR_{ivtyp,ildv,icl,iregn,year}$ = vehicle price in dollars;

$BRCOST25_{ivtyp,ildv,icl,year}$ = battery replacement cost;

$HFUEL_{ivtyp,ildv,icl,iregn,year}$ = electric vehicle home refueling capability dummy variable (0,1 value);

$MAINT_{ivtyp,ildv,icl,iregn,year}$ = maintenance cost in dollars;

$LUGG_{ivtyp,ildv,icl,iregn,year}$ = luggage space indexed to gasoline vehicle; and

$MMAVAIL_{ivtyp,ildv,icl,iregn,year}$ = vehicle make and model diversity availability relative to gasoline exogenously determined in trnldv.xlsx.

Exponentiate the utility value for each vehicle powertrain (*jt*) and sum across all vehicle technologies within a given group (*jg*)

$$ESUM_{jt} = e^{UISUM_{jt}},$$

[7] If available, bi-fuel vehicles would use *GENCOST* estimated from Level 3 of the NMNL in the place of *FLCOST* shown here.

$$ETOT_{jg} = \sum_{jt \subset jg} ESUM_{jt} \tag{86}$$

$$XSHARE_{jg,jt} = \frac{ESUM_{jt}}{ETOT_{jg}},$$

where

$XSHARE_{jg,jt}$ = powertrain market share within the five vehicle groups and by powertrain.

Level one

First, calculate the generalized cost function, *GCOST*, as a function of the sum of the exponentiated utility values for each group

$$GCOST_{jg} = \frac{\ln(ETOT_{jg})}{nmlmco_{1,icl,igp}} \tag{87}$$

Calculate the utility value, *UISUM*, based on the generalized cost function, for *jg*=1,5

$$UISUM_{jg} = nmlmco_{12,icl,igp} * GCOST_{jg} \tag{88}$$

Exponentiate the utility value, then sum up exponentiated utility values across the groups. The share of each group is then estimated as exponentiated utility value divided by the sum of the values.

$$ESUM_{jg} = e^{UISUM_{jg}},$$

$$YSHARE_{jg} = \frac{ESUM_{jg}}{\sum_{jg=1}^{5} ESUM_{jg}} \tag{89}$$

$$APShrGrp_{igp,icl,iregn,ildv,year} = XSHARE_{jg,jt} * YSHARE_{jg},$$

where

$YSHARE_{jg}$ = market share of alternative vehicles by the five vehicle groups; and

$APShrGrp_{igp,icl,iregn,ildv,year}$ = percent of total light-duty vehicles sales by powertrain type.

Calculate CAFE and tailpipe GHG performance (subroutine *CAFECALC*)

This routine calculates the corporate average fuel economy (CAFE) and CO_2 credit or debits for each of the 11 manufacturer groups:

1. Domestic car
2. Asian car
3. European car
4. Luxury car
5. Exotic car

1. Truck 1—Domestic
2. Truck 2—Domestic
3. Truck 3—Domestic
4. Truck 4—Import
5. Truck 5—Import
6. Truck 6—Luxury

For each vehicle group the CAFE compliance calculation proceeds as follows. First the corporate average fuel economy is calculated for each manufacturer group (*CafeMpgGrp*) based on a sales-weighted harmonic mean. The calculation uses sales by size class and powertrain determined in the MTCC and CVCC (*cafesales*) along with the average fuel economy of each of those size class / powertrain groupings (*femmpg*).

$$CafeMpgGrp_{igp,year} = \frac{\sum_{ildv=1}^{16}\sum_{icl=1}^{8} cafesales_{igp,icl,year,ildv}}{\sum_{ildv=1}^{16}\sum_{icl=1}^{8} \frac{cafesales_{igp,icl,year,ildv}}{femmpg_{igp,icl,year,ildv}}} \quad (90)$$

The above equation is modified to account for the impact of using the Petroleum Equivalency Factor (PEF) to estimate fuel economy for electrified vehicles (BEVs, PHEVs, and FCEVs) as well as air conditioning and off-cycle credits noted in the CAFE regulations. Fuel economy for each manufacturer is then harmonically weighted based on vehicle sales by size class and fuel type to calculate a total market average for car, light-truck, and all light-duty vehicles (*NewMPG*).

The CAFE estimate is then compared with the legislative standard for each of the 11 manufacturer groups in each year. The standard (*FPMpg*) is computed for each class in each group based on the footprint (*FPrint*). 2010 and 2011 standards are calculated as follows, with each of the *CF* and *TF* variables representing coefficients explicitly defined in the enacted CAFE regulations

$$FPMpg_{class,group,Year} =$$

$$\left(\left(\frac{1}{CFCoefA_{year}}\right) + \left(\frac{1}{CFCoefB_{year}} - \frac{1}{CFCoefA_{year}}\right) * \frac{e^{\frac{FPrint_{icl,igp,year} - CFCoefC_{year}}{CFCoefD_{year}}}}{1 + e^{\frac{FPrint_{icl,igp,year} - CFCoefC_{year}}{CFCoefD_{year}}}} \right)^{-1} \quad (91)$$

The CAFE standard for 2012 and subsequent years for cars and light trucks are calculated as follows, with each of the *CF* and *TF* variables representing coefficients explicitly defined in the enacted CAFE regulations:

$$FPMpg_{icl,igp,year} = \frac{1}{MIN\left(MAX\left(\left((CFCoefC2 * FPrint) + CFCoefD2\right), \frac{1}{CFCoefA2}\right), \frac{1}{CFCoefB2}\right)} \quad (92)$$

$$FPMpg_{icl,igp,year} = MAX\left(\frac{1}{MIN\left(MAX\left(\left((TFCoefC2 * FPrint) + TFCoefD2\right), \frac{1}{TFCoefA2}\right), \frac{1}{TFCoefB2}\right)}, \frac{1}{MIN\left(MAX\left(\left((TFCoefG2 * FPrint) + TFCoefH2\right), \frac{1}{TFCoefE2}\right), \frac{1}{TFCoefF2}\right)} \right) \quad (93)$$

Finally, the individual manufacturer group's CAFE is compared with the CAFE standard and passes if greater or equal to the standard used.

Banking MPG credits occurs in the first pass of the fuel economy calculation. On the first pass, if the manufacturing group passes CAFE, then it banks its excess MPG credits. Otherwise, it pulls the credit values out of the bank and withdraws the older credits first. The model does not have a credit trading option.

Compliance with EPA's tailpipe GHG regulation is estimated parallel to CAFE. Production-weighted fleet average CO_2 emissions (gCO_2 per mile, *EPAghgGrp*) is estimated using 1) sales by size class and powertrain determined by the MTCC and CVCC (*cafesales*) and 2) average fuel economy of each size class / powertrain grouping (*femmpg*) converted to gCO_2 per mile. Zero-emission vehicles (BEVs and FCEVs) are assigned 0 gCO_2 per mile per the regulation, and therefore reduce fleet average CO_2 emissions by increasing the denominator, but not the numerator, of the calculation below. PHEV charge-sustaining operation CO_2 emissions are accounted for while charge-depleting operation is assigned 0 gCO_2 per mile. Additionally, air conditioning efficiency and off-cycle credits are included in the calculation (*ac_oc_credits*) along with maximum allowable air conditioning leakage credits (*AC_CO2_OFFSET*).[8]

$$EPAghgGrp_{igp,year} = \frac{\sum_{ildv=1}^{16}\sum_{icl=1}^{8} cafesales_{igp,icl,year,ildv} * \left(\frac{8887}{femmpg_{igp,icl,year,ildv}} - ac\_oc\_credits_{igp,year}\right)}{\sum_{ildv=1}^{16}\sum_{icl=1}^{8} cafesales_{igp,icl,year,ildv} * EPAALTMULT_{ildv,year}} - AC\_CO2\_OFFSET_{igp,year} \quad (94)$$

where

$EPAALTMULT_{ildv,year}$ = Advanced technology multiplier incentive applied to BEVs, FCVs, and PHEVs.

The footprint-based gCO_2 per mile standard (*FPghg*) is calculated using coefficients (*CF* and *TF* variables) from the applicable EPA regulation. The equation specification differs for car and light truck manufacturer groups, as follows:

$$FPghg_{icl,igp\ [CAR],year} = MIN(CFCoefEPAB2_{year}, MAX(CFCoefEPAA2_{year}, CFCoefEPAC2_{year} * Fprint_{icl,igp,year} + CFCoefEPAD2_{year}))$$

$$FPghg_{icl,igp\ [LIGHT\ TRUCK],year} = MIN\left(MIN\left(TFCoefEPAB2_{year}, MAX(TFCoefEPAA2_{year}, TFCoefEPAC2_{year} * Fprint_{icl,igp,year} + TFCoefEPAD2_{year})\right),\ MIN(TFCoefEPAF2_{year}, MAX(TFCoefEPAE2_{year}, TFCoefEPAG2_{year} * Fprint_{icl,igp,year} + TFCoefEPAH2_{year}))\right) \quad (95)$$

For each manufacturer group, the calculated fleet average gCO_2 per mile is subtracted from the CO_2 per mile standard and scaled up to account for the lifetime megagrams of CO_2 for the fleet using total sales

[8] BEVs are not eligible for A/C efficiency or off-cycle credits starting in MY2027 per EPA's Final Rule: Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles.

(*cafesales*) and lifetime miles driven by those sales (*lifetime_vmt*, 195,264 miles for cars and 225,865 miles for light trucks).

$$MgGhgGrp_{igp,year} = \left(FPghgGrp_{igp,year} - EPAghgGrp_{igp,year}\right) * \sum_{ildv=1}^{16} \sum_{icl=1}^{8} cafesales_{igp,icl,year,ildv} * lifetime\_vmt \div 1{,}000{,}000 \qquad (96)$$

A negative value (“debit”) indicates the group is out of compliance, while a positive value (“credit”) indicates the group is in compliance.

Compliance with CAFE and EPA GHG standards is first checked at the aggregate market level. If the total market average fuel economy is greater than or equal to the total market average standard, and no more than 2 miles per gallon is traded between the aggregate car and light truck fleets, the model has passed CAFE in that year. Regarding EPA GHG standards, if the total market has CO_2 credits (positive *MgGhgGrp*) the model has passed EPA GHG in that year. If either of the above conditions are not met – CAFE or EPA GHG – the model marks the individual groups that are out of compliance and continues looping through the MTCC and CVCC to improve fuel economy and emissions performance of those groups. If the market remains out of compliance after three loops, it runs subroutine *CAFETEST* as described below.

CAFE standard compliance (subroutine *CAFETEST*)

This algorithm, which is called after the third pass of the MTCC, adjusts electric and hybrid light-duty vehicle sales so that CAFE standards are met, followed by a corresponding decrease in the sale of gasoline vehicles. New vehicle sales are re-computed for the alternative fuel types, *CAFEVEH*, in the most cost-effective order determined by incremental vehicle cost and fuel savings over a specified period. For each vehicle group, the CAFE calculation proceeds as follows.

The first time CAFETEST is called in a given year, it calculates the maximum allowable increase in alternative powertrain vehicles for each manufacturer group and size class. This “compliance burden” is distributed across all of the manufacturer groups that are out of compliance, and is calculated based on either:

1. in a case where only NHTSA CAFE is enforced (no EPA GHG), the distribution of conventional non-hybrid gasoline vehicles across groups and size classes where a BEV, PHEV, or HEV is available; or
2. in a case where both NHTSA CAFE and EPA GHG are enforced, the distribution of $MgCO_2$ credit deficits across manufacturer groups.

After the initialization, CAFETEST walks through each size class in a given manufacturer group, shifting sales from conventional gasoline to the most cost-effective alternative powertrains incrementally until the group or total market is in compliance. The size of each individual sales increment is set in the subroutine parameters *MAXPASS* and *MAXADJ*, where the former is the maximum number of increments and the latter is the maximum number of sales (in millions) that can be shifted in the whole market in a given year.

If, at any time, sales of conventional gasoline vehicles become negative, sales of these vehicles are increased until sales reach a non-negative number, and vehicle sales of alternative powertrain vehicles are correspondingly decreased.

Combine manufacturer group vehicle attributes (subroutine *CAFECALC*)

In subsequent submodules of the TDM, vehicle sales by manufacturer group are not treated separately. Each vehicle characteristic for each size class of car and light truck needs to have an aggregate estimate. Aggregate vehicle characteristics are computed as weighted sums of vehicle size class totals, where each vehicle size class is weighted by its relative share of the market. Vehicle characteristics calculated include: fuel economy (*LDV_MPG_CL*), horsepower (*LDVHPW*), purchase price (*LDV_PRI*), range (*LDV_RNG*), and weight (*WGT*). Additionally, sales-weighted regional-average curb weight and horsepower are calculated separately for cars and light trucks (*AWTCAR, AWTTRUCK, AHPCAR, AHPTRUCK*), as inputs to the size class share model in subroutine *CGSHARE*.

LDV Fleet Component

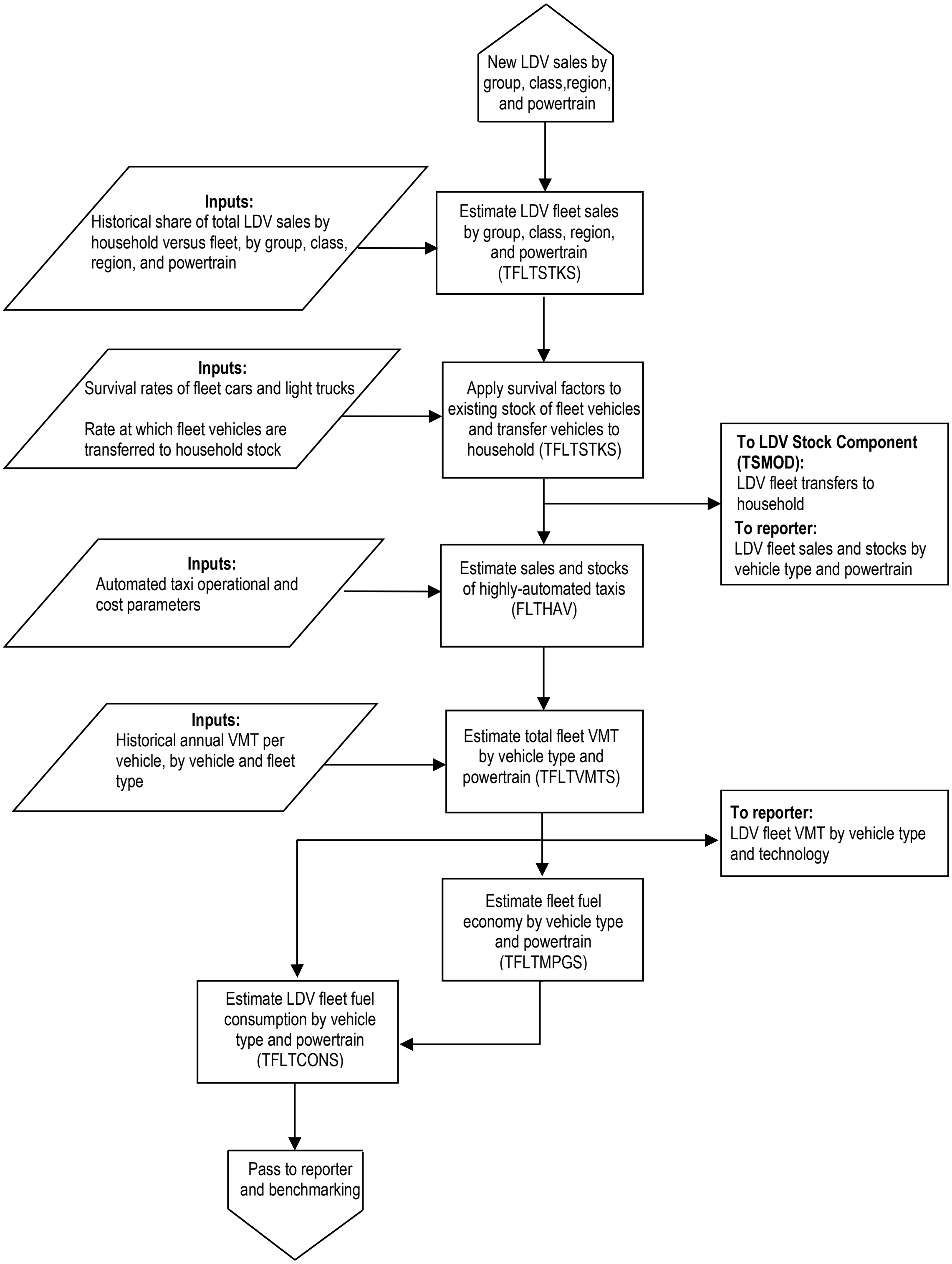
The Light-Duty Vehicle Fleet Component generates estimates of the inventory (stock) of cars and trucks used in business, government, utility, and taxi fleets and, subsequently, estimates travel demand, fuel efficiency, and energy consumption. Because of the special characteristics of these fleet vehicles, separate estimates distinct from those for personal light-duty vehicles, are generated before their transition to the private sector at predetermined ages (vintages).[9]

The component uses the same names as the variable names for cars and light trucks, which are distinguished by the value of an index designating vehicle type (*ivtyp*). Vehicles are also distinguished by their assigned type of fleet. Business, government, utility, and taxi fleets are assumed to have different operating characteristics and retirement rates. This component includes three stages: 1) determine total vehicle purchases, surviving fleet stock, and travel demand; 2) calculate the fuel economy of fleet vehicles; and 3) estimate fuel consumption.

The flowchart for the LDV Fleet Component is presented in Figure 9.

[9] Taxis are estimated to be 5% of the commercial fleet. Separating out taxis allows us to specify different vehicle characteristics (annual VMT and scrappage rate) and to distribute within the fleet by size class and fuel type compared to the business fleet. This new fleet includes both conventional and automated taxis and ride-hailing/transportation network provider services (for example, Uber and Lyft).

Figure 9. Light-duty fleet Component of the Transportation Sector Demand Module, NEMS



Data source: U.S. Energy Information Administration

Fleet sales and stocks (subroutine TFLTSTKS)

The model calculates fleet acquisitions of cars and light trucks (*fltechsal*) based on the historical split between household and fleet sales within each manufacturer group, size class, and region (*ownsaletemp*) applied to total LDV sales from subroutine *TLDV* (*ldv_sales*).

$$fltechsal_{iregn,ivtyp=1,ifleet,icl,ildv,ihav=1} = \sum_{cargrp} ldv\_sales_{igp,icl,ildv,iregn,year} * ownsaletemp_{ifleet+1,igp,icl,iregn,year} * 1000000.$$

$$fltechsal_{iregn,ivtyp=2,ifleet,icl,ildv,ihav=1} = \sum_{ltrkgrp} ldv\_sales_{igp,icl,ildv,iregn,year} * ownsaletemp_{ifleet+1,igp,icl,iregn,year} * 1000000. \quad (97)$$

where

ifleet = index of fleet type: 1 = business, 2 = government, 3 = commercial/utility, 4 = taxi. *ifleet* is a subset of *iown*, which is: {1: household, 2: business, 3: government, 4: commercial/utility, 5: taxi}.

The next step is to modify the array of surviving fleet stocks from previous years (*FLT_STOCK*) and to add new acquisitions by applying the appropriate survival factors (*SURVFLT*) to the current vintages and inserting *fltechsal* into the most recent vintage

$$FLT\_STOCK_{iregn,ivtyp,ifleet,ildv,iage,ihav,year} = FLT\_STOCK_{iregn,ivtyp,ifleet,ildv,iage-1,ihav,year-1} * SURVFLT_{ifleet,iage-1,ivyp}, \quad (98)$$

and

$$FLT\_STOCK_{iregn,ivtyp,ifleet,ildv,iage=1,year,ihav} = fltechsal_{iregn,ivtyp,ifleet,ildv,ihav} \quad (99)$$

where

iage = index referring to vintage of fleet vehicles.

Fleet vehicles are transferred to the household vehicle fleet as they age. Historical data informs the transfer shares by age and fleet type for both cars and light trucks (variable *FLTTRANS*). The stock allocated for transfer, *OLDFSTK*, is removed from the fleet stock and sent to the LDV Stock Component to augment the fleet of private vehicles. Taxi fleet vehicles are not transferred to the private fleet because of their high mileage at end-of-life.

$$OLDFSTK_{iregn,ivtyp,ifleet,ildv,iage,year} = FLT\_STOCK_{iregn,ivtyp,ifleet,ildv,iage,ihav=1,year} * FLTTRANS_{ifleet,iage,ivtyp},$$

$$FLTSTOCK_{iregn,ivtyp,ifleet,ildv,ihav=1,year} = FLTSTOCK_{iregn,ivtyp,ifleet,ildv,ihav=1,year} - OLDFSTK_{iregn,ivtyp,ildv,iage} \quad (100)$$

Total surviving fleet vehicles are then summed across vintages, resulting in total fleet stock by vehicle type, fleet type, powertrain, and highly-automed vehicle (HAV) level (*TFLTECHSTK*). Additionally, the final detailed fleet stock (*FLT_STOCK*) is used to fill the variable containing all LDV stocks, *LDV_STOCK*.

$$TFLTECHSTK_{ivtyp,flt,ildv,ihav} = \sum_{iage=1}^{25} FLT\_STOCK_{iregn,ivtyp,ifleet,ildv,iage,year,ihav,year} \quad (101)$$

$$LDV\_stock_{iregn,ivtyp,ifleet+1,ildv,iage,ihav,year} = FLT\_STOCK_{iregn,ivtyp,ifleet,ildv,iage,year,ihav,year} \quad (102)$$

Estimate taxi fleet Highly Automated Vehicles (HAV) adoption (subroutine FLTHAV)

After calculating the total fleet sales and stocks, the model estimates fleet adoption of HAV taxis. HAVs include three automation levels: Level 4a (L4a), Level 4b (L4b), and Level 5 (L5). L4a autonomous operation is restricted to low-speed (less than 35 mph) in limited geofenced areas such as urban centers. Low-speed-only operation requires a less sophisticated, lower-resolution, and lower-cost HAV system. L4b autonomous operation is restricted to limited geofenced areas, but it includes any (legal) speed roads and includes controlled environments such as limited-access highways. Highway speed operation requires a more sophisticated, higher-resolution, and more expensive HAV control system to accurately sense and react to its environment at longer range. It also needs faster computational speed because of the shorter response times needed at higher speeds. L5 vehicles can operate autonomously on all roads and road types and at all (legal) road speed limits and have no operational domain limitations. The L5 HAV system is marginally more expensive than the L4b system because it needs a more capable and expensive processor and controller.

Calculate HAV system costs

HAV systems include: a light-detection and ranging (LiDAR) array, a lithium ion battery that powers the system, and the remaining HAV system sensors, wiring, and supporting hardware.

LiDAR cost is modeled at the package level, assuming that cost and functionality would be technology-independent and similar whether the manufacturers implemented a single high-resolution, 360-degree field of view LiDAR unit or multiple LiDAR units with limited fields of view. Cost curves are estimated for two different LiDAR systems (represented by the *iLiDAR* subscript in the equation): high-resolution (capable of both high- and low-speed operation) and low-resolution (capable of low-speed operation only). Each of the two cost curves has five different production phases with production thresholds specified in trnldv.xlsx: R&D, Revolutionary, Evolutionary, Mature, and High-Volume. These phases are characterized by different learning rates. Faster learning takes place during the Revolutionary and Evolutionary phases, and slower learning occurs during the Mature and High-Volume phases.

$$lidar\_cost_{ihav,t} = a_t * cumul\_lidar\_prod_{ilidar,t-1}^{-b_t} \quad (103)$$

where,

$LiDAR\_cost_{ihav,t}$ = cost of LiDAR system ($) used for HAV level *ihav*;

a_t = represents the (hypothetical) initial cost for the first unit produced;

$cumul\_LiDAR\_prod_{ilidar,t}$ = cumulative production of *iLiDAR* LiDAR systems; and

b_t = parameter based on the learning rate.

The input R&D production, along with the R&D phase of the cost curve, ensures that LiDAR system cost reduction continues even if HAVs do not penetrate the market to account for HAV testing and other uses (for example, defense, science, drones, and agriculture). The subroutine outputs are LiDAR system costs for high- and low-resolution systems based on cumulative production. The outputs are mapped from high- versus low-resolution (subscript *iLiDAR*) to Level 4a, 4b, or 5 (subscript *ihav*) for use in the HAVCALC subroutine. Level 4a uses low-resolution LiDAR, and Levels 4b and 5 use high-resolution LiDAR.

Total HAV system costs for L4a, L4b, and L5 are estimated in subroutine HAVCALC using the equation below. The equation uses a time-based cost reduction curve and an initial cost (defined in trnldv.xml) to calculate system cost less the LiDAR and battery. The existing LIONCOSTCALC subroutine determines the battery cost per kWh for the HAV system battery.

$$hav\_sys\_cost_{ihav,t} = hav\_sys\_lrn_{ihav,t} * hav_{init_{cost}\,_{ihav}} + Li_{ion_{cost}\ t} * hav_{battery_{kWh}\,_{ihav}} + lidar\_cost_{ihav,t} \tag{104}$$

where

hav_sys_cost$_{ihav,t}$ = total HAV system cost ($);

HAV_sys_lrn$_{ihav,t}$ = time-based HAV system cost reduction curve;

hav_init_cost$_{ihav}$ = initial cost of HAV system, less LiDAR and battery ($);

Li_ion_cost$_{t}$ = li-ion battery cost ($/kWh);

HAV_battery_kWh$_{ihav}$ = HAV system battery capacity (kWh); and

LiDAR_cost$_{ihav,t}$ = LiDAR system cost ($).

The subroutine outputs are HAV system incremental costs for HAV levels L4a, L4b, and L5.

The FLTHAV subroutine uses a logit choice equation to estimate sales shares of each HAV level (levels 4a, 4b, and 5), based on revenue, operation and maintenance costs, operational domain, and new technology limitations. A time-dependent new technology variable is included to represent factors that limit adoption of new technologies, such as the lack of consumer knowledge, perceived risk, large capital requirements, limited model availability, production capacity restrictions, and other potential limitations. HAV levels 4a and 4b include a parameter characterizing the disutility of the levels' operational domain (speed, geography, weather) limitations.

$$taxi\_util_{iregn,ihav} = hav\_newtech\_lim_{ihav} + hav\_oper\_limit_{iregn,ihav} + taxi_{rev_{coef}} * taxi_{npv}\,_{iregn,ihav} \tag{105}$$

$$flt\_hav\_shares_{iregn,ivtyp,icl,ildv,year,ihav} = \frac{e^{taxi\_util_{iregn,ihav}}}{\sum_{ihav=1}^{4} e^{taxi\_util_{iregn,ihav}}}, \tag{106}$$

where,

$taxi\_util_{iregn,ihav}$ = utility of each HAV level.

hav_newtech_lim = time-dependent function for new technology limitations;

$hav\_oper\_limit_{iregn,ihav}$ = operational domain disutility for HAV levels 4a and 4b;

taxi_rev_coeff = revenue coefficient per $1,000 (1990$);

$taxi\_npv_{iregn,ihav}$ = net present value of lifetime taxi revenue, less operational costs; and

$flt\_hav\_shares_{iregn,ivtyp,icl,ildv,year,ihav}$ = HAV level *ihav* adoption.

The net present value of lifetime taxi revenue is calculated from up-front vehicle cost, trip revenue, driver salary (if applicable), and operating costs that include fuel, maintenance, insurance, and data fees.

$$taxi\_npv_{iregn,ihav} = -VehPrice + \sum_{t=1}^{life}\left[\left((1+taxi\_disc\_r)^{-t}\right) * \left(taxi\_mo\_rev_{iregn,ihav} - taxi\_mo\_cost_{iregn,ihav} - fuelpriceproj_t * taxi\_fuel_{iregn,ihav}\right)\right], \tag{107}$$

where,

$taxi\_npv_{iregn,ihav}$ = net present value of per vehicle taxi lifetime revenue ($);

VehPrice = vehicle price ($);

taxi_disc_r = taxi fleet discount rate;

$taxi\_mo\_rev_{iregn,ihav}$ = monthly per vehicle taxi revenue ($);

$taxi\_mo\_cost_{iregn,ihav}$ = monthly per vehicle taxi operating cost ($);

$fuelpriceproj_t$ = projected regional fuel price ($);

$taxi\_fuel_{iregn,ihav}$ = monthly per vehicle fuel consumption including motoring and idling; and

life = expected taxi lifetime in months

The outputs are:

- Ride-hailing/taxi fleet HAV level (that is, levels 0–3, 4a, 4b, and 5) distribution within vehicle type, class, powertrain, and census division
- Ride-hailing/taxi fleet HAV sales by vehicle type, class, powertrain, census division, and HAV level

FLTHAV modifies one fleet sales variable (*fltechsal*) and two fleet stock variables (*flt_stock* and *fltechstk*) to ensure that the HAV sales and stock can be tracked and used in later calculations.

Calculate Fleet VMT (subroutine TFLTVMTS) and fuel economies (subroutine TFLTMPGS)

The fleet vehicle stock VMT (*fltechvmt*) is calculated from fleet stocks (*fltechstk*) and annual VMT per vehicle (*fltvmtyr*) in *TFLTVMTS* as follows

$$fltechvmt_{iregn,ivtyp,ifleet,ildv,ihav} = fltechstk_{iregn,ivtyp,ifleet,ildv,ihav} * fltvmtyr_{ifleet,year,ivtyp} \tag{108}$$

Average new vehicle fuel economies (*fltmpgnew*) are then calculated using a sales-weighted harmonic mean using sales from *TFLTSTKS* (*fltgrpsal*) and fuel economy from the MTCC and CVCC (*femmpg*). This aggregates the manufacturer groups (index *igp*) and size classes (index *icl*) into car and light truck (index *ivtyp*).

$$fltmpgnew_{iregn,ivtyp,ifleet,ildv,year} = \frac{\sum_{igp}\sum_{icl} fltgrpsal_{iregn,ifleet,igp,icl,ildv}}{\sum_{igp}\sum_{icl}\frac{fltgrpsal_{iregn,ifleet,igp,icl,ildv}}{femmpg_{igp,icl.year.ildv}}} \tag{109}$$

The fuel efficiency of new vehicles is then adjusted to account for degradation from 2-cycle *tested* fuel economy to *on-road* fuel economy using factors derived from historical data (*degfac*), and is assigned to the array of fleet stock efficiencies by vintage (*fltmpgstk*).

$$fltmpgstk_{iregn,ivtyp,ifleet,ildv,iage=1,year} = fltmpgnew_{iregn,ivtyp,ifleet,ildv,year} * degfac_{ivtyp,ildv,year} \tag{110}$$

Vintaged fuel economies are shifted to account for vehicle aging, for *iage*=2 to *maxage* (maximum vintage for light duty vehicles in NEMS TDM)

$$fltmpgstk_{iregn,ivtyp,ifleet,ildv,iage,year} = fltmpgstk_{iregn,ivtyp,ifleet,ildv,iage-1,year-1} \tag{111}$$

Average stock fuel efficiency by vehicle and fleet type (*MPGFLTSTK*) is then calculated

$$MPGFLTSTK_{iregn,ivtyp,ifleet,ildv} = \frac{\sum_{iage=1}^{maxage}\sum_{ihav=1}^{maxhav} flt\_stock_{iregn,ivtyp,ifleet,ildv,iage,ihav,year}}{\sum_{iage=1}^{maxage}\sum_{ihav=1}^{maxhav}\frac{flt\_stock_{iregn,ivtyp,ifleet,ildv,iage,ihav,year}}{fltmpgstk_{iregn,ivtyp,ifleet,ildv,iage,year}}} \tag{112}$$

The overall fleet average mpg, *FLTMPGTOT*, is calculated for cars and light trucks

$$FLTTOTMPG_{ivtyp} = \frac{\sum_{ifleet=1}^{4}\sum_{ildv=1}^{16}\sum_{ihav=1}^{4} FLTECHSTK_{mnumcr,ivtyp,ifleet,ildv,ihav}}{\sum_{ifleet=1}^{4}\sum_{ildv=1}^{16}\sum_{ihav=1}^{4}\frac{TFLTECHSTK_{mnumcr,ivtyp,ifleet,ildv,ihav}}{MPGFLTSTK_{mnumcr,ivtyp,ifleet,ildv}}}, \tag{113}$$

Calculate Fuel Consumption by Fleet Vehicles (subroutine TFLTCONS)

Fleet fuel consumption, *fltechgge*, is the quotient of fleet travel demand and fuel efficiency, which have been addressed above

$$fltechgge_{iregn,ivtyp,ifleet,ildv,year} = \frac{\sum_{ihav=1}^{4} FLTVMTTECH_{iregn,ivtyp,ifleet,ildv,ihav}}{MPGFLTSTK_{iregn,ivtyp,ifleet,ildv}}, \tag{114}$$

Consumption is then summed across fleet types and converted to values in British thermal units using NEMS motor gasoline energy content *CFMGQ*, in variable *fltldvbtu*

$$fltldvbtu_{iregn,ivtyp,ildv,year} = \sum_{fleet=1}^{4} fltechgge_{iregn,ivtyp,ifleet,ildv,year} * \frac{CFMGQ_{year}}{42}, \quad (115)$$

Consumption totals for trucks and cars are added, and total consumption *FLTFUELBTU* is distributed among highway fuel types

$$FLTFUELBTU_{iregn,ifuel,year} = \sum_{ivtyp=1}^{2} FLTFCLDVBTU_{ivtyp,ildv,year} * PctXX_{iregn,year}, \quad (116)$$

where

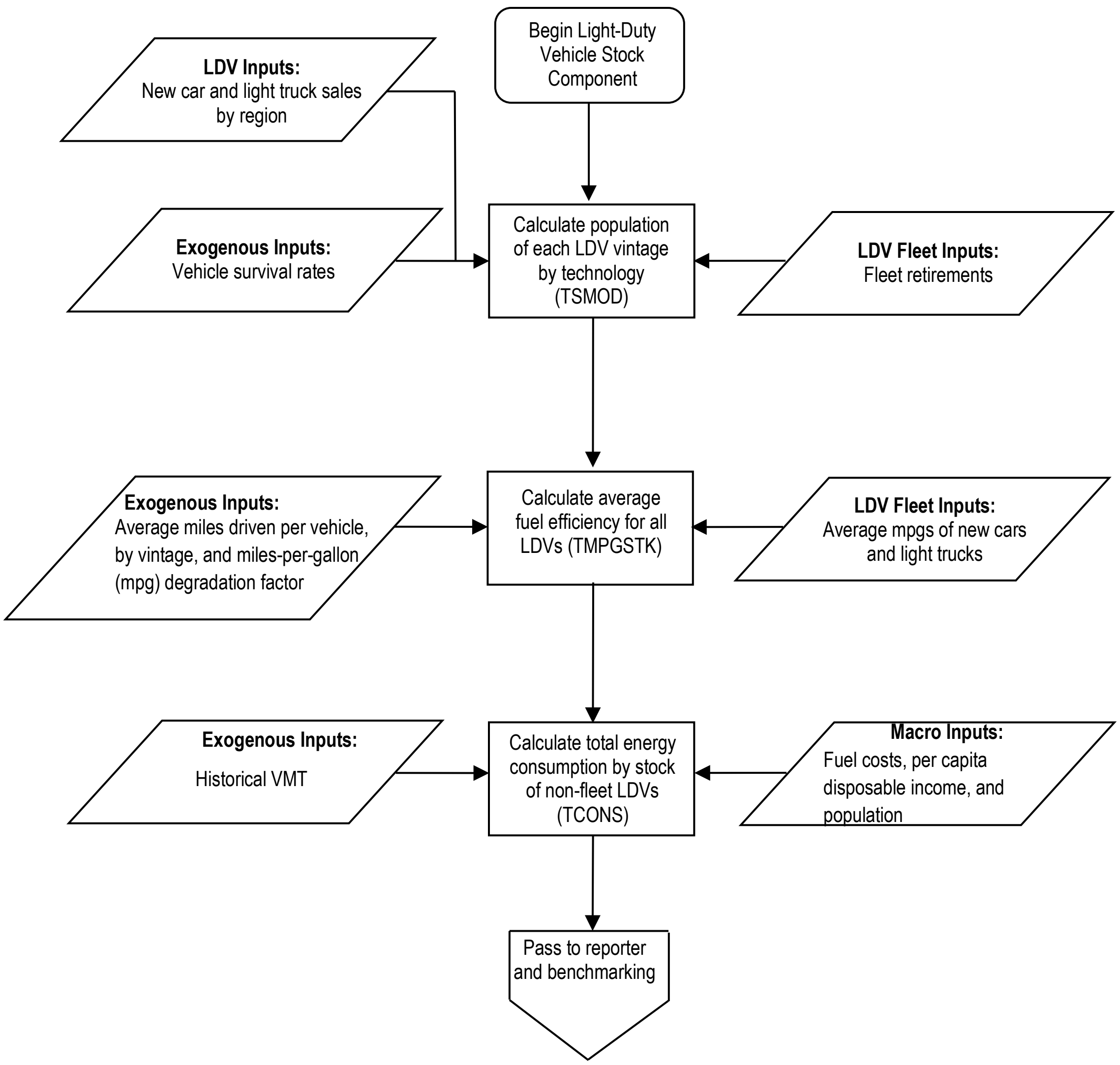
$PctXX_{iregn,year}$ = share of VMT for each bi-fuel powertrain type that is on fuel 2, where XX = {AF, PHEV20,PHEV50}, for example, PctPHEV20 is the share of PHEV20 miles that are electric.

Non-Fleet LDV Stock, VMT, and consumption

Next, the TDM takes sales and efficiency estimates for new cars and light trucks from the LDV Submodule and returns the number and characteristics of the total surviving fleet of household-owned light-duty vehicles, the total miles traveled, and the energy consumed to meet that travel demand (steps shown in Figure 10).

These characteristics – most importantly, total vehicle counts and the fuel economy of each subset of vehicles – are passed to the VMT Component, which determines the average number of miles driven by each vehicle in each projection year. The vehicle characteristics and VMT are then used to project fuel consumption.

Figure 10. Non-fleet Light-duty Vehicle Stock, VMT, and Consumption for the Transportation Sector Demand Module, NEMS



Data source: U.S. Energy Information Administration

LDV Stock Component (subroutine TSMOD)

The variable *LDV_STOCK* contains the annual counts of LDVs by region, vehicle type (car and light truck), ownership type (household or one of four LDV fleet types), powertrain, age, and level of automation.

The first step is to fill the first vintage of current year *LDV_STOCK* with the current year household vehicle sales, *hhtechsal*.

$$LDV\_STOCK_{iregn,ivtyp,iown=1,ildv,iage=1,ihav=1,year} = \sum_{icl} hhtechsal_{iregn,ivtyp,icl,ildv,year} \quad (117)$$

For *iage* = 2 to 24 let

$$LDV\_STOCK_{iregn,ivtyp,iown=1,ildv,iage,ihav,year} = LDV\_STOCK_{iregn,ivtyp,iown=1,ildv,iage-1,ihav,year-1} * SSURV25_{iregn,iage-1,ivtyp}, \quad (118)$$

where

$SSURV25_{iregn,iage,ivtyp}$ = regional survival rate of cars and light trucks by vehicle type and vintage; and

iown = owner type {1:household, 2:business, 3:government, 4:utility, 5:taxi}.

For *iage* = 25 (*maxage*) let

$$LDV\_STOCK_{iregn,ivtyp,iown=1,ildv,iage,ihav,year} = LDV\_STOCK_{iregn,ivtyp,iown=1,ildv,iage-1,ihav,year-1} * SSURV25_{iregn,,maxage-1,ivtyp} + LDV_{STOCK}{}_{iregn,ivtyp,iown=1,ildv,iage,ihav,year-1} * SSURV25_{iregn,maxage,ivtyp} \quad (119)$$

The component encompasses 25 vintages, and the 25th vintage is an aggregate of all vehicles 25 years or older. *SSURV25* contains 25 values measuring the percentage of vehicles of each vintage that survive into the next year. The stock of selected vintages and technologies calculated above is then augmented by a number of fleet vehicles that are assumed to roll over into the non-fleet population after a number of years of fleet service (*OLDFSTKT*).

$$LDV\_STOCK_{iregn,ivtyp,iown=1,ildv,iage,ihav,year} = LDV\_STOCK_{iregn,ivtyp,iown=1,ildv,iage,ihav,year} + OLDFSTKT_{iregn,ivtyp.ildv,iage}, \quad (120)$$

Total stocks of non-fleet cars and trucks (*STKCAR* and *STKTR*) are then determined by summing over regions, vintages and powertrain types

$$STKCAR_{year} = \sum_{iregn=1}^{9} \sum_{ildv=1}^{16} \sum_{iage=1}^{25} \sum_{ihav=1}^{4} LDV\_STOCK_{iregn,ivtyp=1,iown=1,ildv,iage,ihav,year},$$

$$STKTR_{year} = \sum_{iregn=1}^{9} \sum_{ildv=1}^{16} \sum_{iage=1}^{25} \sum_{ihav=1}^{4} LDV\_STOCK_{iregn,ivtyp=2,iown=1,ildv,iage,ihav,year} \quad (121)$$

The above variables are then used to determine average fuel efficiencies of the current year's stock of non-fleet vehicles.

Calculate Stock Efficiencies for Cars and Light Trucks (subroutine TMPGSTK)

Average new vehicle fuel economies (*hhmpgnew*) are then calculated using a sales-weighted harmonic mean using final household sales (*hhgrpsal*) and fuel economy from the MTCC and CVCC (*femmpg*). This aggregates the manufacturer groups (index *igp*) and size classes (index *icl*) into car and light truck (index *ivtyp*).

$$hhmpgnew_{iregn,ivtyp,ildv,year} = \frac{\sum_{igp}\sum_{icl} hhgrpsal_{iregn,igp,icl,ildv}}{\sum_{igp}\sum_{icl}\frac{hhgrpsal_{iregn,igp,icl,ildv}}{femmpg_{igp,icl.year.ildv}}} \quad (122)$$

The fuel efficiency of new vehicles is then adjusted to account for degradation from 2-cycle *tested* fuel economy to *on-road* fuel economy using factors derived from historical data (*degfac*), and is assigned to the array of fleet stock efficiencies by vintage (*hhmpgstk*).

$$hhmpgstk_{iregn,ivtyp,ildv,iage=1,year} = hhmpgnew_{iregn,ivtyp,ildv,year} * degfac_{ivtyp,ildv,year} \quad (123)$$

Vintaged fuel economies are shifted to account for vehicle aging, for *iage*=2 to *maxage* (maximum vintage for light duty vehicles in NEMS TDM)

$$hhmpgstk_{iregn,ivtyp,ildv,iage,year} = hhmpgstk_{iregn,ivtyp,ildv,iage-1,year-1} \quad (124)$$

The overall fuel efficiency of cars and light trucks is then calculated across the 25 vintages addressed in the component. Older vehicles are driven less than newer vehicles, the fuel efficiencies of each vintage need to be weighted according to the average number of miles driven. The weighting of fuel economy by travel is done by summing the total number of miles driven across all vintages and technologies[10]

$$VMT\_STK\_HH_{ivtyp,ildv,iage,ihav,iregn} = LDV\_STOCK_{iregn,ivtyp,iown=1,ildv,iage,ihave,year} * XVMT_{iage,year,iregn} \quad (125)$$

where

$VMT\_STK\_HH_{ivtyp,ildv,iage,ihav,iregn}$ = total miles driven by LDVs; and

$XVMT_{iage,year,iregn}$ = average miles driven by each vintage of LDV, where X = {P: car, L:light truck}.

The next step is to calculate the total energy consumed, in gallons of gasoline, across all vintages and technologies of cars and light trucks, CMPGT and TMPGT respectively.

$$CMPGT_{year,iregn} = \sum_{ildv=1}^{16}\sum_{ihav=1}^{4}\sum_{iage=1}^{25}\frac{VMT\_STK\_HH_{ivtyp=1,ildv,iage,ihav,iregn}}{hhmpgstk_{iregn,ivtyp=1,ildv,iage,year}},$$

[10] Vehicle miles calculated in this step are used to establish relative driving rates for the various technologies. Actual travel demand is generated by the model in a subsequent step.

$$TMPGT_{year,iregn} = \sum_{ildv=1}^{16} \sum_{ihav=1}^{4} \sum_{iage=1}^{25} \frac{VMT\_STK\_HH_{ivtyp=2,ildv,iage,ihav,iregn}}{hhmpgstk_{iregn,ivtyp=2,ildv,iage,year}}, \tag{126}$$

Stock fuel efficiency for cars and light trucks (*SCMPG* and *STMPG* respectively) is the ratio of total travel to total consumption.

$$SCMPG_{year} = \frac{\sum_{ildv} \sum_{iage} \sum_{ihav} \sum_{iregn} VMT\_STK\_HH_{ivtyp=1,ildv,iage,ihav,iregn}}{\sum_{iregn} CMPGT_{year,iregn}},$$

and

$$STMPG_{year} = \frac{\sum_{ildv} \sum_{iage} \sum_{ihav} \sum_{iregn} VMT\_STK\_HH_{ivtyp=2,ildv,iage,ihav,iregn}}{\sum_{iregn} TMPGT_{year,iregn}}, \tag{127}$$

Combining the results provides the average fuel efficiency for all household light-duty vehicles, *MPGHH*

$$MPGHH_{year} = \frac{\sum VMT\_STK\_HH}{\sum_{iregn} [CMPGT_{year,iregn} + TMPGT_{year,iregn}]}, \tag{128}$$

Calculate the average fuel efficiency for cars and light trucks by powertrain (*CMPGT_IT* and *TMPGT_IT*).

$$CMPG\_IT_{ildv,year} = \frac{\sum_{iregn} \sum_{ivtyp} \sum_{iage} \sum_{ihav} VMT\_STK\_HH_{ivtyp=1,ildv,iage,ihav,iregn}}{\sum_{iregn} \sum_{iage} \sum_{ihav} \frac{VMT\_STK\_HH_{ivtyp=1,ildv,iage,ihav,iregn}}{Chhmpgstk_{iregn,ivtyp=1,ildv,iage,year}}},$$

$$TMPG\_IT_{ildv,year} = \frac{\sum_{iregn} \sum_{ivtyp} \sum_{iage} \sum_{ihav} VMT\_STK\_HH_{ivtyp=2,ildv,iage,ihav,iregn}}{\sum_{iregn} \sum_{iage} \sum_{ihav} \frac{VMT\_STK\_HH_{ivtyp=2,ildv,iage,ihav,iregn}}{hhmpgstk_{iregn,ivtyp=2,ildv,iage,year}}}, \tag{129}$$

These fuel efficiency figures are combined with the results of the subsequent VMT Component to determine the actual fuel consumption by light-duty vehicles.

VMT Component (subroutine TVMT)

The Vehicle Miles Traveled Component of NEMS is a subcomponent of the LDV Stock Component that uses NEMS estimates of fuel price and personal income, along with population projections, to generate a projection of the demand for personal travel, expressed in vehicle miles traveled per licensed driver. This component is subsequently combined with projections of car fleet efficiency to estimate fuel consumption.

Projecting VMT per licensed driver in the mid- to long-term primarily seeks to address those effects that alter historical growth trends. The factors affecting future VMT trends in the model are the fuel cost of driving (*COSTMI*), disposable personal income (*INC00_D_16*), employment (*EMP_RATE_VMT*), vehicles per licensed driver (*VPLD*), and past VMT trends. The Federal Highway Administration (FHWA) provides historical licensed driver rates by age cohort, gender, and region. All macroeconomic inputs are calculated based on a chain-weighted average.

$$\log(VMTLD_{year}) - \beta_1 \log VMTLD_{year-1} = \alpha + \beta_2 \log(INC00\_D\_16_{year}) + \beta_3 \log(COSTMI_{year}) + \beta_4 \log(VPLD_{year}) + \beta_5 \log(EMP\_RATE\_VMT_{year}), \tag{130}$$

where

VMTLD$_{year}$ = VMT per licensed driver for the driving age population, by age cohort and gender; and

α, β = coefficient estimates for the VMT per driver estimation, varying by age cohort and gender.

The generalized difference equation used to estimate the VMT per driver is given below

$$VMTLD_{year} = \exp\big(\alpha + \beta_1 \ln\big(VMTLD_{year-1,}\big) + \beta_2 * \ln\big(INC00\$16_{year}\big) + \beta_3 \ln\big(COSTMI_{year}\big) + \beta_4 \ln\big(VPLD_{year}\big) + \beta_5 \ln\big(EMP\_RATE\_VMT_{year}\big)\big) \quad (131)$$

Air Travel Submodule

The Air Travel Submodule (*TRANAIR*) of the NEMS transportation sector demand module contains two components: the Air Travel Demand Component (*TAIRT*) and the Aircraft Fleet Efficiency Component (*TAIREFF*). These components use NEMS (U.S.) and Oxford Economics (non-U.S.) projections of macroeconomic activity and population growth, as well as assumptions about aircraft retirement rates and technological improvements, to generate projections of global passenger and freight travel demand and the fuel required to meet that demand. *TRANAIR* receives exogenous estimates of aircraft load factors and other operational specifications that determine the average number of available seat-mile (passenger aircraft) or revenue ton-mile (dedicated cargo aircraft) capacity each plane will supply in a year, enabling it to estimate the aircraft supply and corresponding fuel consumption required to meet passenger and freight demand (Figure 11).

TAIRT projects domestic and international per-capita passenger travel demand by 16 world regions (defined in Table 2), measured in revenue passenger-miles (RPM) per-capita, and world regional air freight demand, measured in revenue ton-miles (RTM).[11] Exogenously defined passenger load factors (PLFs) are applied to separately estimate the available seat-mile (ASM) capacity required to meet domestic and international RPM demand across each of three aircraft types: wide body, narrow body, and regional jets.

Cargo load factors (CLFs) for dedicated cargo aircraft are assumed to be constant at 2022 levels; cargo supply and demand are therefore both measured in RTMs. Freight RTMs are allocated to passenger aircraft (belly freight) or dedicated freighters based on historical trends; a conversion factor is applied to the former so that is can be aggregated with passenger RPMs.[12]

TAIREFF projects the efficiency of aircraft across different aircraft types and by region. The module contains a stock accounting model to track regional aircraft stocks by type, age, and status. Aircraft can either be active—prepared to carry passengers and/or freight—or parked. Parked aircraft are not decommissioned and are therefore available for re-activation if needed. *TAIREFF* ensures that aircraft stocks meet both the seat-mile demand and the dedicated freighter RTM demand for each aircraft type, by either re-activating parked planes, purchasing new jets, or in the case of dedicated freighter demand, converting older passenger aircraft. It also estimates sales and stock fuel efficiencies by region, domestic/international flights, and aircraft body type.

[11] In *TRANAIR,* domestic travel means both takeoff and landing occur in the same region (intra-region), while international travel means that either takeoff or landing is in the region but not both (inter-region).

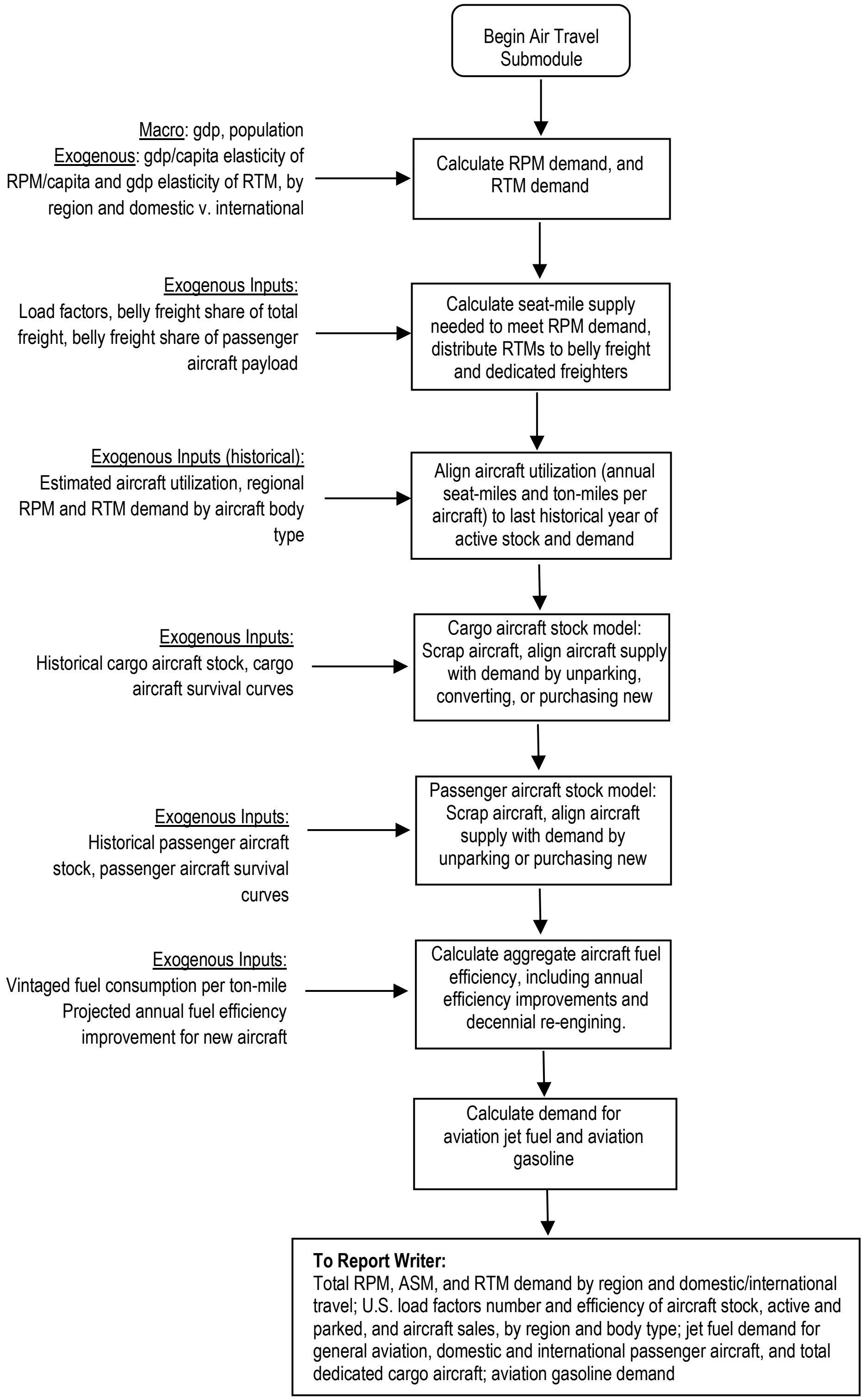
[12] Belly freight, initially in units of revenue ton-miles, is converted to revenue passenger-miles using an average passenger weight of 200 pounds (including luggage).

Table 2. World Regions used in NEMS air travel submodule

Region Number	Region	Countries in Region
1	United States	United States
2	Canada	Canada
3	Mexico	Mexico
4	Western Europe	Albania,Austria,Belgium,Bosnia and Herzegovina,Bulgaria,Croatia, Cyprus, Czech Republic, Denmark, Estonia, Faroe Islands, Finland, France, Germany, Gibraltar, Greece, Hungary, Iceland, Ireland, Italy, Kosovo, Latvia, Lithuania, Luxembourg, Macedonia, Malta, Montenegro, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, U.K.
5	Japan	Japan
6	Australia and New Zealand	Australia and New Zealand
7	South Korea	South Korea
8	Russia	Russia
9	Eastern Europe and Eurasia	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
10	China	China
11	India	India
12	Other Asia Pacific	Afghanistan, American Samoa, Bangladesh, Bhutan, Brunei, Cambodia, Cook Islands, Fiji, French Polynesia, Guam, Hong Kong, Indonesia, Kiribati, Korea, Democratic People's Republic of, Laos, Macao, Malaysia, Maldives, Micronesia, Federated States of, Mongolia, Myanmar, Nauru, Nepal, New Caledonia, Niue, Northern Mariana Islands, Pakistan, Papua New Guinea, Philippines, Samoa, Singapore, Solomon Islands, Sri Lanka, Taiwan, Province of China, Thailand, Timor-Leste, Tonga, Tuvalu, Vanuatu, Viet Nam, Wake Island
13	Middle East	Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestine, State of, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates, Yemen
14	Africa	Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo-Brazzaville, Congo-Kinshasa, Cote dIvoire, Djibouti, Egypt, Equatorial Guinea, Eritrea, Eswatini, Ethiopia, Gabon, The Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Réunion, Rwanda, Saint Helena, Ascension and Tristan da Cunha, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, South Sudan, Sudan, Tanzania, Togo, Tunisia, Uganda, Western Sahara, Zambia, Zimbabwe
15	Brazil	
16	Other Americas	Antarctica, Antigua and Barbuda, Argentina, Aruba, Bahamas, Barbados, Belize, Bermuda, Bolivia, Cayman Islands, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, Falkland Islands, French Guiana, Greenland, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Montserrat, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Pierre and Miquelon, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Turks and Caicos, Uruguay, Venezuela, Bolivia, Virgin Islands, British, Virgin Islands, U.S.

Data source: U.S. Energy Information Administration

Figure 11. Air travel submodule of the Transportation Sector Demand Module, NEMS



Data source: U.S. Energy Information Administration

Air Travel Demand Component

The Air Travel Demand Component (subroutine *TAIRT*) operates under the assumption that travel demand is primarily influenced by economic conditions and population. It applies an econometric relationship for air travel demand by region and travel type (domestic and international) estimated over the period 1995 to 2022 and is also informed by domestic and international travel propensities and projected travel demands from outlooks published by aircraft manufacturers and industry groups. Population growth is introduced in the equation by expressing GDP in per capita form. Key model relationships and the steps involved in calculating air passenger and cargo demand are presented below:

1) Calculate per-capita revenue passenger-miles (RPMs) for domestic and international travel in the 16 world regions using the following econometric relationship:

$$\frac{RPMT\_PC_{iwreg,di,year}}{RPMT\_PC_{iwreg,di,year-1}} = e^{intercept\_rpm_{iwreg,di}} * \left[\frac{GDP\_PC_{iwreg,year}}{GDP\_PC_{iwreg,year-1}}\right]^{beta1\_rpm_{iwreg,di}}, \quad (132)$$

where

$RPMT\_PC_{iwreg,di,year}$ = RPM per capita for domestic (di=1) and international (di=2) travel by region;

$GDP\_PC_{iwreg,year}$ = $WLD\_GDP_{iwreg,year}$ / $WLD\_POP_{iwreg,year}$, where WLD_GDP and WLD_POP are gdp and population by region, respectively;

$intercept\_rpm_{iwreg,di}$ = intercept per capita RPM for domestic and international travel by region;

$beta1\_rpm_{iwreg,di}$ = gdp per capita elasticity of RPM per capita for domestic and international travel by region; and

iwreg = world regions = 1 through 16.

2) Calculate regional domestic and international RPM totals using RPM per capita and population projections.

$$RPMT_{iwreg,di,year} = RPMT\_PC_{iwreg,di,year} * WLD\_POP_{iwreg,year}, \quad (133)$$

where

$RPMT_{iwreg,di,year}$ = total RPMs for domestic and international travel by region.

3) Distribute *domestic* and international RPMs across aircraft body types (*iatyp*), defined as narrow

body, wide body, and regional jet aircraft.[13]

$$RPM_{iwreg,di,iatyp,year} = RPMT_{iwreg,di,year} * SHR\_RPM\_BODY_{iatyp,year,di}, \quad (134)$$

where

$RPM_{iwreg,di,iatyp,year}$ = revenue passenger-miles for domestic and international travel by region, by aircraft type; and

$SHR\_RPM\_BODY_{iatyp,year,di}$ = distribution of RPMs by aircraft type, for domestic and international travel and by region. Historical values from EIA analysis of U.S. BTS Schedule T2 data,[14] and projected through 2050 based on industry trends.[15]

4) Calculate regional domestic and international RTM totals and distribute by aircraft type.

$$RTM_{iwreg,year} = e^{intercept\_rtm_{iwreg}} * \left(WLD\_GDP_{iwreg,year}\right)^{beta1\_rtm_{iwreg}} \quad (135)$$

and

$$RTM\_TYP_{iwreg,di,iatyp,year} = RTM_{iwreg,year} * SHR\_RTM_{iwreg,iatyp,di,year}, \quad (136)$$

where

$RTM_{iwreg,year}$ = total revenue ton-miles, by region;

$intercept\_rtm_{iwreg}$ = intercept RTM for domestic and international travel, by region; and

$beta1\_rtm_{iwreg}$ = gdp coefficient for RTM for domestic and international travel, by region.

$SHR\_RTM_{iwreg,iatyp,di,year}$ = distribution of RTMs by aircraft type, for domestic and international air cargo and by region. Derived from EIA analysis of U.S. BTS Schedule T2 and World Jet Inventory stock datasets; [16,17] and

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[13] Narrow-body aircraft (e.g Boeing 737 Airbus 320) typically seat 120-200 passengers and are characterized by two banks of seats separated by a center aisle. Wide-body aircraft (e.g. Boeing 777, Airbus A330) typically carry from 250-400+ passengers. Regional jets, such as the Canadair RJ-100, have seating for approximately 50-110 passengers.

[14] U.S. Department of Transportation, Research and Innovative Technology Administration, Bureau of Transportation Statistics, T2: U.S. Air Carrier Traffic And Capacity Statistics by Aircraft Type, (2020).

[15] The confluence of several air travel industry trends, including but not limited to the development of hub and spoke systems, interest in greater route flexibility, and potential savings from higher fuel efficiency, has led airlines to invest in smaller passenger aircraft. In 1995, narrow-body aircraft accounted for approximately 58% of total U.S. available seat-miles and wide-body aircraft accounted for 39%, with regional jets accounting for the remaining 3%. By 2019, narrow-body aircraft accounted for 68% of total U.S. available seat-miles and wide-body aircraft accounted for 23%, with regional jets accounting for the remaining 9%.

[16] U.S. Department of Transportation, Research and Innovative Technology Administration, Bureau of Transportation Statistics, T2: U.S. Air Carrier Traffic And Capacity Statistics by Aircraft Type, (2020).

[17] Jet Inventory Services, World Jet Inventory: Year-End 2020, (March 2021).

$RTM\_TYP_{iwreg,di,Iatyp,year}$ = revenue ton-miles for domestic and international travel by region, by aircraft type.

5) Estimate the portion of air cargo demand that is filled by passenger aircraft belly capacity (*$BELLY\_RPM\_EQ_{iwreg,iatyp,di,year}$*), using exogenous shares.

$$BELLY\_RPM\_EQ_{iwreg,iatyp,di,year} = MIN\left[RPM_{iwreg,di,iatyp,year} * \frac{PCT\_BELLY\_PLOAD_{iatyp,year,di}}{(1-PCT\_BELLY\_PLOAD_{iatyp,year,di})}, RTM\_TYP * PCT\_BELLY\_FRT_{iatyp,year,di} * \frac{2000}{pass\_weight}\right] \quad (137)$$

where

$PCT\_BELLY\_PLOAD_{iatyp,year,di}$ = percent of passenger aircraft payload (passenger and freight) that is freight, or "belly freight";

$PCT\_BELLY\_FRT_{iatyp,year,di}$ = percent of total freight (belly and dedicated freighter) that is belly freight; and

pass_weight = 200 pounds, the average weight per passenger, including luggage, used to convert belly freight from RTMs to RPMs.

5) Calculate final demand for both passenger and dedicated freight aircraft.

$$PASSAC\_RPM\_DMD_{iwreg,iatyp,di,year} = RPM_{iwreg,di,iatyp,year} + BELLY\_RPM\_EQ_{iwreg,iatyp,di,year}$$

and

$$CARGOAC\_RTM\_DMD_{iwreg,iatyp,di,year} = RTM\_TYP_{iwreg,iatyp,di,year} - BELLY\_RPM\_EQ_{iwreg,iatyp,di,year} * \frac{pass\_weight}{2000} \quad (138)$$

where

$PASSAC\_RPM\_DMD_{iwreg,iatyp,di,year}$ = total payload demand for passenger aircraft, in RPMs, for domestic and international travel, by aircraft body type and region; and

$CARGOAC\_RTM\_DMD_{iwreg,iatyp,di,year}$ = total payload demand for dedicated cargo aircraft, in RTMs, for domestic and international travel, by aircraft body type and region.

6) Calculate seat-mile capacity required to meet RPM demand, not including belly freight.[18]

$$ASM_{iwreg,di,iatyp,year} = \frac{RPM_{iwreg,di,iatyp,year}}{LoadFactor_{iwreg,di,iatyp,year}}, \quad (139)$$

where

$ASM_{iwreg,di,iatyp,year}$ = domestic and international demand for available seat-miles, by aircraft body type and region;

$Load\_Factor_{iwreg,di,iatyp,year}$ = exogenously determined load factor for domestic and international travel, by aircraft type and region.

Aircraft Fleet Efficiency Component

The Aircraft Fleet Efficiency Component (subroutine *TAIREFF*) is a structured accounting mechanism that estimates the number of aircraft available to meet passenger and freight travel demand subject to user-specified parameters. Total fleet efficiency, using a harmonically weighted average of the characteristics of active aircraft and those acquired to meet demand, is based on separate estimates of the stock and efficiency of the three types of aircraft considered by the component: narrow-body, wide-body, and regional jets.

The intent of this component is to provide a quantitative approach for estimating aircraft fleet energy efficiency. The rate of new aircraft acquisition significantly affects the average energy intensity of the fleet and, subsequently, the projection of energy demand. Fuel efficiency of new acquisitions of aircraft are calculated based on estimates of annual efficiency improvements, which follow historical trends.

A structured accounting method provides estimates of aircraft status—active, parked, and converted—within regions and defines a priority scheme to determine how aircraft supply is matched to demand. The fleet average efficiency for each body type is calculated as a weighted harmonic mean of efficiencies for the active aircraft stock. The resulting fleet average efficiencies along with the demand for travel provide the projection of commercial passenger and freight carriers' jet fuel consumption to the year 2050.

Regional fleets in this component represent the aircraft that meet domestic and international travel demand attributed to a given region, rather than the aircraft fleet specifically flagged in that region.[19] The model's regional fuel efficiencies are therefore closer to the world average fleet fuel efficiency, implying increasing efficiency homogeneity across the global fleet. This increasing homogeneity is evident in historical fuel efficiency trends and stock turnover. Improvements in aircraft efficiency have slowed since 1990; estimates indicate fuel consumption per ton-mile of new aircraft fell by nearly 3%

[18] CLFs for passenger aircraft belly freight are assumed to be constant, based on the minimum of historical belly freight share of total freight and belly freight share of total payload. The model assumes aircraft carry a constant amount of belly freight per unit of passenger air travel demand.

[19] Foreign carriers often account for a significant portion of a region's international air travel demand. For example, foreign carriers accounted for more than half of U.S. international RPM demand in 2020 [U.S. Department of Transportation, Research and Innovative Technology Administration, Bureau of Transportation Statistics, T-100 Segment (All Carriers), (2019)].

throughout the 1980s, followed by 30 years of average reductions of around 1%.[20] As the pre-1990 aircraft in each region reach 25+ years of service, they are being replaced with either used or new jets whose fuel efficiency varies less.[21]

The air travel submodule estimates only commercial aircraft efficiencies. Efficiencies and fuel use of general aviation aircraft and military planes are not addressed. U.S. military jet fuel use is estimated in another model using projections of military budgets. Non-U.S. military jet fuel demand is not modeled.

The component operates in five stages:

1) align aircraft utilization to latest historical demand and fleet size
2) determine and meet the demand for cargo aircraft
3) determine and meet the demand for passenger aircraft
4) calculate fleet efficiency improvements due to newly acquired aircraft
5) estimate fuel consumption

Aircraft utilization

Before adjusting aircraft supply to meet travel demand, the component ensures that aircraft utilization – available seat-miles per aircraft for passenger and revenue ton-miles per aircraft for dedicated freight – aligns with historical stock and demand in each region. This utilization, which is only calculated in the last year of historical data, is then held constant through 2050.

$$RTMAC_{iwreg,year,iatyp} = \frac{\sum_{di} CARGOAC\_RTM\_DMD_{iwreg,iatyp,di,year}}{\sum_{iage} STKCARGO\_ACTIVE_{iwreg,iatyp,iage,year}} \quad (140)$$

and

$$ASMAC_{iwreg,year,iatyp} = \frac{\sum_{di} ASM_{iwreg,di,iatyp,year}}{\sum_{iage} STKPASS\_ACTIVE_{iwreg,iatyp,iage,year}} \quad (141)$$

where

$STKCARGO\_ACTIVE_{iwreg,iatyp,iage,year}$ = active cargo aircraft stock, by region, body type, and vintage; and

$STKPASS\_ACTIVE_{iwreg,iatyp,iage,year}$ = active passenger aircraft stock, by region, body type, and vintage.

Aircraft stock model

Accurately portraying the age distribution of commercial aircraft is important because of the relatively small size of the world fleet, which in 2022 numbered 28,959.[22] The age distribution informs annual aircraft retirement estimates and, as a result, has a strong influence on the number of new aircraft acquired to meet air travel demand. Due to the international nature of the market for aircraft,

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[20] "Fuel burn of new commercial jet aircraft: 1960 to 2019", Zheng and Rutherford, International Council on Clean Transportation. (2020)

[21] This is particularly evident in Russia, which over the past 10-15 years has replaced many of its older Tupolev aircraft with units that are significantly more efficient.

[22] Jet Inventory Services, *World Jet Inventory: Year-End 2022*, (March 2024).

constructing a survival algorithm using only domestic deliveries and stocks is not feasible because aircraft of different vintages are regularly bought and sold on the international market and the surviving domestic stock of a given vintage may exceed the number of aircraft of that vintage that had originally been delivered domestically. The problem is mitigated by assuming that the scrappage rate of aircraft on a worldwide basis also characterizes that of domestic aircraft. The available aircraft capacity is calculated once the number of surviving aircraft by type is established.

The model first determines the initial stock of both passenger and dedicated cargo aircraft available for each region and body type by applying survival curves to the previous year's stock.

$$STKCARGO\_ACTIVE_{iwreg,iatyp,iage,year} = STKCARGO\_ACTIVE_{iwreg,iatyp,iage-1,year-1} * SURVAC_{iatyp,iage,passfrt}, \quad (142)$$

and

$$STKPASS\_ACTIVE_{iwreg,iatyp,iage,year} = STKPASS\_ACTIVE_{iwreg,iatyp,iage-1,year-1} * SURVAC_{iatyp,iage,passfrt}, \quad (143)$$

where

$STKCARGO\_ACTIVE_{iwreg,iatyp,iage,year}$ = stock of surviving dedicated cargo aircraft by aircraft type, region, and given age;

$STKPASS\_ACTIVE_{iwreg,iatyp,iage,year}$ = stock of surviving passenger aircraft by aircraft type, region, and given age; and

$SURVAC_{iatyp,iage,passfrt}$ = survival rate (1-scrappage rate) of aircraft of a given age, where *passfrt* = {1: Passenger, 2: Cargo}.

Survival curves are not applied to parked aircraft, which are assumed to remain available for re-activation or parts for active aircraft.

The model then calculates the supply deficit to identify how many additional aircraft are needed to meet demand and acquires aircraft until the supply deficit is eliminated. This calculation is implemented for the cargo fleet first, due to the potential for converting passenger aircraft to freighters, and then for the passenger fleet.

Dedicated cargo freighter stock

Cargo aircraft utilization, measured in annual RTMs per aircraft (*RTMAC*), is applied to the dedicated cargo aircraft RTM demand to determine whether the current stock is sufficient to meet demand:

$$CARGOAC\_NEEDED_{iwreg,iatyp} = \frac{\sum_{di} CARGOAC\_RTM\_DMD_{iwreg,iatyp,di,year}}{RTMAC_{iwreg,year,iatyp}} - \sum_{iage} STKCARGO\_ACTIVE_{iwreg,iatyp,iage,year} \quad (144)$$

where

$CARGOAC\_NEEDED_{iwreg,iatyp}$ = aircraft supply deficit needed to meet dedicated cargo RTM demand.

In the case of a negative supply deficit, the model will park aircraft (oldest first) until demand is matched. In all other cases, additional dedicated cargo aircraft are sourced from four options that are offered sequentially:

1) Re-activate parked dedicated cargo aircraft, starting with the newest to optimize fuel efficiency.
2) Convert and re-activate parked passenger aircraft, starting with the oldest and limited to aircraft older than 20 years.
3) Convert older active passenger aircraft, starting with the oldest and limited to aircraft older than 25 years.
4) Purchase new dedicated cargo freighters.

Passenger aircraft stock

Passenger aircraft utilization, measured in annual ASMs per aircraft (*ASMAC*), is applied to the ASM demand (not including belly freight) to determine whether the current stock is sufficient to meet demand:

$$PASSAC\_NEEDED_{iwreg,iatyp} = \frac{\sum_{di} ASM_{iwreg,iatyp,di,year}}{ASMAC_{iwreg,year,iatyp}} - \sum_{iage} STKPASS\_ACTIVE_{iwreg,iatyp,iage,year} \quad (145)$$

where

PASSAC_NEEDED$_{iwreg,iatyp}$ = aircraft supply deficit needed to meet passenger travel demand.

In the case of a negative supply deficit, the model will park aircraft until demand is matched. In all other cases, additional passenger aircraft are sourced from two options that are offered sequentially:

1) Re-activate parked passenger aircraft, starting with the newest to optimize fuel efficiency and limited to aircraft 35 years old and newer. In a given year, a maximum of 10% of parked aircraft can be re-activated [*MAX_UNPARK*].[23]
2) Purchase new passenger aircraft.

The total stock of aircraft ($STK\_SUP\_TOT_{iwreg,iatyp,year}$) is then computed as follows

$$STK\_SUP\_TOT_{iwreg,iatyp,year} = \sum_{iage} STKPASS\_ACTIVE_{iwreg,iatyp,iage,year} + \sum_{iage} STKPASS\_PARKED_{iwreg,iatyp,iage,year} + \sum_{iage} STKCARGO\_ACTIVE_{iwreg,iatyp,iage,year} + \sum_{iage} STKCARGO\_PARKED_{iwreg,iatyp,iage,year}, \quad (146)$$

Fuel efficiency

TAIREFF requires three key inputs to estimate total regional fuel consumption, corresponding to travel demand and characteristics of the aircraft supply to meet that travel demand:

[23] Exceptions are implemented for 2021, 2022, and 2023 – 90%, 70%, and 40% respectively – due to the significant portion of passenger jets parked from reduced demand during the coronavirus pandemic.

1) ASM demand by region and body type
2) Aircraft stock by region, body type, and vintage
3) Aircraft fuel efficiency by region, body type, and vintage in the last available historical year

Input (1) is available from *TAIRT*, and input (2) is available from the *Aircraft Stock Model* that directly precedes the fuel efficiency module. Input (3) exogenous, and is estimated in *gallons per payload ton-mile* (GPTM) to provide multiple degrees of endogenous adjustments throughout the projection period and across different regions, body types, and domestic and international travel. U.S. GPTM estimates are from EIA analysis of U.S. BTS Schedule T2 data[24] and are adjusted to develop non-US regional GPTM based on differences in fleet age distribution, fleet make/model composition, and the average seating density.[25]

Raw GPTM values from U.S. BTS Schedule T2 data are based on actual flights with a wide range of passenger and freight payloads. *TRANAIR* uses load factors that can vary over time, region, aircraft body type, and domestic versus international travel. Adjusting load factors, in addition to affecting the fleet stock capacity requirements as discussed above, also changes aircraft GPTM (equation below). For example, an increase in load factor would increase both numerator, due to a heavier plane, and denominator, due to a higher payload, in equation below.[26]

$$GPTM = \frac{fuel\ consumed}{payload\text{-}mile} \tag{147}$$

Therefore, during pre-processing, GPTM inputs are scaled up to estimate the equivalent of gallons per available seat-mile, that is, a load factor of 100%, to allow for endogenous adjustments to both fuel consumption and payload by region, aircraft body type, and domestic versus international. The percentage increase in fuel consumption is assumed to be linearly related to the percentage increase in aircraft weight. A sample calculation is shown below, for a single aircraft body type.

$$FuelBurn_{full} = FuelBurn_{actual} * \left(1 + \left[\frac{(ASM - RPM)}{RPM}\right] * \frac{WGT\_PASS}{WGT\_AIRCRAFT}\right)$$

Percent increase in total passenger weight

Percent of aircraft weight that is passengers

$$GPTM_{all\ seats\ filled} = \frac{FuelBurn_{full}}{ASM * \frac{pass\_weight}{2000} + RTM_{belly\_freight}} \tag{148}$$

where

WGT_PASS = the total weight of passengers in the raw GPTM calculation; and

---

[24] U.S. Department of Transportation, Research and Innovative Technology Administration, Bureau of Transportation Statistics, T2: U.S. Air Carrier Traffic And Capacity Statistics by Aircraft Type, (2020).

[25] Jet Inventory Services, *World Jet Inventory: Year-End 2020*, (March 2021).

[26] The impact on payload is typically much larger than the impact on fuel consumption, due to the small proportional increase in weight of a single additional passenger and luggage on a large aircraft.

WGT_AIRCRAFT = the average aircraft weight, equal to *maximum takeoff weight* (MTOW) minus half of the maximum fuel capacity weight.

These *fully-loaded* GPTM values—a single value for each body type, separately for domestic and international travel—are estimated for the United States for each year between 1995 and 2022. As discussed above, non-US GPTM values are estimated based on differences in fleet age distribution, fleet make/model composition, and the average seating density and are further calibrated using historical regional jet fuel consumption estimates from our International Energy Statistics.[27]

Estimating the fuel consumption impacts of stock turnover requires a history of new aircraft, or *vintaged*, GPTM in the last historical year, which for AEO2025 is 2022. Vintaged GPTM is developed from the total regional fleet GPTM in 2019 using research estimates of the average annual reduction in fuel consumption per ton-mile for new aircraft.[28] New aircraft GPTM in 2022 is estimated using the average efficiency improvement between 2010 and 2019. This vintaged GPTM is converted to ASMPG using the *pass_weight* factor:

$$ASMPG\_VINT_{iwreg,iatyp,iage,di,2020} = \frac{1}{GPTMX\_PASS\_VINT_{iwreg,iage,iatyp} * \frac{pass\_weight}{2000}} \quad (149)$$

where

GPTMX_PASS_VINT$_{iwreg,iage,iatyp}$ = fully-loaded passenger aircraft fuel consumption per ton-mile, by region, vintage, and body type, in 2022, where *X* = {*D*: domestic, *I*: international}

ASMPG_VINT$_{iwreg,iatyp,iage,di,2020}$ = fully-loaded passenger aircraft ASM per gallon, by region, vintage, body type, and domestic/international, in 2022

The rate of efficiency improvements of new aircraft, represented as a reduction in fuel consumption per ton-mile (*FUEL_BURN_RED*), are assumed to be constant at 0.8% per year based on historical trends (Equation below).[29] In addition, *TAIREFF* assumes new jet engines are installed in aircraft every 10 years, resulting in a 1% improvement in fuel efficiency for each re-engining (equation below).

$$ASMPG\_VINT_{iwreg,iatyp,1,di,year} = \frac{ASMPG\_VINT_{iwreg,iatyp,1,di,2020}}{(1-FUEL\_BURN\_RED)^{year-2020}} \quad (150)$$

and

$$ASMPG\_VINT_{iwreg,iatyp,iage,di,year} = 1.01 * ASMPG\_VINT_{iwreg,iatyp,iage,di,year} \quad (151)$$

[27] U.S. Energy Information Administration, International Energy Statistics. https://www.eia.gov/international/data/world

[28] "Fuel burn of new commercial jet aircraft: 1960 to 2019", Zheng and Rutherford, International Council on Clean Transportation. (2020)

[29] Ibid.

The fuel efficiency module then proceeds with a series of transformations and aggregations to report fuel efficiency and fuel consumption using different metrics across varied dimensions:

1) Aggregate across aircraft age, using a stock-weight harmonic mean

$$ASMPG\_AVG\_AGE_{iwreg,iatyp,di,year} = \frac{STKPASS\_ACTIVE\_TOT_{iwreg,iatyp,year}}{\sum_{iage} \frac{STKPASS\_ACTIVE_{iwreg,iatyp,iage,year}}{ASMPG\_VINT_{iwreg,iatyp,iage,di,year}}} \quad (152)$$

where

$ASMPG\_AVG\_AGE_{iwreg,iatyp,di,year}$ = fully-loaded passenger aircraft ASM per gallon, by region, body type, and domestic/international

2) Calculate GPTM, including above adjustments to account for stock turnover, annual fuel efficiency improvement, and aircraft re-engining ($GPTM_{iwreg,iatyp,di,year}$)

$$GPTM_{iwreg,iatyp,di,year} = \frac{1}{ASMPG\_AVG\_AGE_{iwreg,iatyp,di,year} * \frac{pass\_weight}{2000}} \quad (153)$$

3) Calculate RPMPG, for reporting and for use in final passenger aircraft fuel consumption calculation that includes belly freight

$$TEMP_{iwreg,iatyp,di,year} = \frac{1-(1-LOAD\_FACTOR_{iwreg,di,iatyp,year} * PCT\_PASS\_MTOW_{iatyp,year})}{1-(1-LOAD\_FACTOR_{iwreg,di,iatyp,year} * \left[1-\frac{BELLY\_RPM\_EQ_{iwreg,iatyp,di,year}}{PASSAC\_RPM\_DMD_{iwreg,iatyp,di,year}}\right]} \quad (154)$$

$$TEMP_{iwreg,iatyp,di,year} = \frac{change\ in\ fuel\ consumed}{change\ in\ payload}$$

and

$$RPMPG_{iwreg,iatyp,di,year} = \frac{1}{GPTM\_(iwreg,iatyp,di,year) * \frac{pass\_weight}{2000} * TEMP_{iwreg,iatyp,di,year}} \quad (155)$$

where

$TEMP_{iwreg,iatyp,di,year}$ = factor that accounts for the impact of load factor on GPTM, including both fuel consumption (change in aircraft weight) and payload. Not a variable in *tranair*; only used here for explanatory purposes.

$RPMPG_{wreg,iatyp,di,year}$ = fuel economy of passenger aircraft, including belly freight and adjustments due to stock turnover, annual fuel efficiency improvement, and aircraft re-engining.

4) Calculate global average new and total fleet ASMs per gallon for commercial passenger aircraft, weighted by travel supply (ASMs), for reporting

$$ASMPGT_{NEW,year} = \frac{\sum_{iwreg} \sum_{di} \sum_{iatyp} ASM_{iwreg,di,iatyp,year}}{\sum_{iwreg} \sum_{di} \sum_{iatyp} \frac{ASM_{iwreg,di,iatyp,year}}{ASMPG\_VINT_{iwreg,iatyp,1,di,year}}} \quad (156)$$

and

$$ASMPGT_{STOCK,year} = \frac{\sum_{iwreg}\sum_{di}\sum_{iatyp} ASM_{iwreg,di,iatyp,year}}{\sum_{iwreg}\sum_{di}\sum_{iatyp}\frac{ASM_{iwreg,di,iatyp,year}}{ASMPG\_AVG\_AGE_{iwreg,iatyp,di,year}}} \quad (157)$$

Fuel consumption

The final step in *TRANAIR* is to calculate fuel consumption with the final demand and fuel economy values estimated in the modules discussed above.

$$QJETR\_DI_{iwreg,di,1,year} = \frac{CFJFK}{42} * \sum_{iatyp} \frac{PASSAC\_RPM\_DMD_{iwreg,iatyp,di,year} * AIR\_MGMT\_ADJ_{iwreg,year,di}}{RPMPG_{iwreg,iatyp,di,year}} \quad (158)$$

and

$$QJETR\_DI_{iwreg,di,2,year} = \frac{CFJFK}{42} * \sum_{iatyp}\left[CARGOAC\_RTM\_DMD_{iwreg,iatyp,di,year} * GPTM_{iwreg,iatyp,di,year}\right] \quad (159)$$

where

$QJETR\_DI_{iwreg,di,passfrt,year}$ = annual jet fuel consumption by region, domestic/international, and passenger versus dedicated cargo aircraft, where *passfrt* = {1: passenger, 2: freight}

$AIR\_MGMT\_ADJ_{iwreg,di,year}$ = additional distance flown due to flight routing, procedural separation rules, and weather. See further explanation below.

CFJFK/42 = conversion factor from jet fuel gallons to quads, where CFJFK = 5.67 million btu per barrel.

In the case of passenger aircraft, the calculation also accounts for the additional distance flown due to flight routing, procedural separation rules, and weather using a factor that varies by both region and domestic versus international travel ($AIR\_MGMT\_ADJ_{iwreg,year,di}$).[30] This percentage increase in miles traveled varies, from nearly 21% in domestic China travel to less than 5% for domestic Australia and New Zealand travel.

U.S. values of *AIR_MGMT_ADJ*, and non-U.S. values which are less than or equal to the United States, are assumed to decrease by 0.1% annually through the projection. Non-U.S. values decrease more quickly, and approach the U.S. projection curve as 2050 nears.

The demand for aviation gasoline is calculated as

$$QAGTR_{iregn,year} = QAGTR_{iregn,year=2013} + GAMMA * e^{-KAPPA*(year-1979)}, \quad (160)$$

where

[30] Database of great circle distance and actual distance traveled between airport pairs, International Civil Aviation Organization, 2018.

$QAGTR_{iregn,year}$ = demand for aviation gasoline, in Btu;

GAMMA = baseline adjustment factor; and

KAPPA = exogenously-specified decay constant.

Aviation energy consumption is then divided into four end-uses in the main *TRAN* model, using $QJETR\_DI_{iwreg,di,passfrt,year}$. General aviation jet fuel consumption is assumed to be 4.7% of the total commercial passenger and freight consumption based on historical data.

$$TRQNHWY_{1,year} = QAGTR + 0.047 * \sum_{di} \sum_{passfrt} QJETR\_DI_{1,di,passfrt,year} \quad \text{[General Aviation]} \quad (161)$$

and

$$TRQNHWY_{2,year} = 0.953 * QJETR\_DI_{1,1,1,year} \quad \text{[Domestic passenger]} \quad (162)$$

and

$$TRQNHWY_{3,year} = 0.953 * QJETR\_DI_{1,2,1,year} \quad \text{[International passenger]} \quad (163)$$

and

$$TRQNHWY_{4,year} = 0.953 * \sum_{di} QJETR\_DI_{1,di,2,year} \quad \text{[Total dedicated freighter]} \quad (164)$$

where

$TRQNHWY_{enduse,year}$ = quads of aviation fuel consumption, where *enduse* = {1: general aviation, 2: domestic passenger, 3: international passenger, 4: total dedicated freighter}.

COVID-19 Impact Assumptions and Methodology

The COVID-19 pandemic significantly affected global air travel and fragmented the traditional relationship between gdp/capita and passenger travel demand. NEMS *tranair* addresses this fragmentation by applying a correction factor [*COVID_MULT*] to passenger travel demand between 2023 and 2029. The correction factor varies by region and domestic versus international travel, and is based on the latest available industry data and projections from October 2024 (Table 3).[31]

Table 3. Percentage reduction in RPM demand versus 2019 levels, AEO2025 Reference case

Region	Type	2023	2024	2025	2026	2027	2028
USA	Domestic	1%	0%	0%	0%	0%	0%
CAN	Domestic	1%	0%	0%	0%	0%	0%
MXC	Domestic	0%	0%	0%	0%	0%	0%
EUR	Domestic	1%	0%	0%	0%	0%	0%
JPN	Domestic	1%	0%	0%	0%	0%	0%

[31] International Air Transport Association (IATA), International Civil Aviation Organization (ICAO), Airlines for America (A4A), Boeing

ANZ	Domestic	4%	1%	0%	0%	0%	0%
SKO	Domestic	0%	0%	0%	0%	0%	0%
RUS	Domestic	0%	0%	0%	0%	0%	0%
URA	Domestic	5%	1%	0%	0%	0%	0%
CHI	Domestic	1%	0%	0%	0%	0%	0%
IND	Domestic	1%	0%	0%	0%	0%	0%
OAS	Domestic	14%	1%	0%	0%	0%	0%
MID	Domestic	1%	0%	0%	0%	0%	0%
AFR	Domestic	7%	1%	0%	0%	0%	0%
BRZ	Domestic	0%	0%	0%	0%	0%	0%
CSA	International	1%	0%	0%	0%	0%	0%
USA	International	1%	0%	0%	0%	0%	0%
CAN	International	5%	1%	0%	0%	0%	0%
MXC	International	0%	0%	0%	0%	0%	0%
EUR	International	7%	1%	0%	0%	0%	0%
JPN	International	24%	1%	0%	0%	0%	0%
ANZ	International	23%	5%	1%	0%	0%	0%
SKO	International	24%	5%	1%	0%	0%	0%
RUS	International	75%	59%	37%	18%	7%	1%
URA	International	26%	20%	14%	10%	6%	1%
CHI	International	38%	6%	1%	0%	0%	0%
IND	International	1%	0%	0%	0%	0%	0%
OAS	International	31%	11%	1%	0%	0%	0%
MID	International	1%	0%	0%	0%	0%	0%
AFR	International	5%	1%	0%	0%	0%	0%
BRZ	International	1%	0%	0%	0%	0%	0%
CSA	International	5%	1%	0%	0%	0%	0%

Data source: U.S. Energy Information Administration, *Annual Energy Outlook 2025* Reference case

Freight Transportation Submodule

The Freight Transportation Submodule addresses the three primary modes of freight transport: truck, rail, and marine. This submodule uses NEMS projections of real fuel prices, trade indexes, coal production, and selected industries' output from the Macroeconomic Activity Module to estimate travel demand for each freight mode and the fuel required to meet that demand. The carriers in each of these modes are characterized by long operational lifetimes and the ability to extend these lifetimes through retrofitting. This ability results in a low turnover of capital stock and the resulting dampening of improvement in average energy efficiency. Given the long projection period, however, this submodule provides estimates of modal efficiency growth, driven by assumptions about systemic improvements and the adoption of new technology.

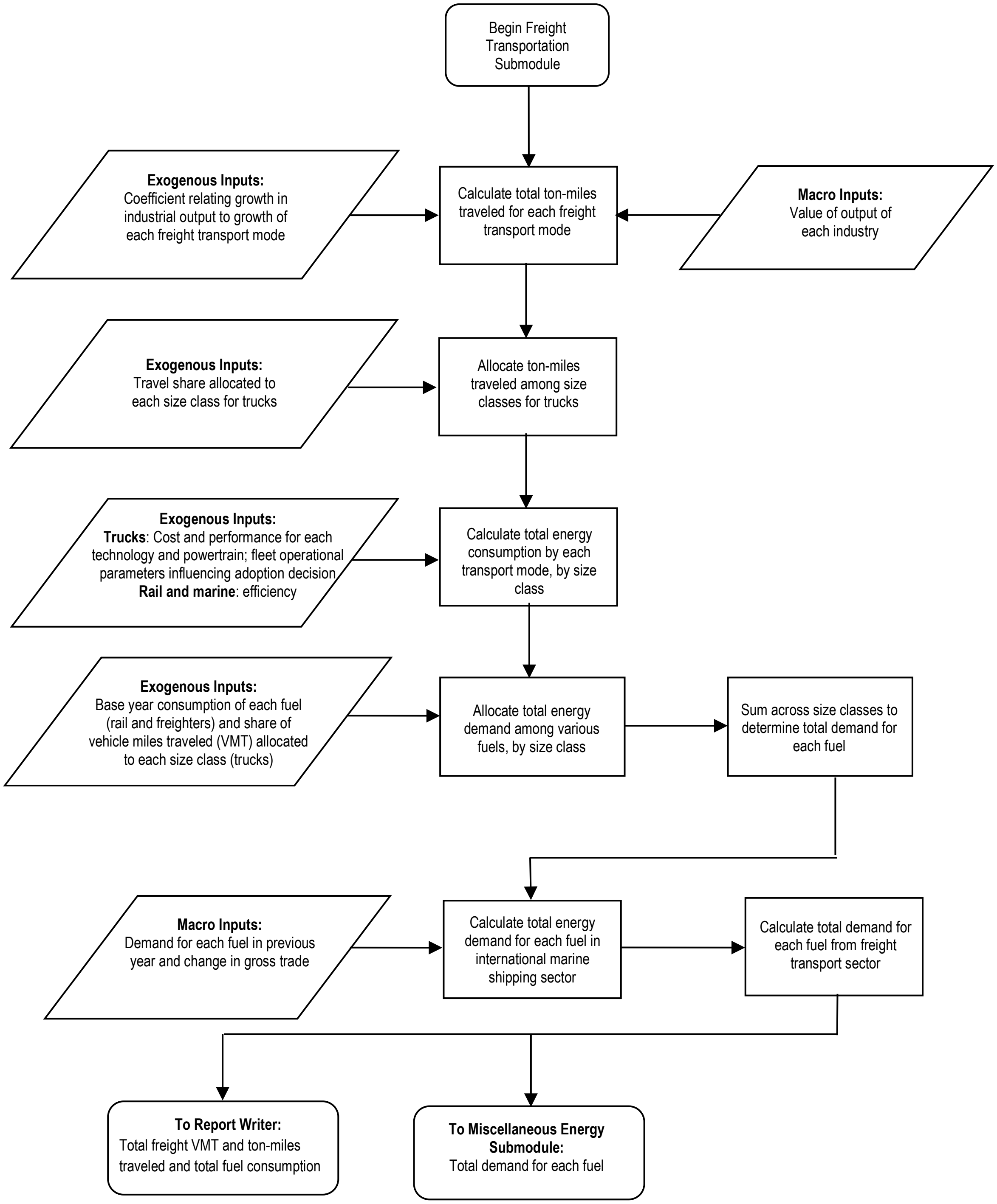
Projections are made for each of the freight modes, and travel projections are based on the industrial output of specific industries and a ton-mile per industrial dollar output measure determined using the U.S. Department of Transportation's Freight Analysis Framework (FAF), based on the U.S. Census Bureau's 2017 Commodity Flow Survey (CFS).[32] For rail, the model also uses NEMS coal projections to account for part of the travel. These values are then converted to energy demand using the average energy intensity for the mode in question. Total energy demand is subsequently shared out to the various types of fuel used for freight transport, taking into consideration the cost effectiveness of alternative fuels when considering fuel prices, travel behavior, and incremental engine and fuel storage costs. Rail and marine are considered in the aggregate with no distinction between classes of carriers.

The truck sector of the Freight Transportation Submodule incorporates additional levels of detail. The trucking sector is divided according to market class with stock adjustments for each market class and fuel type.

The Freight Transportation Submodule aggregates the value of output from various industries into a reduced classification scheme, relating the demand for transport to the growth in the value of output of each industrial category. The relationships used for truck, rail, and waterborne freight are presented in sequence below (Figure 12).

[32] CFS, which is undertaken through a partnership between the U.S. Census Bureau and the Bureau of Transportation Statistics (BTS), is conducted every five years (years ending in *2* and *7*) as part of the Economic Census.

Figure 12. Freight Transportation Submodule of the Transportation Sector Demand Module, National Energy Modeling System



Data source: U.S. Energy Information Administration

Freight Truck Component

The Freight Truck Componenet (FTC) allows us to manipulate a number of important parameters, including the market penetration of existing and future fuel-saving technologies as well as alternative fuel heavy-duty vehicles to meet market demand and fuel efficiency standards. The FTC uses projections of real fuel prices and selected industries' output from the Macroeconomic Activity Module to estimate freight truck travel demand and purchases. Projections of retirements of freight trucks, important truck stock characteristics such as fuel technology market share and fuel economy, and fuel consumption are also estimated.

The FTC projects the consumption of

1. Diesel
2. Motor gasoline
3. LPG
4. CNG
5. Flex-fuel
6. Electricity
7. Hydrogen accounted for by freight trucks

based on projections of adoption and efficiency of the following powertrains (index *ifuel* in the equations that follow):

1. Diesel
2. Gasoline
3. LPG
4. CNG
5. Flex-fuel
6. Battery electric
7. Plug-in hybrid diesel
8. Plug-in hybrid gasoline
9. Hydrogen fuel cell, fuell cell dominant
10. Hydrogen fuel cell, battery dominant
11. Gasoline hybrid
12. Hydrogen internal combustion engine

Throughout each submodule, 34 truck vintages, 19 truck market classes, 14 regulatory market subclasses, 2 fleet types, and 11 annual vmt per vehicle bins are tracked (Table 7). These correspond to the following indices in the code: *iage*, *icafe19*, *icafe14*, *iflt,* and *ivmt*. The results, aggregated for reporting by four truck market classes (index *icafe4* in the code), are defined as follows:

1. Class 2b includes trucks 8,501 to 10,000 GVWR
2. Class 3 includes trucks 10,001 to 14,000 pounds GVWR
3. Classes 4 through 6 include trucks 14,001 to 26,000 pounds
4. Classes 7 and 8 include trucks more than 26,000 pounds[33]

The 14 regulatory market subclasses include one breakout for Classes 2b3 pickups and vans, three breakouts for vocational vehicles—Classes 2b–5, Classes 6–7, and Class 8, nine breakouts for tractors, and one heavy-haul. The 10 subclasses for heavy trucks include parceling the class by Class 7 or Class 8;

[33] Class 2b, 3, 4 to 6, and 7 to 8 trucks are also referred to as commercial light-, light medium-, medium heavy-, and heavy trucks, respectively.

day cab or sleeper cab; and low-, mid- or high-roof. This section presents and describes the methodology used by the component to project characteristics of each class (Table 4).

Four main steps are executed for each projection year of the model run to produce estimates of fuel consumption. First, fuel economies of the incoming class of new trucks are estimated, allowing for market penetration of existing and new fuel-saving technologies to comply with minimum fuel efficiency requirements or consumer-driven demand. Relative fuel economies are used in this routine to determine the market share of each fuel technology in the current year's truck purchases. The second routine determines the composition of the existing truck population, using the characteristics of the current year's class of new trucks along with exogenously estimated vehicle scrappage and fleet transfer rates. New truck sales data from the Macroeconomic Activity Module are used to determine new truck purchases in the fourth routine. In the third routine, VMT demand is allocated among truck types and divided by fuel economy to determine fuel consumption. Finally, the truck stocks are rolled over into the next vintage, and the component is prepared for the next projection year.

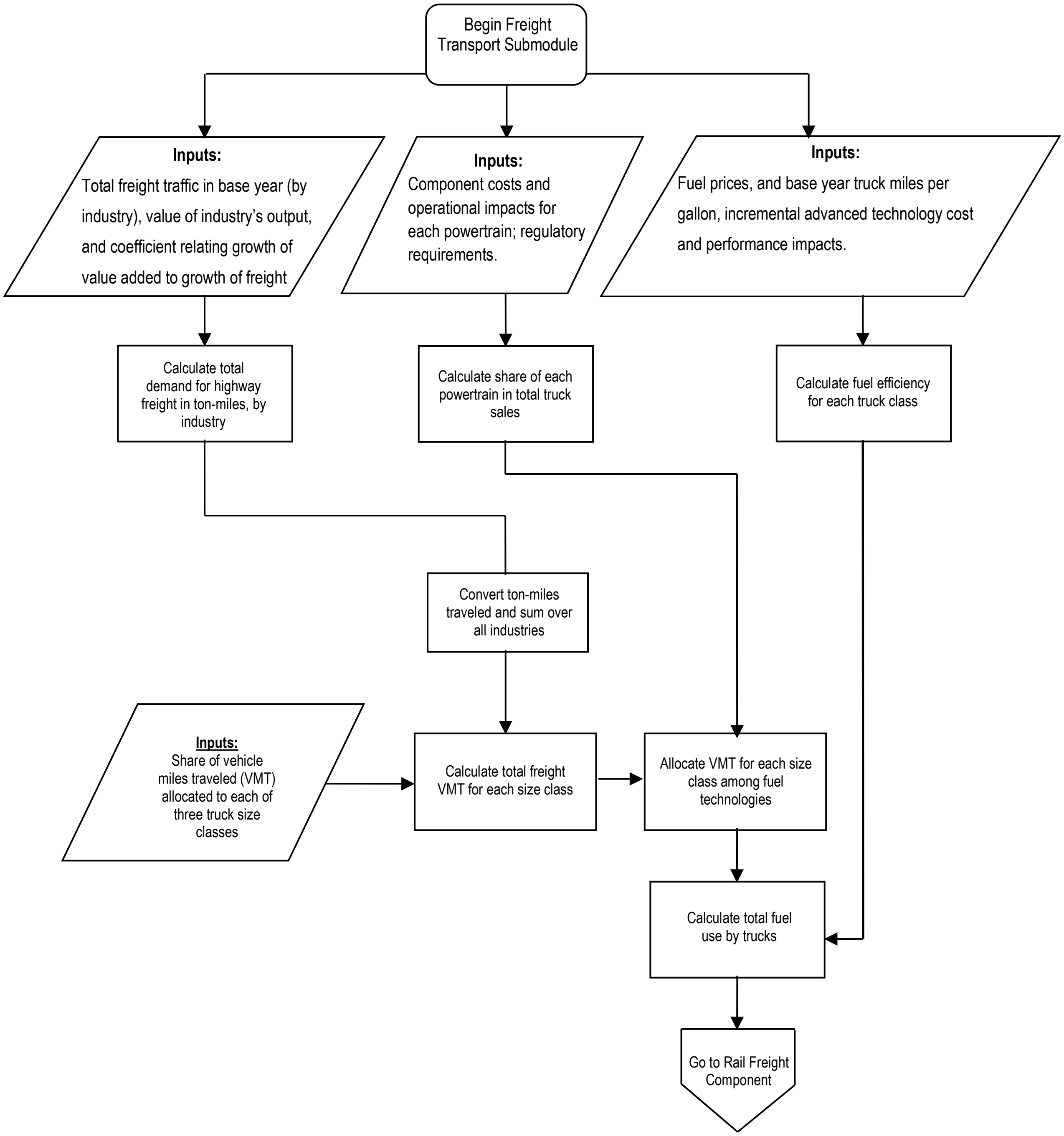
Table 4. Freight truck vehicle fuel-efficiency market subclass categories for the Transportation Demand Module, NEMS

Vehicle category	Reporting size class	FHWA GVWR class	Macroeconomic module market segments	Historical registration data segments	Regulatory market segments	Roof[1]
1	2b	2b	2	2b	2b–3 pickup and van	-
2	2b	2b	2	2b vocational	2b–5 vocational	-
3	3	3	3	3	2b–3 pickup and van	-
4	3	3	3	3 vocational	2b–5 vocational	-
5	4–6	4	4-8	4 vocational	2b–5 vocational	-
6	4–6	5	4-8	5 vocational	2b–5 vocational	-
7	4–6	6	4-8	6 vocational	6–7 vocational	-
8	7–8	7	4-8	7 vocational	6–7 vocational	-
9	7–8	7	4-8	7 tractor	Tractor—day cab	Low
10	7–8	7	4-8	7 tractor	Tractor—day cab	Mid
11	7–8	7	4-8	7 tractor	Tractor—day cab	High
12	7–8	8	4-8	8 vocational	8 vocational	-
13	7–8	8	4-8	8 tractor	Tractor—day cab	Low
14	7–8	8	4-8	8 tractor	Tractor—day cab	Mid
15	7–8	8	4-8	8 tractor	Tractor—day cab	High
16	7–8	8	4-8	8 tractor	Tractor—sleeper cab	Low
17	7–8	8	4-8	8 tractor	Tractor—sleeper cab	Mid
18	7–8	8	4-8	8 tractor	Tractor—sleeper cab	High
19	7–8	8	4-8	8 heavy-haul	Heavy-haul	-

Data source: U.S. Energy Information Administration

[1]Applies to Class 7 and Class 8 day and sleeper cabs only.

Figure 13. Freight Truck Component of the Transportation Sector Demand Module, NEMS



Data source: U.S. Energy Information Administration

Freight Truck Sales Component (subroutine TRUCK_NEW)

The first step in the FTC is to estimate sales and fuel economies for the current year new truck fleet. This is accomplished in the Freight Truck Sales Component (FTSC), summarized in Figure 14. The FTSC estimates adoption of fuel-efficient technologies within each powertrain as well as the change in adoption of each powertrain within each size class, resulting in aggregate sales and fuel economies for use in calculating stocks and consumption later in the FTC. It also enforces relevant federal and state regulations, such as fuel economy and tailpipe GHG standards and zero-emission vehicle mandates.

The first step is to segment aggregate truck sales by size class and fleet type, which enables us to account for key operational differences among diverse truck duty cycles and applications. This segmentation is based on the following inputs exogenous to TDM:

1. projected truck sales from the Macroeconomic Activity Module (*MC_Vehicles* and *MC_SUVTHAM*),
2. historical truck sales from S&P/Polk registration data (*trnstockx.xlsx*, populating history in variable *TRKSTK_19R*),
3. historical share of Class 1-2 light truck sales that were Class 2b (*LTSPLIT*, *trnldvx.xlsx*), and
4. historical share of new sales that are fleet versus non-fleet, derived from S&P/Polk registration data (*FLTSHR_SALES*, *trnhdvx.xlsx*).

These values are combined to estimate total truck sales (*NEWTRUCKS_regn*) by NEMS size class (*icafe19*) and fleet versus non-fleet (*iflt*) as shown below

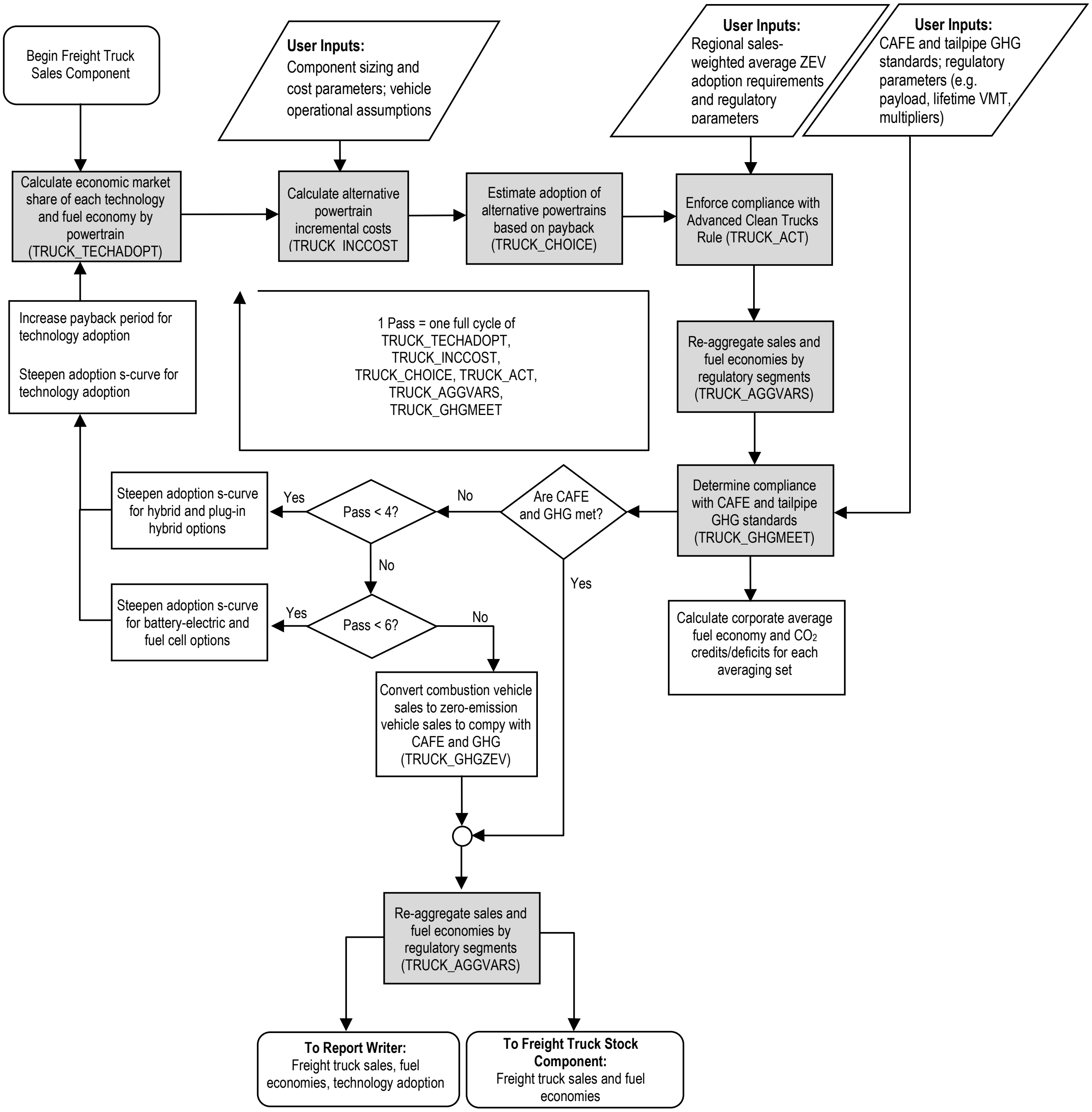
$$NEWTRUCKS\_regn_{year,icafe19=\{1:2\},iflt=flt,iregn} = \left(1 - LTSplit_{year}\right) * \sum_{i=1}^{2} MC\_Vehicles_{i,year} * \frac{\sum_{ifuel}\sum_{iflt} TRKSTK\_19R_{year-1,icafe19,iage=1,ifuel,iflt,iregn}}{\sum_{ifuel}\sum_{iflt}\sum_{icafe19=1}^{2} TRKSTK\_19R_{year-1,icafe19,iage=1,ifuel,iflt,iregn}} * FLTSHR\_SALES_{year,icafe19}$$

$$NEWTRUCKS\_regn_{year,icafe19=\{3:4\},iflt=flt,iregn} = MC\_Vehicles_{3,year} * \frac{\sum_{ifuel}\sum_{iflt} TRKSTK\_19R_{year-1,icafe19,iage=1,ifuel,iflt,iregn}}{\sum_{ifuel}\sum_{iflt}\sum_{icafe19=3}^{4} TRKSTK\_19R_{year-1,icafe19,iage=1,ifuel,iflt,iregn}} * FLTSHR\_SALES_{year,icafe19}$$

$$NEWTRUCKS\_regn_{year,icafe19=\{5:19\},iflt=flt,iregn} = MC\_SUVTHAM_{year} * \frac{\sum_{ifuel}\sum_{iflt} TRKSTK\_19R_{year-1,icafe19,iage=1,ifuel,iflt,iregn}}{\sum_{ifuel}\sum_{iflt}\sum_{icafe19=}^{19} TRKSTK\_19R_{year-1,icafe19,iage=1,ifuel,iflt,iregn}} * FLTSHR\_SALES_{year,icafe19}$$

(165)

Figure 14. Freight Truck Sales Component of the Transportation Sector Demand Module, NEMS



Data source: U.S. Energy Information Administration

Determining adoption of fuel-saving technologies and alternative fuel powertrains requires fuel price estimates. Fuel prices are read in from other NEMS modules, and an average over the current and past 4 years is calculated for use in the next sections of the FTSC.

$$FUELPRICE\_R\_AVG_{ifuel,iregn} = \frac{\sum_{year-4}^{year} FUELPRICE\_R_{iyr,ifuel,iregn}}{5} \quad (166)$$

The next step in the FTSAC is to determine the characteristics of the slate of powertrain options offered in the powertrain choice model (subroutine *TRUCK_CHOICE*). Adoption of technology improvements within each powertrain type and the corresponding impacts on fuel economy and purchase price are estimated endogenously in subroutine *TRUCK_TECHADOPT*. Incremental cost and performance of alternative powertrains, compared to a baseline conventional internal combustion engine vehicle, are estimated endogenously in subroutine *TRUCK_INCCOST*.

Technology adoption (subroutine *TRUCK_TECHADOPT*)

Future technologies are adapted from the currently enforced EPA and NHTSA Final Rulemakings to establish greenhouse gas emissions standards and fuel efficiency standards for medium- and heavy-duty engines and vehicles. Phase 2 of the regulation applies to Model Years 2021-2026, and Phase 3 (EPA only) applies to Model Years 2027-2032.[34,35] Non-vocational commercial light trucks (Class 2b pickups and vans) are covered by NHTSA's latest CAFE standards for heavy-duty pickups and vans.[36] The Phase 3 regulation does not account for any further improvements in conventional diesel powertrain efficiency NEMS TDM continues to offer the same Phase 2 technology menu for the remainder of the projection.

Technologies include advanced transmissions, lightweight materials, synthetic gear lube, advanced drag reduction, advanced tires, electronic engine controls, turbo-compounding, hybrid powertrains, and direct-injection. Future technologies can enter the market throughout the component run, depending on the year in which they become commercially available and on the level of fuel prices relative to a calculated cost-effective fuel price (based on capital costs) at which the technology becomes economically viable. Because prices vary by fuel type, the market shares of fuel-saving technologies are specified separately by powertrain.

The first step in the component is to calculate the fuel trigger price at which the technology (identified by index *itechp2*) becomes economically viable (*TRIGGERPRICE_p2*). This is calculated based on the cost of the technology in question, *TECHCOST*, and the annual energy saved by that technology over the full payback period:

$$TRIGGERPRICE\_p2_{itechp2,icafe19,ifuel} =$$

[34] U.S. Environmental Protection Agency and National Highway Traffic Safety Administration, "Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles-Phase 2; Final Rule," *Federal Register*, Vol. 81, No. 206 (October 25, 2016).

[35] U.S. Environmental Protection Agency and National Highway Traffic Safety Administration, "Final Rule: Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles – Phase 3," *Federal Register*, Vol. 89, No. 78 (April 22, 2024).

[36] National Highway Traffic Safety Administration, "Corporate Average Fuel Economy Standards for Passenger Cars and Light Trucks for Model Years 2027 and Beyond and Fuel Efficiency Standards for Heavy-Duty Pickup Trucks and Vans for Model Years 2030 and Beyond," *Federal Register*, Vol. 89, No. 121 (June 24, 2024).

$$\frac{TECHCOST_{itechp2,icafe19}}{\sum_{IP=1}^{PAYBACK_{icafe19,itechp2}}\left\{\frac{TEMP\_BTU\_pX_{icafe14,ifuel}*\left(\frac{ANNVMT\_19_{icafe19,ip,ifuel}}{ANNVMT\_19_{icafe19,1,ifuel}}\right)*TECHEFF\_pX_{itechp2,icafe14}}{(1+DISCRTXG)^{ip}}\right\}},$$

(167)

where

PAYBACK$_{icafe,itech}$ = payback period for a given technology and market class, in years, and is incrementally adjusted upward if the size class segment is out of compliance with CAFE or tailpipe GHG standards;

TECHCOST$_{itech,isc19}$ = incremental cost of a technology;

TEMP_BTU_pX$_{isc19,ifuel}$ = average annual truck fuel usage;

ANNVMT_19$_{icafe19,ip,ifuel}$ = average annual VMT traveled per truck;

TECHEFF_pX$_{itech,icafe19,ifuel}$ = incremental fuel economy improvement;

DISCRTXG = discount rate;

ip = index for payback periods.

Whether a future technology enters the market during a particular year depends on the cost-effective price of that technology relative to the average price of each fuel over the past five years (*FUELPRICE_R_AVG*).

Technology market penetration depends on the level of fuel prices relative to the technology's cost-effective price. For each technology that has entered the market, and for existing technologies, the effect of fuel prices on market penetration is determined for the current year by the equation

$$PREFF\_p2_{itechp2,icafe19,ifuel} = 1 + TECHVAR_{itechp2,icafe14} * \left(\frac{FUELPRICE\_R\_AVG_{ifuel,mnumcr}}{TRIGGERPRICE\_p2_{itechp2,icafe19,ifuel}} - 1\right),$$

(168)

where

PREFF_p2$_{itech,icafe19,ifuel}$ = effect of fuel price on market penetration rates for each freight technology; and

TECHVAR$_{itech,icafe14}$ = exogenously determined fuel price sensitivity parameter for each freight technology, representing the percentage increase in technology market share if fuel price exceeds cost-effective price by 100%. Currently set to 0.5 for all technologies.

For each available technology, including existing technologies, by regulatory market class and powertrain, the submodule determines the share of the available market in the current year.

For each regulatory market class, technology, and powertrain, the market penetration over time is estimated using an S-shaped logistical equation defined as follows

$$P_{year} = MIN(TECHSHR\_p2_{year-1,itechp2,icafe19,ifuel}, TECHBASE\_P2_{itechp2,icafe19,ifuel}) + (TECHMAX_{(itechp2,icafe14)} - TECHBASE\_p2_{itechp2,icafe19,ifuel}) * \left(\frac{1}{1+e^{-\frac{TECHPENYR\_p2_{year,itechp2,icafe19,ifuel}-TECHMID\_P2\_adj_{itechp2,icafe14}}{TECHSHAPE_{itechp2,icafe14}}}}\right) \quad (169)$$

where

P_{year} = market penetration by year;

$TECHSHR\_p2_{year,itechp2,icafe19,ifuel}$ = market share of fuel-saving technology, by market size class and fuel type;

$TECHBASE\_p2_{itechp2,icafe19,ifuel}$ = base year market penetration parameter;

$TECHMAX_{itechp2,icafe14}$ = maximum market penetration parameter;

$TECHMID\_P2\_adj_{itechp2,icafe14}$ = parameter for existing technologies;

$TECHPENYR\_p2_{year,itechp2,icafe19,ifuel}$ = counter to iterate up the s-curve each year; and

$TECHSHAPE_{itechp2,icafe14}$ = market penetration curve for existing technologies.

If the technology is an emission control technology or if the fuel price has reached the trigger price, then the technology share is as estimated by the following

$$TECHSHR\_p2_{year,itechp2,icafe19,ifuel} = PREFF\_p2_{itechp2,icafe19,ifuel} * P_{year} \quad (170)$$

However, if the technology is a fuel-efficiency technology and the fuel price has not reached the trigger price but the previous year’s technology market share is non-zero, then the current year’s market share is assumed to grow at the same rate as the market penetration price sensitivity multiplier

$$TECHSHR\_p2_{year,itechp2,icafe19,ifuel} = TECHSHR\_p2_{year-1,itechp2,icafe19,ifuel} * PREFF\_p2_{itechp2,icafe19,ifuel}. \quad (171)$$

If technology A is superseded by another mutually exclusive technology B, technology A’s market share must be adjusted to reflect the smaller pool of vehicles in the base market

$$TECHSHR\_P2_{year,A,icafe19,ifuel} = TECHSHR\_P2_{year,A,icafe19,ifuel} - TECHSHR\_ADJ\ , \quad (172)$$

where

TECHSHR_ADJ = superseding effect, where the share of “child” technologies are adjusted until the maximum share of combined “child” and “parent” technologies is not exceeded.

Once the market shares in a given year are established, the effects of the technologies on the base fuel cost are tallied and combined to form a vector of *mpg effects*, which is used to augment the base fuel economy of new trucks of each market class and fuel type. The mpg effects are computed as follows

$$MPGEFF\_19_{ifuel,icafe19} = \prod_{itech=1}^{Techp2}(1 - TECHEFF\_p2_{itechp2,icafe19,ifuel} * TECHADJSHR\_p2_{year,itechp2,icafe19,ifuel}), \quad (173)$$

where

$MPGEFF\_19_{ifuel,icafe19}$ = total effect of all fuel-saving technologies on new truck fuel economy in a given year, market class, and size class;

Techp2 = the number of technologies; and

$TECHADJSHR\_p2_{year,itech,icafe19,ifuel}$ = difference between the current tech share and the base tech share.

Fuel economy of new vintage, AGE = 1, freight trucks by market class (*NEW_MPG_19*) can finally be determined from the above calculated improvement and the base vehicle fuel economies (*BASE_MPG_P2*)

$$NEW\_MPG\_19_{year,ifuel,icafe19} = \frac{BASE\_MPG\_p2_{ifuel,icafe19}}{MPGEFF\_p2_{ifuel,icafe19}}, \quad (174)$$

Determine the share of each fuel type in current year's class of new trucks

Another major characteristic of each projection year's class of new trucks is the market share of each powertrain type. Market share for freight trucks is divided among twelve powertrain types:

1. Diesel
2. Gasoline
3. LPG
4. CNG
5. Flex-fuel
6. Battery electric
7. Plug-in hybrid diesel
8. Plug-in hybrid gasoline
9. Hydrogen fuel cell, fuell cell dominant
10. Hydrogen fuel cell, battery dominant
11. Gasoline hybrid
12. Hydrogen internal combustion engine

Market penetration of alternative fuel freight trucks can be driven by legislative or regulatory action as well as by economic cost or benefit consideration. The powertrain choice routine described below is intended to simulate economic competition among fuel types after the creation of a market for alternative fuel trucks by government action.

Powertrain incremental costs (subroutine *TRUCK_INCCOST*)

The first step is to estimate the incremental costs of each powertrain. This requires estimating both the change in cost of the base conventional powertrains as well as the change in cost of the advanced powertrains.

Several components are sized and/or costed separately, including:

1. Propulsion batteries
2. Electric motors and power electronics

3. Hydrogen storage tanks
4. Fuel cell stacks
5. On-board charger

The remaining differences in powertrain, drivetrain, and fuel storage costs are estimated from various literature sources in the last historical year, and are read in and adjusted for each of the 19 regulatory classes (variable *cost_ICE* in *trnhdvx.xlsx*). The baseline vehicle for each of the regulatory classes varies: for Classes 2b through 6, the baseline for all non-hybrid alternative powertrains is a composite gasoline/gasoline-hybrid/diesel vehicle based on sales-weighted average costs of those powertrains. For Classes 7 and 8, the baseline is a diesel vehicle.

The first step is to calculate the cost of ICE technology adopted in subroutine *TRUCK_TECHADOPT* (*cost_icetech*) using the individual cost totals from that subroutine (*inc_tech_cost_19*), to adjust costs for each powertrain. For Classes 2b-6, this calculation is sales-weighted using previous year sales (*TRKSTK_19R*) to develop the composite base vehicle:

$$cost\_icetech_{icafe19,year} = \frac{\sum_{ifuel=1}^{2} inc\_tech\_cost\_19_{year,icafe19,ifuel} * TRKSTK\_19R_{year-1,icafe19,ifuel,mnumcr}}{\sum_{ifuel=1}^{2} TRKSTK\_19R_{year-1,icafe19,ifuel,mnumcr}} \quad (175)$$

For Classes 7 and 8, *cost_icetech* is simply equal to *inc_tech_cost_19*. These costs are then adjusted to be incremental to the last historical year (*bsyr*), as follows:

$$cost\_ICE_{icafe19,year} = cost\_ICE_{icafe19,bsyr} + (cost\_icetech_{icafe19,year} - cost\_icetech_{icafe19,bsyr}) \quad (176)$$

Each of the alternative ICE powertrains which start with exogenous incremental costs – gasoline hybrid, gasoline PHEV, diesel PHEV, and hydrogen ICE – are then adjusted to account for their own adoption of incremental technology improvements from subroutine *TRUCK_TECHADOPT*.

$$cost\_ICE\_XX_{icafe19,year} = cost\_ICE\_XX_{icafe19,bsyr} + (inc\_tech\_cost\_19_{year,icafe19,YY} - inc\_tech\_cost\_19_{year,icafe19,YY}) \quad (177)$$

where

$cost\_ICE\_XX_{icafe19,year}$ = incremental cost of ICE-related components for powertrain XX, where XX = gasoline hybrid, gasoline PHEV, diesel PHEV, or hydrogen ICE

YY = corresponding ICE against which the exogenous incremental costs were based: *gasoline* for gasoline hybrid and PHEV and *diesel* for diesel PHEV and hydrogen ICE

The module then estimates the cost to comply with EPA's Low NOx regulation in MY2027 and forward (*lonox_cost*) based on EPA's estimates of compliance costs (*cost_lonox*) and for Classes 2b-6, weighted by sales to develop a composite gasoline/diesel cost.[37] The compliance cost for Classes 7 and 8 are simply the compliance costs for diesel powertrains.

$$lonox\_cost_{icafe19,year} = \frac{\sum_{ifuel=1}^{2} cost\_lonox_{icafe19,ifuel} * TRKSTK\_19R_{year-1,icafe19,ifuel,mnumcr}}{\sum_{ifuel=1}^{2} TRKSTK\_19R_{year-1,icafe19,ifuel,mnumcr}} \quad (178)$$

The next stage of the incremental cost subroutine steps through each of the advanced powertrains, building up total incremental costs based on both the detailed endogenous component cost estimates (battery, electric motor, hydrogen tank, fuel cell stack, on-board charger) as well as the technology costs for the other components estimated above (*cost_icetech*, *cost_ice_xx*, and *lonox_cost*).

All Class 8 truck incremental costs except for the infrastructure installation cost (*BEV_infra_cost*), are adjusted to account for the 12% Federal Excise Tax.[38]

On-board storage

In most cases, diesel and gasoline vehicles are able to store enough fuel on-board to meet daily driving demand without the need to refuel; in other words, to complete the vehicle duty cycle, these vehicles are assumed to need refueling at most once per day.

Alternative fuel powertrain vehicles, which rely on compressed natural gas (CNG), hydrogen, and/or electricity for propulsion, require significantly more storage volume on-board the vehicle due to the lower fuel energy density compared to diesel or gasoline. On-board storage requirements are estimated for each of these powertrains based on the average daily range required to meet the duty cycle, fuel economy, and maximum available volume for storage tanks and/or batteries on-board the vehicle. Starting points for these storage requirements – measured in DGE-equivalent for CNG, kg of hydrogen for fuel cell and hydrogen ICE, and nominal kWh for battery electric – are estimated exogenously for the last historical year (2023 for AEO2025) based on EIA analysis of available data sources. These requirements are estimated for each of the 19 regulatory classes, across 11 annual VMT bins.

On-board storage must enable the vehicle to meet its daily VMT demand requirement. If the vehicle does not have sufficient space on-board to carry the fuel needed to achieve its daily VMT, it is equipped with the maximum storage capacity and is penalized with additional costs due to extra refuelings during the day. Additionally, the model requires a minimum amount of on-board storage; BEVs must achieve a minimum of 100 miles of range, hydrogen and CNG ICEs must achieve 250 miles of range, and fuel cells must have at least one full hydrogen tank installed (6kg tanks for Classes 2b-5, 12kg tanks for Classes 6-8).

On-board storage requirements change throughout the projection as fuel economy improves (less storage required). For battery electric trucks, projected improvements in energy density increase the maximum possible pack capacity that can fit on-board the vehicle, thereby reducing the loss of productivity and additional labor costs resulting from additional stops to recharge.

[37] U.S. Environmental Protection Agency, “Control of Air Pollution From New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards” *Federal Register*, Vol. 88, No. 15 (January 24, 2023). Tables V-2 and V-3.
[38] 26 U.S. Code § 4051 - Imposition of tax on heavy trucks and trailers sold at retail.

Compressed natural gas (CNG) trucks, in addition to the net cost savings versus diesel due to removal of complex aftertreatment systems (*cost_ice_CNG*), require the addition of a CNG storage tank (*cost_NGtank_DGE, PT_tanksize_CNG*) and additional technology adopted in *TRUCK_TECHADOPT* (*inc_tech_cost_19*).

$$
\begin{aligned}
INC\_COST\_CNG_{ivmt,icafe19,year} &= cost\_NGtank\_DGE_{isc4,year} * PT\_tanksize\_CNG_{ivmt,icafe19} \\
&+ \left(inc\_tech\_cost\_19_{year,icafe19,cng} - inc\_tech\_cost\_19_{baseyr,icafe19,cng}\right) \\
&- cost\_ice\_CNG_{icafe19} - cost\_icetech_{icafe19,year}
\end{aligned} \tag{179}
$$

Battery electric trucks do not require any of the internal combustion engine components, but require the addition of a battery pack, electric motor, power electronics, on-board charger, and infrastructure (for return-to-base fleet vehicles). The first step is to estimate battery prices for the current year (*cost_battkWh_trki)*, based on the cumulative production across the whole transportation sector (*cumulative_gwh*) and battery learning rate parameters (*cost_battpack_a, cost_battpack_b, cost_battmat_a, cost_battmat_b*). The battery cost equation is similar to that used in the Light Duty Component of the NEMS TDM, with the same learning rate (16.5% in AEO2025) but different starting prices depending on the vehicle type (represented by index *ibatt*).

$$
\begin{aligned}
cost\_battkWh\_trk_{ibatt,year} &= cost\_battpack\_a_{ibatt} * cumulative\_gwh_{year-1}{}^{-cost\_battpack\_b_{ibatt}} \\
&+ cost\_battmat\_a_{ibatt} * cumulative\_gwh_{year-1}{}^{-cost\_battmat\_b_{ibatt}}
\end{aligned} \tag{180}
$$

The module then estimates electric motor costs, in dollars per kW based on exogenously defined cost reductions of 3% per year between 2026-2030, 2% per year between 2031-2035, and 1% per year after 2035. Calculations on battery size requirements then proceed as follows:

1. Estimate the kWh capacity needed on board to meet the daily VMT (annual VMT, *VMT_VEH*, divided by the number of working days, 250), using the fuel economy calculated in the previous year (*new_mpg_19*). The final battery capacity must be able to meet 100 miles of range, or the daily VMT, whichever is larger.

$$
kWh\_needed_{ivmt,icafe19,year} = \frac{VMT\_VEH_{ivmt,icafe19}}{250} \Big/ new\_mpg\_19_{year-1,BEV,icafe19} \tag{181}
$$

2. Nominal battery capacity (*kWh_nominal*) is estimated using the exogenously-specified maximum depth-of-discharge (*TRK_BEV_DOD*), which accounts for extra capacity (on top of the usable kWh) required to complete the vehicle duty cycle for the expected ownership period, to ensure sufficient resale value and to ensure safety. At this point, the model also ensures that the maximum installable battery capacity (*max_kWh_cap,* based on volume available on-board the vehicle) is not exceeded.

$$
\begin{aligned}
&kWh\_nominal_{ivmt,icafe19,year} = \\
&MIN\left(max\_kWh\_cap_{icafe19,year}, \frac{kWh\_needed_{ivmt,icafe19,year}}{TRK\_BEV\_DOD}\right)
\end{aligned} \tag{182}
$$

3. Finally, the usable capacity (*kWh_usable*) is calculated

$$kWh\_usable_{ivmt,icafe19,year} = kWh\_nominal_{ivmt,icafe19,year} * TRK\_BEV\_DOD \quad (183)$$

With all of the individual cost components estimated, we build up the total incremental cost for a BEV (*INC_COST_BEV*). This includes the electric motor (using exogenous sizing, *PT_emotorkW*), battery, incremental technology adoption versus the base year, charging station installation cost (exogenous, *BEV_infra_cost*), and on-board charger cost (exogenous, *cost_OBC*). The equivalent-ICE costs – *cost_ICE* and *lonox_cost* – are subtracted off.

$$\begin{aligned} INC\_COST\_BEV_{ivmt,icafe19,year} &= PT\_emotorkW_{icafe19,BEV} * cost\_motorkW_{year} + cost\_battkWh\_trk_{ibatt,year} \\ &* kWh\_nominal_{ivmt,icafe19,year} \\ &+ \left(inc\_tech\_cost\_19_{year,icafe19,BEV} - inc\_tech\_cost\_19_{baseyr,icafe19,BEV}\right) \\ &+ BEV\_infra\_cost_{icafe19,year} + cost\_OBC_{year} - cost\_ICE_{icafe19,year} \\ &- lonox\_cost_{icafe19,year} \end{aligned} \quad (184)$$

A large portion of freight trucks are operated relatively few miles in a given year, particularly in the lighter weight classes. For those vehicles which are used for significantly more miles each year, there is not enough volume available on board the vehicle to install a battery sufficiently sized to cover the daily range without stopping to charge. This extra stop results in additional labor costs, which are accounted for in *TRUCK_INCCOST* using an estimated value of time (*refuel_timeval*, 75 2022USD/hour in AEO2025) and estimated time to recharge (*daily_hours*). To estimate *daily_hours*, we calculate the capacity shortfall and divide it by the charging speed (*charging_speed*).

$$daily\_hours_{ivmt,icafe19,year} = MAX(0.0, \frac{kWh\_used_{ivmt,icafe19,year} - kWh\_usable_{ivmt,icafe19,year}}{charging\_speed_{icafe19}}) \quad (185)$$

The additional cost per year of operation (*bev_refuelopcost*) is then calculated for use in the payback calculations in subroutine *TRUCK_PBK*.

$$bev\_refuelopcost_{ivmt,icafe19,year} = daily\_hours_{ivmt,icafe19,year} * refuel\_timeval * 250 \quad (186)$$

Plug-in hybrid electric vehicles – both gasoline and diesel – require the addition of a battery pack, electric motor, power electronics, and on-board charger and often use a different engine and transmission compared to an equivalent vehicle that only relies on an ICE for propulsion. Battery sizing depends on the relationship between electric range (*PHEV_daily_Evmt*) and installed battery capacity from the vehicles simulated by EPA in support of the Phase 3 rulemaking. Electric range is estimated via an exogenous-defined utility factor (*PHEVElecVMT*). EIA adjusted the EPA battery capacities to account for a continuous linear degradation curve, and then estimated regression coefficients by broader size class to calculate battery capacities endogenously (coefficients *battsize_a_PHEV* and *battsize_b_PHEV*).[39]

---

[39] Truck purchasers are expected to account for battery degradation in their vehicle specification by requiring additional capacity so they are able to meet the duty cycle throughout the expected ownership period. EPA's version of the HDTRUCS tool (in support of the Phase 3 regulation) accounts for this behavior, but only if the battery pack will be used 2,000 cycles or more

$$PHEV\_daily\_Evmt = \frac{VMT\_VEH_{ivmt,icafe19}}{250} * PHEVElecVMT_{icafe19} \tag{187}$$

$$PT\_battkWh\_PHEV_{ivmt,icafe19} = battsize\_a\_PHEV_{icafe19} * PHEV\_daily\_Evmt^{battsize\_b\_PHEV_{icafe19}} \tag{188}$$

The final incremental costs (*INC_COST_PHEVX*) are estimated as follows, where the *X* represents either gasoline (“G”) or diesel (“D”). The final cost estimate includes the electric motor, battery, technology adoption from *TRUCK_TECHADOPT*, on-board charger, and incremental engine and transmission cost (*cost_ICE_PHEV*).

$$\begin{aligned} INC\_COST\_PHEVX_{ivmt,icafe19,year} &= PT\_emotorkW_{icafe19,phevX} * cost\_motorkW_{year} + cost\_battkWh\_trk_{ibatt=2,year} \\ &* PT\_battkWh\_PHEV_{ivmt,icafe19} \\ &+ \left(inc\_tech\_cost\_19_{year,icafe19,phevX} - inc\_tech\_cost\_19_{baseyr,icafe19,phevX}\right) \\ &+ cost\_OBC_{year} - cost\_ICE\_PHEV_{icafe19,phevX,year} \end{aligned} \tag{189}$$

Gasoline hybrid electric trucks require the addition of an electric motor and small battery pack, but often have cost savings due to engine downsizing and in many cases the removal of a conventional transmission. The incremental cost, *INC_COST_HEV*, is calculated as follows. Note that it does not vary by annual VMT bin, since none of the hybrid-specific components typically require significant re-sizing for different vehicle ranges.

$$\begin{aligned} INC\_COST\_HEV_{icafe19,year} &= PT\_emotorkW_{icafe19,HEV} * cost\_motorkW_{year} + cost\_battkWh\_trk_{ibatt=5,year} \\ &* PT\_battkWh\_HEV_{icafe19} \\ &+ \left(inc\_tech\_cost\_19_{year,icafe19,HEV} - inc\_tech\_cost\_19_{baseyr,icafe19,HEV}\right) \\ &- cost\_ICE\_HEV_{icafe19,year} - lonox\_cost_{icafe19,year} \end{aligned} \tag{190}$$

Hydrogen powertrains

Three different hydrogen powertrains are offered: hydrogen fuel cell, battery-dominant hydrogen fuel cell, and hydrogen internal combustion engine. Each of these requires hydrogen storage tanks, and the fuel cell options require a fuel cell stack for propulsion. The cost of these components is estimated using an experience curve driven by cumulative production, with learning rates and initial costs set exogenously in the input file (*cost_fcstack_a, cost_fcstack_b, cost_h2tank_a, cost_h2tank_b*). An R&D-based curve is used in the case of no hydrogen truck adoption (*cost_fcstk_rd, cost_h2tank_rd*).

$$\begin{aligned} cost\_FCkW_{year} = MIN\Big(&cost\_fcstack\_a \\ &* \left(cumulative\_fc\_stacks_{year-1}{}^{-cost\_fcstack\_b}\right), cost\_FCkW_{baseyr} \\ &* 1 - cost\_fcstk\_rd^{\ year-baseyr}\Big) \end{aligned} \tag{191}$$

(15% degradation). This initial 15% is stepped up by an additional 5% at 2,250 cycles and 2,400 cycles (25% degradation total). https://www.regulations.gov/document/EPA-HQ-OAR-2022-0985-3877. EIA linearly interpolates the degradation between 0 and 2,000 cycles to account for a continuous decline in range.

$$cost\_h2tank_{year} = MIN\left(cost\_h2tank\_a * \left(cumulative\_h2\_tanks_{year-1}{}^{-cost\_h2tank\_b}\right), cost\_h2tank_{baseyr} * 1 - cost\_h2tank\_rd^{\ year-baseyr}\right) \quad (192)$$

Hydrogen internal combustion engine (H2 ICE) trucks are similar to CNG trucks in that they require engine modifications (e.g. injectors, controls), the addition of high pressure fuel storage tanks, and the removal of some of the aftertreatment equipment needed for diesel engines. To determine the size of the on-board hydrogen storage tanks, we use an approach similar to that discussed in the battery electric truck section above.

a. Estimate the amount of hydrogen (kg) required (*PT_tankkg_h2ice*) to meet daily travel needs (annual VMT, *VMT_VEH*, divided by the number of working days, 250), using the fuel economy calculated in the previous year (*new_mpg_19*). This is converted to nominal kgH2 based on the share of tank capacity that is usable (*usable_h2*). Note that unit conversions are left out of the below equation for clarity.

$$PT\_tankkg\_h2ice_{ivmt,icafe19} = \frac{\left[\frac{\frac{VMT\_VEH_{ivmt,icafe19}}{250}}{new\_mpg\_19_{year-1,h2ice,icafe19}}\right]}{usable\_h2} \quad (193)$$

b. Estimate the number of hydrogen tanks installed on the vehicle (*PT_tankcnt_H2ICE*). Tanks are assumed to be standard sizes to increase production scale and reduce cost, and are assumed to hold 6kgH2 each for Classes 2b-5 and 12kgH2 each for Classes 6-8 (*h2_kg_per_tank*). Each regulatory size class has a maximum tank constraint based on the volume available for on-board fuel storage (*h2_max_tanks*). The installed tank count is the smaller of 1) the number of tanks that would meet the daily range and 2) the maximum number of tanks that can be installed.

$$PT\_tankcnt\_H2ICE_{ivmt,icafe19} = MIN\left(, CEILING\left(\frac{PT\_tankkg\_h2ice_{ivmt,icafe19}}{h2\_kg\_per\_tank_{icafe19,h2ice}}\right)\right) \quad (194)$$

The final incremental costs for an H2 ICE (*INC_COST_H2ICE*) are then calculated each year as follows, including the estimated tank cost.

$$INC\_COST\_H2ICE_{ivmt,icafe19,year} = cost\_h2tank_{year} * PT\_tankcnt\_H2ICE_{ivmt,icafe19} * h2\_kg\_per\_tank_{icafe19,h2ice} + \left(inc\_tech\_cost\_19_{year,icafe19,h2ice} - inc\_tech\_cost\_19_{baseyr,icafe19,h2ice}\right) - cost\_ICE\_H2ICE_{icafe19,year} \quad (195)$$

Similar to battery electric trucks, the maximum feasible on-board fuel storage will be insufficient for many high-mileage duty cycles. Therefore, additional daily refueling time is accounted for via labor costs using an estimated value of time (*refuel_timeval*, 75 2022USD/hour) and estimated time to complete a full tank refill (*h2_refuel_time*). The additional cost per year of operation (*h2_refuelopcost*) is used in the payback calculations in subroutine *TRUCK_PBK*.

$$h2\_refuelopcost_{ivmt,icafe19} = MAX\left(0, \left(\frac{PT\_tankkg\_H2ICE_{ivmt,icafe19}}{PT\_tankcnt\_H2ICE_{ivmt,icafe19} * h2\_kg\_per\_tank_{icafe19}} - 1\right) * 250 * h2\_refuel\_time * refuel\_timeval\right) \quad (196)$$

Hydrogen fuel cell trucks require the addition of a fuel cell stack, hydrogen storage tank, battery pack, electric motor, and other related components. The internal combustion engine, transmission, aftertreatment, and other related components are removed. As noted above, the Freight Truck Component offers two fuel cell powertrain options: one that is fuel cell dominant (FCEV) and one that is battery dominant (FCHEV). The former requires more hydrogen storage and less battery capacity, while the latter requires more battery capacity and less hydrogen storage. The on-board tank size (*PT_tankkg_FCEV/FCHEV*), tank count (*PT_tankcnt_FCEV/FCHEV*), and labor cost of additional refueling stops (*h2_refuelopcost*) are all estimated with the same approach used for hydrogen ICEs above.

The final incremental cost (*INC_COST_FCXX*) is estimated as follows, where XX is either "EV" or "HEV", representing the two different fuel cell powertrains.

$$\begin{aligned} INC\_COST\_FCXX_{ivmt,icafe19,year} &= cost\_FCkW_{year} * PT\_fckW_{FCXX_{ivmt,icafe19}} + cost\_motorkW_{year} \\ &* PT\_emotorkW_{icafe19,fcxx} + cost\_h2tank_{year} * PT\_tankcnt\_FCXX_{ivmt,icafe19} \\ &* h2\_kg\_per\_tank_{icafe19,fcxx} + cost\_battkWh\_trk_{ibatt=2,year} \\ &* PT\_battkWh\_FCXX_{ivmt,icafe19} \\ &+ \left(inc\_tech\_cost\_19_{year,icafe19,fcxx} - inc\_tech\_cost\_19_{baseyr,icafe19,fcxx}\right) \\ &- cost\_ICE_{icafe19,year} - lonox\_cost_{icafe19,year} \end{aligned} \quad (197)$$

2022 Inflation Reduction Act: Commercial Clean Vehicle Credit and Alternative Fuel Vehicle Refueling Property Credit

As part of the 2022 Inflation Reduction Act (IRA), qualified commercial vehicles are eligible for a tax credit to offset the incremental cost compared to a conventional ICE option through 2032 (Section 45W).[40] This credit is applied to the final vehicle incremental price calculated for each of the above qualified alternative powertrains (battery electric, plug-in hybrid, hydrogen fuel cell). Three constraints are applied to the credit amount:

1. it cannot exceed the final calculated incremental price;
2. it cannot exceed 15% (plug-in hybrid) or 30% (battery electric, hydrogen fuel cell) of the total vehicle MSRP (exogenous estimate, *IRA_45W_max*); and
3. it cannot exceed $7,500 for Classes 2b-3, and $40,000 for Classes 4-8.

[40] U.S. Internal Revenue Service, "Commercial Clean Vehicle Credit". https://www.irs.gov/credits-deductions/commercial-clean-vehicle-credit. Accessed June 2, 2025.

Additionally, the IRA implemented an Alternative Fuel Vehicle Refueling Property Credit (Section 30C) through 2032.[41] The Freight Truck Component applies this credit to the cost of charging equipment and installation (*BEV_infra_cost*).

Both of these tax credits – Section 45W and Section 30C – are controlled by a switch in the input file (*IRA_switch*, trnhdvx.xlsx), where a value of “1” implements the credits and a value of “0” does not.

Powertrain choice component (subroutine *TRUCK_CHOICE*)

With the vehicle fuel economies (subroutine *TRUCK_TECHADOPT*) and vehicle purchase costs (subroutine *TRUCK_INCCOST*) calculated, the Freight Truck Component proceeds with estimating the market adoption of different powertrains within each of the census divisions, regulatory size classes, fleet types, and annual VMT bins.

Operating costs

Before calculating market shares, fuel, diesel exhaust fluid (DEF), and maintenance and repair (M&R) costs are estimated on a per mile basis. Fuel and DEF cost per mile (*CPM_R*) are based on current year fuel economy (*new_mpg_19*), fuel prices (*fuelprice_r_avg*), DEF dosing (*DEF_dose*), and DEF cost (*cost_DEF*). Note that conversion factors are omitted below for clarity.

For **all vehicles except for battery electric**,

$$CPM\_R_{year,ifuel,icafe19,iflt,iregn} = \frac{FUELPRICE\_R\_AVG_{ifuel,iregn}}{new\_mpg\_19_{year,ifuel,icafe19}} \quad (198)$$

For **diesel vehicles**, the cost of DEF is added to the fuel cost

$$CPM\_DEF_{year,icafe19,iregn} = \frac{1}{new\_mpg\_19_{year,ifuel,icafe19}} * DEF\_dose * cost\_DEF_{year} \quad (199)$$

$$CPM\_R_{year,diesel,icafe19,iflt,iregn} = CPM\_R_{year,diesel,icafe19,iflt,iregn} + CPM\_DEF_{year,icafe19,iregn} \quad (200)$$

In cases where the EPA Low NOx regulation is in effect (e.g. AEO2025 Reference case), a higher DEF dose rate (*DEF_dose_LoNOx*) is used in the calculation of *CPM_DEF*.

For **battery electric vehicles**, the electricity cost varies depending on whether the vehicle is expected to charge at a depot (“fleet”, price *PELIBCM*) or at a public/retail charging facility (“non-fleet”, price *PELFNCM*). Class 8 trucks equipped with sleeper cabs are all assumed to charge at public/retail facilities (price *PELFNCM*).

$$CPM\_R_{year,BEV,icafe19,fleet,iregn} = \frac{\sum_{iyr=year-4}^{year} PELIBCM_{iregn,iyr}/5}{new\_mpg\_19_{year,ifuel,icafe19}} \quad (201)$$

[41] U.S. Internal Revenue Service, “Alternative Fuel Vehicle Refueling Property Credit”. https://www.irs.gov/credits-deductions/alternative-fuel-vehicle-refueling-property-credit. Accessed June 2, 2025.

$$CPM\_R_{year,BEV,icafe19,non-fleet,iregn} = \frac{\sum_{iyr=year-4}^{year} PELFNCM_{iregn,iyr}/5}{new\_mpg\_19_{year,ifuel,icafe19}} \quad (202)$$

Battery electric vehicle charging costs must also account for charging station maintenance (*evse_maint*) and charging losses (*CHRG_EFF*).

$$CPM\_R_{year,BEV,icafe19,iflt,iregn} = \frac{CPM\_R_{year,BEV,icafe19,iflt,iregn} + evse\_maint}{CHRG\_EFF_{year}} \quad (203)$$

M&R costs typically increase as a vehicle ages, due to the accumulation of miles on key wear components. M&R for each powertrain is based on the M&R cost for diesel vehicles (*MR_cost*), which is calculated for each year of operation based on exogenous parameters (*MR_intercept* and *MR_slope*) up to the maximum number of payback years considered (*PBK_YR* = 7 for AEO2025).

$$MR\_cost_{icafe19,diesel,year\_pbk,year} = MR\_intercept_{icafe19} + MR\_slope_{icafe19} * year\_index \quad (204)$$

M&R costs for all other powertrains are estimated based on multipliers applied to the diesel *MR_cost*, all of which are defined exogenously in the input file *trnhdvx.xlsx*.

As noted previously, Class 2b-6 alternative powertrains aside from gasoline hybrid are competed against a composite baseline – a sales-weighted average of conventional gasoline, gasoline hybrid, and diesel ICE vehicles – while Class 7&8 alternative powertrains are competed against a diesel baseline vehicle. The fuel, DEF, and maintenance costs above are weighted and re-assigned into *base vehicle* arrays: *CPM_R_ICE* and *MR_ICE* respectively.

Alternative powertrain adoption

The alternative powertrain adoption decision occurs at a disaggregate level. Each vehicle cohort is defined by a combination of three categories:

1. Regulatory size class (*icafe19*, 19 total)
2. Annual VMT bin (*ivmt*, 11 total)
3. Fleet type (*iflt*, 2 total)

The distribution of sales across each of the categories is based on shares derived from historical data. Within each of these *icafe19*/*ivmt*/*iflt* cohorts, three components are calculated to estimate adoption of each alternative powertrain:

1. The **net present value (npv) of cumulative savings** versus the baseline vehicle, over each of the possible payback periods. This includes fuel (regional prices), DEF, M&R, labor cost for additional daily refuelings, and insurance.
2. The **incremental purchase price** for the powertrain being offered and electric vehicle charging station if applicable, including sales tax (regional average).
3. A logistic curve representing the maximum rate of adoption increase, and the corresponding **maximum market penetration**, of each powertrain. This curve is triggered in the year that the powertrain hits an exogenously defined baseline market share within a given vehicle cohort.

The net present value of savings for each powertrain is estimated from the annual fuel and DEF savings (*ann_savings*), insurance cost (*insure_rate*), vehicle purchase price (*veh_cost*), M&R cost for the baseline (*mr_ice*) and current powertrain (*mr_cost*), annual VMT (*ann_vmt_per_veh*), and discount rate (*DISCRTXG_P2*). This calculation is completed for *each* of the possible payback periods (index *y*) – between one and seven years.

$$npv\_choice_{icafe19,ifuel,ivmt,y,iregn,year} = \frac{ann\_savings - (insure\_rate * veh\_cost) + \left(mr\_ice_y - mr\_cost_{icafe19,ifuel,y,year}\right) * ann\_vmt\_per\_veh}{1 + DISCRTXG\_P2^y} \quad (205)$$

The vehicle cost *including electric vehicle charger* (*inc_cost*) is directly from subroutine *TRUCK_INCCOST*. The only modification made before comparing to the npv of savings is the addition of sales tax, which varies regionally (*sales_tax_rate*).

If the npv of savings (*npv_choice*) is larger than the up front cost including sales tax (*inc_cost*), that slice of the vehicle cohort – defined by the length of payback period required – adopts the maximum possible share of the powertrain under assessment. The sum of adoption within each individual cohort (*buy_shr*) across all payback periods (*buy_shr_agg*) is then passed forward to be applied to the logistical curve.

$$buy\_shr_y = pback\_shr_y * veh\_shr\_vmt\_bin \quad (206)$$

$$buy\_shr\_agg = \sum_y buy\_shr_y \quad (207)$$

To account for manufacturing scale-up and lead time, refueling infrastructure buildout, re-training of technicians, and retrofits of maintenance facilities, alternative powertrain adoption growth is limited based on an s-curve. This maximum market penetration for a given regulatory size class, fleet type, powertrain, and annual VMT (*mpath*) is defined by four parameters, shown in the equation below. *BFSHXG* represents the market share at which the curve is triggered, *EFSHXG* represents the peak market share, and *SLOPE_choice* and *MIDYR_choice* define the shape and growth rate of the curve.

$$mpath = \frac{BFSHXG_{isc4,ifuel,iflt} + (EFSHXG_{isc4,ifuel,iflt} - BFSHXG_{isc4,ifuel,iflt})}{1 + e^{SLOPE\_choice_{icafe19,ifuel,iflt,ivmt} * (curcalyr - MIDYR\_choice_{icafe19,ifuel,iflt,ivmt})}} \quad (208)$$

If this is not the first pass through *TRUCK_CHOICE* – in other words, if the Truck Sales Component has run at least once through and determined that additional run(s) would be necessary due to noncompliance with CAFE or GHG standards – the maximum possible share (*mpath*) is incrementally adjusted to allow for quicker growth in alternative powertrain adoption in those size classes that are out of compliance.

Finally, the powertrain sales share (*fuel_shr_ivmt*) is calculated. Note that this is not the sales share *within* a given *ivmt* bin. It is the share of all vehicles – within *icafe19*, *iflt*, and *iregn* – that are in a given *ivmt* bin and powertrain.

$$fuel\_shr\_ivmt_{year,ivmt,iflt,icafe19,ifuel,iregn} = buy\_shr\_agg * mpath \quad (209)$$

Conventional powertrain adoption

After estimating adoption of alternative powertrains, the subroutine estimates the share of vehicle sales that are diesel and gasoline. The share of diesel, *ifuel* = 1, in conventional truck sales is projected through a time-dependent exponential decay function based on historical data that is defined by

$$MPATH\_regn_{icafe19,ifuel,iflt,iyear,iregn} = BFSHXG_{isc4,ifuel,iflt} + \left(EFSHXG_{isc4,ifuel,iflt} - BFSHXG_{isc4,ifuel,iflt}\right) * \left(1 - e^{CSTDXG_{isc4,iflt} + CSTDVXG_{isc4,iflt} * curcalyr}\right) \quad (210)$$

where

$CSTDXG_{isc19,iflt}$, $CSTDVXG_{isc19,iflt}$ = exogenously determined market penetration curve parameters for diesel trucks.

Because any fuel type could exceed the user-specified *maximum* because of cost advantages over other technologies, market penetration must be capped at 100%. Diesel market share is calculated as the projected share of diesel in conventional truck sales multiplied by the share occupied by conventional trucks. The remainder of truck purchases is assumed to be gasoline, *ifuel*=2

$$fuel\_shr\_ivmt_{yr,ivmt,iflt,icafe19,ifuel=2,iregn} = max\left[0.0, veh\_shr_{ivmt,iflt,icafe19} - \sum_{ifuel<>2} fuel\_shr\_ivmt_{year,ivmt,iflt,icafe19,ifuel,iregn}\right] \quad (211)$$

The final step in the powertrain adoption subroutine *TRUCK_CHOICE* is to renormalize the sales shares to ensure they sum to 100% within each cohort.

Enforcing the Advanced Clean Trucks Regulation (subroutine TRUCK_ACT)

The Advanced Clean Trucks (ACT) regulation requires truck manufacturers to meet ZEV sales share targets which escalate over time.[42] The targets are specified across three regulatory groupings: Class 2b-3 (C2b3), Class 4-8 Vocational (C48V), and Class 7&8 Tractor (C78T). The Freight Truck Sales Component enforces ACT compliance by converting non-ZEV sales to ZEV sales as needed. This is accomplished *before* determining and enforcing CAFE and GHG compliance.

The following summary is focused on those implications most relevant to modeling the impact of the ACT regulation.

Summary of the ACT

Regulatory compliance is determined by calculating *deficits* and *credits*. Manufacturers must offset the deficits generated in each model year using credits generated in the same or previous model years (*banking*). A manufacturer's deficit is calculated by multiplying each vehicle sale by the weight class modifier, summing those products across the three regulatory groupings, and multiplying the totals by the corresponding ZEV share requirement (see Table 5 below).

[42] California Air Resources Board, "Advanced Clean Trucks Regulation." https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2019/act2019/fro2.pdf

Table 5. Sales share requirements (left) and weight class modifiers (right) for ACT regulation

	Class 2b-3	Class 4-8 Vocational	Class 7-8 Tractor
2024	5%	9%	5%
2025	7%	11%	7%
2026	10%	13%	10%
2027	15%	20%	15%
2028	20%	30%	20%
2029	25%	40%	25%
2030	30%	50%	30%
2031	35%	55%	35%
2032	40%	60%	40%
2033	45%	65%	40%
2034	50%	70%	40%
2035+	55%	75%	40%

Group	Modifier
Class 2b-3	0.8
Class 4-5V	1
Class 6-7V	1.5
Class 8V	2
Class 7&8 Tractor	2.5

There are two types of credits: ZEV and NZEV. ZEV credits – from sales of BEVs and FCEVs – are calculated as follows: multiply each ZEV sale by the weight class modifier (Table 5) and sum the products across the three regulatory groupings. NZEV credits – from sales of PHEVs – are determined by applying an additional multiplier, calculated as 0.01 multiplied by the all-electric range.

C78T deficits can only be met using C78T ZEV and C78T NZEV credits. In other words, a manufacturer can't sell Class 2b ZEVs to make up for a C78T deficit.

The NZEV credits cannot be used to meet the full deficit in any given model year. Specifically, total NZEV credits may only meet *up to 50%* of the annual summed deficit for C2b3 and C48V, and C78T NZEV credits may only meet *up to 50%* of the annual summed deficit for C78T.

Credits expire according to the following specifications:

1. ZEV and NZEV credits generated in 2021-2023 model years can be used *through* MY2030
2. ZEV and NZEV credits generated in 2024+ model years can be used for 5 model years after their generation. E.g., a credit generated in MY2024 can be used *through* MY2029.

Enforcing the ACT in NEMS TDM

Rather than detailing the specific equations used to enforce this regulation, here we will present the methodological approach used to ensure ACT compliance for new commercial light and freight truck sales in subroutine *TRUCK_ACT*.

NEMS TDM represents the freight truck market across 19 size classes and is therefore able to capture the full range of variation specified in the ACT vehicle groupings (Tables 1 and 2). Additionally, it includes BEVs, two types of FCEVs, and two types of PHEVs, thereby capturing the full range of ACT-specified ZEV and NZEV powertrain options.

NEMS TDM *does not* represent individual truck manufacturers, and therefore applies the ACT to each of the nine census divisions as a whole. This is reasonable given the credit trading and transfer flexibility in the ACT regulation, which allows manufacturers to sell and purchase credits from each other. Given that the ACT is only enforced in certain states, we only apply it to the sales share of California and Section 177 states which have adopted the ACT.

Additionally, NEMS TDM does not capture the possibility of making up a deficit in the following year ("deficit make up" option in 1963.3(b)). It requires regional sales to align with the ACT in the current model year, using the current credit bank. It also does not track the age of the generated credits, and therefore doesn't enforce the expiration schedule noted above.

Given the above considerations, the *TRUCK_ACT* subroutine estimates compliance according to the following logic:

1. Calculate **deficits** for C2b3, C48V, and C78T based on total sales in that region.
2. Calculate the **ZEV and NZEV credits** generated for C2b3, C45V, C67V, C8V, and C78T based on sales of BEVs, FCVs, and PHEVs.
3. Add the ZEV and NZEV credits to the existing ZEV and NZEV credit banks for each region. The MY2024 credit bank includes the accumulated credits from MY2021-MY2023.
4. Determine compliance, using the following retirement schedule per the regulation (1963.3(c)(2)). Credits are removed from the current bank to meet the deficits, and the NZEV limitations noted above (50% maximums) are enforced.
    a. Apply C78T NZEV credits to meet C78T deficits
    b. Apply C2b3 and C48V NZEV credits to meet C2b3 and C48V deficits
    c. Apply C78T NZEV credits to meet C2b3 and C48V deficits
    d. Apply C78T ZEV credits to meet C78T deficits
    e. Apply C2b3 and C48V ZEV credits to meet C2b3 and C48V deficits
        i. C2b8 credit bank is allocated to C2b3 and C48V deficits *proportional* to the relative deficit sizes.
        ii. Alternate code available (commented out) to meet C48V deficits first, and then if any credits left, meet C2b3. Results in massive ZEV adoption in C2b3 and very little in C48V (still meets ACT).
    f. Apply C78T ZEV credits to meet C2b3 and C48V deficits

The remaining deficit is then met by requiring regions to adopt additional ZEVs or NZEVs, based on two considerations:

1. **Size class**. *TRUCK_ACT* allocates the deficit as follows:
    a. C2b3: Deficit is allocated based on the distribution of conventional and hybrid internal combustion engine across the four size classes: Class 2b pickup/van, Class 2b vocational, Class 3 pickup/van, Class 3 vocational.
    b. C48V: Deficit is allocated based on the distribution of conventional and hybrid internal combustion engine across the five vocational size classes: Class 4, Class 5, Class 6, Class 7, and Class 8. This deficit is then converted to sales based on the weight modifier.

c. C78T: All deficits are applied to daycab tractors (roof height distribution based on sales distribution in the module)

2. **Net present value of financial losses.** Within each size class grouping and annual VMT bin, *TRUCK_ACT* distributes ZEV sales requirements across BEV, FCEV, and FCHEV powertrains according to the size of loss to the operator (versus a conventional vehicle). We assume the maximum payback period (7 years for AEO2025) for this calculation. Class 2b/3 trucks are assumed to adopt BEV (no FCEV/FCHEV adoption for compliance).

The resulting sales by powertrain – having been modified to comply with the ACT – are passed on to subroutine *TRUCK*_AGGVARS to re-estimate aggregate fuel economy and tailpipe GHG performance.

NHTSA CAFE and EPA tailpipe GHG compliance

The final step in the Freight Truck Sales Component estimates compliance with CAFE and tailpipe GHG regulations (*TRUCK_GHGMEET*). If the fleet continues to be noncompliant after exhausting available incremental adjustments in market dynamics, the Component resorts to converting sales to ZEV options until compliance is achieved (*TRUCK_GHGZEV*).

The compliance metric used is *megagrams of tailpipe* CO_2. *Credits* are generated when vehicles emit less CO_2 than the standard and *deficits* when vehicles emit more CO_2 than the standard. EPA specifies 14 different gCO2/ton-mile standards depending on the regulatory class; the difference between those and tested gCO2/ton-mile is multiplied by lifetime mileage and payload to estimate CO_2 credits or deficits. The total aggregate $MgCO_2$ *within each averaging set* must be greater than zero for each manufacturer. Table 6 below shows which standards are applied to each of the 19 NEMS size classes, and how those are further aggregated into averaging sets for compliance purposes.

Table 6. Freight truck market segmentation for enforcing compliance with U.S. EPA tailpipe GHG standards.

Vehicle category	Size class	EPA standard applied	Averaging set
1	Class 2b pickup and van	1	1
2	Class 2b vocational	2	2
3	Class 3 pickup and van	1	1
4	Class 3 vocational	2	2
5	Class 4 vocational	2	2
6	Class 5 vocational	2	2
7	Class 6 vocational	3	3
8	Class 7 vocational	3	3
9	Class 7 tractor day cab low roof	6	3
10	Class 7 tractor day cab mid roof	7	3
11	Class 7 tractor day cab high roof	3	3
12	Class 8 vocational	4	3
13	Class 8 tractor day cab low roof	8	4
14	Class 8 tractor day cab mid roof	9	4
15	Class 8 tractor day cab high roof	10	4

16	Class 8 tractor sleeper cab low roof	11	4
17	Class 8 tractor sleeper cab mid roof	12	4
18	Class 8 tractor sleeper cab high roof	13	4
19	Class 8 heavy-haul	14	4

Data source: U.S. Energy Information Administration

Trading is allowed *within* averaging sets for the Phase 2 standards, and both *within* and *among* them for Phase 3. Manufacturers can also bank credits for later use (expire after 5 years). NEMS TDM applies these standards across the entire aggregate market, rather than separating and enforcing them for each manufacturer.

Compliance is estimated for the aggregate market as follows.

1. The first step is to calculate the fleet-average gCO_2 per ton-mile (*new_gco2tonmi_p2*). This is calculated by converting the fuel economy for each powertrain and size class (*new_mpg_19*) using the CO_2 emitted from burning each gallon of fuel (*GCO_2_gal*) and the assumed payload per vehicle used in EPA's rulemaking (*EPA_PAYLOAD*).

$$new\_gco2tonmi\_p2_{year,ifuel,icafe19} = \frac{1}{new\_mpg\_19\_(year,ifuel,icafe19)} * \frac{GCO2\_gal_{ifuel,icafe14}}{EPA\_PAYLOAD_{icafe14}/2000} \tag{212}$$

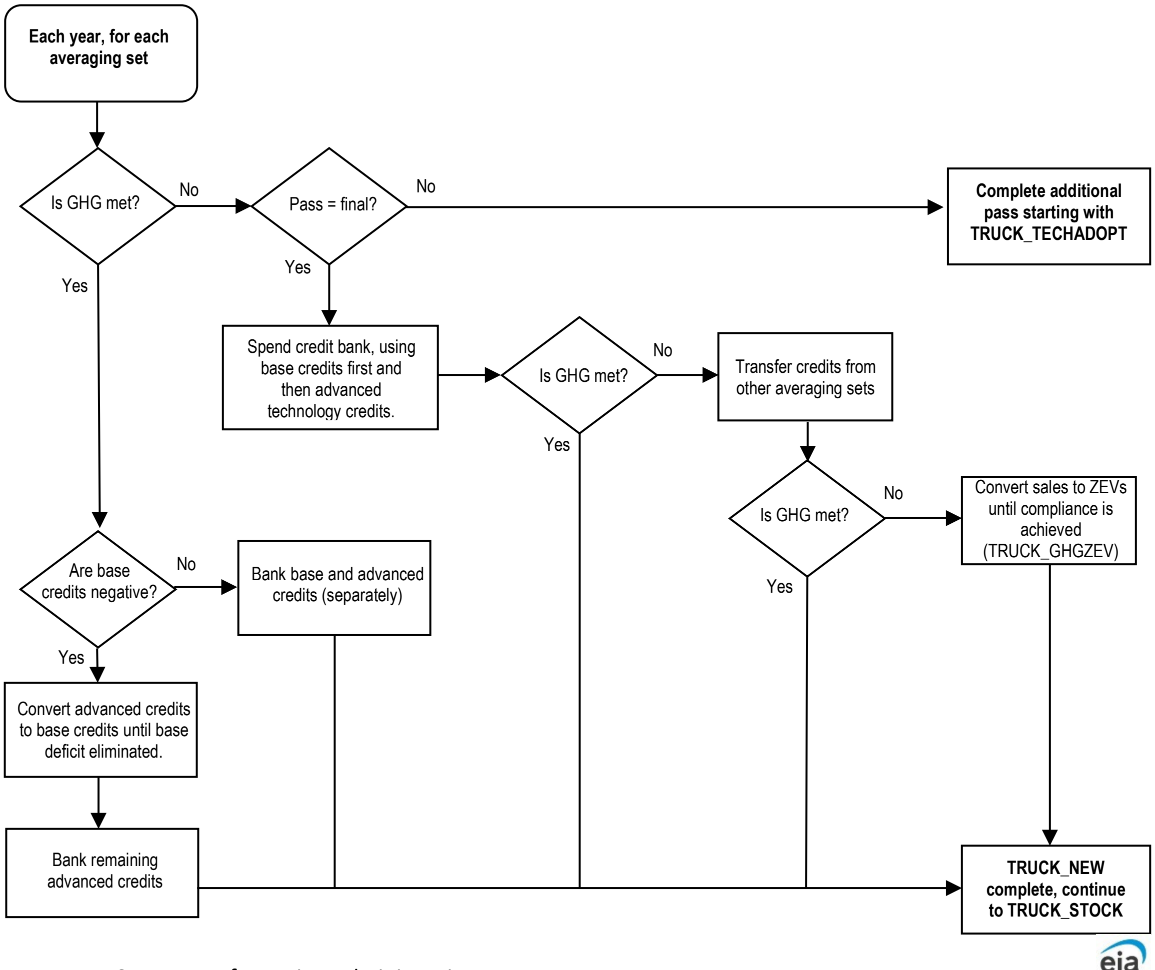
2. The fleet-average gCO_2 per ton-mile is then differenced with the standard (*HDV_GHGSTD*), and converted to $MgCO_2$ using total sales (*TRKSTK_19R*) and the regulatory expected useful life in miles (*HDV_USEFULLIFE*). Certain low-tailpipe-emission powertrains are eligible for advanced technology multipliers (*HDV_AFV_CREDITS*). Note that at this stage, the 19 NEMS size classes are being aggregated up to EPA's 14 regulatory classes.

$$\begin{aligned} GHG\_creds_{year,icafe14,ifuel} &= GHG\_creds_{year,icafe14,ifuel} \\ &+ \left(HDV\_ghgSTD_{icafe14,year,ifuel} - new\_gco2tonmi\_p2_{year,ifuel,icafe19}\right) \\ &* \frac{EPA\_PAYLOAD_{icafe14}}{2000} * \sum_{iflt,iregn} TRKSTK\_19R_{year,icafe19,new,ifuel,iflt,iregn} \\ &* HDV\_AFV\_CREDITS_{ifuel,year} * HDV\_USEFULLIFE_{ifuel,icafe14} * 10E-6 \end{aligned} \tag{213}$$

3. Finally, the total $MgCO_2$ is summed for each averaging set, and for each powertrain within each averaging set. These values are stored in *GHG_creds_agg* and *GHG_creds_avgset* respectively.

As noted in the introductory discussion for the Freight Truck Sales Component (see Figure 14 and surrounding text), the model attempts to meet GHG regulations several times before resorting to conversion of sales to ZEV (subroutine *TRUCK_GHGZEV*). Figure 15 illustrates the credit accounting logic in subroutine *TRUCK_GHGMEET*. Credits are spent from oldest to newest and expire after 5 years.

Figure 15. Freight truck CAFE/GHG compliance estimation and enforcement



Data source: U.S. Energy Information Administration

The model ensures that advanced technology credits are only earned through MY2027, and are only available to be spent through MY2029 per the Phase 3 regulation. After MY2029 the advanced technology credits are converted to base credits. Additionally, Class 2b-3 pickup and van credits can only be transferred *to* Light HDV and Medium HDV averaging sets; they cannot receive credits from other averaging sets and cannot be transferred to the Heavy HDV averaging set.

If any of the averaging sets are still out of compliance after the maximum allowed passes, the model steps into subroutine *TRUCK_GHGZEV* to convert sales in non-compliant averaging sets from ICE to ZEV. Note that in the case of EPA Phase 3 GHG standards, eligible ZEVs include BEV, FCEV, FCHEV, and H2 ICE.

The approach is similar to that used in subroutine *TRUCK_ACT*. Within each size class grouping and annual VMT bin, *TRUCK_GHGZEV* distributes ZEV sales requirements across BEV, FCEV, FCHEV, and H2 ICE powertrains according to the size of loss to the operator (versus a conventional vehicle). We assume the maximum payback period (7 years for AEO2025) for this calculation. Class 2b/3 trucks are assumed to choose BEV. We assume that the number of vehicles converted from ICE to ZEV is dependent on the distribution of ICE vehicles across size class and annual VMT bin; in other words, all size classes and VMT bins in a non-compliance averaging set are required to convert sales from ICE to ZEV, if they have ICE vehicle sales available for conversion. Fuel shares within each size class and VMT bin are updated as the sales conversions are made to ensure the energy impacts are accurately captured.

After finalizing projected sales and vehicle attributes, *TRUCK_NEW* calculates the corresponding battery, fuel cell stack, and hydrogen tank production to estimate the impact on future price declines. Battery production is added to the global TDM variable *cumulative_gWh* (which includes LDV battery production as well), while fuel cell stack and hydrogen tank production are added to *cumulative_fc_stacks* and *cumulative_h2_tanks* respectively.

Additionally, the subroutine calculates the electric VMT share for PHEVs, *PHEV_eVMT_share*. Adoption across annual VMT bins varies over the projection period, resulting in different electric VMT shares over time.

Determine composition of existing truck stock (subroutine *TRUCK_STOCK*)

Once the characteristics of the incoming class of new trucks are determined, the next step is to determine the composition of the stock of existing trucks, *TRKSTK_19R*. Survival rates (*SURV_RATE*), which vary by vehicle age (*iage*, between 1-34), are applied to the previous year's truck population estimates.

$$TRKSTK\_19R_{year,icafe19,iage,ifuel,iflt,iregn} = TRKSTK\_19R_{year-1,icafe19,iage-1,ifuel,iflt,iregn} * SURV\_RATE_{iage,iregn,icafe19,ifuel}, \quad (214)$$

Trucks are then transferred from fleet ownership to non-fleet owners, based on the transfer rate estimated from historical data (*TFFXGRT*).

$$\begin{aligned} TRK\_19\_regn_{year,icafe19,iage,ifuel,iflt=NOT\ FLEET,iregn} &= TRK\_19\_regn_{year,icafe19,iage,ifuel,iflt,iregn} \\ &+ \left(TFFXGRT_{isc,iage} * TRK\_19\_regn_{year,icafe19,iage,ifuel,iflt=2,iregn}\right), \end{aligned}$$

and

$$\begin{aligned} TRKSTK\_19R_{year,icafe19,iage,ifule,iflt=FLEET,iregn} &= TRKSTK\_19R_{year,icafe19,iafe,ifuel,iflt,iregn} \\ &- \left(TFFXGRT_{isc,iage} * TRKSTK_{19R_{year,icafe19,iage,ifuel,iflt=2,iregn}}\right) \end{aligned} \quad (215)$$

Calculate fuel consumption

The next stage of the component estimates the total miles driven by trucks of each market class, fuel type, and age (subroutine *TRUCK_VMT*) and divides by fuel economy to determine fuel consumption (subroutine *TRUCK_FUEL*).

Estimating VMT demand

The aggregate VMT growth in each economic sector, *TVMT*, is estimated based on exogenous VMT distribution inputs as well as endogenous economic growth from the macroeconomic module.

The model first estimates the static *ton miles per dollar of industrial output* parameter by industrial sector (*TTM_OUTPUT*), based on the last historical year of Freight Analysis Framework (FAF) ton-mile demand data and NEMS Macroeconomic Activity Module (MAM) industrial output data. The latter is aggregated from over 40 output sectors into 18 sectors (*isec*), as shown in Table 7 below. The ratio of historical ton-mile demand (*TTONMI_ORIG*) and this re-aggregated industrial output (*TSIC*) in the last available historical year (*iFAFyear*) are used to estimate the static parameter *TTM_OUTPUT* for each region and sector.

$$TTM\_OUTPUT_{iregn,isec} = \frac{TTONMI\_ORIG_{iregn,isec}}{TSIC_{isec,iregn,iFAFyear}} \quad (216)$$

Projected ton-mile demand (*TTONMI*) is then coupled to growth in industrial output.

$$TTONMI_{year,iregn,isec} = TTM\_OUTPUT_{iregn,isec} * TSIC_{isec,iregn,year} \quad (217)$$

Table 7. Crosswalk of NEMS Macroeconomic Activity Module industrial output sectors into NEMS TDM sectors for freight movement projections

Index (Macro)	NEMS Macro description	Index (TDM, *isec*)	Description
1	**Food products**	--	--
2	Grain and oil seed milling	3	Processed food
3	Dairy products	3	Processed food
4	Animal slaughter and seafood products	3	Processed food
5	Other food products	3	Processed food
6	Beverages and tobacco products	11	Beverage and tobacco
7	Textile mills and products	8	Other manufacturing
8	Wood products	8	Other manufacturing
9	Furniture and related products	16	Furniture
10	**Paper products**	--	--
11	Pulp and paper mills	4	Paper products
12	Paperboard container	4	Paper products
13	Other paper	4	Paper products
14	Printing	8	Other manufacturing
15	Bulk chemicals: inorganic	1	Basic chemicals
16	Bulk chemicals: organic	1	Basic chemicals
17	Bulk chemicals: organic: ethanol	1	Basic chemicals
18	Bulk chemicals: resin, synthetic rubber, and fibers	1	Basic chemicals
19	Bulk chemicals: agricultural chemicals	13	Fertilizers
20	**Other Chemical Products**	--	--
21	Other chemical products: pharma products	12	Pharmaceuticals
22	Other chemical products: paint products	1	Basic chemicals
23	Other chemical products: soaps and cleaning	1	Basic chemicals
24	Other chemical products: other	1	Basic chemicals
25	Petroleum refineries	5	Petroleum products
26	Other petroleum and coal products	5	Petroleum products
27	Plastics and rubber products	14	Rubber and plastics
28	Glass and glass products	6	Stone, clay, glass, concrete
29	Flat glass (subset of 28)	6	Stone, clay, glass, concrete

30	Cement	6	Stone, clay, glass, concrete
31	Lime	--	--
32	Other nonmetallic mineral products	6	Stone, clay, glass, concrete
33	Iron and steel mills and products	2	Primary metals
34	Alumina and aluminum products	2	Primary metals
35	Other primary metal products	2	Primary metals
36	Fabricated metal products	7	Metal durables less computers
37	Machinery	7	Metal durables less computers
38	Computers and electronics	15	Computers
39	Transportation equipment	7	Metal durables less computers
40	Electrical equipment	7	Metal durables less computers
41	Miscellaneous manufacturing	8	Other manufacturing
42-44	Agriculture	9	Agriculture
45-47	Mining	10	Mining
Services (3-4)	Utility	17	Utility
Services (10)	Government	18	Government

Data source: U.S. Energy Information Administration

In historical years, truck VMT (*VMTDMDR*) is read in exogenously and distributed across census divisions based on FAF ton-mile demand data (*TTONMI_ORIG*). In projection years, varying growth in VMT across census divisions is captured alongside the variation in ton-mile demand growth (*TTONMI*, driven by industrial sector output as noted above). This sectoral VMT, *TVMT*, is then aggregated to total freight truck VMT, *VMTDMR*.

$$TVMT_{year,iregn,isec} = TVMT_{year-1,iregn,isec} * \frac{TTONMI_{year,iregn,isec}}{TTONMI_{year-1,iregn,isec}} \quad (218)$$

$$VMTDMDR_{year,iregn} = \sum_{isec} TVMT_{year,iregn,isec} \quad (219)$$

We use several different *annual VMT per vehicle* curves to allocate the above total freight truck VMT demand (V*MTDMDR*) to the various powertrains, size classes, and vehicle ages. These vintaged annual VMT curves, developed from historical data from VIUS and S&P Polk, are read in from *trnhdvx.xlsx*. The curves are then modified over the projection as the adoption of powertrains varies across annual VMT bins. For example, if BEVs are only adopted in the lowest annual VMT bin for Class 8 sleeper cab tractors, with diesel accounting for the remainder of sales, the model would adjust the average VMT for new BEV Class 8 sleeper cabs to be lower than that of new diesel Class 8 sleeper cabs. This ensures a more accurate accounting of energy consumption impacts from diverse fleet purchase decisions. This adjustment is made according to the following steps:

1. Calculate the distribution of sales across annual VMT bins for each size class and powertrain (*temp_stk_vmt_shr*) based on adoption shares and sales from the Freight Truck Sales Component (*fuel_shr_ivmt, TRKSTK_19R*)

$$temp\_stk\_vmt\_shr_{year,icafe19,ivmt,ifuel} = \sum_{iregn}\sum_{iflt}\frac{fuel\_shr\_ivmt_{year,ivmt,iflt,icafe19,ifuel,iregn}}{\sum_{ivmt} fuel\_shr\_ivmt_{year,ivmt,iflt,icafe19,ifuel,iregn}} * TRKSTK\_19R_{year,icafe19,new,ifuel,iflt,iregn} \quad (220)$$

2. Calculate a ratio of the weighted-average annual VMT per vehicle for *each powertrain* – by applying the share weights estimated in (1) above to the overall fleet-average VMT (*VMT_VEH*) – versus the overall average annual VMT per vehicle (*vmt_10yr_avg*).

$$temp\_stk\_vmt\_ratio_{year,icafe19,new,ifuel} = \frac{\sum_{ivmt}\left[temp\_stk\_vmt\_shr_{year,icafe19,ivmt,ifuel} * VMT\_VEH_{ivmt,NEW,icafe19}\right]}{vmt\_10yr\_avg_{icafe19}} \quad (221)$$

3. This ratio is applied to the exogenous base year new-vehicle annual VMT. The adjustment is carried through all vintages as each vehicle cohort ages.

$$ANNVMT\_19_{year,icafe19,new,ifuel} = ANNVMT\_19_{base\_year,icafe19,new,diesel} * temp\_stk\_vmt\_ratio_{year,icafe19,new,ifuel} \quad (222)$$

The resulting annual VMT curves (*ANNVMT_19*) are then adjusted so that the total aggregated VMT aligns with the total freight truck VMT estimated from industrial output (*VMTDMDR*). The adjustment factor *VMTADJR*, which is applied to all annual VMT curves, is calculated as the ratio of projected total VMT (*VMTDMDR*) to calculated VMT from the annual VMT per vehicle curves (*ANNVMT_19*) and truck stocks (*TRKSTK_19R*).

$$VMTADJR = \frac{VMTDMDR_{year}}{\sum_{icafe19}\sum_{iflt}\sum_{ifuel}\sum_{iage}\left[ANNVMT\_19_{year,icafe19,iage,ifuel} * TRKSTK\_19R_{year,icafe19,iage,ifuel,iflt}\right]}$$

$$ANNVMT\_19_{year,:,:,:} = ANNVMT\_19_{year,:,:,:} * VMTADJR \quad (223)$$

Class 2b Commercial Light Truck (CLT) VMT projections are estimated from a different set of indicators, including 1) industrial output from agriculture, mining, construction, and manufacturing sectors; 2) utility service sector output, and 3) household vehicle travel. VMT growth is then estimated based on the ratio of growth in the above indicators (*CLTSIC*) and growth in CLT on-road stocks (*CLTSTK*).

$$ANNVMT\_19_{year,CLT,:,:} = ANNVMT\_19_{year-1,CLT,:,:} * \frac{\frac{CLTSIC_{year}}{CLTSIC_{year-1}}}{\frac{CLTSTK_{year}}{CLTSTK_{year-1}}} \quad (224)$$

Total CLT VMT (*CLTVMT*) is then calculated from the annual VMT per vehicle (*ANNVMT_19*) and vehicle stocks (*CLTSTK*).

$$CLTVMT_{year,ifuel,iage} = \sum_{icafe19=1:2} \left[CLTSTK_{year,ifuel,iage,icafe19} * ANNVMT\_19_{year,icafe19,iage,ifuel}\right] \quad (225)$$

The final VMT values are combined into a single variable (*VMTFLT_19*) for use in energy calculations.

$$VMTFLT\_19_{year,icafe19,iage,ifuel} = ANNVMT\_19_{year,icafe19,iage,ifuel} * \sum_{iflt} TRKSTK\_19R_{year,icafe19,iage,ifuel,iflt} \quad (226)$$

Estimating fuel consumption (*TRUCK_FUEL*)

Fuel consumption in gasoline- or diesel-gallons equivalent (*FUELDMDR*)[43] is calculated by dividing VMT (*VMTFLTR*) by on-road fuel economy (*HDV_MPG*). The impact of truck platooning is accounted for via the share of miles that are platooned (*VMTFLTR_CAV_SHR*) and the fuel economy improvement over those miles (*HDV_MPG_CAV_ADJ*).

$$FUELDMDR_{year,isc,ifuel,iflt,iregn} = \sum_{iage=1}^{34} (1 - VMTFLTR\_CAV\_SHR) * \frac{VMTFLTR_{year,isc,iage,ifuel,iflt,iregn}}{HDV\_MPG_{year,isc,iage,ifuel}} + VMTFLTR\_CAV\_SHR * \frac{VMTFLTR_{year,isc,iage,ifuel,iflt,iregn}}{\frac{HDV\_MPG_{year,isc,iage,ifuel}}{1 - HDV\_MPG\_CAV\_ADJ}} \quad (227)$$

Fuel consumption is then aggregated from powertrain fuel type to highway fuel type and is then converted from gallon equivalent to trillion Btu. This conversion requires multiplying by *HRATE*, the heat rate of gasoline or diesel

$$FUELBTUR_{isc,ifuel,iflt,iregn} = FUELDMDR_{isc,ifuel,iflt,iregn} * HRATE_{isc,ifuel} * PCT\_VMT_{ifuel,ifuel7,iregn} \quad (228)$$

where

$FUELBTUR_{isc,ifuelifuel7,iflt,iregn}$ = total fleet truck fuel consumption by market class, fuel type, and region in trillion Btu;

$PCT\_VMT_{ifuel,ifuel7,iregn}$ = percentage of VMT traveled on each highway fuel (*ifuel7*) used in bi-fuel powertrains: flex-fuel (gasoline/ethanol) or plug-in hybrid electric (gasoline/electric or diesel/electric); and

ifuel7 = index for freight truck fuel type.

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[43] Freight truck fuels tracked in gasoline-gallons equivalent: gasoline, LPG, CNG, E85, and PHEV gasoline. Fuels tracked in diesel-gallons equivalent: diesel, LNG, electric, PHEV diesel, and hydrogen.

Rail Freight Component

Rail projections use a simpler version of the freight truck approach, in that only one class of freight rail and vehicle technology is considered (Figure 16). Projections of energy use by rail are driven by projections of coal production and of ton-miles traveled for each of the industrial categories used in the trucking sector. The algorithm used to estimate energy consumption of rail freight is similar to the one used for trucks and is calculated in the following steps.

First, project the growth of coal rail freight ton-miles by census division using coal ton-mile demand endogenously estimated in the NEMS coal submodule (*TTONMILE*).

$$RPROJ\_CTONMI_{year,iregn} = RPROJ\_CTONMI_{year-1,iregn} * \left(1 + \left[\frac{TTONMILE_{year} - TTONMILE_{year-1}}{TTONMILE_{year-1}}\right]\right) \quad (229)$$

Next, project the growth of non-coal rail freight ton-miles by census division and industrial sector

$$RPROJ\_NCTONMI_{year,iregn,isic} = \left(\frac{TSIC_{iregn,isic,year}}{1000}\right) * RTM\_OUTPUT_{iregn,isic}, \quad (230)$$

where

$RPROJ\_NCTONMI_{year,iregn,isic}$ = rail ton-miles traveled for non-coal in a given year;

$RTM\_OUTPUT_{iregn,isic}$ = rail ton-miles traveled per dollar of industrial output, *ISIC=1,16*; and

$TSIC_{iregn,isic,year}$ = value of output of industry *ISIC*, in base year dollars.

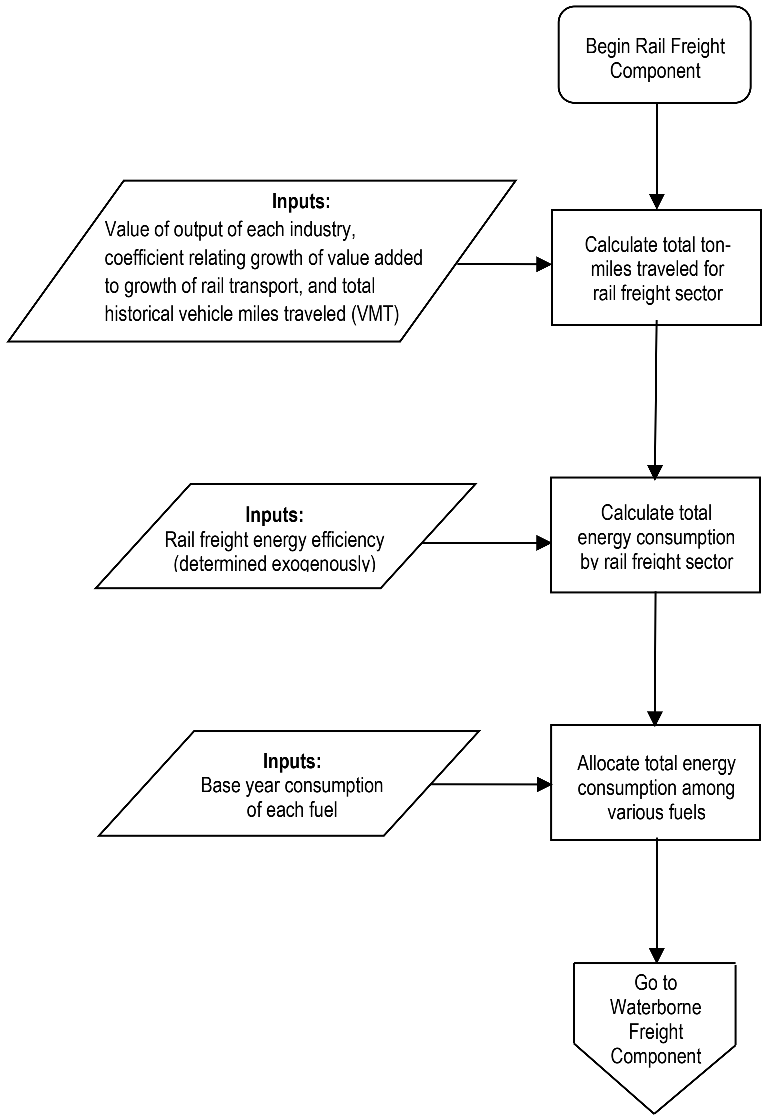
Calculate aggregated rail ton-miles traveled, *RTMTT*, as follows

$$RTMTT_{year,iregn} = \sum_{iregn=1}^{9} \sum_{isic=1}^{16} RPROJ\_NCTONMI_{year,iregn,isic} + \sum_{REG=1}^{9} RPROJ\_CTONMI_{year,iregn}, \quad (231)$$

Energy consumption (*TQFRAILT*) is then estimated using the projected rail energy efficiency *FREFF*.

$$TQFRAILT_{year,iregn} = RTMTT_{year,iregn} * FREFF_{year}, \quad (232)$$

Figure 16. Rail Freight Component for the Transportation Sector Demand Module, NEMS



Data source: U.S. Energy Information Administration

Rail efficiency gains resulting from technological development and increased system efficiency are based on an exogenous analysis of trends. To estimate the demand for the various fuels used for rail transport, the potential to switch from diesel to LNG based on cost-effectiveness is calculated. The net present value of switching to LNG is calculated by the following

$$NPV\_LNG_{year} = \frac{ANN\_FUEL\_SAVINGS_{PAYBK=1}}{1+DISCRT} + \frac{ANN\_FUEL\_SAVINGS_{PAYBK}}{1+DISCRT^{PAYBK}}, \qquad (233)$$

where

NPV_LNG_{year} = net present value of switching to LNG in year*, Year*;

ANN_FUEL_SAVINGS = annual fuel savings from switching to LNG from diesel;

DISCRT = discount rate for freight locomotives; and

PAYBK = payback period demanded for freight railroads.

If the net present value of switching to LNG is greater than the freight locomotive incremental cost, then the LNG fuel share is determined by the maximum LNG penetration. If the net present value is less than the incremental cost, the LNG fuel share maintains at previous year values. Fuel consumption (*TQRAILR*) is then allocated to each region using fuel share *RAIL_FUEL_SHR*.

$$TQRAILR_{Rail\_Fuel,iregn,year} = TQFRAILR_{iregn,year} * RAIL\_FUEL\_SHR_{Rail\_Fuel,year}, \qquad (234)$$

Waterborne Freight Component

Two classes of waterborne freight transportation are considered in this component: domestic marine traffic and freighters conducting foreign trade (Figure 17). This method is useful because vessels that make up freighter traffic on rivers and in coastal regions have different characteristics than those that travel in international waters.

Domestic marine

The estimate of total domestic waterborne transportation demand is driven by projections of industrial output and a measure of ton-mile per dollar of industrial output, as defined by

$$STMTT_{iregn,year} = \sum_{isic=1}^{16} TSIC_{iregn,isic.year} * DSTM_{OUTPUT}{}_{iregn,isic} * \left(1 + ANN_{DECLINE}{}_{year}\right) \qquad (235)$$

where

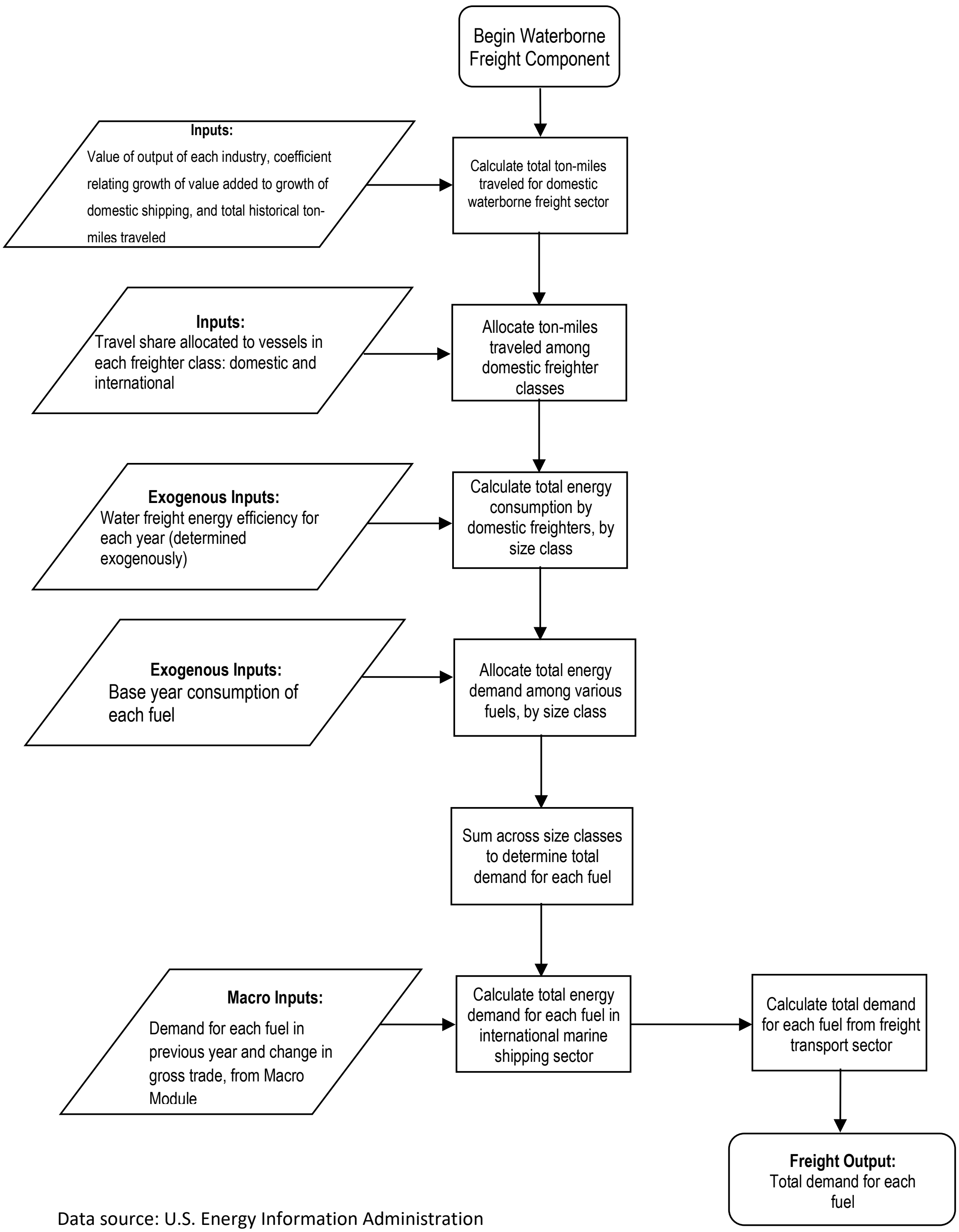
$STMTT_{iregn,year}$ = total ton-miles of waterborne freight by census division in year, *Year*;

$TSIC_{iregn,isic,year}$ = value of industrial output, *ISIC*, in base year dollars;

$DSTM\_OUTPUT_{iregn,isic}$ = domestic marine ton-mile per dollar of industrial output; and

$ANN\_DECLINE_{year}$ = domestic marine annual rate of ton-mile per dollar output decline.

Figure 17.Waterborne Freight Component for the Transportation Sector Demand Module, NEMS



Data source: U.S. Energy Information Administration

Energy use is subsequently estimated, using average energy efficiency

$$TQDSHIPT_{year,iregn} = STMTT_{year,iregn} * DSEFF_{year} \text{ ,} \tag{236}$$

where

$TQDSHIPT_{year,iregn}$ =domestic ship energy demand (thousand Btu) by census division; and

$DSEFF_{year}$ = average fuel efficiency, in thousand Btu per ton-mile.

Estimated changes in energy efficiency are exogenous. The next step in the component is allocating total energy consumption among four fuel types (distillate fuel, residual fuel oil, CNG, and LNG) using domestic shipping shares

$$TQDSHIPR_{Ship\_Fuel,iregn,year} = TQDSHIPT_{iregn,year} * DOMSHIP\_FUEL\_SHR_{Ship\_Fuel,year}, \tag{237}$$

where

$TQDSHIPR_{Ship\_Fuel,iregn,year}$ = total regional domestic ship energy demand, by fuel and census division;

$DOMSHIP\_FUEL\_SHR_{Ship\_Fuel,year}$ = domestic shipping fuel share; and

Ship_Fuel = index referring to the four shipping fuel types.

The factor that allocates energy consumption among the four fuel types is based on 2006 data[44] for distillate and residual fuel. Starting in 2013, LNG is allowed to penetrate the domestic shipping fuel demand, and therefore it reduces the share of both distillate and residual fuel throughout the projection period.

International marine

Fuel demand in international marine shipping is directly estimated, linking the level of international trade with the lagged consumption of the fuel in question as follows

$$ISFDT_{year} = ISFDT_{year-1} + 0.5 * ISFDT_{year-1} * \left[\frac{GROSST_{year}}{GROSST_{year-1}} - 1\right], \tag{238}$$

where

$ISFDT_{year}$ = total international shipping energy demand in year *Year*; and

$GROSST_{year}$ = value of gross trade (imports and exports), from the Macroeconomic Activity Module.

Total energy demand is then allocated among the four fuels by the following

$$ISFD_{Ship\_Fuel,year} = ISFDT_{year} * INTSHIP\_FUEL\_SHR_{Ship\_Fuel,year}, \tag{239}$$

[44] Oak Ridge National Laboratory, *Transportation Energy Data Book Edition 28*, June 2009.

where

$ISFD_{Ship\_Fuel,year}$ = international freighter energy demand, by fuel; and

$INTSHIP\_FUEL\_SHR_{Ship\_Fuel,year}$ = international shipping fuel share.

Regional fuel consumption is then calculated as

$$TQISHIPR_{Ship\_Fuel,iregn,year} = ISFD_{Ship\_Fuel,year} * SEDSHRXX_{iregn,year}, \quad (240)$$

where

$TQISHIPR_{Ship\_Fuel,iregn,year}$ = total regional energy demand by international freighters; and

$SEDSHRXX_{iregn,year}$ = regional share of fuel demand, from SEDS, by fuel, XX=DS (distillate), XX=RS (residual).

Emission Control Area (ECA) marine fuel

The North American ECAs generally extend 200 nautical miles (nm) from U.S. and Canadian ports (50 nm for the U.S. Caribbean ECA). TDM estimates a 2012 baseline of fuel consumption (by billion British thermal units [Btu]) for ships traveling in each of the nine U.S. census divisions and Puerto Rico. Projections include auxiliary power and account for ship efficiency improvements, shipping demand changes, and fuel price fluctuations.

Baseline (2012) energy demand is estimated by the following

$$FUELCONS_{2012,class,iregn} = TRANSITFUELCONS_{2012,class,iregn} + AUXFUELCONS_{2012,class,iregn}, \quad (241)$$

The fleet turnover (*FLEETTO*) variable was computed from MARAD data to represent the rate new vessels are introduced into the fleet moving through the North American ECA. The new vessels are assumed to be more efficient than their predecessors.

Projections of ECA energy demand are estimated by the following

$$ECAFUELCONS_{iregn,year} = \sum_{class}\Big(FUELCONS_{2012,class,iregn} * MAX[0,1-(year-2012) * FLEETTO_{class}] * FUELCONS_{2012,class,iregn} * \{1 - MAX[0,1-(year-2012) * FLEETTO_{class}]\} * [1 - EFFINC_{class}]^{0.5*(year-2012)} * GEEFFECTS_{class,year}\Big), \quad (242)$$

where

$FLEETTO_{class}$ = vessel fleet turnover, by vessel class;

$EFFINC_{class}$ = marine fuel efficiency improvement, by vessel class;

$GEFFECTS_{class,year}$ = fuel consumption from the various vessel classes may be directly related to AEO scenario outputs, imports of petroleum and products, by class and year; and class = tanker, container, gas (LPG/LNG), roll-on/roll-off, bulk, or general cargo.

ECA fuel shares are revised each year based on changes in fuel prices since the base year. The fuel sharing is calculated using a logit formulation. The fuel sharing equation for each vessel *CLASS* is as follows

$$FLTPROF_{mftype,iregn,year} = \frac{P_{mftype}^{alpha} * beta_{mftype}}{\sum_{mftype} P_{mftype}^{alpha} * beta_{mftype}}, \quad (243)$$

ECA fuel demand, by fuel type, is incorporated into international marine fuel demand (TQISHIPR).

Miscellaneous Energy Demand Submodule

The Miscellaneous Energy Demand (MED) Submodule addresses the projection of demand for several transportation fuels and sums total energy demand from all end-use categories (Figure 18). These categories include military operations, mass transit (passenger rail and buses), recreational boating, and lubricants used in all modes of transportation.

Military Demand Component

In the Military Demand Component, fuel demand for military operations is considered to be proportional to the projected military budget (Figure 19). The fractional change in the military budget is first calculated as follows

$$MILTARGR_{year} = \frac{MC\_GFMLR_{year}}{MC\_GFMLR_{year-1}}, \quad (244)$$

where

$MILTARGR_{year}$ = growth in the military budget from the previous year; and

MC_GFMLR_{year} = total defense purchases in year, *Year*, from the Macroeconomic Activity Module.

Total consumption of each of four fuel types is then determined by

$$MFD_{Mil\_Fuel,year} = MFD_{Mil\_Fuel,year-1} * MILTARGR_{year}, \quad (245)$$

where

$MFD_{Mil\_Fuel,year}$ = total military consumption of the considered fuel in year, *Year*; and

Mil_Fuel = index of military fuel type: 1=Distillate, 2=Jet Fuel(Naptha), 3=Residual, 4=Jet Fuel(Kerosene).

Consumption is finally distributed among the nine census divisions by the following equation

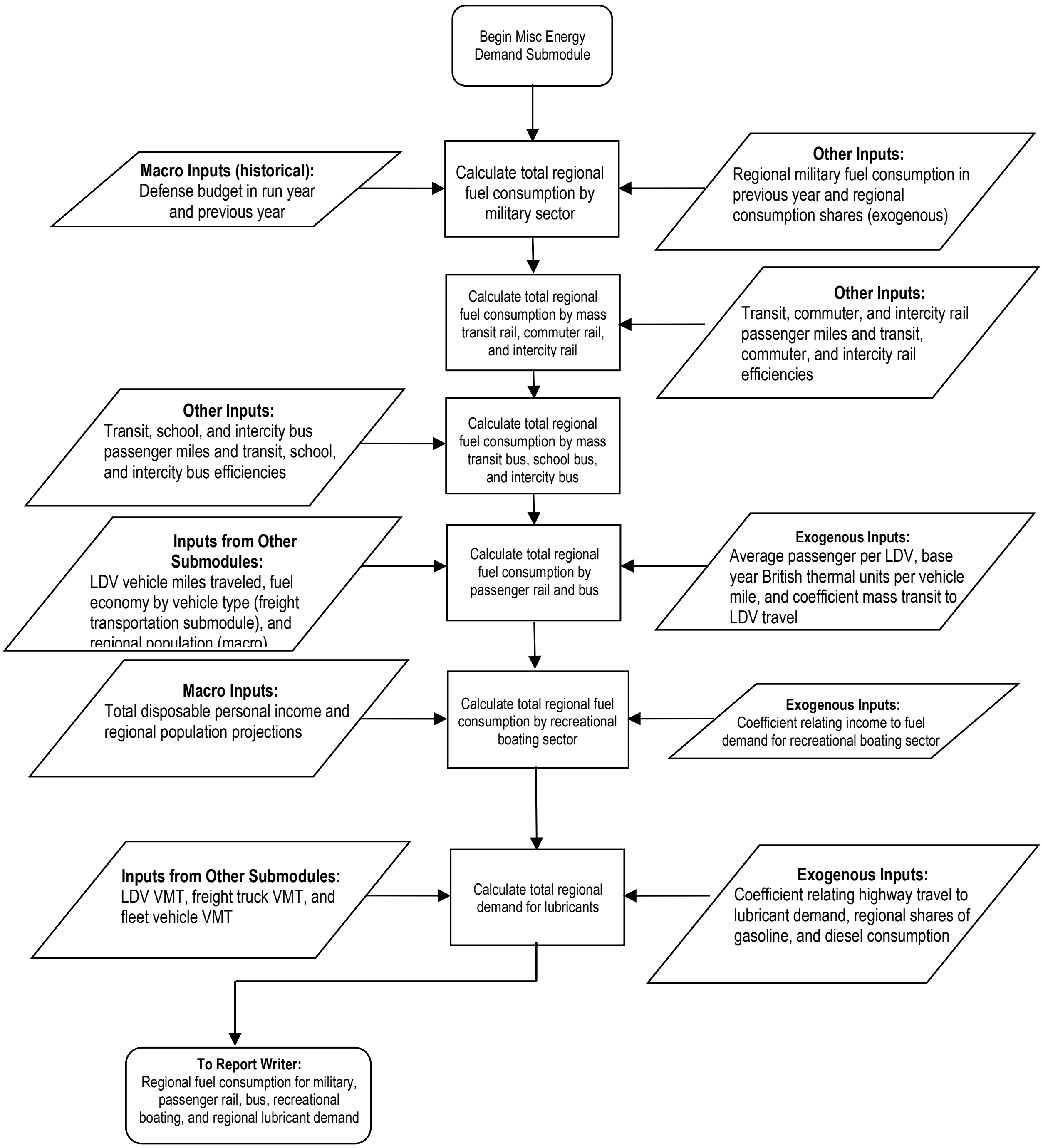
$$QMILTR_{Mil\_Fuel,iregn,year} = MFD_{Mil\_Fuel,year} * MILTRSHR_{Mil\_Fuel,iregn,year}, \quad (246)$$

where

$QMILTR_{Mil\_Fuel,iregn,year}$ = regional fuel consumption, by fuel type, in Btu; and

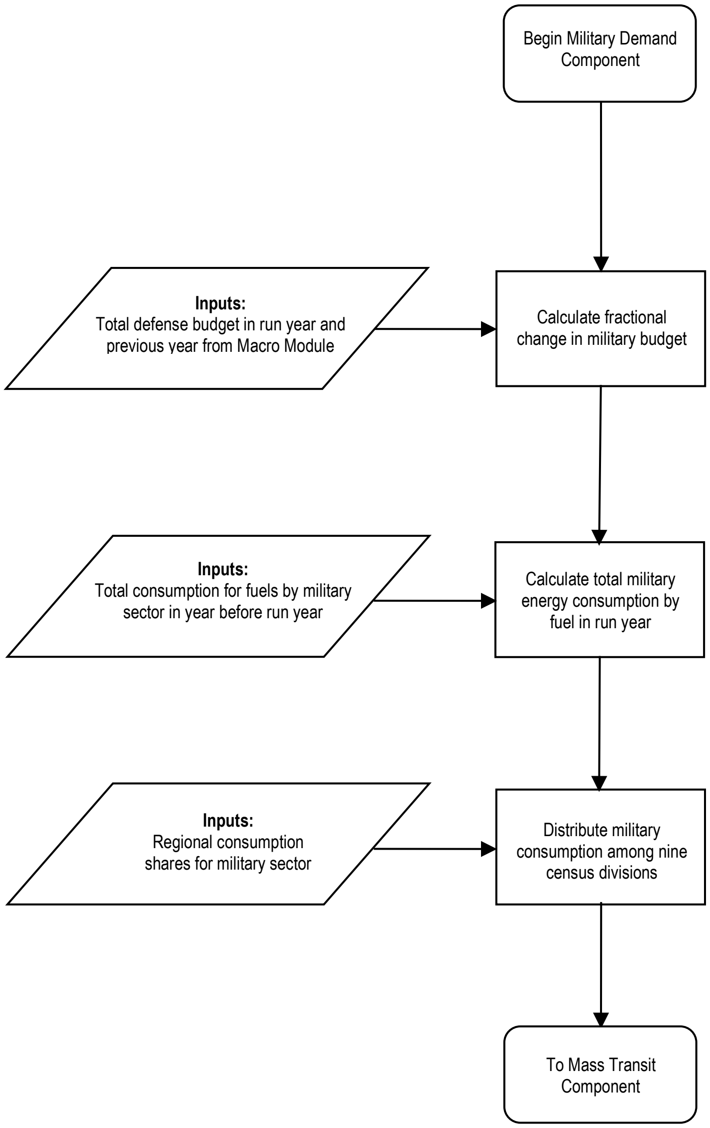
$MILTRSHR_{Mil\_Fuel,iregn,year}$ = regional consumption shares, from 1991 data, held constant.

Figure 18. Miscellaneous Energy Demand Submodule for the Transportation Sector Demand Module, NEMS



Data source: U.S. Energy Information Administration

Figure 19. Military Demand Component in the Transportation Demand Module, NEMS



Data source: U.S. Energy Information Administration

Mass Transit Demand Component

The growth of passenger-miles in each mode of mass transit is assumed to be proportional to the growth of passenger-miles in light-duty vehicles. Changes to the Mass Transit Demand Component reflect passenger travel and energy demand by census division in the regional transit rail, regional commuter rail, and the regional intercity rail models (Figure 20). For each of these rail transit modes, the passenger-miles traveled, historical efficiencies, and travel demand log of income are read in. The sum of the three rail modes is captured by the following equation

$$QMTRR_{ifuel,iregn,year} = TRED_{iregn,year} + CREDE_{iregn,year} + IREDER_{iregn,year} \ , \qquad (247)$$

where

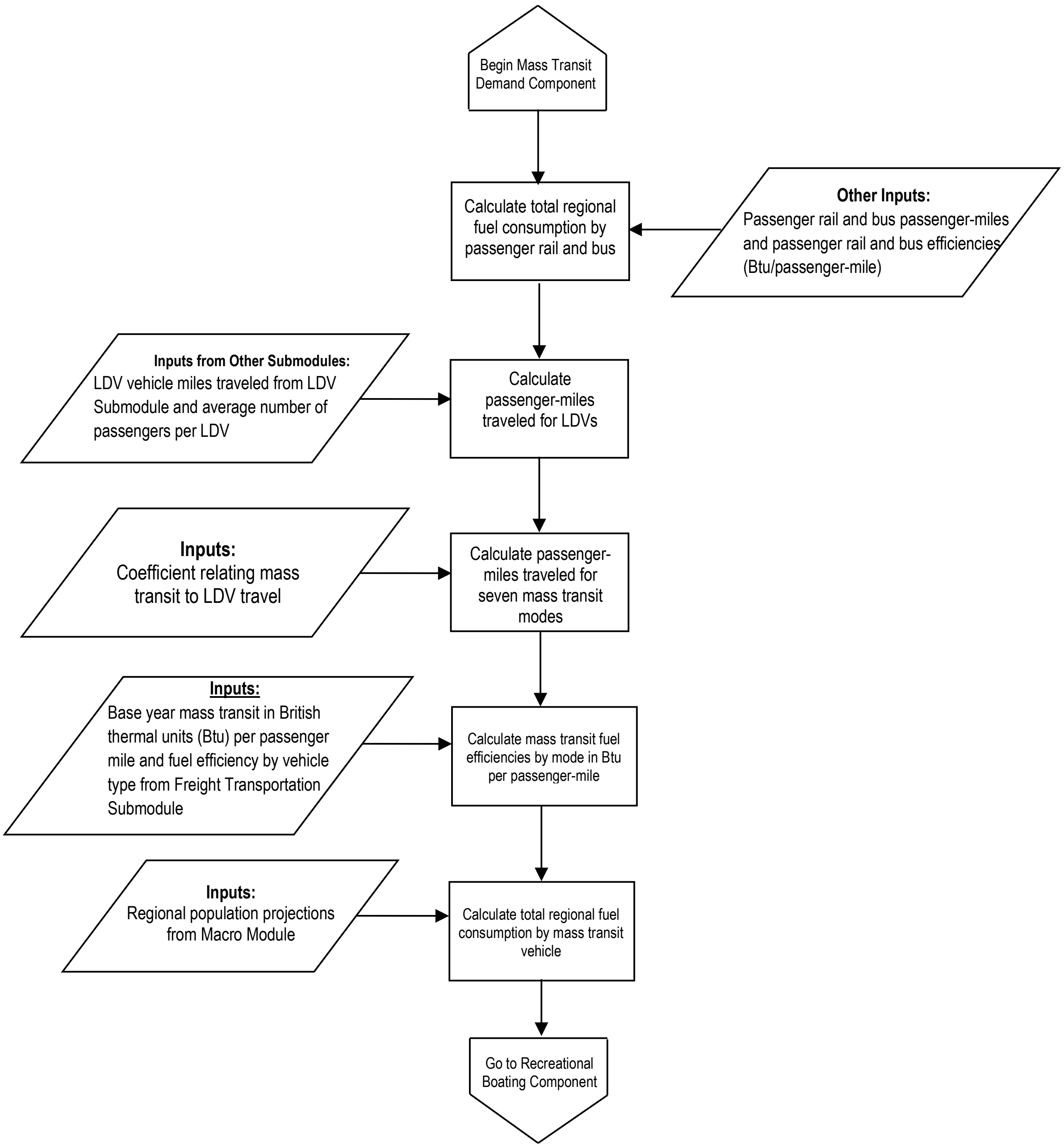
$QMTRR_{ifuel,iregn,year}$ = passenger rail energy demand by fuel by census division;

$TRED_{iregn,year}$ = transit rail energy demand by census division;

$CREDE_{iregn,year}$ = commuter rail energy demand by census division; and

$IREDER_{iregn,year}$ = intercity rail energy demand by census division.

Figure 20. Mass Transit Demand Component for the Transportation Sector Demand Module, NEMS



Data source: U.S. Energy Information Administration

The first set of equations describes the bus segment of the component for the transit bus mode

$$TBPMT_{iregn,year} = TBPMTPC_{iregn,yearn} * nonfarmemp_{iregn,year} - CAV\_ADJ_{iregn,year}, \quad (248)$$

where

$TBPMT_{iregn,year}$	=	passenger-miles traveled for the transit bus mode;
$TBPMTPC_{iregn,year}$	=	passenger-miles traveled per capita for the transit bus mode;
$nonfarmemp_{iregn,year}$	=	U.S. non-farm employment; and
$CAV\_ADJ_{iregn,year}$	=	change in travel demand as a result of ride hailing.

Fuel efficiencies, in Btu per vehicle mile, are obtained from the Freight Submodule for buses (*TBSYSEFF*). Mass transit efficiencies in Btu per passenger-mile (*TBBTUPM*) are calculated as

$$\begin{aligned} TBBTUPM_{iregn,year} &= TBBTUPM_{iregn,year-1} * TBSYSEFF_{iregn} * 1 \\ &- \left(\left(1 - \left(\frac{TRFTMPG_{year-1}}{TRFTMPG_{year}}\right) * TBFSHR_{iregn,ifuel=diesel,year}\right)\right) * 1 \\ &+ \left(\left(TBFSHR_{iregn,ifuel=CNG,year} - TBFSHR_{iregn,ifuel=CNG,year-1}\right) * 0.25\right) \quad (249) \end{aligned}$$

where

$TRFTMPG_{year}$ = freight mpg, by vehicle type, from the Freight Transportation Module;

$TBFSHR_{iregn,ifuel,year}$ = projected fuel share for transit buses, by fuel type.

Total consumption *QMTBR* is calculated and distributed among regions according to their populations.

$$QMTBR_{im,ifuel,iregn,year} = TBPMT_{iregn,year} * TBBTUPM_{iregn,year} * TBFSHR_{iregn,ifuel,year} \quad (250)$$

The following equations describe the model for intercity and school bus passenger-mile demand (*TMOD*), which is based on gdp per capita (*MC_GDPR* and population *MCNP16A*) for intercity and child population for school. Each also uses an exogenously defined variable representing the recovery in travel after the 2020 COVID pandemic related shutdowns (*TMCOVID*).

$$\begin{aligned} TMOD_{intercity,year} &= \left(X1_{intercity} + X2_{intercity} * \frac{MC\_GDPR_{year}}{MC\_NP16A_{year}}\right) * MC\_NP16A_{year} * (1 - (X3_{intercity} \\ &* TMCOVID_{intercity,year} \end{aligned}$$

$$\begin{aligned} TMOD_{school,year} = (X1_{school} + year * X2_{school}) * \left(MC\_NP_{year} - MC\_NP16A_{year}\right) * (1 - \\ (X3_{school} * TMCOVID_{school,year}) \quad (251) \end{aligned}$$

where

X = equation coefficients for intercity and school bus passenger miles.

Fuel efficiencies in Btu per vehicle mile (*TMEFF*) are obtained from the Freight Transportation Submodule for buses and rail and mass transit efficiencies, in Btu per passenger-mile, are calculated as

$$TMEFF_{im,year} = TMEFF_{im,year-1} * BUSSYSEF_{im} * 1 - \left(\left(1 - \left(\frac{TRFTMPG_{year-1}}{TRFTMPG_{year}}\right) * QMODFSHR_{im,ifuel=diesel,year}\right)\right) * 1 + \left(\left(QMODFSHR_{im,ifuel=CNG,year} - QMODFSHR_{im,ifuel=CNG,year-1}\right) * 0.25\right) \quad (252)$$

where

$BUSSYSEF_{im}$ = bus system efficiency by mode, in Btu per passenger.

Total fuel consumption is calculated and distributed among regions based on population shares (*MC_NP*)

$$QMTBR_{IM,ifuel,iregn,year} = TMOD_{IM,year} * TMEFF_{IM,year} * \frac{MC\_NP_{iregn,year}}{\sum_{iregn=1}^{9} MC\_NP_{iregn,year}} * QMODFSHR_{IM,ifuel,iregn}, \quad (253)$$

where

$QMODFSHR_{IM,ifuel,iregn}$ = projected fuel share for intercity and school buses, by fuel type

Recreational Boating Demand Component

The growth in fuel use by recreational boats (*RBEDPC*) is related to the growth in GDP per capita (*MC_GDPR* divided by population *MC_NP16A*). Initially, the recreational boating fuel consumption per capita is estimated for all years and is used subsequently to determine the national and regional fuel consumption for this activity (Figure 21). The following equations describe the model used

$$RBEDPC_{gasoline,year} = \frac{MC\_GDPR_{year}}{MC\_NP16A_{year}} * X1 * e^{X2*year} * X3 * e^{X4*year},$$

$$RBEDPC_{diesel,year} = \frac{MC\_GDPR_{year}}{MC\_NP16A_{year}} * X1 * e^{X2*year} * X5 \quad (254)$$

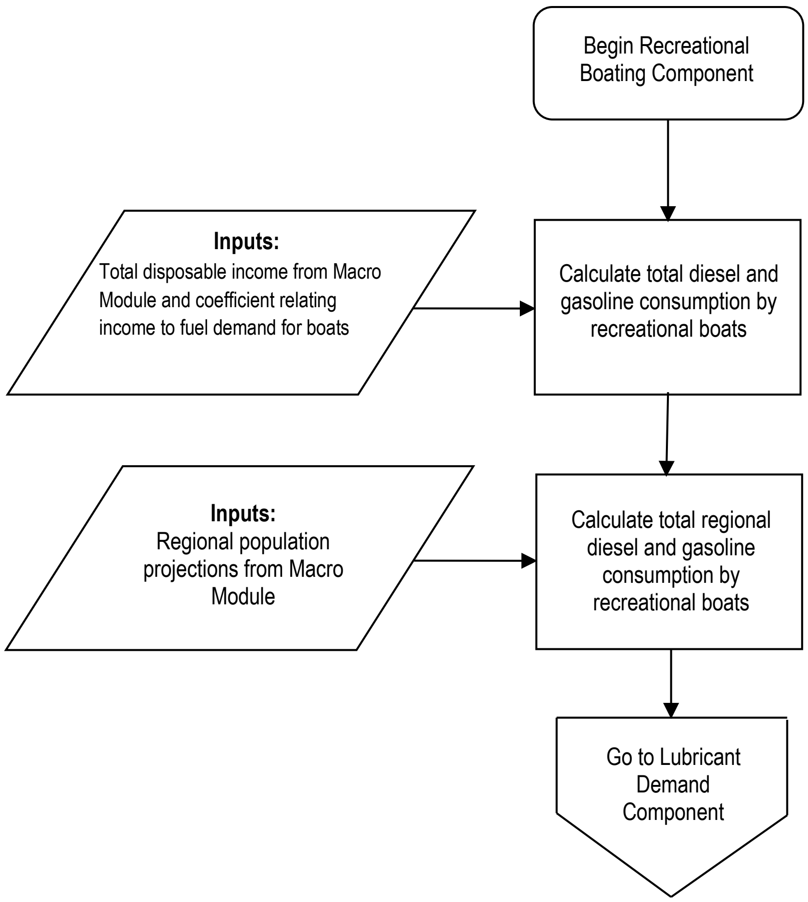
where

X1-X5 = consumption equation coefficients.

Consumption is then regionalized (*QRECR*) using population shares (*MC_NP*)

$$QRECR_{ifuel,iregn,year} = RBEDPC_{ifuel,year} * \frac{MC\_NP_{iregn,year}}{\sum_{iregn=1}^{9} MC\_NP_{iregn,year}}, \quad (255)$$

Figure 21. Recreational Boating Demand Component for the Transportation Sector Demand Module, NEMS



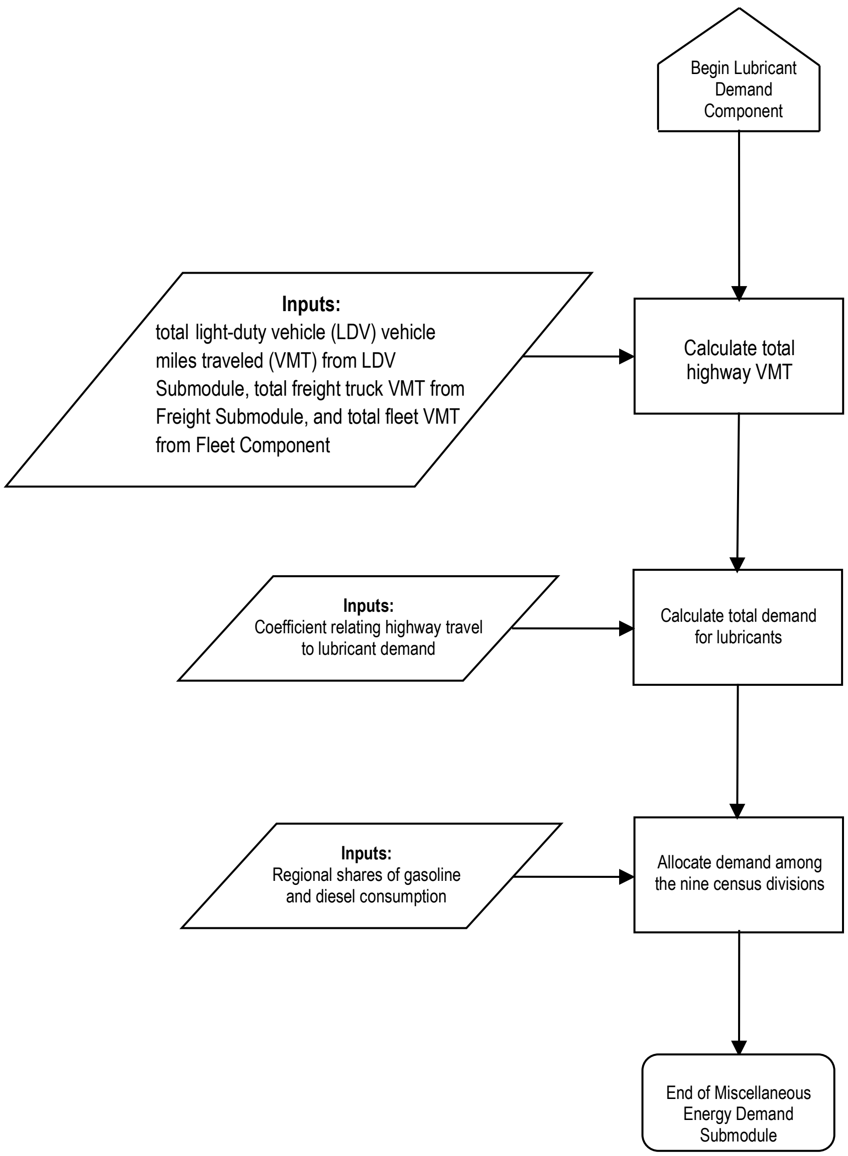
Data source: U.S. Energy Information Administration

Lubricant Demand Component

The growth in demand for lubricants is considered to be proportional to the growth in highway travel by all types of vehicles (Figure 21). Total highway travel (*HYWAY*) is first determined from total household light-duty VMT (*VMTHH*), total freight truck VMT (*FTVMT*), and total fleet vehicle VMT (*FLTVMT*).

$$HYWAY_{year} = \sum VMTHH_{year} + FTVMT_{year} + \sum FLTVMT_{year}, \tag{256}$$

Figure 22. Lubricant Demand Component for the Transportation Sector Demand Module, NEMS



Data source: U.S. Energy Information Administration

Lubricant demand *LUBFD* is then estimated based on the following

$$LUBFD_{year} = LUBFD_{year-1} * \left[\frac{HYWAY_{year}}{HYWAY_{year-1}}\right]^{BETALUB}, \quad (257)$$

where

BETALUB = constant of proportionality, relating highway travel to lubricant demand.

The lubricant demand is allocated to regions by a regional weighting of all types of highway travel as follows

$$QLUBR_{iregn,year} = LUBFD_{year} * \left[\frac{(\sum VMTHH_{year})*SHRMG_{iregn,year}+(\sum FTVMT_{year})*SHRMG_{iregn,year}+FTVMT_{year}*SHRDS_{iregn,year}}{HYWAY_{year}}\right], \quad (258)$$

where

$QLUBR_{iregn,year}$ = regional demand for lubricants in year,*Year*, in Btu;

$SHRMG_{iregn,year}$ = regional share of motor gasoline consumption, from SEDS; and

$SHRDS_{year}$ = regional share of diesel consumption, from SEDS.

Appendix A. Model Abstract

Model name

Transportation Sector Demand Module (TDM)

Description

The TDM is part of NEMS and incorporates an integrated modular design that is based on economic, engineering, and demographic relationships that model transportation sector energy consumption at the census division level. The TDM is made up of the following submodules:

1. Light-Duty Vehicles (including light-duty household and fleet vehicles)
2. Air Travel
3. Freight Transportation (Class 3-8 freight trucks, Class 2b commercial light trucks, rail, and marine)
4. Miscellaneous Energy Demand (military, mass transit, and recreational boats)

The model provides sales estimates of 2 conventional and 14 alternative fuel light-duty vehicles and consumption estimates of 12 fuel types.

Purpose of the model

As a component of the National Energy Modeling System, the transportation model generates projections (through 2050) of transportation sector energy consumption. The transportation model facilitates policy analysis of energy markets, technological development, environmental issues, and regulatory development as they affect transportation sector energy consumption.

Documentation

Model Documentation Report: Transportation Sector Demand Module of the National Energy Modeling System, DOE/EIA-M070 (2025), August 2025.

Energy system described

Domestic transportation sector as well as international aviation and marine energy consumption.

Coverage

1. Geographic: nine census divisions: New England, Middle Atlantic, East North Central, West North Central, South Atlantic, East South Central, West South Central, Mountain, and Pacific
2. Time unit/frequency: annual, 1995 through 2050
3. Products: motor gasoline, aviation gasoline, diesel (distillate), residual oil, electricity, jet fuel, LPG, CNG, LNG, methanol, ethanol, hydrogen, lubricants, and pipeline fuel
4. Economic sectors: projections are produced for personal and commercial travel, freight trucks, railroads, domestic and international marine, aviation, mass transit, and military use

Independent expert reviews conducted

- Independent Expert Review of Transportation Sector Component Design Report, June, 1992, conducted by David L. Greene, Oak Ridge National Laboratory.

- Report of Findings on the NEMS Freight Transport Model, April 3, 2001, by David L. Greene, Oak Ridge National Laboratory.
- Report of Findings, NEMS Freight Transport Model Review, April 4, 2001, by Mike Lawrence, Laurence O'Rourke, Jack Faucett Associates.
- Independent Evaluation of EIA's Freight Transportation Model, Draft Report, April 11, 2001, by James S. Moore, Jr. P.E. TA Engineering, Inc.

DOE input sources:

1. State Energy Data (SEDS), June 2022
2. Short-Term Energy Outlook, December 2024
3. Macroeconomic Activity Module Inputs: new vehicle sales, economic and demographic indicators, and defense spending
4. NEMS supply models: fuel prices

Non-DOE input sources:

1. U.S. Department of Transportation, Bureau of Transportation Statistics: Air Carrier Summary Data, various years
2. Jet Information Services Inc., World Jet Inventory: Year-End, various years.
3. Federal Highway Administration, Highway Statistics Series, various years.
4. Oak Ridge National Laboratory, Transportation Energy Data Book, various years.
5. Department of Commerce, Bureau of the Census, Vehicle Inventory and Use Survey 2002, December 2004.
6. Department of Commerce, Bureau of the Census, Vehicle Inventory and Use Survey 2021, December 2023.
7. U.S. Environmental Protection Agency, Engines and Vehicles Compliance Information System, various years.
8. U.S. Department of Transportation, National Highway Traffic Safety Administration, Corporate Average Fuel Economy Standards for Model Years 2024–2026 Passenger Cars and Light Trucks; Federal Register Vol. 87, No. 84, Monday, May 2, 2022.
9. U.S. Department of Transportation, National Highway Traffic Safety Administration, CAFE Standards for MYs 2027–2031 Passenger Cars and Light Trucks; Federal Register Vol. 89, No. 121, Monday, June 24, 2024.
10. U.S. Environmental Protection Agency, Revised 2023 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions Standards; Federal Register Vol. 86, No. 248, Thursday, December 30, 2021.
11. U.S. Environmental Protection Agency, Multi-Pollutant Emissions Standards for Model Years 2027 and Later Light-Duty and Medium-Duty Vehicles; Federal Register Vol. 89, No. 76, Thursday, April 18, 2024.
12. S&P Polk, National Vehicle Population Profile, various years.
13. S&P Polk, Trucking Industry Profile, various years.
14. Federal Highway Administration , Freight Analysis Framework, 2017
15. Federal Transit Administration, National Transit Database, various years

Appendix B. Acronyms

Acronym
AEO2025: *Annual Energy Outlook 2025*
AFV: alternative fuel vehicle
AFVADJ: alternative fuel vehicle adjustment subroutine
ASM: available seat miles
ATPZEV: advanced technology partial zero emission vehicle
ATV: advanced technology vehicle
Btu: British thermal units
CAV: connected and automated vehicle
CFS: Commodity Flow Survey
CNG: compressed natural gas
CVCC: Consumer Vehicle Choice Component
CAFE: corporate average fuel economy
$/kWh: dollars per kilowatthour
$/kW: dollars per kilowatt
DOT: Department of Transportation
RPMD: domestic revenue passenger-miles
EV: electric vehicle
EV100: electric vehicle with less than or equal to 150 miles driving range
EV200: electric vehicle with between 151 and 250 miles driving range
EV300: electric vehicle with greater than 250 miles driving range
ECA: Emission control area
EPACT1992: Energy Policy Act of 1992
EPA: Environmental Protection Agency
FAF: Freight analysis framework
FC: fuel cell
FCEV: fuel cell electric vehicle
FCHEV: fuel cell hybrid electric vehicle (battery-dominant)
FHWA: Federal Highway Administration
FFV: flex-fuel vehicle
FTSAC: freight truck stock adjustment component
GDP: gross domestic product
GVWR: gross vehicle weight rating
HAV: highly automated vehicle (subset of CAV)
HEV: hybrid electric vehicle
ICE: internal combustion engine
kWh: kilowatthour
RPMI: international revenue passenger-miles
LNG: liquefied natural gas
LDV: light-duty vehicle

LPG: liquefied propane gas
LEV: low-emission vehicle
MTCC: Manufacturers Technology Choice Component
mpg: miles per gallon
MEDS: Miscellaneous Energy Demand Submodule
NEMS: National Energy Modeling System
NHTSA: National Highway Traffic Safety Administration
NiMH: nickel metal hydride
PHEV: plug-in hybrid electric vehicle
PHEV20: plug-in hybrid electric vehicle with 10 miles all electric range
PHEV50: plug-in hybrid eletric vehicle with 40 miles all electric range
REG: census division
R&D: research and development
RPM: revenue passenger-miles
RTM: revenue ton-miles
SMD: seatmiles demanded
SUV: sport utility vehicle
SEDS: State Energy Data System
TMT: ton-miles traveled
ULEV: ultra-low-emission vehicle
VIUS: Vehicle and Inventory Use Survey
VMT: vehicle miles traveled
VMTC: Vehicle Miles Traveled Component
ZEV: zero-emission vehicle

Appendix C. Details of Subroutines Used in the Model

A flowchart of the calls made by the TDM is provided in the Figures below. They show the first level subroutines on the left side and the subsequent calls made by the first level subroutine in the second, third, and fourth levels. A description of each of these subroutines, is also provided in this section. TRAN is a subroutine that is called by the NEMS main module several times. To optimize the convergence time for the solution, some of the subroutines that provide data for TRAN subroutine are only called once. These subroutines include READNHTSA, READHIST, and READSTOCK.

SUBROUTINE: TRAN

Description: The NEMS transportation model encompasses a series of semi-independent modules that address different aspects of the transportation sector. Projections are generated through separate consideration of energy consumption within the various modes of transport, including private and fleet light-duty vehicles; aircraft; marine, rail, and truck freight; and various modes with minor overall impacts such as mass transit and recreational boating. The model also provides projections of selected intermediate values that are generated to determine energy consumption. These elements include estimates of passenger travel demand by light vehicle, air, or mass transit; estimates of the efficiency with which that demand is met; projections of vehicle stocks and the penetration of new technologies; and estimates of the demand for freight transport that are linked to projections of industrial output. The NEMS TDM consists of four submodules developed to represent a variety of travel modes that are very different in design and use, except for their intended purpose of conveying passengers or freight, or both. The four submodules are Light-Duty Vehicle, Air Travel, Freight Transportation (heavy truck, commercial light truck, rail, and marine), and Miscellaneous Energy Demand.

Called by: NEMS Main Module

Calls: READLDV; READSTOCK; TMAC; NEWLDV; TMPGNEW; TREG; TFLTSTKS; FLTHAV; TFLTVMTS; TSMOD; TMPGSTK; TCURB; TFLTMPGS; TFLTCONS; TRANFRT; TVMT; TMPGAG; TRAIL; TSHIP; TRANAIR; TMISC; TCONS; TINTEG; TBENCHMARK; TREPORT

SUBROUTINE: READLDV

Description: Reads the spreadsheet input file trnldvx.xlsx.

Called by: TRAN

SUBROUTINE: READSTOCK

Description: Reads the spreadsheet input file trnstockx.xlsx.

Called by: TRAN

SUBROUTINE: TMAC

Description: This subroutine reassigns MACRO data to TRAN subroutine local variables.

Called by: TRAN

SUBROUTINE: NEWLDV

Description: This subroutine segments new light vehicle sales by cars, light trucks less than 8,500 pounds GVWR and light trucks from 8,500 pounds GVWR to 10,000 pounds GVWR.

Called by: TRAN

SUBROUTINE: TMPGNEW

Description: This subroutine loads data inputs and runs the fuel economy module, including the manufacturer technology component, consumer choice component, and regulatory compliance components.

Called by: TRAN

Calls: READNHTSA ; READHIST; LIONCOSTCALC; AFVADJ; FEMCALC; CGSHARE; TLDV; CAFECALC; CAFETEST

SUBROUTINE: READNHTSA

Description: This subroutine reads the EPA/NHTSA historical vehicle sales and attributes data post-MTCC base year from trnnhtsax.xlsx.

Called by: TMPGNEW

SUBROUTINE: READHIST

Description: This subroutine reads new light-duty vehicle sales data for 1990 through the MTCC base year from trnfemx.xlsx. These data are required to support output beginning in 1990. This subroutine assigns historical attribute data to report writer variables, historical technology penetration data to report writer variables, and historical ATV offsets to report writer variables.

Called by: TMPGNEW

SUBROUTINE: AFVADJ

Description: This subroutine calculates the base (and historical) year price, weight, fuel economy, and horsepower for alternative fuel vehicles that are introduced after the base year (XYR). Most are set relative to the gasoline vehicle values. All of the incremental adjustments used for alternative fuels have been exogenously determined and are included in the data input file, *trnldvx.xlsx*.

Called by: TMPGNEW

Calls: EVCALC; HEVCALC; PHEVCALC; FCCALC

SUBROUTINE: FEMCALC

Description: This subroutine determines the cost-effective market shares of technologies for each vehicle class and manufacturer group. The resulting fuel economy, weight, horsepower, and price are calculated. This subroutine then calculates possible market share in the absence of any engineering notes and the basic incremental technology cost by incorporating learning/volume production cost effects. It also determines number of years into production for scientific and design learning and the probabilistic cost change because of scientific learning. This subroutine tracks cumulative penetration as a surrogate for cumulative production. It calculates manufacturing cost adjustments and volume production cost adjustments. The mandatory and supersedes engineering notes are then applied to calculate annual horsepower adjustment as a result of technology introduction alone. This subroutine calculates the horsepower demand required to maintain a minimum horsepower-to-weight ratio and adjusts fuel economy up or down in accordance with the sum of consumer-driven horsepower adjustment and any horsepower giveback.

Called by: TMPGNEW

Calls: NOTE_SUPER; EVCALC; HEVCALC; PHEVCALC; FCCALC; FEMRANGE; CALIBNHTSA

SUBROUTINE: NOTE_SUPER

Description: This subroutine ensures that related technologies do not exceed a specific cumulative penetration. Although individual technology penetrations are controlled via the basic allowable maximum penetrations, the combined penetrations of two or more technologies are controlled here. Accordingly, this subroutine will never add market penetration, but it can subtract excess penetration initially allocated to a superseded technology. The maximum allowable market penetration for a related technology chain is taken as the greater of the maximum penetrations for each component technology and can thus be adjusted externally through the maximum market penetration matrix in the *trnldvx.xlsx* file. Even though the maximum penetration for the chain may exceed that of an individual technology, no problems arise because the penetration of that individual technology is constrained by its specific maximum in the individual technology market penetration algorithms.

Called by: TRAN

SUBROUTINE: EVCALC

Description: This subroutine calculates electric vehicle battery pack size and cost, curb weight, horsepower, fuel economy, range, and MSRP.

Called by: FEMCALC, AFVADJ

SUBROUTINE: HEVCALC

Description: This subroutine calculates hybrid electric vehicle battery pack size and cost, curb weight, horsepower, fuel economy, range, and MSRP.

Called by: FEMCALC, AFVADJ

SUBROUTINE: LIONCOSTCALC

Description: This subroutine calculates lithium ion battery cost ($/kWh) for BEVs, PHEVs, and HEVs. It accumulates all of the lithium-ion battery production each year and calculates the corresponding battery cost based on assumed learning rates from *trnldvx.xlsx*.

Called by: TMPGNEW

SUBROUTINE: PHEVCALC

Description: This subroutine calculates plug-in hybrid electric vehicle battery pack size and cost, curb weight, horsepower, fuel economy, range, and MSRP.

Called by: FEMCALC, AFVADJ

SUBROUTINE: FCCALC

Description: This subroutine calculates several parameters that include base fuel cell cost and input fuel cell costs in $/kW, base cost of an onboard battery to start the vehicle, and retail price of the fuel cell and battery. The vehicle price is then adjusted to include the price of the fuel cell and battery. This subroutine also estimates fuel cell vehicle fuel economy using estimates of gallons per mile per 1,000 pounds of vehicle weight.

Called by: FEMCALC, AFVADJ

SUBROUTINE: CALIBNHTSA

Description: This subroutine calibrates vehicle sales and attributes based on historical EPA/NHTSA data through the last available data year. This is done for every year between the base year for FEM (*XYR*) and the last available year of historical EPA/NHTSA data (*EPALYR*).

Called by: FEMCALC

SUBROUTINE: FEMRANGE

Description: This subroutine calculates vehicle range estimates.

Called by: FEMCALC

SUBROUTINE: CGSHARE

Description: This subroutine calculates light vehicle market class shares, average horsepower, and weight for cars and light trucks. It sets domestic and import shares of total cars and light trucks using historical NHTSA sales data. It then calculates non-fleet non-commercial sales of cars and light trucks by market class and overall non-fleet, as well as non-commercial class shares for cars and light trucks. The domestic and import groups are combined to calculate market class shares and sales of conventional vehicles. This subroutine also estimates average horsepower and weight for new cars and light trucks.

Called by: TMPGNEW

SUBROUTINE: TREG

Description: This subroutine estimates the regional values for fuel demand.

Called by: TMPGNEW

SUBROUTINE: TLDV

Description: This subroutine initiates the vehicle choice routine.

Called by: TMPGNEW

Calls: TATTRIB; TALT2

SUBROUTINE: TATTRIB

Description: This subroutine adjusts the LDV attributes such as mpg, price, range, and horsepower so they can be used throughout the model.

Called by: TLDV

Calls: FLEXSHR

SUBROUTINE: FLEXSHR

Description: This subroutine calculates the VMT shares for flex-fuel and bi-fuel vehicles. After parameters for minimum alternative fuel use in flex-fuel and bi-fuel vehicles are set, it calculates an arithmetic average ethanol (E85) price. It then calculates regional price ratios for the minimum amount of alternative fuel that is used to fill the alternative fuel station availability array. This subroutine uses an alternative fuel choice logit model based on fuel price and fuel availability. It can also simulate an aggressive E85 vehicle penetration with no consideration regarding fuel availability. It then calculates the national average alternative fuel use percentage for flex- and bi-fuel vehicles. Weighted mpg and VMT shares for PHEVs are then calculated. Because the mpg for the gasoline engine and the electric motor are very different, VMT shares are weighted with the mpgs.

Called by: TATTRIB

SUBROUTINE: TALT2

Description: This subroutine calculates regional fuel availability for highway fuels that include gasoline, diesel, ethanol, methanol, CNG/LNG, LPG, electricity, and hydrogen. It estimates the vehicle stocks used to calculate the number of refueling stations by weighting flex-fuel and bi-fuel at 25%. It calculates the total number of refueling stations needed based on an historical ratio of vehicle stock per refueling station. It regionalizes the predicted stations by regional vehicle sales and estimates fuel availability.

Called by: TLDV

SUBROUTINE: TALT2X

Description: This subroutine calculates level 1 and level 2 light vehicle market penetration estimates in the AFV model. It increases flexfuel make/model availability when E85 is price competitive. Fuel availability and range are calculated in call statements.

Called by: TLDV

Calls: TALT314; TALT315; TALT316

SUBROUTINE: TALT314

Description: This subroutine calculates fuel cost, vehicle range, and fuel availability for ethanol flex-fuel vehicles.

Called by: TALT2X

SUBROUTINE: TALT315

Description: This subroutine calculates fuel cost, vehicle range, and fuel availability for CNG bi-fuel and LNG bi-fuel vehicles.

Called by: TALT2X

SUBROUTINE: TALT316

Description: This subroutine calculates fuel cost, vehicle range, and fuel availability for LPG bi-fuel vehicles.

Called by: TALT2X

SUBROUTINE: TFLTSTKS

Description: This subroutine calculates sales and stocks of fleet vehicles used in business, government, utility, and taxi fleets. It calculates the fleet acquisitions for cars and light trucks. It calculates fleet stock by fleet type, technology, and vintage and assigns fleet vehicles of retirement vintage to another variable, before removal from the fleet. Taxis do not transfer to the passenger vehicle fleet because of their high mileage. The total surviving vehicles, by vehicle, fleet type, and engine technology are calculated.

Called by: TRAN

SUBROUTINE: TLEGIS

Description: This subroutine adjusts vehicle sales and market shares to reflect legislative mandates on sales of ZEV, including TZEV and ATPZEV. Participating states include California, Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, and Vermont. After estimating the total adjusted vehicle sales, calculations are made for new absolute market shares for each vehicle technology.

Called by: None (switched off starting AEO2025)

SUBROUTINE: CAFECALC

Description: This subroutine combines fuel economies from all vehicles and checks whether each manufacturer group complies with NHTSA CAFE and EPA tailpipe GHG standards.

Called by: TMPGNEW

SUBROUTINE: CAFETEST

Description: This subroutine ensures that NHTSA CAFE and EPA tailpipe GHG standards are met by increasing the sales of electric, plug-in hybrid, and hybrid vehicles.

Called by: TMPGNEW

SUBROUTINE: TFLTVMTS

Description: This subroutine calculates VMT for fleets.

Called by: TRAN

SUBROUTINE: TSMOD

Description: This subroutine calculates light vehicle stocks by technology type. Total new vehicle sales by technology and fraction of a given vintage that survive are calculated. This subroutine adds retired fleet vehicles to the appropriate vintage of the non-fleet population and calculates total stocks of cars and light trucks. Vehicle stock by fuel type and LDV shares of each technology are also calculated.

Called by: TRAN

SUBROUTINE: TMPGSTK

Description: This subroutine calculates light vehicle stock mpg by technology and also calculates new car and light truck sales for eight market classes. It computes the average mpg of the 14 AFV technologies, average new car and light truck mpg, and stock mpg for cars and light trucks. It also calculates total miles driven by each type of vehicle (cars and light trucks) by vintage, household vehicle stock mpg for cars and light trucks, average mpg of light-duty vehicles, average vehicle mpg by technology, and average car and light truck mpg by technology.

Called by: TRAN

SUBROUTINE: TCURB

Description: This subroutine calculates the stock average weight (by vintage) of cars and light trucks.

Called by: TRAN

SUBROUTINE: TFLTMPGS

Description: This subroutine calculates mpg for new fleet cars and light trucks, as well as fleet stock. It adjusts the vintage array of fleet stock efficiencies to account for new additions. This subroutine then calculates overall fleet average mpg by fuel technology.

Called by: TRAN

SUBROUTINE: TFLTCONS

Description: This subroutine calculates fuel consumption of fleet vehicles by region.

Called by: TRAN

SUBROUTINE: TRANFRT

Description: This subroutine calculates fuel consumption for freight trucks, Classes 2b–8. It applies scrappage rates to truck populations, excluding new trucks. It then calculates stock transfers from fleet to non-fleet ownership, processes new truck sales from the Macroeconomic Activity Module, and distributes new truck sales into market classes and ownership classes. It then estimates fuel shares of new truck sales under technology penetration assumptions. Aggregate VMT and per truck VMT are estimated and used to calculate fuel demand by sector and vintage.

Called by: TRAN

Calls: TFRTRPT; INIT; TRUCK_NEW; TRUCK_STOCK; TRUCK_VMT; TRUCK_FUEL

Equations: 182-211

SUBROUTINE: TFRTRPT

Description: This subroutine writes reports that support the freight model.

Called by: TRANFRT

SUBROUTINE: INIT

Description: This subroutine initializes variables in TRANFRT and assigns variables for each run. It copies inputs for prices and macroeconomic output from the NEMS global data call for each year.

Called by: TRANFRT

Calls: CFREAD

SUBROUTINE: CFREAD

Description: This subroutine reads input for the freight model from spreadsheet input file trnhdvx.xlsx, including variables such as non-fleet VMT per truck by fuel and vintage, new truck sales, and Class 4–6 shares of Class 4–8 trucks, etc.

Called by: INIT

SUBROUTINE: CFREADSTOCK

Description: This subroutine reads input for the freight model from spreadsheet input file trnstockx.xlsx, including variables such as fleet stocks by fuel, vintage, gross vehicle weight, and vocational versus non-vocational.

Called by: INIT

SUBROUTINE: TRUCK_VMT

Description: This subroutine estimates aggregate VMT growth by economic sector by factoring VMT per truck such that the total VMT of the stock, including new trucks, matches the aggregate across sectors. It calculates aggregate VMT growth based on growth in real economic output by sector.

Called by: TRANFRT

SUBROUTINE: TRUCK_FUEL

Description: This subroutine calculates fuel demand from VMT and mpg by market class, fuel, and fleet/non-fleet. This subroutine is called by TRANFRT during history years. It determines fuel consumption in gallons of gasoline equivalent and passes VMT to TRAN for benchmarking.

Called by: TRANFRT

SUBROUTINE: TRUCK_NEW

Description: This subroutine determines the characteristics and sales of the new truck fleet each year. It builds each of the 12 powertrain options in each of the 19 regulatory classes. Fuel economy is adjusted based on incremental advanced technology adoption in TRUCK_TECHADOPT. Incremental costs for alternative powertrains are estimated in

TRUCK_INCCOST. Powertrain selection based on net present value of fuel and maintenance savings is calculated in TRUCK_CHOICE. Regulatory compliance is checked in TRUCK_GHGMEET, and is enforced if not met after several iterations in TRUCK_GHGZEV.

Called by: TRANFRT

Calls: TRUCK_TECHADOPT; TRUCK_INCCOST; TRUCK_CHOICE; TRUCK_AGGVARS; TRUCK_GHGMEET; TRUCK_GHGZEV

SUBROUTINE: TRUCK_TECHADOPT

Description: This subroutine estimates adoption of incremental advanced technology for each powertrain and regulatory class. It estimates the fuel price at which each technology will generate payback in the exogenously determined payback period, and applies the technology cost and efficiency improvements if that fuel price threshold is crossed.

Called by: TRUCK_NEW

SUBROUTINE: TRUCK_INCCOST

Description: This subroutine estimates the incremental cost of alternative powertrains, including: CNG, BEV, PHEV gasoline, PHEV diesel, FCEV, FCHEV, and hydrogen ICE. This is accomplished using exogenous inputs as well as endogenous cost reduction estimates based on cumulative component production.

Called by: TRUCK_NEW

SUBROUTINE: TRUCK_CHOICE

Description: This subroutine estimates adoption of alternative powertrains. It compares the incremental purchase price from TRUCK_INCCOST to the net present value of fuel and maintenance savings within each region, regulatory class, and annual VMT bin to determine adoption.

Called by: TRUCK_NEW

Calls: TRUCK_PBK

SUBROUTINE: TRUCK_AGGVARS

Description: This subroutine calculates aggregate sales, CAFE/GHG credits, and fuel economy variables for use in the various TRUCK_NEW subroutines.

Called by: TRUCK_NEW

SUBROUTINE: TRUCK_GHGMEET

Description: This subroutine groups disaggregate sales by regulatory class into averaging sets per EPA regulation. It then determines whether each set is in compliance with EPA Phase 2 and Phase 3 tailpipe GHG standards. If the set is in compliance, it banks the credits for later use. If the set is not in compliance, it attempts to reach compliance via spending previously accumulated credits; if those credits are insufficient, it will jump back to TRUCK_NEW and proceed to TRUCK_GHGZEV.

Called by: TRUCK_NEW

SUBROUTINE: TRUCK_GHGZEV

Description: In a situation where any average set is unable to comply with EPA GHG standards via adoption of cost-effective technology, this subroutine converts ICE vehicle sales to ZEVs to ensure compliance.

Called by: TRUCK_NEW

SUBROUTINE: TRUCK_STOCK

Description: This subroutine estimates truck stocks using previous year stocks and current year new truck sales.

Called by: TRANFRT

SUBROUTINE: TRAIL

Description: This subroutine calculates energy consumption by rail by region and fractional change in fuel efficiency.

Called by: TRAN

SUBROUTINE: TSHIP

Description: This subroutine calculates energy use for shipping. It calculates the international shipping fuel use (including use within Emission Control Areas of North America) split by the fuel types: distillate fuel oil, LNG, and residual fuel oil. It calculates ton-miles traveled for domestic shipping and the fractional change in fuel efficiency.

Called by: TRAN

SUBROUTINE: TRANAIR

Description: This subroutine calls the air subroutines TAIRT and TAIREFF.

Called by: TRAN

Calls: TAIRT; TAIREFF

SUBROUTINE: TAIRT

Description: This subroutine calculates total seat miles demanded for domestic and international air travel as well as revenue ton-miles for air freight. After initializing the variables representing aircraft sales, active aircraft, and stock for narrow-body, wide-body, and regional jets, it calculates the yield (ticket price), load factors, and revenue passenger-miles for domestic and international by aircraft type. It also calculates dedicated revenue ton-miles of air freight, available seat miles demanded (domestic and international), demand for available seat miles, and revenue ton-miles.

Called by: TRANAIR

SUBROUTINE: TAIREFF

Description: This subroutine calculates aircraft sales, stocks, new technology penetration, efficiency improvement, and energy use for air travel. It calculates total fuel efficiency improvements for aircraft for domestic and international combined. It calculates seat miles demanded, incorporating revenue ton-miles, jet fuel demand in gallons, aviation gas demand, and regionalizes commercial jet fuel and aviation gasoline.

Called by: TRANAIR

SUBROUTINE: TMISC

Description: This subroutine calculates miscellaneous transportation energy use from the military, mass transit (buses and rail), recreational boating, and lubricant demand. It also calculates bus efficiency in Btu/passenger-mile, bus energy demand by segment, and regionalizes commuter bus energy demand by regional population. It also calculates demand growth and regional recreational boating energy demand by population. It calculates regional lubricant demand by summing VMT shares for freight and light-duty vehicles.

Called by: TRAN

SUBROUTINE: TCONS

Description: This subroutine combines VMT and efficiencies by technology to estimate fuel consumption for light-duty vehicles by fuel type. It calculates gasoline, methanol, ethanol, CNG, LNG, and LPG consumption as well as electric, liquid hydrogen, and diesel consumption. It sums total consumption of all fuels.

Called by: TRAN

SUBROUTINE: TINTEG

Description: This subroutine calculates total transportation energy consumption by fuel type for all modes.

Called by: TRAN

SUBROUTINE: TBENCHMARK

Description: This subroutine is used for benchmarking transportation-specific consumption variables. It benchmarks consumption by fuel type for various transport modes including light-duty vehicles, commercial light trucks, freight trucks by fuel type and market class, domestic shipping, international shipping, rail, military, and mass transit. It also is used to benchmark commercial fleet vehicle consumption by fuel type and VMT by technology for commercial fleets, commercial light trucks, and freight trucks as well as ton-miles traveled (TMT) for rail and ships.

Called by: TRAN

SUBROUTINE: TREPORT

Description: This subroutine generates the parameters used in the model's report writer. It generates tables for total freight truck VMT and energy efficiency index. It calculates energy use by fuel type within light-duty vehicles.

Called by: TRAN

SUBROUTINE: LIDARCOSTCALC

Description: This subroutine calculates the LiDAR system cost using a classic experience curve model, based on the cumulative production of all LiDAR systems to date for five phases: R&D, Revolutionary, Evolutionary, Mature, and High-Volume. Two levels of LiDAR system costs are estimated: high- and low-resolution, the latter applying to L4a vehicles and the former to L4b and L5 vehicles.

Called by: HAVCALC

SUBROUTINE: HAVCALC

Description: This subroutine calculates the total HAV system incremental cost using output from LIONCOSTCALC, LIDARCOSTCALC, and an exogenous time-based cost reduction curve for the remainder of the HAV system components

Called by: FLTHAV

Calls: LIDARCOSTCALC

SUBROUTINE: FLTHAV

Description: This subroutine determines HAV adoption within the taxi fleet based on revenue and fuel, maintenance, and operational costs, as well as operational domain and new technology limitations. The output includes 1) ride-hailing/taxi fleet HAV distribution within vehicle type, class, powertrain, and census division by level (that is, Levels 0–3, 4a, 4b, and 5) and 2) ride-hailing/taxi fleet HAV sales by vehicle type, class, powertrain, census division, and HAV level.

Called by: TLDV

Calls: HAVCALC

FUNCTION: FUNCMAX

Description: This function returns the maximum possible market share given previous period values. It is intended to reflect institutional factors leading to production lags.

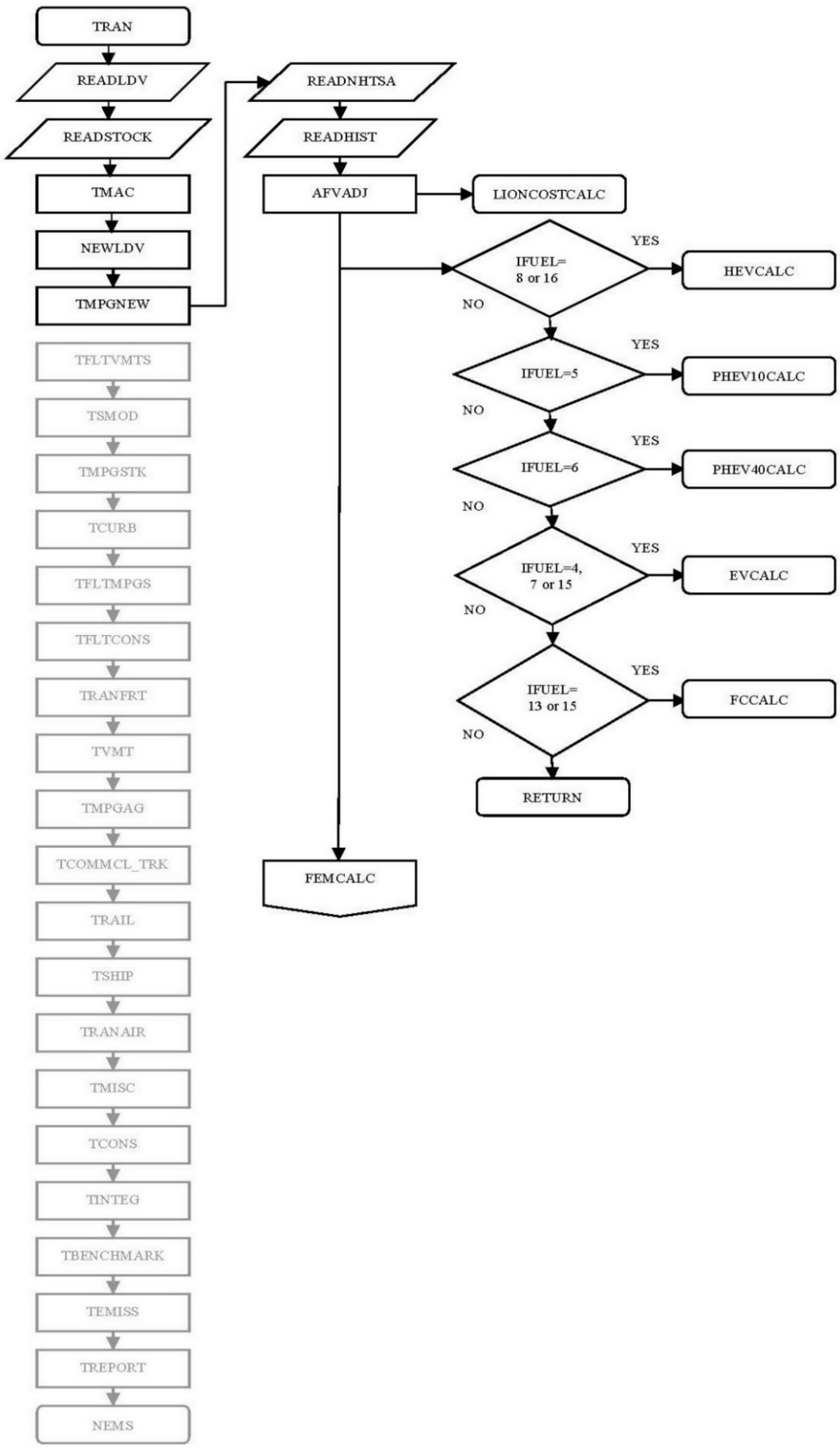
Called by: FEMCALC

FUNCTION: HARMONIC_MEAN

Description: This function computes a harmonic mean, used for averaging fuel economy measured in miles per gallon. The calculation essentially takes the reciprocal of mpg, or efficiency, and computes the quantity-weighted average and then converts the result back to miles per gallon by taking the reciprocal.

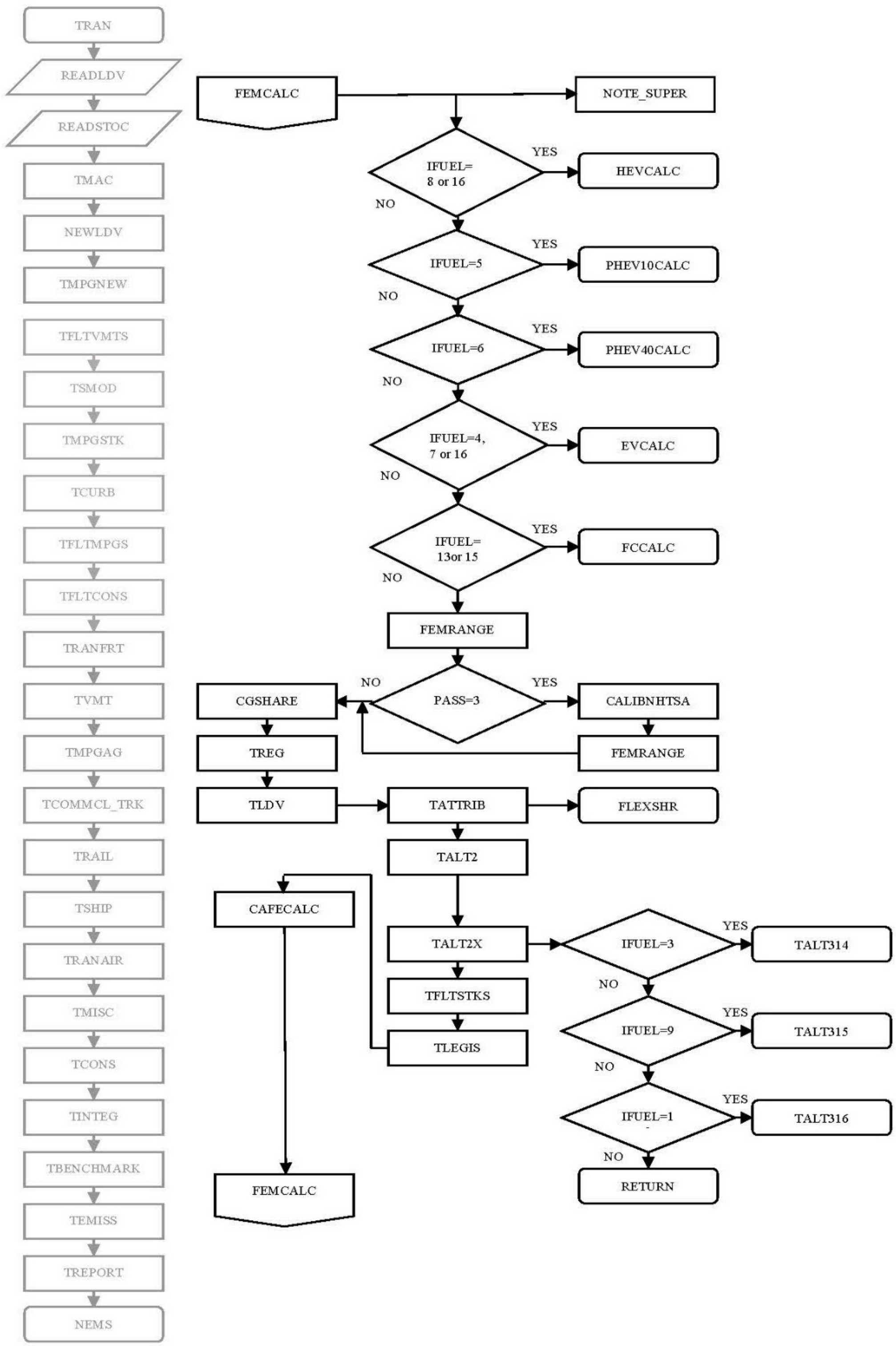
Called by: TRANFRT; TRUCK_STOCK; TFRTRPT

Figure 23. Flowchart of calls made by TMPGNEW subroutine of the Transportation Sector Demand Module, NEMS



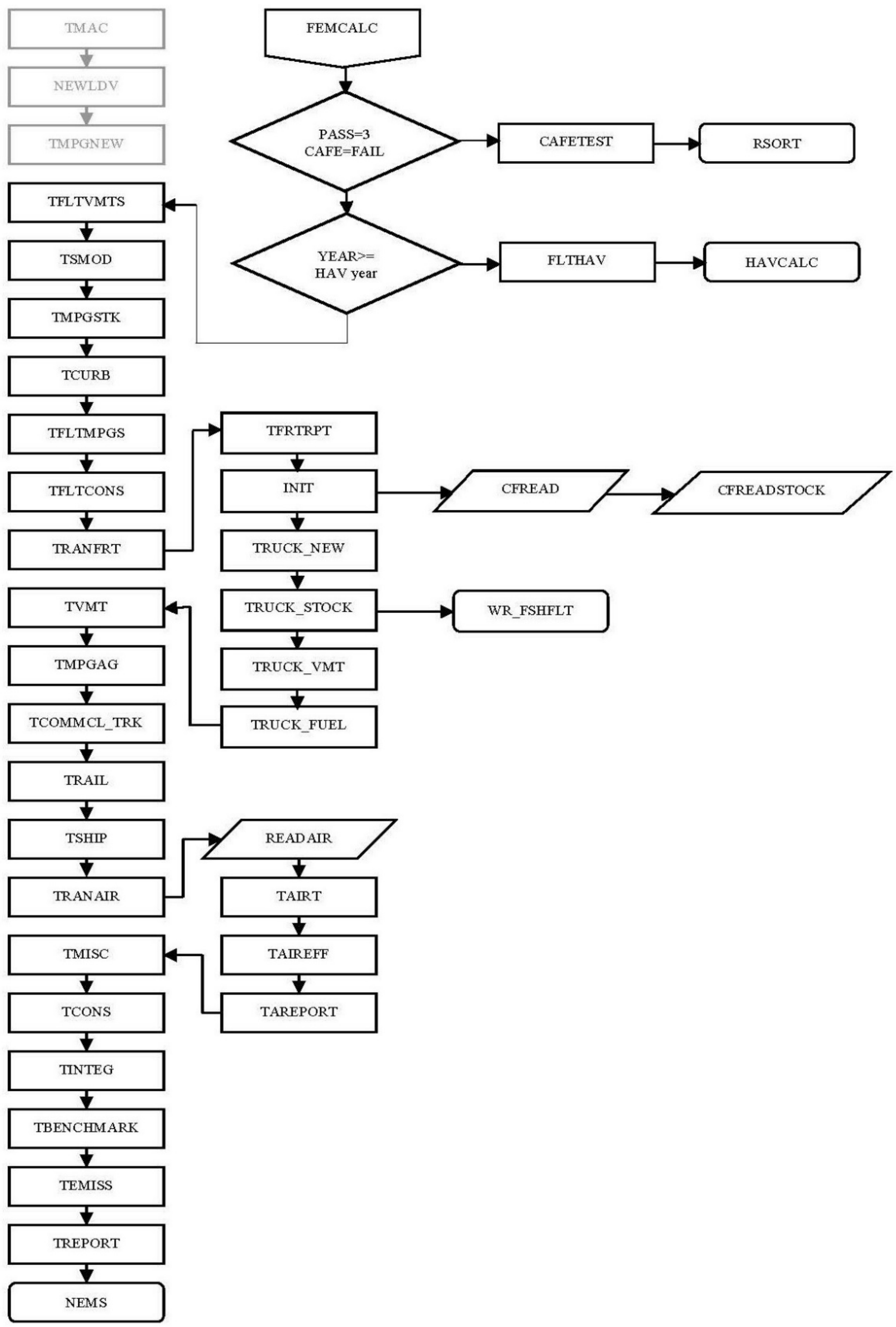
Source: U.S. Energy Information Administration

Figure 24. Flowchart of calls made by FEMCALC subroutine of the Transportation Sector Demand Module, NEMS



Source: U.S. Energy Information Administration

Figure 25. Flowchart of calls made by TRANFRT and TRANAIR subroutines of the Transportation Sector Demand Module, NEMS



Source: U.S. Energy Information Administration