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

July 2022

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Update Information

This 24th edition of the *Transportation Sector Demand Module of the National Energy Modeling System: Model Documentation* 2022 reflects changes made to various sections and submodules of the Transportation Sector Demand Module (TDM) during the past two years for the *Annual Energy Outlook 2022* (AEO2022). These changes include the following:

- Light-Duty Vehicle (LDV) Submodule updates
- Freight Transportation Submodule updates
- A new LDV battery cost model
- Greater representation of regional LDV stocks and sales
- New air travel submodule
- Revised plug-in hybrid electric vehicle (PHEV) range bins to align with the current market

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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 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:

- Estimates of passenger travel demand by light-duty vehicles, air, and mass transit
- Estimates of the energy requirements to meet transportation demand
- Projections of vehicle stock and the penetration of new technologies
- 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 2022* (AEO2022).

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Model Overview

The TDM has two objectives:

- Generate projections of transportation energy demand at the national and the census division level
- 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 policy issues, including:

- Fuel taxes and subsidies
- Fuel economy performance by market class
- Fuel economy standards for light-, medium-, and heavy-duty vehicles[1]
- Vehicle pricing by market class
- Demand for vehicle performance within market classes
- Fleet vehicle sales by technology type
- Alternative fuel vehicle sales share
- The California Low-Emission Vehicle Program
- 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 also 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 fuel efficiency 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

[1] Additional information on fuel economy standards is available at the National Highway Traffic Safety Administration see www.nhtsa.gov/fuel-economy.

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, market shares of alternative fuel vehicles (AFVs), and sales of vehicles to fleets. This information is passed to the LDV Fleet Component, a stock-vintaging submodule that generates estimates of travel demand, fuel efficiency, and energy consumption by business, government, utility, and taxi[2] fleets. The LDV Fleet Component subsequently passes estimates of vehicles transferred from the non-taxi fleets to private service to the LDV Stock Component, which also receives estimates of new LDV sales and fuel efficiency from the LDV Submodule. The LDV Stock Component generates travel, fuel economy, and fuel consumption estimates of the entire stock of household LDVs. Information from the LDV Stock Component is subsequently passed to the Miscellaneous Energy Demand Submodule.

Air Travel Submodule

The Air Travel Submodule receives macroeconomic input from NEMS, including world regional population and world regional GDP. 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.

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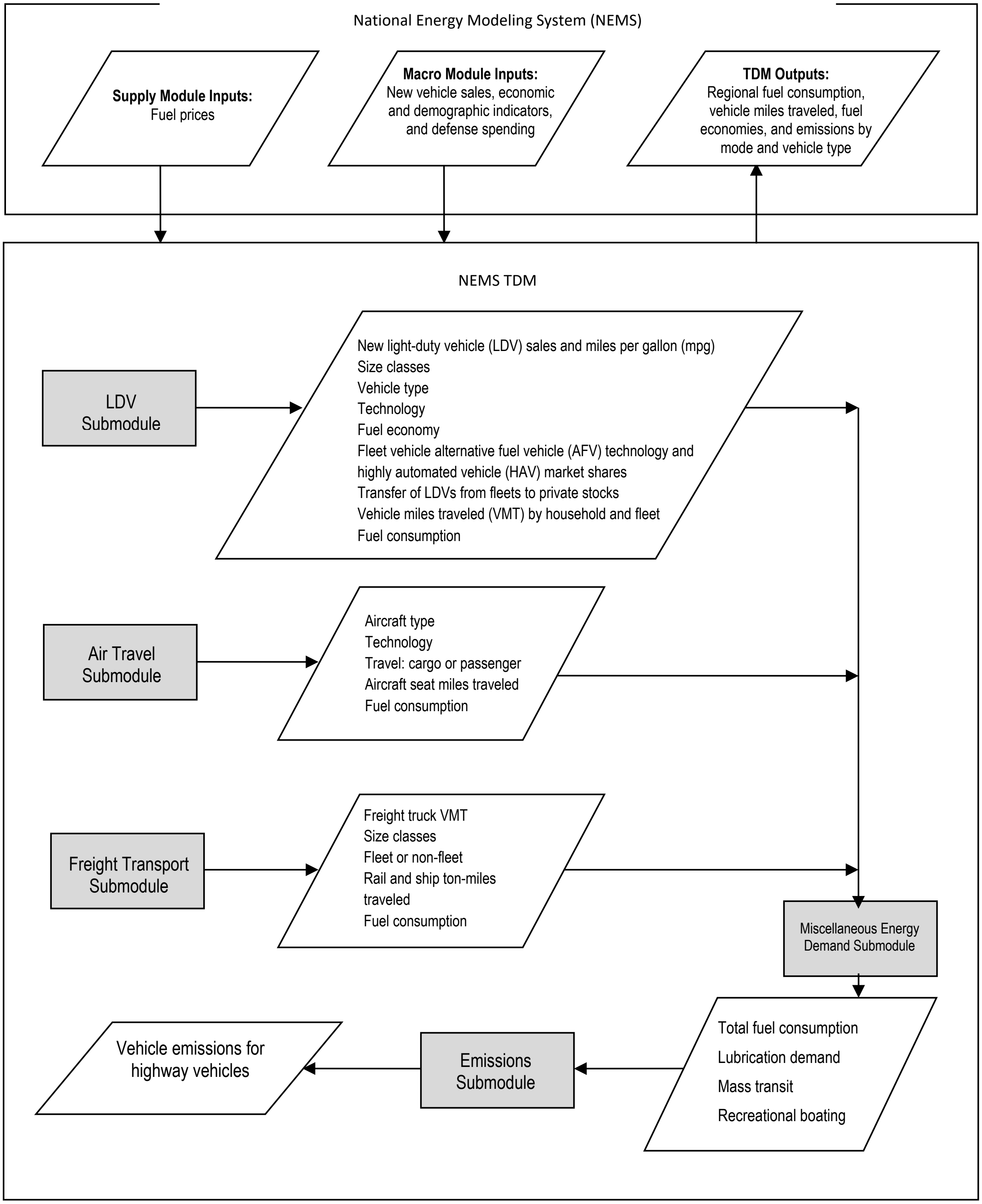
[2] The taxi fleet includes all ride-hailing service fleets including traditional taxicab fleets and mobility-as-a-service/transportation network companies (for example, Lyft and Uber). Taxi fleets can include both highly automated vehicles (HAVs) and non-HAVs.

Figure 1. Structure of the NEMS Transportation Sector Demand Module (TDM)



Data source: U.S. Energy Information Administration
Note: Shaded boxes represent the module's main submodules. The Emissions Submodule is currently inactive.

Emissions Submodule

This submodule estimates certain air emissions resulting from fuel consumption of highway vehicles. It is currently inactive.

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 the 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 conventional and alternative vehicle technology, vehicle stock 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. In several statements, a variable name will appear on both sides of an equal sign. These statements are not to be interpreted as mathematical equations. They are computer assignment statements that allow a previously calculated variable to be updated (for example, multiplied by a factor) and re-stored under the same variable name.

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 (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 seven components (Figure 2):

- Manufacturer Technology Choice Component (MTCC)
- Regional Sales Component
- Consumer Vehicle Choice Component (CVCC)
- LDV Fleet Component
- Class 2b Vehicle Component
- LDV Stock Accounting Component
- Vehicle Miles Traveled Component (VMTC)

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 price 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[3] 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:

- Technology penetration
- Level of acceleration performance achieved
- Mix of vehicle size classes and vehicle powertrain types (for example, hybrid and diesel) sold
- Vehicle fuel economy, safety, and emission standards

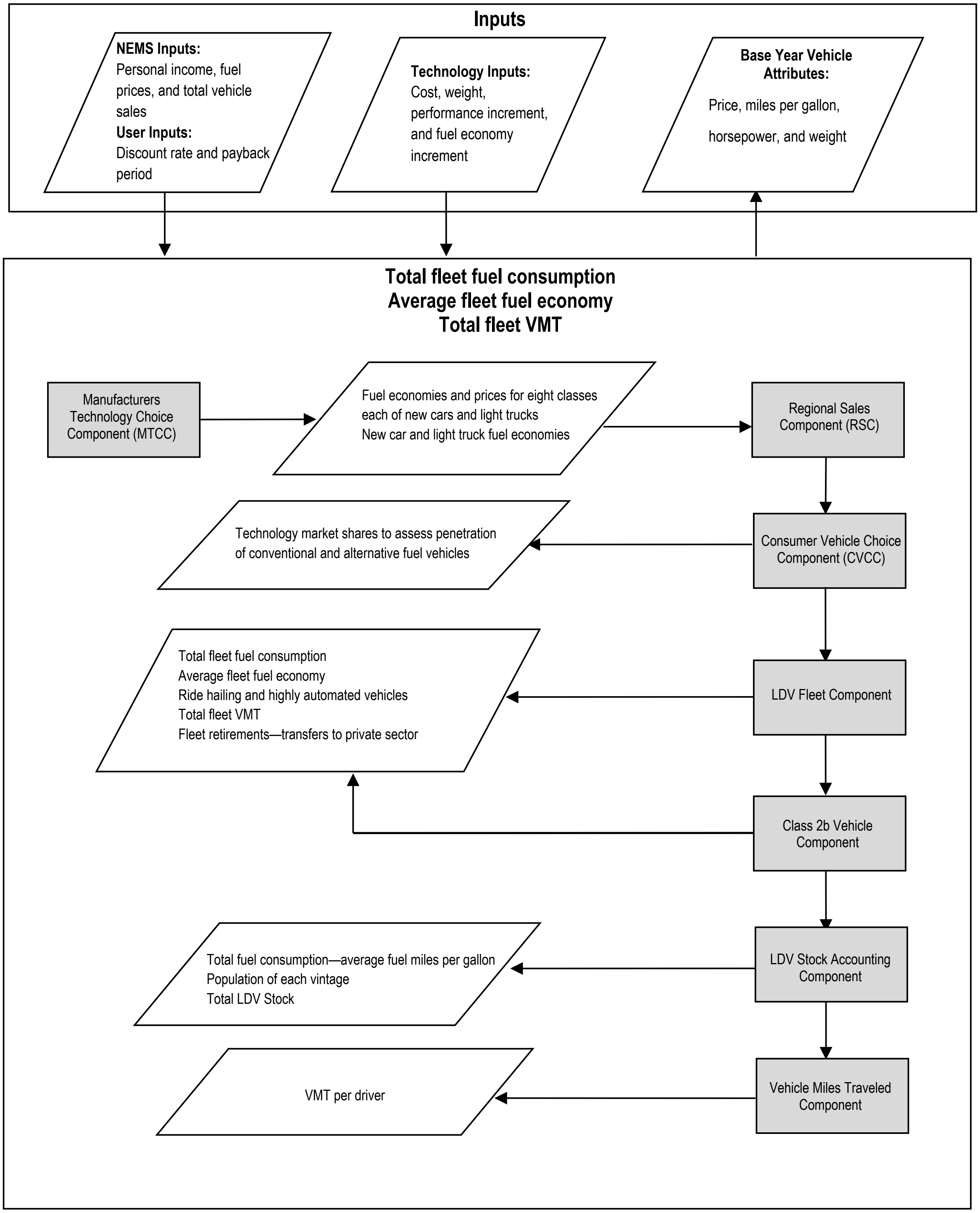
Technological improvements to each of these size classes are then projected based on the availability of new technologies to improve fuel economy as well as their cost-effectiveness under two user-specified alternative cases. The central assumptions involved in this technological projection are:

- 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).
- 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 manufacturers, size classes, and powertrain types.

[3] *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 (LDV) Submodule of the National Energy Modeling System (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.[4] The submodule projects sales mix for the eight car and eight light-truck classes, and import market shares are held at fixed values by size class based on historical estimates.

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)[5].

Manufacturers Technology Choice Component (MTCC)

The MTCC in the LDV Submodule produces estimates of new light-duty vehicle fuel economy. Fuel economy is a significant aspect of the Transportation Sector Demand Module because automotive fuel demand is directly affected by the efficiency with which that fuel is used. Because of the disparate characteristics of the various classes of LDVs, this component addresses the commercial viability of up to 92 separate technologies within each of 16 vehicle size classes, 11 manufacturer groups, and 16 powertrain types. The MTCC projects fuel economy by size class Figure 3). The model begins with 2019 data. Baseline vehicle attributes that describe the fuel economy, weight, horsepower, and price for each size class for 2019 are read in and calibrated to the National Highway Traffic Safety Administration (NHTSA) data. For each projection year, the component identifies technologies that are available.

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 cost-effectiveness test is used to generate an economic market share for the technology. In certain cases, we must adjust the calculated market shares to reflect the effects of engineering limitations or external forces that require certain types of technologies, including both safety and emissions technologies. All of these adjustments are referred to collectively as *engineering notes*. There are four types of engineering notes: mandatory, supersedes, requires, and synergistic.

After all of the technology market shares have been determined, the baseline fuel economy, weight, and price values for each vehicle size class are updated to reflect the impact of the various technology

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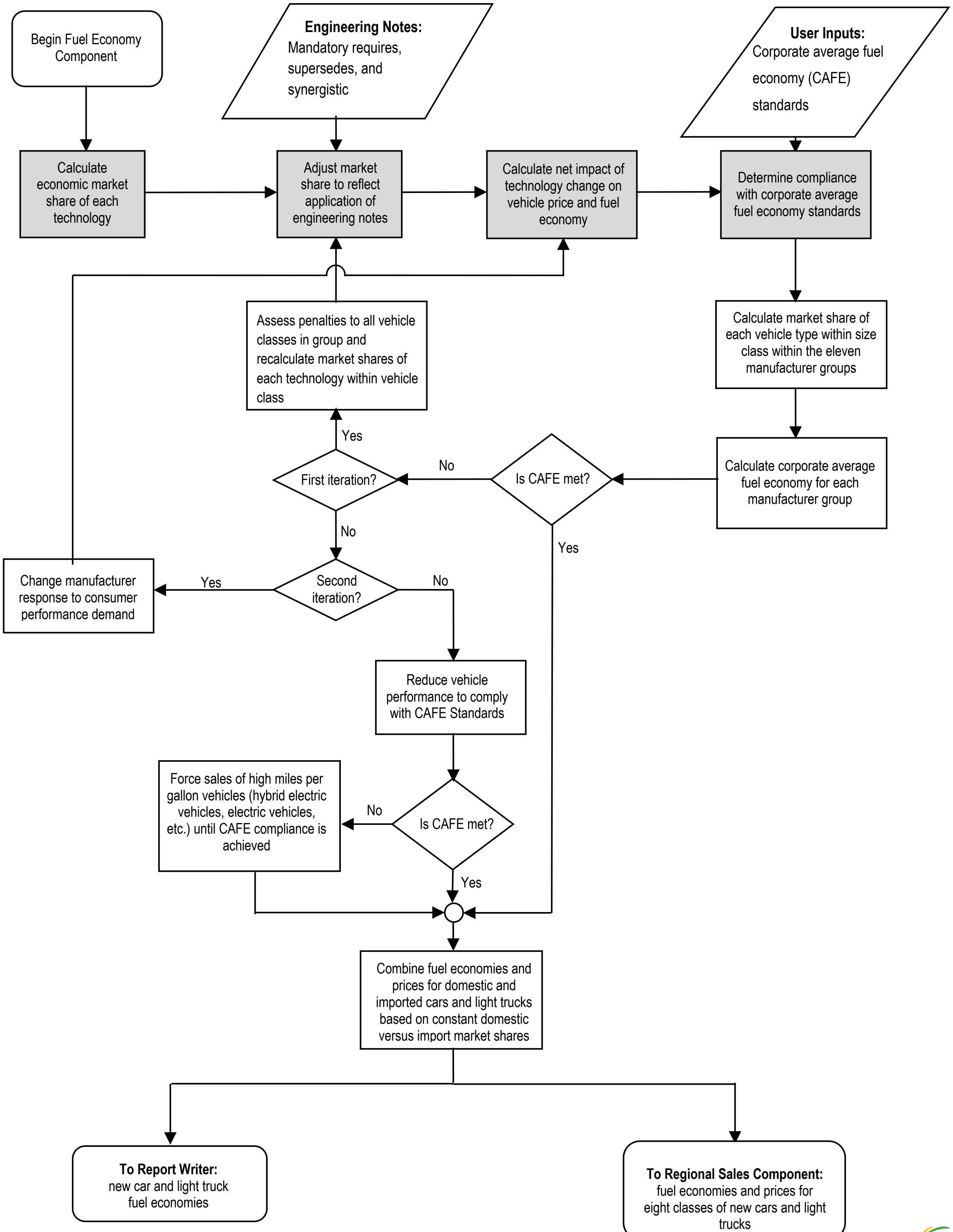
[4] Goldberg, U.S. Department of Commerce, Bureau of Economic Analysis, 1998.

[5] The ZEV mandate subroutine was inactive in the AEO2022 Reference Case.

choices. Next, based on the new vehicle weight, a no-performance-change adjustment is made to horsepower. Then, a technology-change adjustment and a performance-change adjustment (based on income, fuel economy, fuel cost, and vehicle class) are made to horsepower. Finally, the fuel economy is adjusted to reflect the new horsepower.

Once these steps have been taken for all vehicle size classes, corporate average fuel economy (CAFE) is calculated for each of the 11 manufacturer groups. Each group is classified as either passing or failing the CAFE standard. When a group fails to meet the standard, penalties are assessed to all of the vehicle size classes in that group, which are then reprocessed through the market share calculations. In the second pass, the technology cost-effectiveness calculation is modified to include the benefit of not having to pay the fine for failing to meet CAFE. After this second pass, the CAFE values are recalculated. The market share determination is bypassed on the third CAFE pass. The third CAFE pass simply alters the manufacturer response to consumer performance demand, so the technology penetrations determined to be cost-effective during the second MTCC pass are equally applicable during the third pass and, therefore, are not recalculated. If CAFE is still not met after the second pass, then the horsepower increases will be deactivated and converted to an equivalent fuel economy improvement. This process assumes manufacturers will minimize their costs by reducing performance to comply with CAFE standards. If, after the third pass, fuel economy requirements are not met, then the model employs an algorithm (subroutine *CAFETEST*) that overrides consumer-derived alternative-fuel vehicle (AFV) sales until it meets the fuel economy standard requirement. Determining if the AFV purchase meets CAFE compliance is based on cost-effectiveness to consumers, which, in turn, is based on incremental vehicle cost relative to fuel savings. The incremental increase in sales of a specific AFV type is limited to 1.25% of the total sales volume within each of the manufacturer's size classes in a given year.

Figure 3. Manufacturers Technology Choice Component of the Transportation Sector Demand Module (TDM), National Energy Modeling System (NEMS)



Data source: U.S. Energy Information Administration

The steps in the MTCC

Establish alternative fuel vehicle (AFV) characteristics relative to conventional gasoline

The *AFVADJ* subroutine in MTCC establishes alternative-fuel vehicle (AFV) characteristics relative to conventional gasoline. This subroutine is an initialization subroutine and calculates the price, weight, fuel economy, and horsepower for AFVs for all historic years through the base year in the MTCC. Most of these factors are initialized relative to the gasoline vehicle values, as shown in the following equations. All of the incremental adjustments used for AFVs have been exogenously determined and are included in the data input file, *trnldv.xlsx*. For the equations that follow, index *ivtyp* represents car and light-truck vehicle types, and the index *iatv* represents the 15 AFV types:

- Turbo direct-injection diesel
- Flex-fuel ethanol
- Plug-in hybrid electric 20- and 50-mile range gasoline vehicles (PHEV20, PHEV50)
- Electric 100-, 200-, and 300-mile range vehicles (EV100, EV200, EV300)
- Diesel/electric hybrid
- Bi-fuel CNG/LNG and bi-fuel LPG (liquefied propane gas)
- Dedicated CNG/LNG and LPG
- Methanol fuel cell and hydrogen fuel cell
- Gasoline/electric hybrid

For each manufacturer and nameplate, prices are estimated for low-production levels (beginning at 2,500 units) and high-production levels (beginning at 25,000 units). Because the TDM does not specifically model individual nameplates, low- and high-production price levels are increased to 5,000 units and 50,000 units, respectively.

1) Calculate base and historical yearly values for car prices at different production levels by applying an additive adjustment to the price of a gasoline-fueled vehicle.

   a) Car and Light Truck at 5,000 units per year

$$PRICE_{icl,igp,year,iatv} = PRICE_{icl,igp,year,iatv} + AFVADJPR_{iatv,ivtyp,year}, \tag{1}$$

where

$PRICE_{icl,igp,year,iatv}$ = low-production vehicle price by market class and group;

$AFVADJPR_{iatv,ivtyp,year}$ = incremental price adjustment for a low-production vehicle.

   b) Car and Light Truck prices at 50,000 units per year

$$PRICEHI_{icl,igp,year,iatv} = PRICEHI_{icl,igp,year,iatv} + AFVADJPRH_{iatv,ivtyp,year}, \tag{2}$$

where

$PRICEHI_{icl,igp,year,iatv}$= high-production vehicle price by market class and group;

$AFVADJPRH_{iatv,ivtyp,year}$ = incremental price adjustment for a high-production vehicle.

2) Calculate historic year values for fuel economy, weight, and horsepower.

   a) Fuel Economy

$$FE_{icl,igp,year,iatv} = FE_{icl,igp,year,gasoline} * \left(1 + AFVADJFE_{iatv,year}\right), \quad \textbf{(3)}$$

where

AFVADJFE$_{iatv,year}$ = percent difference in fuel economy relative to gasoline vehicles.

   b) Weight

$$WEIGHT_{icl,igp,year,iatv} = WEIGHT_{icl,igp,year,gasoline} * \left(1 + AFVADJWT_{iatv,year}\right), \quad \textbf{(4)}$$

where

AFVADJWT$_{iatv,year}$ = percent difference in weight relative to gasoline vehicles.

   c) Horsepower

$$HP_{icl,igp,year,iatv} = HP_{icl,igp,year,gasoline} * (1 + AFVADJHP_{iatv,year}), \quad \textbf{(5)}$$

where

AFVADJHP$_{iatv,year}$ = percent difference in horsepower relative to gasoline vehicles.

The characteristics of electric drivetrain vehicles—price, weight, fuel economy, and horsepower—are calculated with a different methodology discussed in Section 5.

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 standard. During this pass, the cost-effectiveness calculation is adjusted to include the regulatory cost of failing to meet CAFE.[6] If a manufacturer group fails to meet CAFE after the second pass, no further adjustments to technology market shares are made. In the third pass, the manufacturer groups focus solely on CAFE compliance at the expense of increased performance.

For each vehicle class, *FEMCALC* follows these steps:

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.

[6] See the variable REGCOST in Equation 12.

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 electric vehicle (EV), plug-in hybrid electric vehicle (PHEV), hybrid electric vehicle (HEV), and fuel cell (FC) 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). Fuel savings value

For each technology, the expected fuel savings associated with incremental fuel economy impacts is calculated. The time 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 will not be 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*), 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

$$FIVEYR\_FUELCOST_1 = \frac{1}{5} * \sum_{i=Year-8}^{Year-4} FUELCOST_i,$$

$$FIVEYR\_FUELCOST_2 = \frac{1}{5} * \sum_{i=Year-7}^{Year-3} FUELCOST_i,$$

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

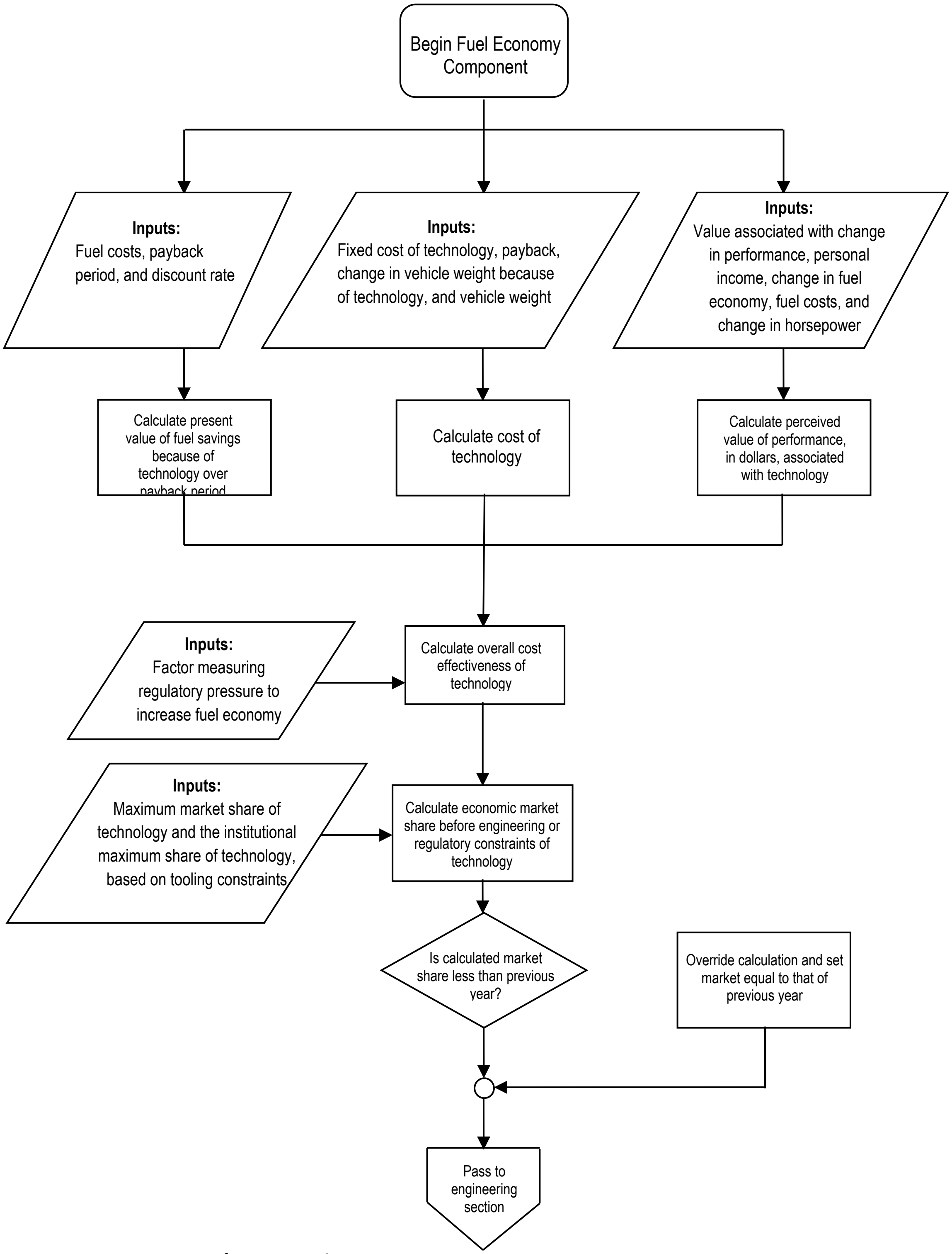
where

$FUELCOST_i$ = the price of fuel in year *i*.

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

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

Figure 4. Economic market share calculation of the Manufacturers Technology Choice Component of the Transportation Sector Demand Module (TDM), National Energy Modeling System (NEMS)



Data source: U.S. Energy Information Administration

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

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

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:

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

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.

$$TECHCOST_{itc} = TECHCOST_{itc} * \prod_{l=1}^{4} LEARN\_COST\_MULTIPLIER_l, \quad \textbf{(10)}$$

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 fuel prices.

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

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 fuel for the given year; and

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

d) 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

$$COSTEF\_FUEL_{itc} = \frac{FUELSAVE_{itc} - TECHCOST_{itc} + (REGCOST * FE_{year-1} * DEL\_FE_{itc})}{TECHCOST_{itc}}, \quad \textbf{(12)}$$

$$COSTEF\_PERF_{itc} = \frac{VAL\_PERF_{itc} - TECHCOST_{itc}}{TECHCOST_{itc}}, \quad \textbf{(13)}$$

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

$$MKT\_PERF_{itc} = \frac{1}{1+e^{MKT\_2COEFF*COSTEF\_PERF_{itc}}}, \quad \textbf{(15)}$$

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[7] = 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.

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

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 Table 1).

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

$$ACTUAL\_MKT_{itc,year} = MAX(MKT\_PEN_{itc,year-1}, ACTUAL\_MKT_{itc,year}), \quad \textbf{(17)}$$

where

[7] 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.

$MKT\_PEN_{itc,year}$ = market share for technology *itc*.

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

$$ACTUAL\_MKT_{itc,year} = MIN(1, MKT\_MAX_{itc}, ACTUAL\_MKT_{itc,year}), \quad \textbf{(18)}$$

where

MKT_MAX_{itc} = maximum market share for technology *itc*.

Apply the engineering notes

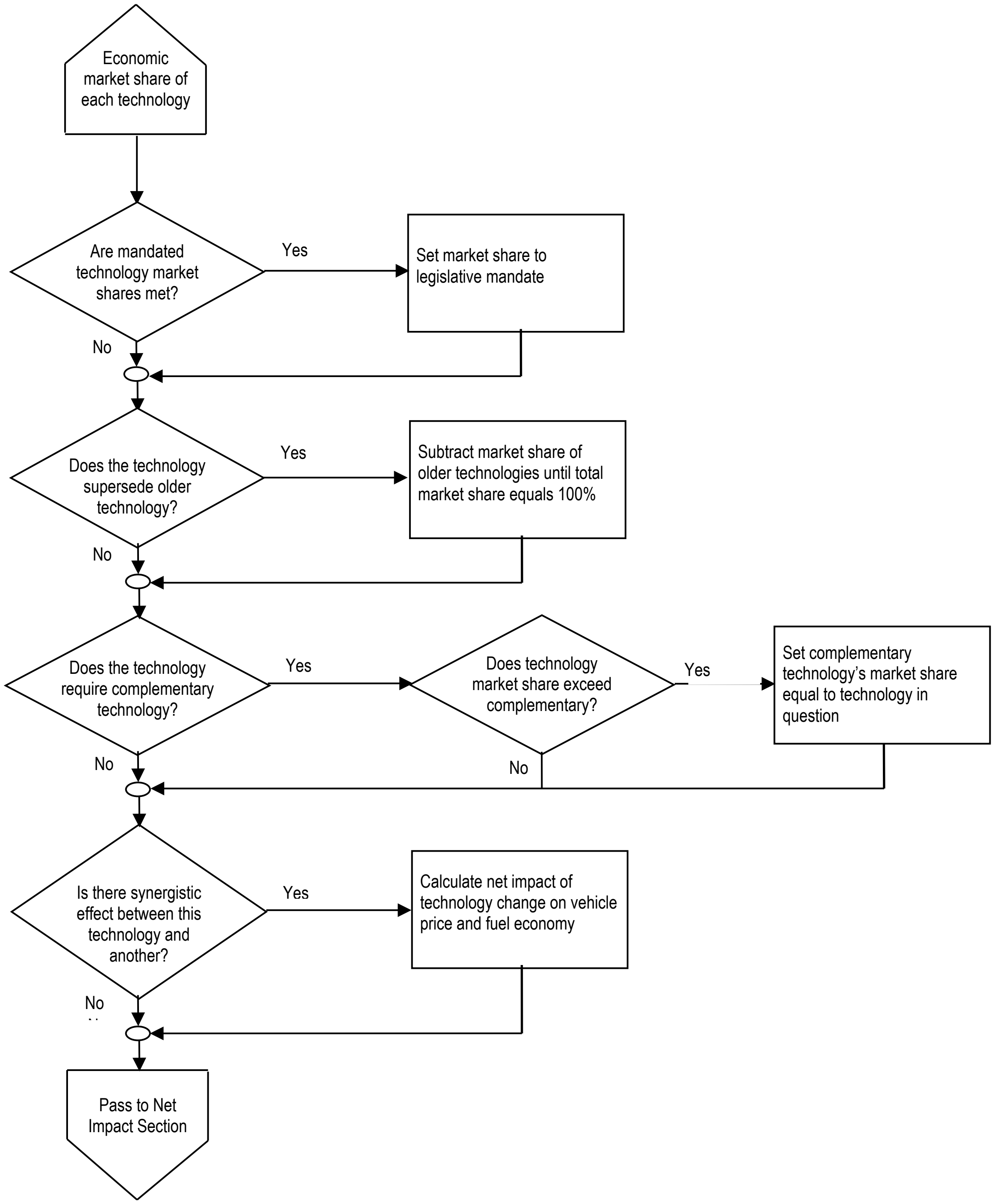
The engineering notes consist of a number of overrides to the economic cost-effectiveness calculations done in the previous step. Three types of notes (mandatory, supersedes, and requires) directly affect the technology market share results obtained above. The synergy note does not affect the market share and is applied after all other engineering notes have been applied (Figure 5).

Table 1. Maximum light-duty vehicle market penetration parameters (percentage)

Years in market	New PMAX
1	0.0%
2	4.8%
3	9.6%
4	14.5%
5	19.3%%
6	24.1%
7	28.9%
8	33.7%
9	38.5%
10	43.4%
11	48.2%
12	53.0%
13	57.8%
14	62.6%
15	67.4%
16	72.2%
17	77.1%
18	81.9%
19	86.9%
20	90.7%
21	93.6%
22	95.7%
23	97.3%
24	98.4%
25	99.2%
26	99.7%
27	100.0%
28	100.0%
29	100.0%
30	100.0%

Data source: U.S. Energy Information Administration

Figure 5. Engineering notes for Manufacturers Technology Choice Component of the Transportation Sector Demand Module (TDM), National Energy Modeling System (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.

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

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

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

where

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

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

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

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

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

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

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*

$$MAX\_SHARE = MAX(MKT\_MAX_{1,} \dots, MKT\_MAX_{num\_sup}), \quad \textbf{(23)}$$

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

$$DEL\_MKT_{itc} = TOT\_MKT_{itc,year} - MAX\_SHARE_{itc,year}, \quad \textbf{(24)}$$

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

$$ACTUAL\_MKT_{itc,year} = ACTUAL\_MKT_{itc,year} - DEL\_MKT_{itc}, \quad \textbf{(25)}$$

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

$$TOT\_MKT_{itc,year} = MAX\_SHARE_{itc,year}, \quad \textbf{(26)}$$

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*.

$$REQ\_MKT_{year} = MIN(\textstyle\sum_{req} MKT\_PEN_{req,year}, 1.0), \quad \textbf{(27)}$$

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

$$ACTUAL\_MKT_{itc,year} = MIN\left(ACTUAL\_MKT_{itc,year}, REQ\_MKT_{year}\right), \quad \textbf{(28)}$$

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

$$MKT\_PEN_{itc,year} = ACTUAL\_MKT_{itc,year}, \quad \textbf{(29)}$$

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 will also be negative and should be treated as an additive parameter.

$$SYNERGY\_LOSS_{itc} = \sum_{syn}(MKT\_PEN_{itc,Year} * MKT\_PEN_{syn,Year}) * SYNR\_DEL_{itc,syn} - \sum_{syn}(MKT\_PEN_{itc,Year-1} * MKT\_PEN_{syn,Year-1}) * SYNR\_DEL_{itc,syn}, \tag{30}$$

where

SYNERGY_LOSS$_{itc}$ = estimated synergy loss for all technologies synergistic with technology, *itc*; and

syn = set of technologies synergistic with technology, *itc*.

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

$$DELTA\_MKT_{itc} = MKT\_PEN_{itc,Year} - MKT\_PEN_{itc,Year-1}, \tag{31}$$

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*

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

where the equal sign is an assignment operator.

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, one term or the other will be zero.

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

where

$WEIGHT_{year,\ ildv}$= vehicle weight, by size class, group, and fuel type, initialized to the previous year value and modified with each iteration of the component.

Vehicle price

The current price for a vehicle class is calculated as the previous price plus the sum of incremental changes in the technology cost because of newly adopted technologies. This calculation is used to equally scale up both low-volume prices, at 5,000 units per year, and high-volume prices, at 50,000 units per year, as described in Equations 1 and 2.

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

where

$PRICE_{year}$ = vehicle price, by market class, group and technology type, initialized to the previous year value and subsequently modified with each iteration of the component.

e) Estimate EV, HEV, PHEV, and FC characteristics (subroutines *EVCALC*, *HEVCALC*, *PHEV20CALC*, *PHEV50CALC*, and *FCCALC*)

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

First, the price of the vehicle is adjusted according to the following assignment statements

$$PRICE_{icl,igp,year,ildv} = PRICE_{icl,igp,year,ildv} + ElecSysIncCost_{icl,igp,year,ildv},$$

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

where

ElecSysIncCost$_{icl,igp,year,ildv}$ = price of storage device for EV, HEV, PHEV20, PHEV50, and FC vehicles.

The price of the storage devices for EV, HEV, PHEV20, PHEV50, and FC vehicles include battery, non-battery systems, and, in the case of FC vehicles, storage tank and fuel cell stack costs.

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

Electric vehicles (EV), hybrid-electric vehicles (HEV), plug-in hybrid-electric vehicles (20-mile range) (PHEV20), plug-in hybrid-electric vehicle (50-miles range) (PHEV50), and fuel-cell electric (FC) 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, FC, and EV. NiMH battery costs measured in dollars per kilowatthour ($/kWh) is read in from *trnldv.xlsx*, and decline is estimated exogenously across the projection period. Lithium-ion battery costs ($/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:

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

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 vehicle weight and battery size for each of the electrified powertrains (EV100, EV200, EV300, PHEV20, PHEV50, HEV, and FC):

$$BatPackSize_{year,icl,igp,ildv} = weight_{icl,igp,year,ildv=1} * EV\_batt\_size\_m_{ildv} + EV\_batt\_size\_b_{ildv}$$
(38)

where

$BatPackSize_{year,icl,igp,ildv}$ = battery pack size for a single vehicle, kWh;

$weight_{icl,igp,year,ildv=1}$ = vehicle weight, gasoline powertrain;

$EV\_batt\_size\_m_{ildv}$ = battery size equation coefficient (slope); and

$EV\_batt\_size\_b_{ildv}$ = battery size equation coefficient (constant);

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: *HEV_sys_$, PHEV_sys_$, or EV_sys_$*, depending on the powertrain in question. Fuel cell vehicle non-battery costs are broken out by component, including the drivetrain cost per kW (*FuelCell$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 EV, HEV, PHEV20, PHEV50, and FC is calculated. HEVs are assumed to have the same horsepower per pound performance requirement as a gasoline vehicle, and the other electrified powertrains are assumed to require 20% less horsepower per pound.

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).

Electric vehicle range is calculated using its historical relationship to battery pack size (*BatPackSize*), modified by the maximum EV depth of discharge (*EV_DOD*).

$$\begin{aligned} EV\_range_{icl,igp,ildv} \\ &= MIN\big(BatPackSize_{year,icl,igp,ildv} * EV\_DOD_{year} * ev\_range\_m_{ildv} \\ &+ ev\_range\_b_{ildv}, EV\_range\_max_{ildv}\big) \end{aligned}$$

(39)

where

$EV\_range_{icl,igp,ildv}$ = electric vehicle range (miles);

EV_DOD_{year} = share of battery capacity available for use;

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

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

$Ev\_range\_max_{ildv}$ = maximum EV range within each range bin {EV100: 150, EV200: 250, EV300: none}.

Fuel economy is then estimated using range (*EV_range*) and battery pack size (*BatPackSize*).

$$FE_{icl,igp,year,ildv} = \frac{EV\_range_{icl,igp,ildv}}{atPackSize_{year,icl,igp,ildv}}, \quad \textbf{(40)}$$

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, 0.00570 for Hydrogen FC, and 0.00667 for Gasoline FC.

$$FE_{icl,igp,year,FC} = \frac{1}{GALPERMILE_{FC} * \frac{WEIGHT_{icl,igp,year,Gasoline}}{1000}}, \quad \textbf{(41)}$$

Impact of technology on horsepower

Calculating the net impact of changes in technology share on vehicle horsepower is a three-step process (Figure 6).

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

$$HP_{icl,igp,year,ildv} = WEIGHT_{year,ildv} * \frac{HP_{year-1,ildv}}{WEIGHT_{year-1,ildv}}, \quad \textbf{(42)}$$

where

$HP_{icl,igp,year,ildv}$ = vehicle horsepower; and

$WEIGHT_{year,ildv}$ = vehicle weight.

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

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 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

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

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 2018, *DEMAND_USED*, must be accounted for through the input parameter *USEDCAP*

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

and

$$PERF\_COEFF_{year} = 1 - (\frac{HP\_WGT_{Year} - HP\_WGT_{BaseYear} + DEMAND\_USED}{PERFCAP - HP\_WGT_{BaseYear} + DEMAND\_USED}), \tag{46}$$

and

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

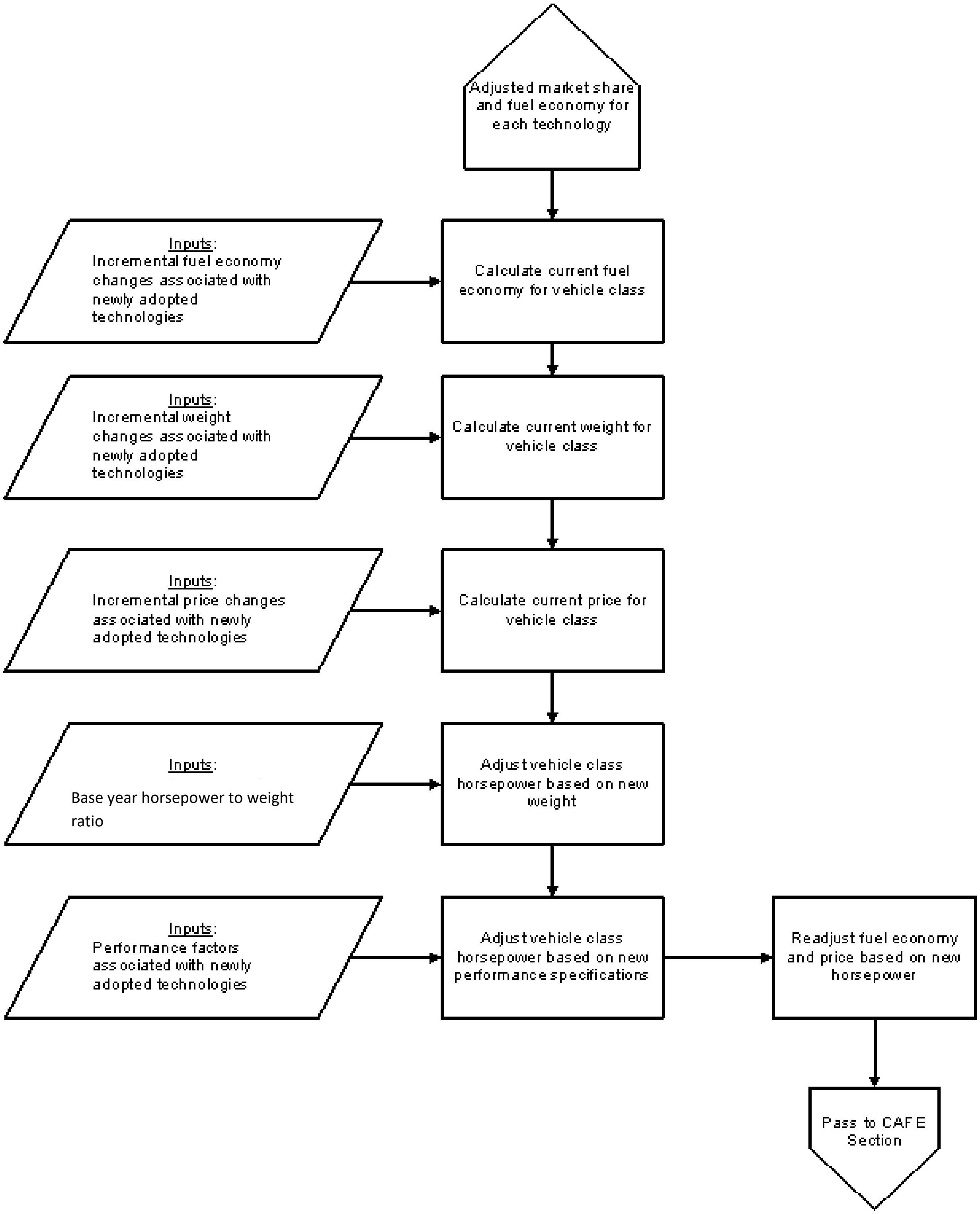
where

$HP\_WGT_{BaseYear}$ = 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.

Figure 6. Weight and horsepower calculation for Manufacturers Technology Choice Component of the Transportation Sector Demand Module (TDM), National Energy Modeling System (NEMS)



Data source: U.S. Energy Information Administration

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

$$TTL\_ADJHP_{Year} = TECH\_ADJHP_{Year} + PERF\_ADJHP_{Year}, \quad \textbf{(48)}$$

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%

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

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

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

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

Now, calculate the modified total horsepower adjustment

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

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

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

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

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

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 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. Sp, a third pass through FEMCALC allows manufacturers to focus solely on CAFE compliance at the expense of increased performance.

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

$$TECH\_ADJHP_{year} = TECH\_ADJHP_{year} - EXCESS\_ADJHP_{year}, \quad \textbf{(53)}$$

$$TTL\_ADJHP_{year} = TECH\_ADJHP_{year} + PERF\_ADJHP_{year}.$$

The model first computes the horsepower give back

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

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

$$HP_{year,FuelType} = HP_{year,ifuel} * (1 + TTL\_ADJHP_{year}). \quad \textbf{(55)}$$

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. 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 to facilitate the series of ensuing fuel economy and price algorithms, recognizing that giveback is *negative demand*

$$PERF\_ADJHP_{year} = PERF\_ADJHP_{year} - HP\_GIVEBACK_{year} \ , \quad \textbf{(56)}$$

$$ADJFE_{year} = -0.22 * PER\_ADJHP_{year} - (0.56 * SIGN * PER\_ADJHP_{year}{}^{2}), \quad \textbf{(57)}$$

where

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

The final vehicle fuel economy is then determined as follows

$$FE_{Year} = FE_{Year} * (1 + ADJFE_{year}). \quad \textbf{(58)}$$

Vehicle price

Vehicle price is finally estimated

$$PRICE_{year} = PRICE_{year} + PERF\_ADJHP_{year} * VALUEPERF_{year}. \quad \textbf{(59)}$$

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:

$$RANGE_{year,ildv} = TANKSIZE * FE_{year,gasoline} * (1 + AFVADJRN_{ildv}) * 0.7, \quad \textbf{(60)}$$

where

$RANGE_{year,ildv}$ = vehicle range (fuel economy x tank size);

TANKSIZE = tank size (gallons) for a gasoline vehicle of the same market class; and

$AFVADJRN_{ildv}$ = range adjustment, relative to gasoline vehicle (exogenous, from Block Data).

The range adjustment factor (*AFVADJRN*) is derived through engineering judgment and is based on current gasoline vehicle tank sizes, which is likely the relative fuel capacity, and the actual base year relative fuel economies of gasoline and AFVs.

The range for EVs is set at a fixed range. For an EV100 vehicle, the range is set to 90 miles; for an EV200, the range is set to 200 miles; and for an EV300, the range is set to 300 miles. The range is an engineering judgment of the best performance likely to be obtained from a production electric-powered vehicle in the near future. The next step is to calculate the market shares of each vehicle class within each CAFE group.

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

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

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*

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

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

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

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

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

Calculate CAFE (subroutine *CAFECALC*)

This routine calculates the corporate average fuel economy (CAFE) for each of the 11 CAFE groups

- Domestic car
- Asian car

- European car
- Luxury Sport car
- HAV car
- Truck—Manufacturer Group 1—Domestic
- Truck—Manufacturer Group 2—Domestic
- Truck—Manufacturer Group 3—Domestic
- Truck—Manufacturer Group 4—Import
- Truck—Manufacturer Group 5—Import
- Truck—Manufacturer Group 6—HAV

For each vehicle group the CAFE compliance calculation proceeds as follows

$$CafeMpgWgt_{ivtyp,icl,igp,year} = \frac{\sum_{icl=1}^{8} CLASS\_SHARE_{ireg,icl,igp,year} * apshr55_{ivtyp,icl,iregn,ildv}}{\sum_{icl=1}^{8} LDV\_MPG\_CL_{ivtyp,ildv,icl,year}}. \quad \textbf{(65)}$$

Flex-fuel and dedicated AFVs earn fuel economy credits that last until 2019 for flex-fuel vehicles and do not expire for dedicated AFVs. Fuel economy for each manufacturer is then harmonically weighted based on vehicle sales by size class and fuel type (*NewMPG*).

This CAFE estimate is then compared with the legislative standard for the 11 manufacturer groups for each year. The two standards are the traditional standard, represented by the exogenous variable, $CAFE\_STAND_{Group,Year}$, and the alternative standard, $FPMpgGrp_{Group,Year}$. $FPMpg_{Class,Group,Year}$ is computed for each class in each group based on the footprint. Passenger cars use the traditional standard before 2011 and the alternative standard for subsequent years.

Light trucks use the traditional standard before 2008. If the year is between 2008 and 2011, the light-truck standard is the lesser of the alternative footprint miles per gallon (MPG) standard and the traditional standard. If the alternative standard is chosen, then light trucks must continue to use it in later years.

The alternative CAFE standard is calculated for 2011 as follows

$$FPMpg_{class,group,Year} = \left(\left(\frac{1}{CFCoefA_{year}}\right) + \left(\frac{1}{CFCoefB_{year}} - \frac{1}{CFCoefA_{year}}\right) * \frac{e^{\frac{FPrint_{icl,igp,year} - CFCoefC_{year}}{CFCoefD_{year}}}}{1 + e^{\frac{FPrint_{icl,igp,year} - CFCoefC_{year}}{CFCoefD_{year}}}} \right)^{-1}, \quad \textbf{(66)}$$

where

$CFCoefA_{year}$ = the maximum fuel economy target for cars or trucks by year;

$CFCoefB_{year}$ = minimum fuel economy target for cars or trucks by year;

$CFCoefC_{year}$ = footprint midway between by year;

$CFCoefD_{year}$ = rate of change parameter by year; and

$FPrint_{icl,igp,year}$ = footprint for each class and group of cars or trucks by year.

The alternative CAFE standard for 2012 and subsequent years is calculated as the greenhouse gas emissions equivalent fuel economy value

$$FPMpg_{icl,igp,year} = \frac{1}{MIN\left(MAX\left(\left((CFCoefC2 * FPrint) + CFCoefD2\right), \frac{1}{CFCoefA2}\right), \frac{1}{CFCoefB2}\right)}, \tag{67}$$

where

CFCoefA2 = the function’s upper fuel economy limit for cars or trucks by year;

CFCoefB2 = the function’s lower fuel economy limit for cars or trucks by year;

CFCoefC2 = the slope of the function; and

CFCoefD2 = the intercept of the sloped portion of the function.

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.

CAFE standard compliance (subroutine *CAFETEST*)

This algorithm, which is called after the third pass of the MTCC, adjusts sales of electric drive train and diesel light-duty vehicles 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, *CAFETYP*, in the most cost-effective order determined by incremental vehicle cost and fuel savings over a specified period. For passenger cars, we use the Environmental Protection Agency (EPA) size classes and for light-duty trucks, gross vehicle weight ratings define the classes for SUVs, pickups, and vans. For each vehicle group, the CAFE calculation proceeds as follows.

For any of the 11 vehicle manufacturing groups described above that fail to meet the CAFE standard, a new set of sales values is computed through the following steps. First, the model calculates the incremental increase in the AFV share of total national sales, *DELTA*.

$$DELTA_{icl,igp,year} = 0.0125 * CLASS\_SHARE_{icl,igp,year} * SALESHR_{igp,year}, \tag{68}$$

where

$SALESHR_{igp,year}$ = car and light-truck sales share by manufacturer group.

New sales are computed up to 20 times at increments of 1.25%. A new set of CAFE calculations is made for each increment and compared with the CAFE standard. Further sales stop after successfully passing the standard. New vehicle sales are computed as follows

$$AVSALES\_NEW_{igp,icl,ildv,year} = AVSALES_{igp,icl,ildv,year} + DELTA_{icl,igp}, \quad (69)$$

$$AVSALES_{igp,icl,gasoline,year} = AVSALES_{igp,icl,gasoline,year} - DELTA_{icl,igp}. \quad (70)$$

The new shares, APSHR55, are then recalculated. Total sales, AVSALEST, remain unchanged.

If, at any time, sales of conventional gasoline or flex-fuel vehicles become negative, sales of these vehicles are increased until sales reach a non-negative number, and vehicle sales of electric drive-train or diesel vehicles are correspondingly decreased. New vehicles sales have some constraints. For each *CAFETYP*, sales adjustments are limited to 20 cycles to meet the standard.

Combine manufacturer group vehicle attributes

In subsequent submodules of the TDM, vehicle sales by manufacturer groups 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 (*PERGRP*). These numbers are assumed to be constant across classes and time, and we obtain these from the National Highway Traffic Safety Administration (NHTSA) data.

$$LDV\_MPG\_CL_{ivtyp,ildv,icl,year} = \frac{1}{\sum_{igp} \frac{PERGRP_{igp,icl,year,ildv}}{FE_{icl,igp,year,ildv}}}, \quad (71)$$

$$LDVHPW_{ivtyp,ildv,icl,year} = \sum_{igp} PERGRP_{igp,icl,year,ildv} * HP_{icl,igp,year,ildv}, \quad (72)$$

$$LDV\_PRI_{ivtyp,ildv,icl,year} = \sum_{igp} PERGRP_{igp,icl,year,ildv} * PRICE_{icl,igp,year,ildv}, \quad (73)$$

$$LDV\_RNG_{ivtyp,ildv,icl,year} = \sum_{igp} PERGRP_{igp,icl,year,ildv} * RANGE_{icl,igp,year,ildv}, \quad (74)$$

$$WGT_{ivtyp,ildv,icl,year} = \sum_{igp} PERGRP_{igp,icl,year,ildv} * WEIGHT_{icl,igp,year,ildv}, \quad (75)$$

where

$LDV\_MPG\_CL_{ivtyp,ildv,icl,year}$ = vehicle fuel economy;

$LDVHPW_{ivtyp,ildv,icl,year}$ = vehicle horsepower;

$LDV\_PRI_{ivtyp,ildv,icl,year}$ = vehicle price;

$LDV\_RNG_{ivtyp,ildv,icl,year}$ = vehicle range;

$WGT_{ivtyp,ildv,icl,year}$ = vehicle weight (lbs); and

$PERGRP_{igp,icl,year}$ = size class market share by manufacturer, for car and light truck.

These numbers are then passed to the Consumer Vehicle Choice Component (CVCC) and the overall fleet stock component to produce estimates of fleet efficiencies.

Regional Sales Component

The Regional Sales Component is a simple accounting mechanism using exogenous estimates of new car and light-truck sales and the results of the MTCC to produce estimates of regional sales and the characteristics of light-duty vehicles that are then passed to the Light-Duty Vehicle Stock Component.

Nationwide estimates of total new vehicle sales come from the NEMS Macroeconomic Activity Module. To comply with the NEMS requirement for regional fuel consumption estimates, the Regional Sales Component allocates new car and light-truck sales among the nine census divisions and permits regional variations in vehicle attributes. Because of geographic representation in this component, the TDM can analyze regional differences in AFV legislation. For example, California's Zero Emission Vehicles Program requires a minimum percentage of vehicles sold to be zero-emission vehicles, transitional zero-emission vehicles, and partial zero-emission vehicles, which are met through credits obtained from their sale. The program has been adopted by Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, and Vermont and is included in the TDM.

The Regional Sales Component is not a separate component in itself, but rather a series of intermediate calculations used to generate several regional variables that are used in subsequent steps in the TDM. It makes up two subroutines: CGSHARE and TREG. The first calculates light-vehicle market class shares and average horsepower and weight for cars and light trucks, and the second generates regional shares of fuel consumption, driving demand, and sales of vehicles by market class.

Redistribute MTCC sale shares among eight size classes

The first stage in this component involves estimating non-fleet sales of cars and light trucks for each of the 8 size classes and 11 manufacturer groups described in the MTCC. The fraction of car and truck sales attributed to fleets is assumed to vary over time across size classes and the estimation period. Although the fuel economies of the 11 manufacturer groups have already been combined, the separate market shares are recorded and the calculations are performed separately for each manufacturer group.

First, car and light-truck sales are determined after getting total sales from the Macroeconomic Activity Module. Total sales of trucks are shared into the following gross vehicle weight rating (GVWR) categories:

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

In addition, the LDV Submodule estimates the allocation of LDV sales between cars and light trucks to capture the changing purchase patterns of consumers in recent years.

First, estimate the percentage of total light vehicles less than 8,500 pounds GVW that are cars by region, *CARSHRT*

$$CARSHRT_{year} = e^{\begin{pmatrix} \beta_0(1-\rho)+(\rho\log(CARSHARE_{year-1}))+ \\ \beta_1[\log(INC00\$16_{year})-\rho\log(INC00\$16_{year-1})]+ \\ \beta_2[\log(PMGTR00\$C_{year})-\rho\log(PMGTR00\$C_{year-1})]+ \\ \beta_3[\log(AHPCAR_{year-1})-\rho\log(AHPCAR_{year-2})]+ \\ \beta_4[\log(AWTCAR_{year-1})-\rho\log(AWTCAR_{year-2})]+ \\ \beta_5[\log(TRUEMPG_{year-1})-\rho\log(TRUEMPG_{year-2})]+ \\ \beta_6[\log(DUMM_{year})-\rho\log(DUMM_{year-1})] \end{pmatrix}}, \quad \textbf{(76)}$$

where

CARSHARE$_{Year}$ = historic car share;

INC00\$16$_{Year}$ = disposable income per capita for population age 16+, expressed in 2000 dollars;

PMGTR00\$C$_{Year}$ = fuel price in 2000$ per gallon;

AHPCAR$_{Year}$ = average car horsepower;

AWTCAR$_{Year}$ = average car weight;

TRUEMPG$_{Year}$ = vehicle fuel economy;

DUMM$_{Year}$ = dummy variable; and

ρ = autocorrelation coefficient for the difference equation.

Calculate new car and light-truck (class 1 and 2a, less than 8,500 pounds GVWR) sales

$$NEWCARS_{iregn,year} = \left(MC\_SUVA_{year} + TEMPCLS12A_{year}\right) * CARSHARE\_REGN_{iregn,year} * REGN\_SHR_{iregn,year},$$

$$NEWCLS12A_{iregn,year} = \left(MC\_SUVA_{year} + TEMPCLS12A_{Year}\right) * \left(1 - CARSHARE\_REGN_{iregn,year}\right) * REGN\_SHR_{iregn,year}, \quad \textbf{(77)}$$

where

NEWCARS$_{iregn,year}$ = Total new car sales;

NEWCLS12A$_{iregn,year}$ = Total new light-truck sales;

MC_SUVA$_{year}$ = Total car sales, from the Macroeconomic Activity Module;

TEMPCLAS12A$_{Year}$ = Sales of class 1 and 2 light trucks;

CARSHARE_REGN$_{iregn,year}$ = Share of light vehicles less than 8,500 GVW that are cars; and

REGN_SHR$_{iregn,year}$ = Share of light-duty vehicles by census division .

Calculate non-fleet, non-commercial sales of cars (*groups=1-5*) and light trucks (*groups=6-11*) across the 8 size classes

$$NVS7SC_{iregn,igp=1-5,icl,year} = CLASS\_SHARE_{iregn,icl,igp=1-5,year} * (NEWCARS_{iregn,year} * OWNER\_SHARE_{iregn,ivtyp=1,iown=1,year}) * SALESHR_{iregn,igp=1-5,year},$$

$$NVS7SC_{iregn,igp=6-11,icl,year} = CLASS\_SHARE_{iregn,icl,igp=6-11,year} * (NEWCLS12A_{iregn,year} * OWNER\_SHARE_{iregn,ivtyp=2,iown=1,year}) * SALESHR_{iregn,igp=6-11,year},$$

(78)

where

NVS7SC$_{iregn,igp,icl,year}$ = Non-fleet, non-commercial sales; and

OWNER_SHARE$_{iregn,ivtyp,iown,year}$ = Share of new vehicle sales by owner type and by region.

Sales are then combined for the 11 manufacturing groups, as follows

$$NCSTSC_{iregn,icl,year} = \sum_{igp=1}^{5} NVS7SC_{iregn,igp,icl,year},$$

$$NLTSTSC_{iregn,icl,year} = \sum_{igp=6}^{11} NVS7SC_{iregn,igp,icl,year}, \quad \textbf{(79)}$$

where

NCSTSC$_{iregn,icl,year}$ = sales of cars by the EPA vehicle size classes; and

NLTSTSC$_{iregn,icl,year}$ = sales of light trucks by vehicle size class.

Estimating non-fleet market shares for cars and light trucks by market class starts with the most recent historical data reported by the NHTSA and assumes growth at the same rate as the non-fleet, non-commercial share of sales of cars and light trucks

$$PASSHRR_{iregn,icl,year} = PASSHRR_{iregn,icl,year-1} * \frac{\left(\frac{NCSTSC_{iregn,icl,year}}{\sum_{icl=1}^{8} NCSTSC_{iregn,icl,year}}\right)}{\left(\frac{NCSTSC_{iregn,icl,year-1}}{\sum_{icl=1}^{8} NCSTSC_{iregn,icl,year-1}}\right)},$$

and

$$LTSSHRR_{iregn,icl,year} = LTSSHRR_{iregn,icl,year-1} * \frac{\left(\frac{NLTSTSC_{iregn,icl,year}}{\sum_{icl=1}^{8} NLTSTSC_{iregn,icl,year}}\right)}{\left(\frac{NLTSTSC_{iregn,icl,year-1}}{\sum_{icl=1}^{8} NLTSTSC_{iregn,icl,year-1}}\right)}, \quad \textbf{(80)}$$

where

PASSHRR$_{iregn,icl,year}$ = non-fleet market share for cars; and

$LTSHRR_{iregn,icl,year}$ = non-fleet market share for light trucks.

The weighted average horsepower of cars and light trucks, weighted by the non-fleet market shares, is then calculated

$$AHPCAR_{iregn,year} = \sum_{icl=1}^{8} \left[PASSHRR_{iregn,icl,year} * LDVHPW_{ivtyp=1,ildv=gas,icl,year}\right],$$

$$AHPTRUCK_{iregn,year} = \sum_{icl=1}^{8} \left[LTSSHRR_{iregn,icl,year} * LDVHPW_{ivtyp=2,ildv=gas,icl,year}\right]. \qquad \textbf{(81)}$$

A similar calculation occurs for the average weight of cars (*AWTCAR*) and light trucks (*AWTTRUCK*), weighted by the non-fleet market shares, as shown in the above equations.

Determine regional values of fuel demand and estimate pre-2012 regional vehicle sales

Regional demand shares for each of the 11 fuels, as defined in the State Energy Data System (SEDS), are initialized, ensuring that no region has a zero share in the preceding period. Shares are then adjusted for change over time, assuming growth at the rate of personal income growth in each region, and they are renormalized so that the shares add to 1.0

$$SEDSHR_{ifuel11,iregn,year} = \frac{SEDHSR_{ifuel11,iregn,year-1} * \frac{MC\_YPDR_{iregn,year}}{MC\_YPDR_{iregn,year-1}}}{\sum_{iregn=1}^{9}\left[SEDHSR_{ifuel11,iregn,year-1} * \frac{MC\_YPDR_{iregn,year}}{MC\_YPDR_{iregn,year-1}}\right]}, \qquad \textbf{(82)}$$

where

$SEDSHR_{ifuel11,iregn,year}$ = regional share of the consumption of a given fuel in period, year; and

$MC\_RegionalYPDR_{iregn,year}$ = regional estimated disposable personal income.

These shares are passed to other submodules in the TDM and used for the first year computation of *VMTLDR* and *VMTEER*, in this case 1995.

The national total of new car and light-truck sales is then allocated among regions, based on the assumption that regional demand for new vehicles is proportional to regional travel demand. The calculation proceeds as follows:

Estimate regional shares of driving demand[8]

$$VMTLDV_{iagr,year,imf,iregn} = VMTLD_{iagr,year,imf} * LICDRIVER_{iagr,imf,iregn,year}, \qquad \textbf{(83)}$$

where

[8] Developing and estimating the VMT equation is described in detail in the VMT Component (Section 3). The calculation here is solely to estimate regional travel shares.

$VMTLDV_{iagr,year,imf,iregn}$ = Total VMT for household and fleet LDVs less than 8,500 GVW;

$VMTLD_{iagr,year,imf,iregn}$ = VMT per licensed driver from historical data; and

$LICDRIVER_{iagr,imf,iregn,year}$ = total regional licensed drivers.

Calculate regional VMT shares (*RSHR*)

$$RSHR_{iregn,year} = \frac{\sum_{iagr=1}^{5}\sum_{imf=1}^{2} VMTLDV_{iagr,year,imf,iregn}}{\sum_{iregn=1}^{9}\sum_{iagr=1}^{5}\sum_{imf=1}^{2} VMTLDV_{iagr,year,imf,iregn}}, \tag{84}$$

For historical data before 2011, regional non-fleet car (*NCS*) and light-truck sales(*NLTS*) are estimated based on historical sales per licensed driver:

$$NCS_{iregn,icl,year} = NCSTSC_{iregn=national,icl,year} * CarShare_{iregn,year},$$

$$NLTS_{iregn,icl,year} = NLTSTSC_{iregn=national,icl,year} * TrkShare_{iregn,year}. \tag{85}$$

Consumer Vehicle Choice Component (CVCC)

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 conventional vehicles and AFVs from 1995 to 2050. To project technology market shares, the component uses estimates of the following variables and vehicle attributes:

- New car fuel economy (obtained from the MTCC)
- Vehicle price
- Vehicle range
- Fuel availability
- Battery replacement cost
- Performance (measured by the horsepower-to-weight ratio)
- Home refueling capability
- Maintenance costs
- Luggage space
- Make and model diversity or availability
- Fuel price estimates generated by NEMS

The component is useful for assessing the market penetration of conventional and AFVs and 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

$$\log\left(\frac{P_k}{1-P_k}\right) = \beta_1 + \beta_2 X_2 + \beta_3 X_3 + \cdots + \beta_k X_k + \varepsilon_k\,, \tag{86}$$

where

P_k = probability of consumer choosing vehicle (k);

β_1 = constant term;

$\beta_{1\ldots}, \beta_k$ = 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 market share estimate for AFV sales is a three-dimensional matrix format. The matrix consists of *I* vehicle technology types, *K* attributes for each technology, and *T* year of projection. Each cell C_{ikt} in the *C* matrix contains a coefficient reflecting the value of attribute *k* of vehicle technology *i* for the given year *t*.

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

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

$$P_{itn} = \frac{e^{V_{itn}}}{\sum_{i=1}^{I} e^{V_{itn}}}, \tag{87}$$

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,

$$V = ß_1X_1 + ß_2X_2 + \ldots + ß_kX_k$$

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

This formulation assumes that the share of each technology is equivalent to the aggregate probability over the population choosing that technology, 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 operates in three stages by using a bottom-up approach to determine the eventual market shares of conventional and AFVs. Results from the lower stages are passed to the next higher stage in the sequence. Because the prices of AFVs are functions of sales volume (estimated in the MTCC), the CVCC goes through two iterations. First, the CVCC estimates sales volume using the previous year's volume-dependent prices and then re-estimates prices and consequent sales.

The component projects market shares for 14 alternative fuel technologies as well as for conventional gasoline and diesel technologies. The tree structure of the CVCC-logit model has three stages. In the first stage, the shares of vehicle sales are determined for five aggregate vehicle groups: conventional, hybrid, dedicated alternative fuel, fuel cell, and electric. The second stage of the logit model subdivides each of the five groups to estimate sales shares for the specific vehicle types within the each group. The conventional vehicles consist of gasoline, diesel, flex-fuel ethanol, CNG/LNG, and LPG bi-fuels. Hybrid-electric vehicles are gasoline and diesel hybrids and gasoline plug-in hybrid electric. Dedicated CNG/LNG and LPG make up the dedicated AFV group. Fuel cell vehicles include methanol reformers and hydrogen-based fuel cells. The fifth group is represented by 100-, 200-, and 300-mile-range electric vehicles. 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.

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

- Vehicle price
- Fuel cost or cost of driving per mile (fuel price divided by fuel efficiency)
- Vehicle range
- Fuel availability
- Battery replacement cost
- Performance (measured by the horsepower-to-weight ratio)
- Home refueling capability
- Maintenance costs
- Luggage space
- Make and model diversity or availability

The vehicle attributes of vehicle purchase price, fuel cost, acceleration, maintenance, battery cost, and fuel availability are discussed in detail below.

The model first reads in the vehicle purchase price calculated in the MTCC

$$PSPR_{ivtyp,ildv,icl,year} = LDV\_PRI_{ivtyp,ildv,icl,year}, \quad \textbf{(88)}$$

where

LDV_PRI$_{ivtp,ildv,icl,year}$ = aggregate vehicle price, obtained from MTCC, and constrained not to drop lower than the gasoline vehicle price plus the high volume differential between gasoline and an advanced technology vehicle (ATV).

Next, the model estimates fuel costs per mile traveled

$$FLCOST_{ivtyp,ildv,icl,iregn,year} = \frac{FPRICE_{ildv,iregn,year}}{LDV\_MPG\_CL_{ivtyp,ildv,icl,year}}, \quad \textbf{(89)}$$

where

FLCOST$_{ivtyp,ildv,icl,iregn,year}$ = fuel operating costs for each technology, in nominal dollars per mile;

FPRICE$_{ildv,iregn,year}$ = vehicle fuel price, in nominal dollars per gallon; and

LDV_MPG_CL$_{ivtyp,ildv,icl,year}$ = aggregate vehicle fuel economy.

The model estimates the time, in seconds, the vehicle needs to accelerate from 0 miles per hoiur (mph) to 60 mph.

$$ACCL_{ivtyp,ildv,icl,year} = e^{-0.00275} * \left(\frac{LDVHPW_{ivtyp,ildv,icl,year}}{WGT_{ivtyp,ildv,icl,year}}\right)^{-0.776}, \quad \textbf{(90)}$$

where

ACCL$_{ivtyp,ildv,icl,year}$ = acceleration time, in seconds, to accelerate from 0 mph to 60 mph;

LDVHPW$_{ivtyp,ildv,icl,year}$ = horsepower; and

WGT$_{ivtyp,ildv,icl,year}$ = weight.

The model then calculates vehicle maintenance and battery costs in nominal dollars

$$MAINT_{ivtyp=1,ildv,icl,year} = MAINTCAR_{ildv,icl} * TMC\_PGDP_{year},$$

$$MAINT_{ivtyp=2,ildv,icl,year} = MAINTTRK_{ildv,icl} * TMC\_PGDP_{year}, \quad \textbf{(91)}$$

where

MAINTCAR$_{ildv,icl}$ = car maintenance and battery costs;

MAINTTRK$_{ildv,icl}$ = light truck maintenance and battery cost; and

TMC_PGDP$_{year}$ = GDP deflator.

Fuel availability (TALT2) subroutine methodology

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 technology groups. The final fuel availability variable is configured as an index relative to the number of gasoline refueling stations.

Table 2. Engine technology fuel type to highway fuel type

Engine technology fuel type	Highway fuel type
Gasoline	Gasoline
Gasoline and diesel hybrid, gasoline plug-in hybrid electric	Gasoline/diesel/electricity
Flex-fuel ethanol	Ethanol/gasoline
Fuel cell methanol	Methanol
Bi-fuel and dedicated compressed natural gas (CNG)/liquefied natural gas (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

The model then calculates 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

$$PREDSTK_{ifuel,year} = \sum_{ildv=1}^{16}\left[W_{ifuel,ildv} * LDVSTK_{ildv,year-1}\right], \quad \textbf{(92)}$$

where

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

$LDVSTK_{ildv,year-1}$ = vehicle stock, by engine technology fuel 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

$$ALTSTAT_{ifuel,year} = ALTSTAT_{ifuel,year-1} + \frac{PREDSTK_{ifuel,year} - PREDSTK_{ifuel,year-1}}{STA\_RAT_{ifuel}}, \quad \textbf{(93)}$$

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 that use a given fuel

$$FUELVSAL_{iregn,ifuel,year} = NCSTECH_{iregn,icl,ifuel,year} + NLTECH_{iregn,icl,ifuel,year},$$

$$AFVSHREG_{iregn,ifuel,year} = \frac{FUELVSAL_{iregn,ifuel,year}}{\sum_{iregn=1}^{9} FUELVSAL_{iregn,ifuel,year}}, \quad \textbf{(94)}$$

$$ALTSTA_{iregn,ifuel,year} = AFVSHREG_{iregn,ifuel,year} * ALTSTAT_{ifuel,n},$$

where

$NCSTECH_{iregn,icl,ifuel,year}$ = regional car sales by fuel type;

$NLTECH_{iregn,icl,ifuel,year}$ = regional light-truck sales by fuel type;

$FUELVSAL_{iregn,ifuel,year}$ = regional vehicle sales within a fuel type;

$AFVSHREG_{iregn,ifuel,year}$ = regional vehicle sales share within fuel type; and

$ALTSTA_{iregn,ifuel,year}$ = regional alternative-fuel refueling stations by fuel type.

Fuel availability is estimated as an index relative to the number of gasoline refueling stations on a regional basis

$$FAVAIL_{ifuel,year,iregn} = \frac{ALTSTA_{iregn,ifuel,year}}{ALTSTA_{iregn,gasoline,year}}, \quad \textbf{(95)}$$

where

$FAVAIL_{ifuel,year,iregn}$ = regional fuel availability index of alternative fuel, by highway fuel type.

The model then populates regional fuel availability variable $FAVL_{ildv,iregn,year}$ by mapping highway fuels (*ifuel*) to vehicle types (*ildv*).

Light vehicle AFV market penetration (TALT2X) subroutine methodology

Operation of this component begins at the third level 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 of the logit model. 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 technology is calculated using the shares computed in level one and level two.

Level three

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

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

$$BETAFA31T_{ivtyp,icl} = X31T1_{ivtyp,icl} * \frac{BETAFA231T_{ivtyp,icl}}{XFC_{ivtyp,icl}}, \quad \textbf{(96)}$$

where

T = technology (3 = methanol flex-fuel, 4 = E85, 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

$BETAFA231T_{ivtyp,icl}$ = 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 Equations 105–107 below vary across other dimensions as indicated in the subsequent glossary, but they are shown with the key dimension for brevity.

$$UISUM_{fueltyp} = X31T1 * FLCOST_{fueltyp} + \frac{X31T2}{VRANG31T_{fueltyp}} + BETAFA31T * e^{BETAFA231T * FAVAL31T_{fueltyp}}, \quad \textbf{(97)}$$

where

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

$VRANG31T_{fueltyp}$ = vehicle range in miles for technology T as defined in Equation 104 above, by vehicle type and market class;

$FAVAL31T_{fueltyp}$ = fuel availability indexed relative to gasoline for technology T as defined in Equation 104 above, 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 and summed

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

$$ETOT = \sum_{fueltyp} ESUM_{fueltyp}, \quad \textbf{(98)}$$

where

$ESUM_{fueltyp}$ = exponentiated utility of value; and

ETOT = sum of ESUM across fuel types gasoline and alternative fuel in flex and bi-fuel vehicles.

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

$$GENCOST = \frac{\log(ETOT)}{X31T1}, \quad \textbf{(99)}$$

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:

- Conventional vehicles (gasoline, diesel, flex-fuel ethanol, and bi-fuels CNG/LNG and LPG)
- Hybrid-electric vehicles (gasoline and diesel hybrid-electric and gasoline plug-in hybrid electric)
- Dedicated AFVs (CNG/LNG and LPG fueled)
- Fuel cell vehicles (methanol and hydrogen fueled)
- 100-, 200-, and 300-mile range electric vehicles

Second-level market shares are estimated separately for flex and bi-fueled vehicles versus shares estimated for dedicated fuel vehicles.

Second-level logit model calculations for the flex and bi-fuel vehicles determine their share within the conventional vehicles, which represents the first of five groups at the first level as follows:

$$\begin{aligned} UISUM_{jt} = {} & X21_{ivtyp,icl} * PSPR_{ivtyp,ildv,icl,year} + X22_{ivtyp,icl} * GENCOST + \\ & X24_{ivtyp,icl} * BRCOST25_{ivtyp,ildv,icl,year} + X25_{ivtyp,icl} * ACCL_{ivtyp,ildv,icl,year} + \\ & X26_{ivtyp,icl} * HFUEL_{ivtyp,ildv,icl,year} + X27_{ivtyp,icl} * MAINT_{ivtyp,ildv,icl,year} + \\ & X28_{ivtyp,icl} * LUGG_{ivtyp,ildv,icl,year} + X29_{ivtyp,icl} * \\ & \log\left(MMAVAIL_{ivtyp,ildv,icl,iregn,year}\right) + X210_{ivtyp,ildv,iregn}, \end{aligned} \quad \textbf{(100)}$$

where

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

$X21_{ivtyp,icl}$ = coefficient for vehicle price at the second level in dollars;

$X24_{ivtyp,icl}$ = coefficient for battery replacement cost at the second level;

$X25_{ivtyp,icl}$ = coefficient for vehicle acceleration time from 0 to 60 miles per hour in seconds;

$X26_{ivtyp,icl}$ = coefficient for electric vehicle and PHEV home refueling capability;

$X27_{ivtyp,icl}$ = coefficient for maintenance cost in dollars;

$X28_{ivtyp,icl}$ = coefficient for luggage space indexed to gasoline vehicle;

$X29_{ivtyp,icl}$ = coefficient for vehicle make and model diversity availability relative to gasoline;

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

$PSPR_{ivtyp,ildv,icl,year}$ = vehicle price at the second level in dollars;

$BRCOST25_{ivtyp,ildv,icl,year}$ = battery replacement cost at the second level;

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

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

$LUGG_{ivtyp,ildv,icl,year}$ = 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.xml.

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

$$\begin{aligned} UISUM_{jt} = {} & X21_{ivtyp,icl} * PSPR_{ivtyp,ildv,icl,year} + X22_{ivtyp,icl} * FLCOST + \\ & X23_{ivtyp,icl} * \frac{1}{VRNG_{ivtyp,ildv,icl,year}} + X24_{ivtyp,icl} * BRCOST25_{ivtyp,ildv,icl,year} + \\ & X25_{ivtyp,icl} * ACCL_{ivtyp,ildv,icl,year} + X26_{ivtyp,icl} * HFUEL_{ivtyp,ildv,icl,year} + \\ & X27_{ivtyp,icl} * MAINT_{ivtyp,ildv,icl,year} + X28_{ivtyp,icl} * LUGG_{ivtyp,ildv,icl,year} + \\ & X29_{ivtyp,icl} * \log\left(MMAVAIL_{ivtyp,ildv,icl,year}\right) + X210_{ivtyp,ildv} + \\ & BETAFA2 * e^{BETAFA22_{ivtyp,icl} * TFAvl}, \end{aligned} \qquad \textbf{(101)}$$

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

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

$$ETOT_{jg} = \sum_{jt \subset jg} ESUM_{jt}\ , \qquad \textbf{(102)}$$

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

where

$XSHARE_{jg,jt}$ = market share of AFVs by the five vehicle groups and by technology.

Level one

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

$$GCOST_{jg} = \frac{\log(ETOT_{jg})}{X21_{ivtyp,icl}}, \qquad \textbf{(103)}$$

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

$$UISUM_{jg} = X11_{ivtyp,icl} * GCOST_{jg}, \qquad \textbf{(104)}$$

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.

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

$$YSHARE_{jg} = \frac{ESUM_{jg}}{\sum_{jg=1}^{5} ESUM_{jg}}, \qquad \textbf{(105)}$$

$$HAPShr44_{ivtyp,icl,iregn,ildv} = XSHARE_{jg,jt} * YSHARE_{jg},$$

where

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

$HAPSHR44_{ivtyp,icl,iregn,ildv}$ = percent of total light-duty vehicles sales by technology type.

Legislation affecting alternative vehicle sales in subroutine TLEGIS

Subroutine TLEGIS adjusts light-duty vehicle sales to select state-level requirements on the sales of Zero Emission Vehicles (ZEV), including allowance for Transitional Zero Emission Vehicles (TZEV) and Advanced Technology Partial Zero Emission Vehicles (ATPZEV), toward credit compliance. States that currently have these legislative requirements are California, Colorado, Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, and Vermont. For this section of the model, the index *iregn* is in the set:

{Census Division 1 (participating states Connecticut, Maine, Massachusetts, Rhode Island, and Vermont), Census Division 2 (participating states New Jersey and New York), Census Division 5 (participating state Maryland), Census Division 8 (participating state Colorado), and Census Division 9 (participating states California and Oregon)}

Calculate regional vehicle sales for cars and light trucks, by technology and market class

$$vsales_{ivtyp=1,icl,iregn,ildv,year} = APSHR44_{ivtyp=1,icl,iregn,ildv,year} * NCS_{iregn,icl,year},$$

$$vsales_{ivtyp=2,icl,iregn,ildv,year} = APSHR44_{ivtyp=2,icl,iregn,ildv,year} * NLTS_{iregn,icl,year}, \qquad \textbf{(106)}$$

where

$APSHR44_{ivtyp,icl,regn,ildv,year}$ = percent of total light-duty vehicles sales by technology type;

$NCS_{iregn,icl,year}$ = regional non-fleet car sales by market class; and

$NLTS_{iregn,icl,year}$ = regional non-fleet light truck sales by market class.

Determine regional ZEV credit mandate compliance requirements

$$ZEV\_COVERED\_SALES_{iregn} = zev\_state\_alloc_{iregn,year} * \sum_{ivtyp=1}^{2} \sum_{icl=1}^{8} \sum_{ildv=1}^{16} vsales_{ivtyp,icl,iregn,ildv},$$

$$ZEV\_CREDIT\_REG_{iregn,izev} = ZEV\_COVERED\_SALES_{iregn} * ZEV\_Requirement_{izev,year}, \qquad \textbf{(107)}$$

where

$ZEV\_COVERED\_SALES_{iregn}$ = total vehicle sales by region covered under ZEV mandate;

$zev\_state\_alloc_{iregn,year}$ = share of census division vehicle sales belonging to a ZEV participating state;

$ZEV\_CREDIT\_REG_{iregn,izev}$ = credit requirement by region and ZEV classification type; and

izev = ZEV requirement classification (1=ATPZEV, 2=TZEV, 3=ZEV).

a) Calculate ZEV-required credits earned through vehicle sales by region

$$ZEV\_CREDIT\_LDV_{iregn,ildv,year} = VSALES\_T_{iregn,ildv,year} * zev\_state\_alloc_{iregn,year} * zev\_mulitplier_{ildv,year}, \qquad \textbf{(108)}$$

where

$ZEV\_CREDIT\_LDV_{iregn,ildv,year}$ = total ZEV credits earned by region, vehicle fuel type, and year;

$VSALES\_T_{iregn,ildv,year}$ = total LDV sales by region, vehicle fuel type, and year; and

$zev\_multiplier_{ildv,year}$ = credits earned by vehicle fuel type per 1 unit new vehicle sale.

b) Add ZEV credits earned from traveling provisions to calculate total ZEV credits earned by region, *ZEV_CREDIT_EARN*

$$ZEV\_CREDIT\_EARN_{iregn,izev,year} = ZEV\_CREDIT\_LDV_{iregn,ildv,year} + \ traveling\_CA\_credits_{iregn,izev,year},$$

(109)

Adjust vehicle sales to reflect ZEV mandate adjustment, including use of credit bank

After calculating ZEV credit compliance requirements and ZEV credits earned, including traveling credit provisions, banked credits may be used for compliance. The credit bank includes ZEV and TZEV credits. TZEV credits include changing existing ATPZEV and PZEV credits into TZEV credits at a discount in 2017. The bank also maintains a time-dependent minimum threshold as a risk mitigation strategy.

$$sales\_adjustment = (ZEV\_CREDIT\_REG_{iregn,izev,year} * (1 + bank\_buffer_{year})) \ / \ (ZEV\_CREDIT\_EARN_{iregn,izev,year} + \ bank\_draw_{iregn,izev,year} \ ), \quad \textbf{(110)}$$

where

sales_adjustment = amount of sales adjustment required to meet ZEV requirement and bank buffer compared with ZEV credits earned and bank draw;

$\text{Bank\_buffer}_{year}$ = amount of credits maintained in bank as a risk mitigation strategy; and

$\text{Bank\_draw}_{iregn,izev,year}$ = amount of credit bank used toward meeting compliance.

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 by these fleet vehicles before their transition to the private sector at predetermined ages (vintages).[9]

Fleet vehicles are treated separately in the TDM because of the special characteristics of these vehicles. The LDV Fleet Component generates estimates of the stock of cars and light trucks, VMT, fuel efficiency, and energy consumption that are distinct from those generated for personal light-duty vehicles in the LDV Submodule and LDV Stock Component. The primary purpose is not only to simulate as accurately as possible the very different sets of characteristics expected in fleets, but also to allow greater opportunity to incorporate regulations and policy-making into fleet-purchasing decisions. Legislative requirements for AFV purchase, such as fleet fuel economy, can be incorporated through the subroutine TFLTSTKS, which has been set up specifically for this purpose.

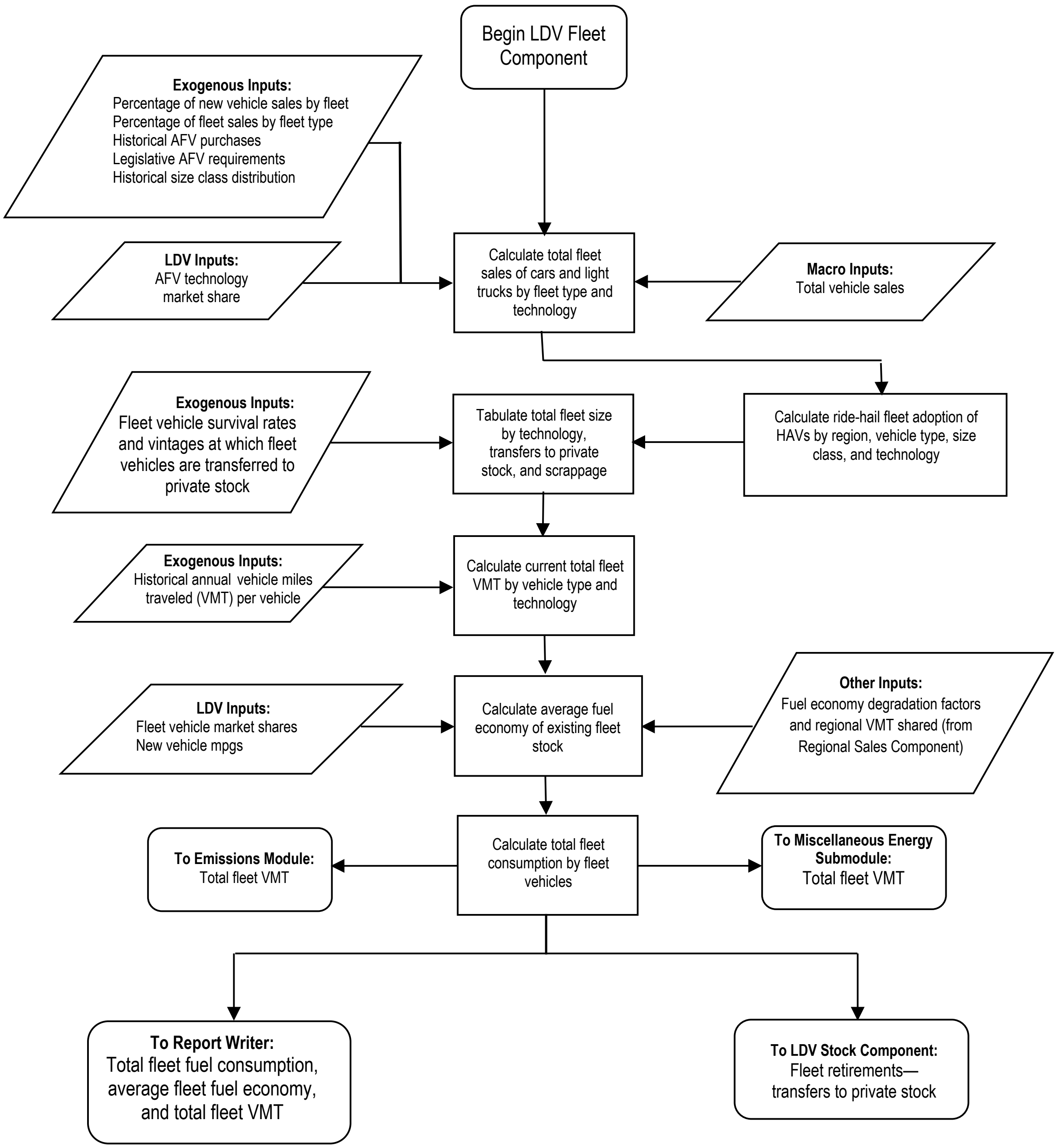
The component uses the same names as the variable names for cars and light trucks, which are distinguished by the value of an index designating vehicle type. Vehicles are also distinguished by their assigned type of fleet. Business, government, utility, and taxi fleets are assumed to have different operating characteristics and retirement rates. This component includes three stages: 1) determine total

[9] Taxis are estimated to be 5% of the business 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 the business fleet. This new fleet includes both conventional and automated taxis and ride-hailing/transportation network provider services (for example, Uber and Lyft).

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 7. Additional flowcharts outlining major LDV Fleet calculations in more detail are presented throughout this section.

Figure 7. Light-duty (LDV) fleet Component of the Transportation Sector Demand Module (TDM), National Energy Modeling System (NEMS)



Data source: U.S. Energy Information Administration
Note: The Emissions Module is currently inactive. VMT=vehicle miles traveled

Fleet sales and stocks (subroutine TFLTSTKS)

The model calculates fleet acquisitions of cars and light trucks (Figure 8).

$$FLTECHSAL_{iregn,ivtyp=1,ifleet,icl,ildv} = LDV\_STOCK_{iregn,ivtyp,ifleet,ildv,ihav,year} * FltAFShrC_{icl,year,ifleet} * 1000000,$$

$$FLTECHSAL_{iregn,ivtyp=2,ifleet,icl,ildv} = LDV\_STOCK_{iregn,ivtyp,ifleet,ildv,ihav,year} * FltAFShrT_{icl,year,ifleet} * 1000000. \quad \textbf{(111)}$$

where

$FLTECHSAL_{iregn,ivtyp,ifleet,icl,ildv}$ = sales to fleets by vehicle and fleet type;

$LDV\_STOCK_{iregn,ivtyp,ifleet,ildv,ihav,year}$ = regional light-duty vehicle stock;

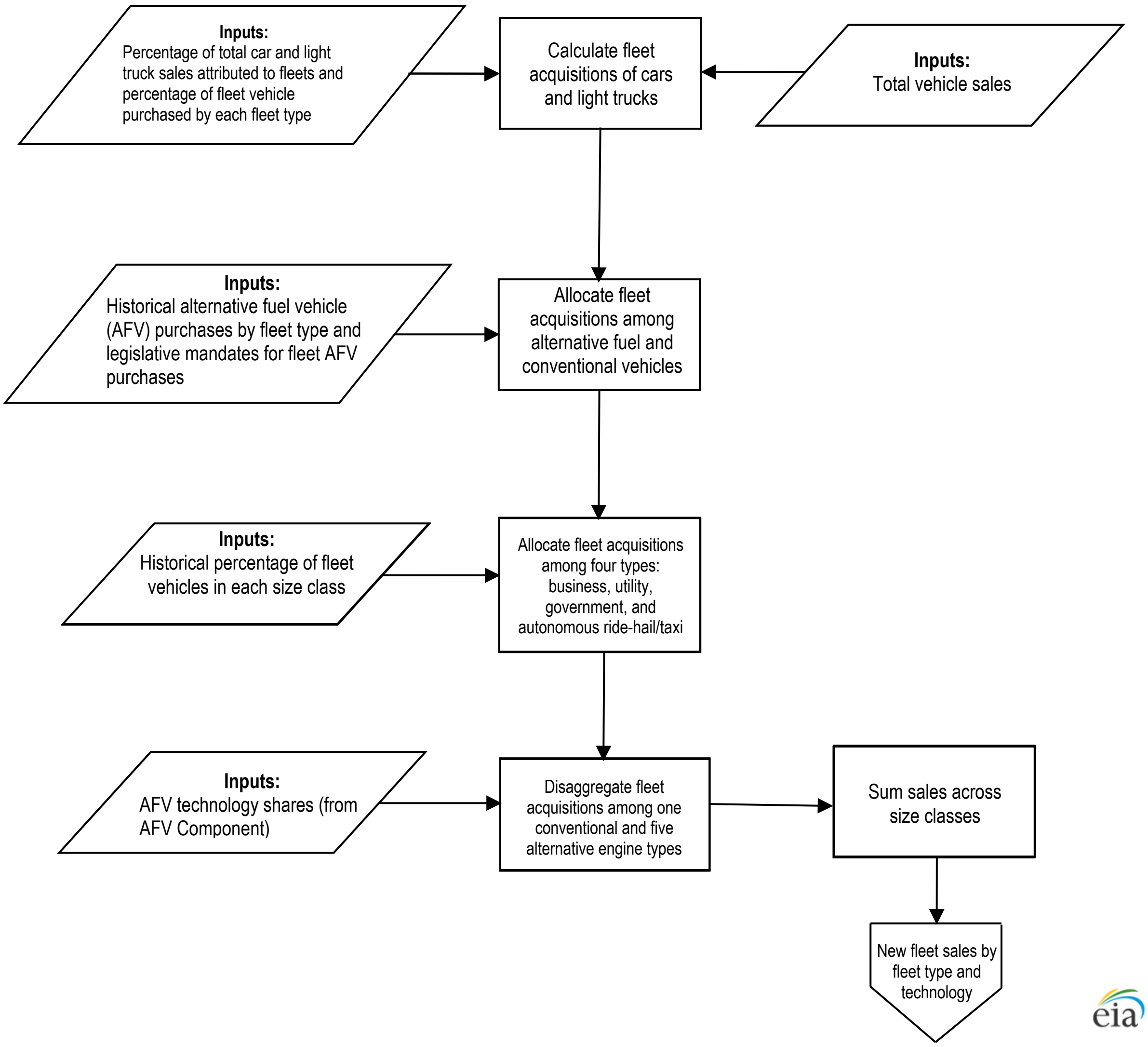
$FltAFShrC_{icl,year,ifleet}$ = fraction of fleet cars purchased by a given fleet type;

$FltAFShrT_{icl,year,ifleet}$ = fraction of fleet trucks purchased by a given fleet type; and

ifleet = index of fleet type: 1 = business, 2 = government, 3 = utility, 4 = taxi.

A new variable is then established which disaggregates AFV sales by engine technology fuel type, *ildv,* namely E85, battery electric, plug-in hybrid electric, CNG/LNG, LPG, hydrogen, diesel, and gasoline.

Figure 8. LDV New Fleet Acquisitions Component of the Transportation Sector Demand Module (TDM), National Energy Modeling System (NEMS)



Data source: U.S. Energy Information Administration

Fleet vehicle sales and market shares are then adjusted on a regional basis to reflect sales of vehicles from state-level Zero Emission Vehicle (ZEV) credit requirements. This process is similar to the process implemented for the household vehicle sales in subroutine *TLEGIS*. The index *iregn* is the same here as in subroutine TLEGIS: it is in the set [Census Division 1 (participating states: Connecticut, Maine, Massachusetts, Rhode Island, and Vermont), Census Division 2 (participating states New Jersey and New York), Census Division 5 (participating state Maryland), Census Division 8 (participating state Colorado), and Census Division 9 (participating states California and Oregon)}].

- Calculate required sales of ZEVs by participating states

a) Determine regional ZEV credit required compliance requirements

$$fltsales_{ivtyp,ifleet,icl,iregn,ildv} = FLTECHSAL_{iregn,ivtyp,ifleet,icl,ildv,ihav=1}$$

$$COVERED\_FLTSALES_{iregn,ifleet} = \sum_{ildv=1:3,9,10,12} fltsales\_t_{iregn,ifleet,ildv,year-6},$$

$$ZEV\_FLTCREDIT\_REG_{iregn,ifleet,izev,year} = COVERED\_FLTSALES_{iregn,ifleet} * ZEV\_Requirement_{izev,year} * zev\_state\_alloc_{iregn,year}, \quad \textbf{(112)}$$

where

$cdXXshr_{iregn,year}$ = regional share of car (XX = car) and light-truck (XX = lt) sales;

$fltsales\_t_{iregn,ifleet,ildv,year}$ = total fleet vehicle sales by region, fleet type, and fuel type, aggregated from variable *fltsales*;

$ZEV\_FLTCREDIT\_REG_{iregn,ifleet,izev,year}$ = credit requirement by region and ZEV classification type;

$COVERED\_FLTSALES_{iregn,ifleet}$ = total vehicle sales by region and fleet type covered under ZEV mandate;

$Zev\_state\_alloc_{iregn,year}$ = share of census division vehicle sales belonging to a ZEV participating state; and

ifleet = fleet type (1=business, 2=government, 3=utilities, 4=taxi).

- Calculate ZEV-required credits earned through vehicle sales and traveling provisions by region

$$ZEV\_FLTCREDIT\_EARN_{iregn,ifleet,izev,year} = ZEV\_FLTCREDIT\_LDV_{iregn,ifleet,ildv,year} + California\_fltcredit_{iregn,ifleet,ildv}, \quad \textbf{(113)}$$

where

$ZEV\_FLTCREDIT\_EARN_{iregn,ifleet,izev,year}$ = total ZEV credits earned by sales and Section 177 states and California credit transfer provisions;

$ZEV\_FLTCREDIT\_LDV_{iregn,ifleet,ildv,year}$ = ZEV compliance credits earned by ildv type requirement by region and fleet type; and

$California\_fltcredit_{iregn,ifleet,ildv}$ = ZEV compliance credits transfer between California and other Section 177 states.

- If ZEV credit requirements are more than ZEV credits earned, including traveling credit provisions, then

$$afltsales_{iregn,izev,year} = COVERED\_FLTSALES_{iregn,ifleet} * FLTSHR_{ifleet,icl,ivtyp} * zev\_state\_alloc_{iregn,year} * ZEV\_Requirement_{izev,year} \; / \; zev\_multiplier_{ildv,year}, \quad \textbf{(114)}$$

where

$afltsales_{iregn,izev,year}$ = amount of sales adjustment required to meet ZEV requirements;

$COVERED\_FLTSALES_{iregn,ifleet}$ = total vehicle sales by region and fleet type covered under ZEV requirement;

$FLTSHR_{ifleet,icl,ivtyp}$ = share of vehicles by fleet type, size class, and vehicle type;

$zev\_state\_alloc_{iregn,year}$ = share of census division vehicle sales belonging to a ZEV participating state;

$ZEV\_Requirement_{izev,year}$ = credit requirement by region and ZEV classification type; and

$zev\_multiplier_{ildv,year}$ = credits earned by vehicle fuel type per 1 unit new vehicle sale.

The sales adjustment *afltsales* is then added to the sales calculated before applying the ZEV requirement, *FLTECHSAL*. Sales for each fleet type are then summed across size classes

$$FLTECH_{iregn,ivtyp,ifleet,ildv,ihav} = \sum_{icl=1}^{8} FLTECHSAL_{iregn,ivtyp,ifleet,icl,ildv,ihav}. \quad \textbf{(115)}$$

The next step is to modify the array of surviving fleet stocks from previous years and to add new acquisitions (**Figure 9**) by applying the appropriate survival factors to the current vintages and inserting *FLTECH* into the most recent vintage

$$FLT\_STOCK_{iregn,ivtyp,ifleet,ildv,iage,ihav,year} = FLT\_STOCK_{iregn,ivtyp,ifleet,ildv,iage-1,ihav,year-1} * SURVFLT_{ifleet,iage-1,ivyp}, \quad \textbf{(116)}$$

and

$$FLTSTOCK_{iregn,ivtyp,ifleet,ildv,iage=1,year,ihav} = FLTECH_{iregn,ivtyp,ifleet,ildv,ihav}, \quad \textbf{(117)}$$

where

FLT_STOCK = fleet stock, by region, vehicle type, fleet type, technology, HAV level, and vintage;

SURVFLT = survival rate of a given vintage; and

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 vintage (age) and fleet type for both cars and light trucks. 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.

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

$$FLTSTOCK_{iregn,ivtyp,ifleet,ildv,ihav=1,year} = FLTSTOCK_{iregn,ivtyp,ifleet,ildv,ihav=1,year} - OLDFSTK_{iregn,ivtyp,ildv,iage} \quad \textbf{(118)}$$

where

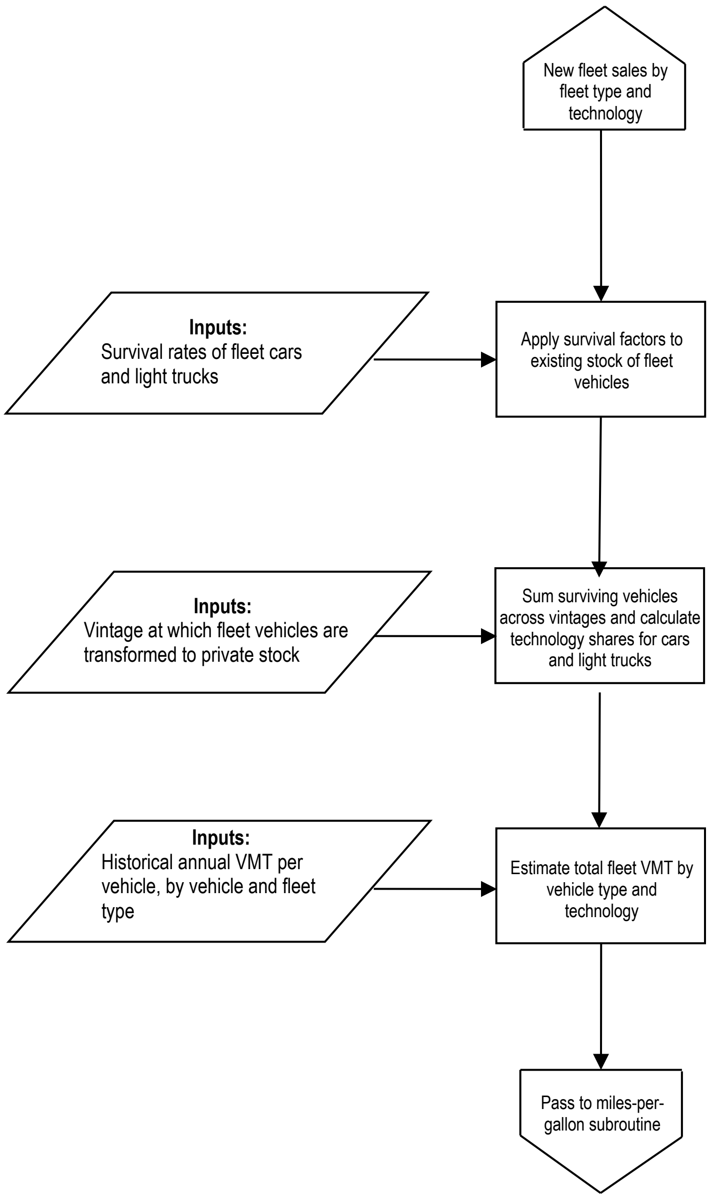
FLTTRANSXX = Share of fleet vehicles that are transferred to the household vehicle stock, by vintage and fleet type. XX = {PC: car, LT: light truck}; and

$OLDFSTK_{iregn,ivtyp,ildv,iage}$ = Old fleet stocks of given types and vintages, transferred to the household vehicle stock.

Taxi fleet vehicles are not transferred to the private fleet because of their high mileage at end-of-life. Total surviving fleet vehicles are then summed across vintages, resulting in total fleet stock by technology, fleet type, fuel type, and HAV level

$$TFLTECHSTK_{vt,flt,ildv,ihav} = \sum_{iage=1}^{25} FLT\_STOCK_{ivtyp,iflt,ildv,iage,year,ihav,year}. \quad \textbf{(119)}$$

Figure 9. Determine characteristics of existing LDV fleets for the Transportation Sector Demand Module (TDM), National Energy Modeling System (NEMS)



Data source: U.S. Energy Information Administration

Table 3. Transfer vintage of fleet vehicles for the Transportation Demand Module, National Energy Modeling System

Vehicle type (vt)	Fleet type (flt)	Transfer vintage (vint) (years)
Car (vt = 1)	Business (flt = 1)	3
Car	Government (flt = 2)	6
Car	Utility (flt = 3)	5
Car	Taxi (flt = 4)	Does not transfer
Light truck (vt = 2)	Business	3
Light truck	Government	6
Light truck	Utility	5
Light truck	Taxi	Does not transfer

Data source: U.S. Energy Information Administration

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

After calculating the total taxi sales by vehicle type, powertrain, size class, and fleet type and ensuring compliance with the ZEV requirements, 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.

$$lidar\_cost_{ihav,t} = a_t * cumul\_lidar\_prod_{ilidar,t-1}^{-b_t}, \qquad \textbf{(120)}$$

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 Equation 120. 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.

$$hav\_sys\_cost_{ihav,t} = hav\_sys\_lrn_{ihav,t} * hav\_init\_cost_{ihav} + Li\_ion\_cost_{\,t} * hav\_battery\_kWh_{ihav} + lidar\_cost_{ihav,t}, \qquad \textbf{(121)}$$

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 includes a parameter characterizing the disutility of the levels' operational domain (speed, geography, weather) limitations.

$$taxi\_util_{iregn,ihav} = hav\_newtech\_lim_{ihav} + hav\_oper\_limit_{iregn,ihav} + taxi_{rev_{coef}} * taxi_{npv_{iregn,ihav}}, \tag{122}$$

$$flt\_hav\_shares_{iregn,ivtyp,icl,ildv,year,ihav} = \frac{e^{taxi\_util_{iregn,ihav}}}{\sum_{ihav=1}^{4} e^{taxi\_util_{iregn,ihav}}}, \tag{123}$$

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.

$$taxi\_npv_{iregn,ihav} = -VehPrice + \sum_{t=1}^{life}\left[\left((1 + taxi\_disc\_r)^{-t}\right) * (taxi\_mo\_rev_{iregn,ihav} - taxi\_mo\_cost_{iregn,ihav} - fuelpriceproj_t * taxi\_fuel_{iregn,ihav})\right], \tag{124}$$

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 two fleet sales variables (*FLTECH* and *FLTECHSAL*) and two fleet stock variables (*FLT_STOCK* and *TFLTECHSTK*) to ensure that the HAV sales and stock can be tracked and used in later calculations.

Calculate Fleet VMT (subroutine TFLTVMTS)

The fleet vehicle stock VMT is calculated as follows

$$FLTVMTECH_{ivtyp,ifleet,ildv,ihav} = TFLTECHSTK_{ivtyp,ifleet,ildv,ihav} * FLTVMTYR_{ifleet,year,ivtyp},$$

(125)

where

$FLTVMTECH_{ivtyp,ifleet,ildv,ihav}$ = fleet VMT by technology, vehicle type, fleet type, and HAV level;

$FLTVMTYR_{ifleet,year,ivtyp}$ = annual miles of travel per vehicle by vehicle type and fleet type; and

$TFLTECHSTK_{ivtyp,ifleet,ildv,ihav}$ = total stock within each technology, fleet type, and HAV level, calculated in Equation 137.

Calculate Fleet Sales and Stock mpg Fuel Economies (subroutine TFLTMPGS)

The average new vehicle fuel economies are calculated as follows (Figure 10)

$$FLTMPG_{ivtyp,ifleet,ildv,year} = \frac{\sum_{ihav=1}^{4}\sum_{icl=1}^{8} FLTECHSAL_{ivtyp,ifleet,icl,ildv,ihav}}{\sum_{ihav=1}^{4}\sum_{icl=1}^{8} \frac{FLTECHSAL_{ivtyp,ifleet,icl,ildv,ihav}}{LDV\_MPG\_CL_{ivtyp,ildv,icl,year}}}$$

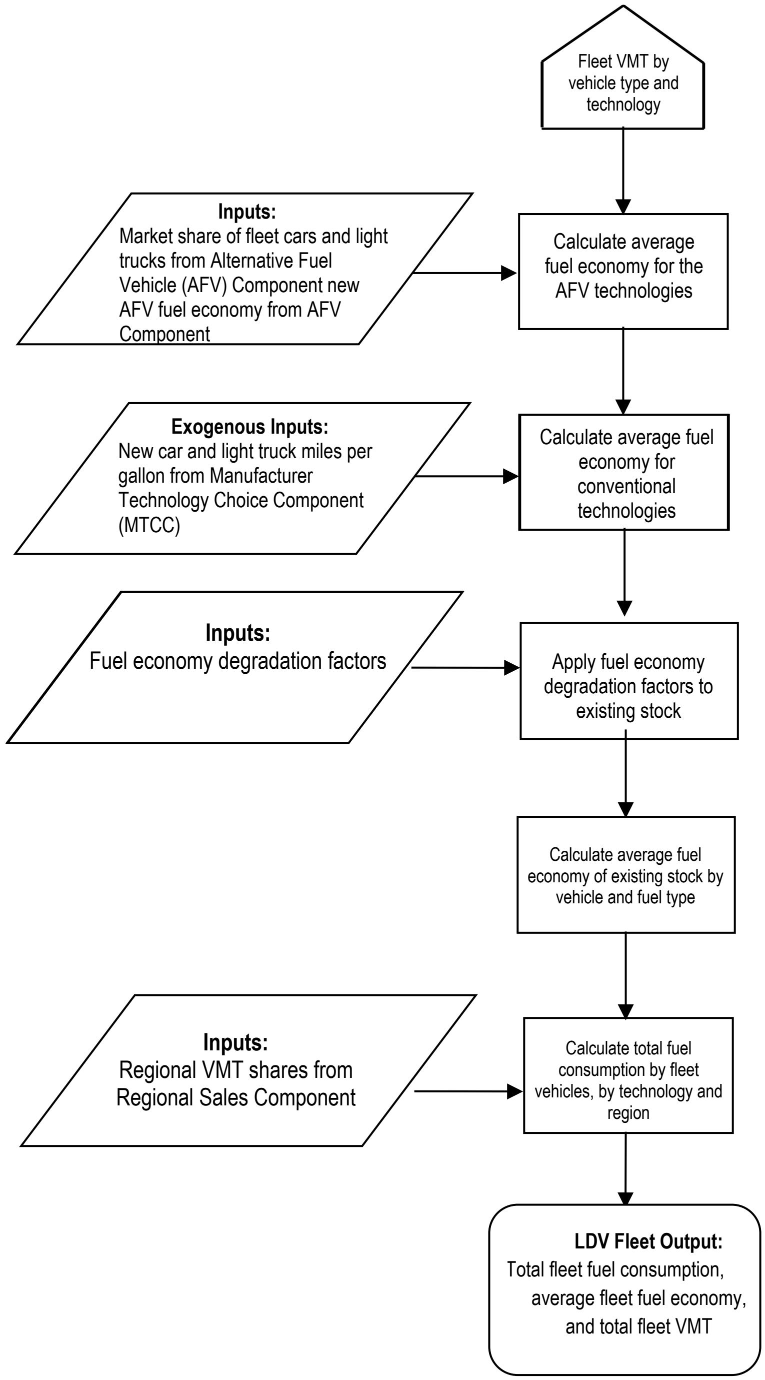
(126)

where

$FLTMPG_{ivtyp,ifleet,ildv,year}$ = new fleet vehicle fuel efficiency, by vehicle type, fleet type and technology type; and

$FLTECHSAL_{ivtyp,ifleet,icl,ildv,ihav}$ = fleet sales by vehicle type, fleet type, size class, technology, fleet type, and HAV level.

Figure 10. Determine fuel economy and consumption for light-duty vehicle (LDV) fleets for the Transportation Sector Demand Module (TDM), National Energy Modeling System (NEMS)



Data source: U.S. Energy Information Administration

The fuel efficiency of new vehicles is then added to an array of fleet stock efficiencies by vintage, which is adjusted to reflect the passage of time.

$$CMPFGSTK_{ifleet,ildv,iage=1,year} = FLTMPG_{ivtyp=1,ifleet,ildv,year},$$

$$TMPGFSTK_{ifleet,ildv,iage=1,year} = FLTMPG_{ivtyp=2,ifleet,ildv,year}, \quad \textbf{(127)}$$

where

CMPGFSTK$_{ifleet,ildv,iage,year}$ = car fleet mpg by fleet type, technology, and vintage;

TMPGFSTK$_{ifleet,ildv,iage,year}$ = light truck fleet mpg by fleet type, technology, and vintage.

For *iage*=2 to maxage

$$CMPGFSTK_{flt,ildv,iage,year} = CMPGFSTK_{flt,ildv,iage-1,year-1},$$

$$TMPGFSTK_{flt,ildv,iage,year} = TMPGFSTK_{flt,ildv,iage-1,year-1}, \quad \textbf{(128)}$$

Average stock fuel efficiency by vehicle and fleet type is then calculated

$$MPGFLTSTK_{ivtyp=1,ifleet,ildv} = \frac{\sum_{iage=1}^{maxage} FLTSTKVN_{ivtyp=1,ifleet,ildv,iage,year,ihav}}{\sum_{iage=1}^{maxage} \frac{FLTSTKVN_{ivtyp=1,ifleet,ildv,iage,year,ihav}}{CMPGFSTK_{ifleet,ildv,iage,year} * CDFRFG_{year}}},$$

$$MPGFLTSTK_{ivtyp=2,ifleet,ildv} = \frac{\sum_{iage=1}^{maxage} FLTSTKVN_{ivtyp=2,ifleet,ildv,iage,year,ihav}}{\sum_{iage=1}^{maxage} \frac{FLTSTKVN_{ivtyp=2,ifleet,ildv,iage,year,ihav}}{TMPGFSTK_{ifleet,ildv,iage,year} * LTDFRFG_{year}}},$$

(129)

where

MPGFLTSTK$_{ivtyp,ifleet,ildv}$ = fleet stock mpg by vehicle, fleet, and technology type, across vintages;

maxage = maximum vintage of vehicle in given fleet type;

CDFRFG$_{year}$ = car fuel efficiency degradation factor; and

LTDFRFG$_{year}$ = light truck fuel efficiency degradation factor.

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

$$FLTTOTMPG_{ivtyp} = \frac{\sum_{ifleet=1}^{4} \sum_{ildv=1}^{16} \sum_{ihav=1}^{4} TFLTECHSTK_{ivtyp,ifleet,ildv,ihav}}{\sum_{ifleet=1}^{4} \sum_{ildv=1}^{16} \sum_{ihav=1}^{4} \frac{TFLTECHSTK_{ivtyp,ifleet,ildv,ihav}}{MPGFLTSTK_{ivtyp,ifleet,ildv}}}, \quad \textbf{(130)}$$

Calculate Fuel Consumption by Fleet Vehicles (subroutine TFLTCONS)

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

$$FLTLDVC_{ivtyp,ifleet,ildv} = \frac{\sum_{ihav=1}^{4} FLTVMTTECH_{ivtyp,ifleet,ildv,ihav}}{MPGFLTSTK_{ivtyp,ifleet,ildv}}, \quad \textbf{(131)}$$

Consumption is then summed across fleet types and converted to values in British thermal units (Btu) in variable *FLTFCLDVBTU*

$$FLTFCLDVBTU_{ivtyp,ildv,year} = \sum_{flt=1}^{4} FLTLDVC_{ivtyp,ifleet,ildv} * 0.1251, \quad \textbf{(132)}$$

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

$$FLTFUELBTU_{iregn,ifuel,year} = \sum_{vt=1}^{2} FLTFCLDVBTU_{ivtyp,ildv,year} * PctXX_{iregn,year} * RSHR_{iregn,year}, \quad \textbf{(133)}$$

where

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

$RSHR_{iregn,year}$ = regional share of total VMT.

Non-Fleet LDV Stock Component (subroutine TSMOD)

The LDV Stock Component 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 light-duty vehicles, along with regional estimates of LDV fuel consumption (Figure 11).

The LDV Stock Component uses vintage-dependent constants, such as vehicle survival, relative driving rates, and fuel economy degradation factors, to obtain estimates of stock efficiency.

The LDV Stock Component is perhaps the most important transportation sector component because the largest portion of transportation energy consumption is accounted for by light-duty vehicles that are at least one year old. The LDV Stock Component takes the results of the LDV Submodule (that is, the number and characteristics of newly purchased cars and light trucks) and integrates those into the existing stock of vehicles, taking into account vehicle retirements and vehicles that are transferred from fleets to private ownership. The result is a snapshot of the *average* car for each region.

These characteristics 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 regional fuel consumption.

The first step is to calculate total vehicle sales by technology for the current iteration

$$TECHNCS_{ildv,year} = \sum_{icl=1}^{8} \sum_{iregn=1}^{9} NCSTECH_{iregn,icl,ildv,year},$$

$$TECHNLT_{ildv,year} = \sum_{icl=1}^{8} \sum_{iregn=1}^{9} NLTTECH_{iregn,icl,ildv,year}, \quad \textbf{(134)}$$

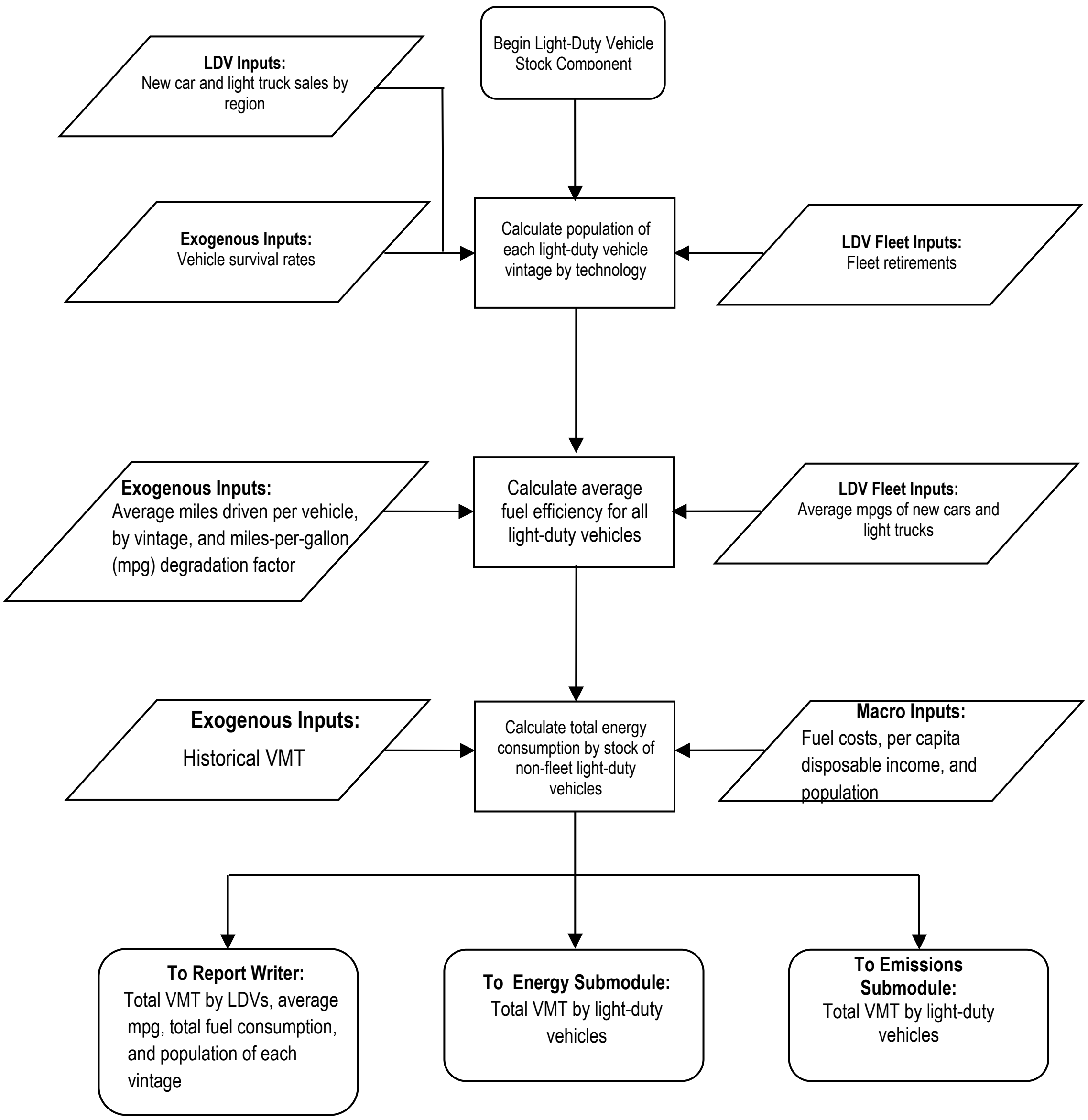
where

$TECHNCS_{ildv,year}$ = total new car sales, by technology type; and

$TECHNLT_{ildv,year}$ = total new light truck sales, by technology type.

Sales are broken out regionally to populate *TECHNCSREGN* and *TECHNLTREGN*. These sales values are assigned to the first vintage of the LDV stock array (*LDV_STOCK*) and the population of subsequent vintages is calculated.

Figure 11. LDV Stock Component for the Transportation Sector Demand Module (TDM), National Energy Modeling System (NEMS)



Data source: U.S. Energy Information Administration
Note: The Emissions Submodule is currently inactive.

For *iage* = 2 to 24 let

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

(135)

where

$LDV\_STOCK_{iregn,ivtyp,iown,ildv,iage,ihav,year}$ = regional light-duty vehicle stock by vehicle type, ownership type, technology type, vintage, and HAV level;

$SSURV25_{iregn,iage,ivtyp}$ = 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

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

(136)

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.

$$LDV\_STOCK_{iregn,ivtyp,iown=1,ildv,iage,ihav,year} = LDV\_STOCK_{iregn,ivtyp,iown=1,ildv,iage,ihav,year} + \left(OLDFSTKT_{ivtyp.ildv,iage} * CDXXSHR_{iregn,year-iage}\right),$$

(137)

where

$OLDFSTKT_{ivtyp,ildv,iage}$ = total vehicles from fleets to households by vehicle and technology type, and vintage; and

$CDXXSHR_{iregn,year}$ = share of total LDVs by region, where XX = {CAR: car, LT: light truck}.

Total stocks of non-fleet cars and trucks are then determined by summing over regions, vintages and technology types

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

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

(138)

where

$STKCAR_{year}$ = total stock of non-fleet cars; and

$STKTR_{year}$ = total stock of non-fleet light trucks.

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)

Overall fuel efficiency is calculated as the weighted average of the efficiencies of new vehicles and the efficiencies of the surviving vintages.

Calculate national LDV sales by vehicle type, size class, and technology type, *NVSALES*

$$NVSALES_{ivtyp=1,icl,ildv,year} = \sum_{iregn=1}^{9} NCSTECH_{iregn,icl,ildv,year},$$

$$NVSALES_{ivtyp=2,icl,ildv,year} = \sum_{iregn=1}^{9} NLTECH_{iregn,icl,ildv,year}, \quad \textbf{(139)}$$

The harmonic average efficiencies of the light-duty vehicles are calculated as follows

$$MPGC_{ildv,year} = \frac{\sum_{icl=1}^{8} NVSALES_{ivtyp=1,icl,ildv,year}}{\sum_{icl=1}^{8} \frac{NVSALES_{ivtyp=1,icl,ildv,year}}{LDV\_MPG\_CL_{ivtyp=1,ildv,icl,year}}},$$

$$MPGT_{ildv,year} = \frac{\sum_{icl=1}^{8} NVSALES_{ivtyp=2,icl,ildv,year}}{\sum_{icl=1}^{8} \frac{NVSALES_{ivtyp=2,icl,ildv,year}}{LDV\_MPG\_CL_{ivtyp=2,ildv,icl,year}}}, \quad \textbf{(140)}$$

here

$LDV\_MPG\_CL_{ivtyp,ildv,icl,year}$ = new car fuel efficiency, by size class;

$MPGC_{ildv,year}$ = new car fuel efficiency, by technology type; and

$MPGT_{ildv,year}$ = new light truck fuel efficiency, by technology type.

The overall fuel efficiency of cars and light trucks is then calculated across the 25 vintages addressed in the component.[10] 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

[10] Initial values for on-road car and light truck fleet mpg are obtained from the Federal Highway Administration, *Highway Statistics, 2018,* U.S. Department of Transportation (2019).

by travel is done by summing the total number of miles driven across all vintages and technologies[11]

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

(141)

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. The on-road fuel efficiency of cars and trucks degrades over time, vintage fuel efficiencies must be adjusted using degradation factors

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

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

(142)

where

$CMPGSTK_{ildv,iage,year,iregn}$ = car stock fuel economy;

$TTMPGSTK_{ildv,iage,year,iregn}$ = truck stock fuel economy;

$CDFRFG_{year,ihav}$ = car fuel economy degradation factor; and

$LTDFRFG_{year,ihav}$ = light truck fuel economy degradation factor.

Stock fuel efficiency for cars and light trucks 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

$$STMPG_{year} = \frac{\sum_{ildv} \sum_{iage} \sum_{ihav} \sum_{iregn} VMT\_STK\_HH_{ivtyp=2,ildv,iage,ihav,iregn}}{\sum_{iregn} TMPGT_{year,iregn}}, \quad \textbf{(143)}$$

[11] 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.

where

SCMPG$_{year}$ = stock car fuel efficiency; and

STMPG$_{year}$ = stock light truck fuel efficiency.

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

$$MPGHH_{year} = \frac{\sum VMT\_STK\_HH}{\sum_{iregn}\left[CMPGT_{year,iregn} + TMPGT_{year,iregn}\right]}, \quad \textbf{(144)}$$

Calculate the average fuel efficiency for cars and light trucks by technology

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

$$TMPG\_IT_{ildv,year} = \frac{\sum_{iregn}\sum_{ivtyp}\sum_{iage}\sum_{ihav} VMT\_STK\_HH_{ivtyp=2,ildv,iage,ihav,iregn}}{\sum_{iregn}\sum_{iage}\sum_{ihav}\frac{VMT\_STK\_HH_{ivtyp=2,ildv,iage,ihav,iregn}}{TTMPGSTK_{ildv,iage,year,iregn} * LTDFRFG_{year,ihav}}},$$

(145)

CMPGT_IT$_{ildv,year}$ = average fuel efficiency of cars by powertrain; and

TMPGT_IT$_{ildv,year}$ = average fuel efficiency of light trucks by powertrain.

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 the 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, disposable personal income, employment, vehicles per licensed driver, and past VMT trends. The Federal Highway Administration (FHWA) provides historical licensed driver rates by age cohort, gender, and region.

Annual vehicle stock, VMT, and fuel consumption data are also available from FHWA. All macroeconomic inputs are calculated based on a chain-weighted average. These data are used to estimate the VMT equation in the NEMS VMT Component

$$\log\left(VMTLD_{year}\right) - \beta_1 \log VMTLD_{year-1} = \alpha + \beta_2 \log\left(INC00\$16_{year}\right) + \beta_3 \log\left(COSTMI_{year}\right) + \beta_4 \log\left(VPLD_{year}\right) + \beta_5 \log\left(EMP\_RATE\_VMT_{year}\right), \quad \textbf{(146)}$$

where

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

$COSTMI_{year}$ = fuel cost of driving;

$VPLD_{year}$ = light-duty vehicles per licensed driver;

EMP_{year} = employment rate of population age 16 and older from the Macroeconomic Activity Module; and

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

Of greater significance is the historical VMT and stock inputs provided by FHWA. In the past, FHWA's estimate of the number and driving patterns of two-axle, four-tire trucks has been interpreted as representing that of light-duty trucks, defined as having a weight of less than 8,500 pounds and so properly within the scope of the LDV Submodule. To further refine the submodule, a category of truck has been defined as Class 2b vehicles, which make up all single-unit trucks in the 8,500 to 10,000 pound range. The travel demands of these trucks are now modeled with the heavy-duty vehicles, based on aggregate measures of industrial output from the Macroeconomic Activity Module.

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

$$VMTLD_{year} = \exp\big(\alpha + \beta_1 \ln\big(VMTLD_{year-1,}\big) + \beta_2 * \ln\big(INC00\$16_{year}\big) + \beta_3 \ln\big(COSTMI_{year}\big) + \beta_4 \ln\big(VPLD_{year}\big) + \beta_5 \ln\big(EMP\_RATE\_VMT_{year}\big)\big), \tag{147}$$

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 (Figure12).

TAIRT projects domestic and international per-capita passenger travel demand by 13 world regions, measured in revenue passenger-miles (RPM) per-capita, and world regional air freight demand, measured in revenue ton-miles (RTM) (Table 4).[12] 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 2020 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.[13]

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.

[12] 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).

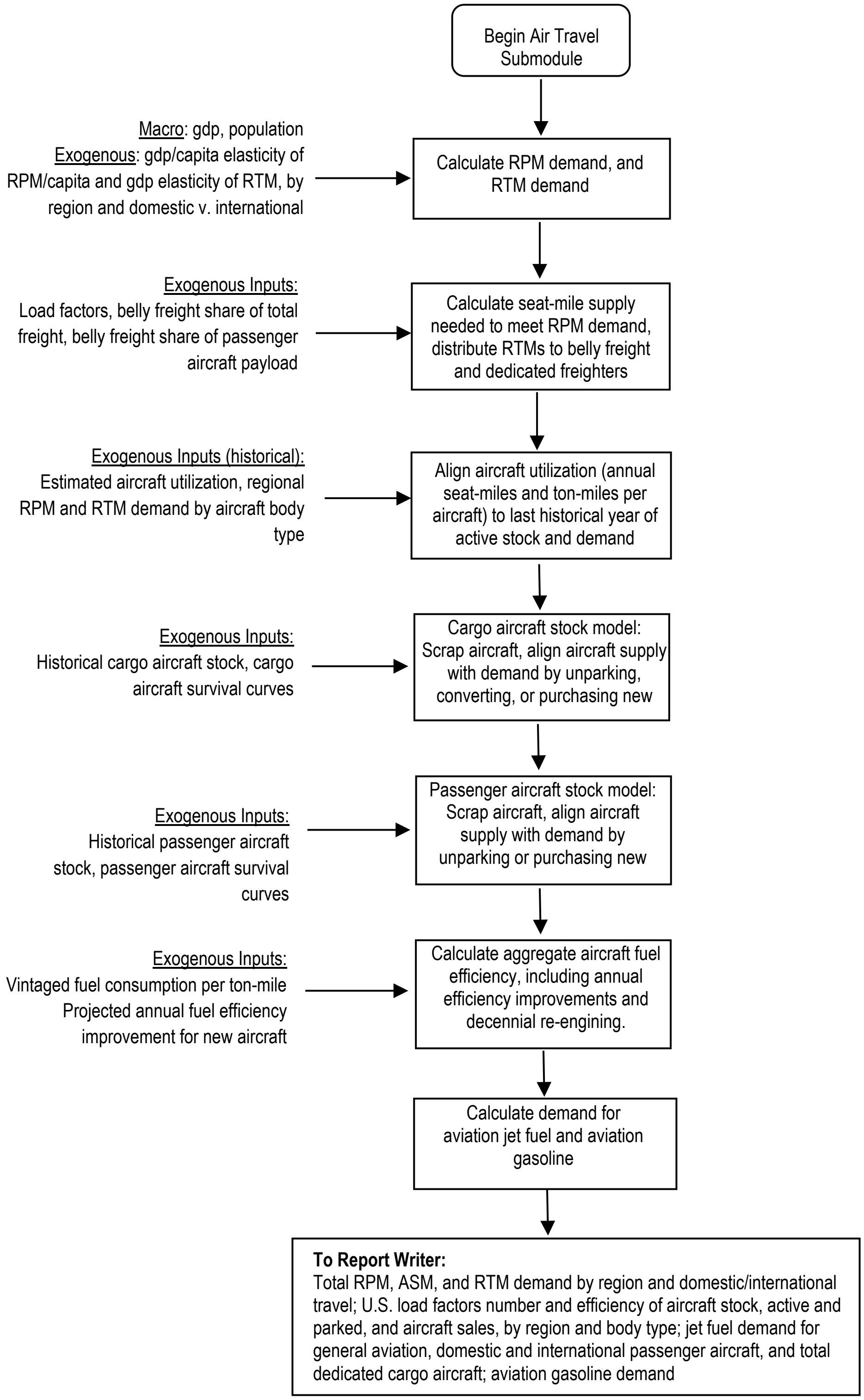
[13] Belly freight, initially in units of revenue ton-miles, is converted to revenue passenger-miles using an average passenger weight of 200 pounds (including luggage).

Table 4. World Regions

Region Number	Region	Major Countries in Region
1	United States	United States
2	Canada	Canada
3	Central America	Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Bermuda, Cayman Islands, Costa Rica, Cuba, Curacao, Dominica, Dominican Republic, El Salvador, Grenada, Guadeloupe, Guatemala, Haiti, Honduras, Jamaica, Martinique, Mexico, Montserrat, Netherland Antilles, Nicaragua, Panama, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and The Grenadines, Saint-Barthelemy, Sint Maarten (Dutch part), St. Kitts and Nevis, Trinidad and Tobago, Turks and Caicos Islands
4	South America	Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Falkland Islands (Malvinas), French Guiana, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela
5	Europe	Albania, Andorra, Austria, Belgium, Bosnia and Herzegovina, Bouvet Island, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Gibraltar, Greece, Hungary, Iceland, Ireland, Italy, Kosovo, Latvia, Liechtenstein, Lithuania, Luxembourg, Macedonia, Malta, Monaco, Montenegro, Netherlands, Norway, Poland, Portugal, Romania, San Marino, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom
6	Africa	Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cabo Verde, Cameroon, Central African Republic, Chad, Comoros, Congo-Brazzaville, Congo-Kinshasa, Côte d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Eswatini, Ethiopia, Gabon, The Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mayotte, Morocco, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Saint Helena, Senegal, Sierra Leone, Somalia, South Africa, South Sudan, Sudan, Togo, Tonga, Tunisia, Uganda, United Republic of Tanzania, Western Sahara, Zambia, Zimbabwe
7	Mideast	Bahrain, Egypt, Iraq, Iran, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates, Yemen
8	CIS	Armenia, Azerbaijan, Belarus, Georgia, Kyrgyzstan, Kazakhstan, Moldova, Republic of Mongolia, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
9	China	China, Hong Kong, Macao
10	Northeast Asia	Japan, North Korea, South Korea
11	Southeast Asia	Bhutan, Brunei, Burma, Cambodia, Guam, Indonesia, Laos, Malaysia, Philippines, Singapore, Taiwan, Thailand, Vietnam
12	Southwest Asia	Afghanistan, Bangladesh, India, Nepal, Pakistan, Sri Lanka
13	Oceania	Australia, Fiji, French Polynesia, Micronesia, Nauru, New Caledonia, New Zealand, Papau New Guinea, Samoa, Solomon Island, Tuvalu, Vanuatu, Wake Island

Data source: U.S. Energy Information Administration

Figure 12. Air travel submodule of the Transportation Sector Demand Module (TDM), National Energy Modeling System (NEMS)



Data source: U.S. Energy Information Administration

Air Travel Demand Component (TAIRT)

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 2020 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 13 world regions using the following econometric relationship:

$$\frac{RPMT\_PC_{iwreg,di,year}}{RPMT\_PC_{iwreg,di,year-1}} = e^{intercept\_rpm_{iwreg,di}} * \left[\frac{GDP\_PC_{iwreg,year}}{GDP\_PC_{iwreg,year-1}}\right]^{beta1\_rpm_{iwreg,di}}, \quad \textbf{(148)}$$

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 13.

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

$$RPMT_{iwreg,di,year} = RPMT\_PC_{iwreg,di,year} * WLD\_POP_{iwreg,year}, \quad \textbf{(149)}$$

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.[14]

$$RPM_{iwreg,di,iatyp,year} = RPMT_{iwreg,di,year} * SHR\_RPM\_BODY_{iatyp,year,di}, \quad \textbf{(150)}$$

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,[15] and projected through 2050 based on industry trends.[16]

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

$$RTM_{iwreg,year} = e^{intercept\_rtm_{iwreg}} * \left(WLD\_GDP_{iwreg,year}\right)^{beta1\_rtm_{iwreg}} \quad \textbf{(151)}$$

and

$$RTM\_TYP_{iwreg,di,iatyp,year} = RTM_{iwreg,year} * SHR\_RTM_{iwreg,iatyp,di,year}, \quad \textbf{(152)}$$

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; [17,18] and

[14] 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.
[15] 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).
[16] 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%.
[17] 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).
[18] 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.

4) 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.

$$BELLY\_RPM\_EQ_{iwreg,iatyp,di,year} = MIN\left[RPM_{iwreg,di,iatyp,year} * \frac{PCT\_BELLY\_PLOAD_{iatyp,year,di}}{(1-PCT\_BELLY\_PLOAD_{iatyp,year,di})}, RTM\_TYP * PCT\_BELLY\_FRT_{iatyp,year,di} * \frac{2000}{pass\_weight}\right] \quad (153)$$

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

$$CARGOAC\_RTM\_DMD_{iwreg,iatyp,di,year} = RTM\_TYP_{iwreg,iatyp,di,year} - BELLY\_RPM\_EQ_{iwreg,iatyp,di,year} * \frac{pass\_weight}{2000} \quad (154), (155)$$

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.[19]

$$ASM_{iwreg,di,iatyp,year} = \frac{RPM_{iwreg,di,iatyp,year}}{LoadFactor_{iwreg,di,iatyp,year}}, \quad \textbf{(156)}$$

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 (TAIREFF)

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.[20] 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

[19] 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 (Equation 153). The model assumes aircraft carry a constant amount of belly freight per unit of passenger air travel demand.

[20] 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)].

slowed since 1990; estimates indicate fuel consumption per ton-mile of new aircraft fell by nearly 3% throughout the 1980s, followed by 30 years of average reductions of around 1%.[21] 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.[22]

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.

$$RTMAC_{iwreg,year,iatyp} = \frac{\sum_{di} CARGOAC\_RTM\_DMD_{iwreg,iatyp,di,year}}{\sum_{iage} STKCARGO\_ACTIVE_{iwreg,iatyp,iage,year}} \quad \textbf{(157)}$$

and

$$ASMAC_{iwreg,year,iatyp} = \frac{\sum_{di} ASM_{iwreg,di,iatyp,year}}{\sum_{iage} STKPASS\_ACTIVE_{iwreg,iatyp,iage,year}} \quad \textbf{(158)}$$

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 2020 numbered approximately 32,650.[23] The age distribution informs annual aircraft retirement estimates and, as a result, has a strong influence on the number of

[21] "Fuel burn of new commercial jet aircraft: 1960 to 2019", Zheng and Rutherford, International Council on Clean Transportation. (2020)
[22] 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.
[23] Jet Inventory Services, *World Jet Inventory: Year-End 2020*, (March 2021).

new aircraft acquired to meet air travel demand. Due to the international nature of the market for aircraft, 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.

$$STKCARGO\_ACTIVE_{iwreg,iatyp,iage,year} = STKCARGO\_ACTIVE_{iwreg,iatyp,iage-1,year-1} * SURVAC_{iatyp,iage,passfrt}, \quad \textbf{(159)}$$

and

$$STKPASS\_ACTIVE_{iwreg,iatyp,iage,year} = STKPASS\_ACTIVE_{iwreg,iatyp,iage-1,year-1} * SURVAC_{iatyp,iage,passfrt}, \quad \textbf{(160)}$$

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:

$$CARGOAC\_NEEDED_{iwreg,iatyp} = \frac{\sum_{di} CARGOAC\_RTM\_DMD_{iwreg,iatyp,di,year}}{RTMAC_{iwreg,year,iatyp}} - \sum_{iage} STKCARGO\_ACTIVE_{iwreg,iatyp,iage,year} \quad \textbf{(161)}$$

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:

$$PASSAC\_NEEDED_{iwreg,iatyp} = \frac{\sum_{di} ASM_{iwreg,iatyp,di,year}}{ASMAC_{iwreg,year,iatyp}} - \sum_{iage} STKPASS\_ACTIVE_{iwreg,iatyp,iage,year} \quad \textbf{(162)}$$

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*].[24]
2) Purchase new passenger aircraft.

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

$$STK\_SUP\_TOT_{iwreg,iatyp,year} = \sum_{iage} STKPASS\_ACTIVE_{iwreg,iatyp,iage,year} + \sum_{iage} STKPASS\_PARKED_{iwreg,iatyp,iage,year} + \sum_{iage} STKCARGO\_ACTIVE_{iwreg,iatyp,iage,year} + \sum_{iage} STKCARGO\_PARKED_{iwreg,iatyp,iage,year}, \quad \textbf{(163)}$$

[24] 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.

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:

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[25] 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.[26]

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 164 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 164 below.[27]

$$GPTM = \frac{fuel\ consumed}{payload\text{-}mile} \tag{164}$$

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.

$$FuelBurn_{full} = FuelBurn_{actual} * \left(1 + \underbrace{\left[\frac{(ASM - RPM)}{RPM}\right]}_{\text{Percent increase in total passenger weight}} * \underbrace{\frac{WGT\_PASS}{WGT\_AIRCRAFT}}_{\text{Percent of aircraft weight that is passengers}}\right)$$

[25] 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).

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

[27] 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.

$$GPTM_{all\ seats\ filled} = \frac{FuelBurn_{full}}{ASM * \frac{pass\_weight}{2000} + RTM_{belly\_freight}} \qquad \textbf{(165)}$$

where

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

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 2020. 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.[28]

Estimating the fuel consumption impacts of stock turnover requires a history of new aircraft, or *vintaged*, GPTM in the last historical year, which for AEO2022 is 2020. 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.[29] new aircraft GPTM in 2020 is estimated using the average efficiency improvement between 2010 and 2019. This vintaged GPTM is converted to ASMPG using the *pass_weight* factor:

$$ASMPG\_VINT_{iwreg,iatyp,iage,di,2020} = \frac{1}{GPTMX\_PASS\_VINT_{iwreg,iage,iatyp} * \frac{pass\_weight}{2000}} \qquad \textbf{(166)}$$

where

$GPTMX\_PASS\_VINT_{iwreg,iage,iatyp}$ = fully-loaded passenger aircraft fuel consumption per ton-mile, by region, vintage, and body type, in 2020, 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 2020

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

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

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

(Equation 167).[30] 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 168).

$$ASMPG\_VINT_{iwreg,iatyp,1,di,year} = \frac{ASMPG\_VINT_{iwreg,iatyp,1,di,2020}}{(1-FUEL\_BURN\_RED)^{year-2020}} \quad \textbf{(167)}$$

and

$$ASMPG\_VINT_{iwreg,iatyp,iage,di,year} = 1.01 * ASMPG\_VINT_{iwreg,iatyp,iage,di,year} \quad \textbf{(168)}$$

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

$$ASMPG\_AVG\_AGE_{iwreg,iatyp,di,year} = \frac{STKPASS\_ACTIVE\_TOT_{iwreg,iatyp,year}}{\sum_{iage}\frac{STKPASS\_ACTIVE_{iwreg,iatyp,iage,year}}{ASMPG\_VINT_{iwreg,iatyp,iage,di,year}}} \quad \textbf{(169)}$$

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 ($GPTM_{iwreg,iatyp,di,year}$)

$$GPTM_{iwreg,iatyp,di,year} = \frac{1}{ASMPG\_AVG\_AGE_{iwreg,iatyp,di,year} * \frac{pass\_weight}{2000}} \quad \textbf{(170)}$$

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

$$TEMP_{iwreg,iatyp,di,year} = \frac{1-(1-LOAD\_FACTOR_{iwreg,di,iatyp,year} * PCT\_PASS\_MTOW_{iatyp,year})}{1-(1-LOAD\_FACTOR_{iwreg,di,iatyp,year} * \left[1-\frac{BELLY\_RPM\_EQ_{iwreg,iatyp,di,year}}{PASSAC\_RPM\_DMD_{iwreg,iatyp,di,year}}\right]} \quad \textbf{(171)}$$

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

and

$$RPMPG_{iwreg,iatyp,di,year} = \frac{1}{GPTM\_(iwreg,iatyp,di,year) * \frac{pass\_weight}{2000} * TEMP_{iwreg,iatyp,di,year}} \quad \textbf{(172)}$$

where

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[30] Ibid.

$TEMP_{iwreg,iatyp,di,year}$ = 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

$$ASMPGT_{NEW,year} = \frac{\sum_{iwreg}\sum_{di}\sum_{iatyp} ASM_{iwreg,di,iatyp,year}}{\sum_{iwreg}\sum_{di}\sum_{iatyp}\frac{ASM_{iwreg,di,iatyp,year}}{ASMPG\_VINT_{iwreg,iatyp,1,di,year}}} \quad \textbf{(173)}$$

and

$$ASMPGT_{STOCK,year} = \frac{\sum_{iwreg}\sum_{di}\sum_{iatyp} ASM_{iwreg,di,iatyp,year}}{\sum_{iwreg}\sum_{di}\sum_{iatyp}\frac{ASM_{iwreg,di,iatyp,year}}{ASMPG\_AVG\_AGE_{iwreg,iatyp,di,year}}} \quad \textbf{(174)}$$

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.

$$QJETR\_DI_{iwreg,di,1,year} = \frac{CFJFK}{42} * \sum_{iatyp}\frac{PASSAC\_RPM\_DMD_{iwreg,iatyp,di,year} * AIR\_MGMT\_ADJ_{iwreg,year,di}}{RPMPG_{iwreg,iatyp,di,year}} \quad \textbf{(175)}$$

and

$$QJETR\_DI_{iwreg,di,2,year} = \frac{CFJFK}{42} * \sum_{iatyp}\left[CARGOAC\_RTM\_DMD_{iwreg,iatyp,di,year} * GPTM_{iwreg,iatyp,di,year}\right] \quad \textbf{(176)}$$

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 (*$AIR\_MGMT\_ADJ_{iwreg,year,di}$*).[31] This percentage increase in miles

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

traveled varies, from nearly 20% in domestic China travel to less than 5% for international Oceania travel.

As discussed in the fuel efficiency estimation section above, GPTM values are based on adjustments to actual U.S. jet fuel consumption from BTS Schedule T2 data; meaning, U.S. GPTM estimates already include jet fuel consumption from this additional adjustment factor. Therefore, *AIR_MGMT_ADJ* is calculated as the *relative difference in air system management efficiency* for each non-U.S. region, compared with the United States. (Table 5).

Table 5. Increase in passenger aircraft miles traveled due to air system management inefficiencies, where *relative* columns are the value relative to that of the U.S. (*AIR_MGMT_ADJ)*

Region	Domestic absolute	International absolute	Domestic relative	International relative
US	8%	6%	1.00	1.00
CN	7%	7%	0.99	1.01
CA	7%	6%	0.99	1.00
SA	6%	5%	0.98	0.99
EU	9%	7%	1.01	1.01
AF	11%	10%	1.03	1.04
ME	8%	10%	1.00	1.04
RU	8%	9%	1.00	1.03
CH	20%	13%	1.11	1.06
NE	12%	11%	1.04	1.05
SE	10%	11%	1.02	1.04
SW	9%	12%	1.01	1.06
OC	7%	5%	0.99	0.99

Data source: U.S. Energy Information Administration

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

$$QAGTR_{iregn,year} = QAGTR_{iregn,year=2013} + GAMMA * e^{-KAPPA*(year-1979)}, \quad \textbf{(177)}$$

where

$QAGTR_{iregn,year}$ = 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.

$$TRQNHWY_{1,year} = QAGTR + 0.047 * \sum_{di} \sum_{passfrt} QJETR\_DI_{1,di,passfrt,year}$$ [General Aviation] **(178)**

and

$$TRQNHWY_{2,year} = 0.953 * QJETR\_DI_{1,1,1,year}$$ [Domestic passenger] **(179)**

and

$$TRQNHWY_{3,year} = 0.953 * QJETR\_DI_{1,2,1,year}$$ [International passenger] **(180)**

and

$$TRQNHWY_{4,year} = 0.953 * \sum_{di} QJETR\_DI_{1,di,2,year}$$ [Total dedicated freighter] **(181)**

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 2020 and 2026. The correction factor varies by region and domestic versus international travel, and is based on the latest available industry data and projections from October 2021 (Table 6).[32]

Table 6. Percentage reduction in RPM demand versus 2019 levels, AEO2022 Reference case

Region	Type	2020	2021	2022	2023	2024	2025
US	Domestic	60%	29%	12%	5%		
Cn	Domestic	60%	29%	12%	5%		
CA	Domestic	67%	65%	36%	16%	8%	
SA	Domestic	62%	56%	31%	14%	7%	
Eu	Domestic	70%	65%	36%	16%	8%	
Af	Domestic	69%	70%	38%	17%	9%	
ME	Domestic	72%	75%	41%	19%	9%	5%
Ru	Domestic	40%	7%				
Ch	Domestic	31%	19%	8%	3%		
NE	Domestic	54%	63%	35%	16%	8%	
SE	Domestic	71%	80%	44%	20%	10%	
SW	Domestic	56%	51%	28%	13%		
Oc	Domestic	70%	59%	32%	15%	7%	
US	International	77%	77%	54%	27%	13%	7%
Cn	International	85%	83%	58%	29%	15%	7%
CA	International	71%	73%	51%	25%	13%	6%
SA	International	75%	77%	54%	27%	13%	7%
Eu	International	81%	77%	54%	27%	13%	7%
Af	International	78%	80%	56%	28%	14%	7%
ME	International	78%	81%	57%	29%	14%	7%
Ru	International	85%	87%	61%	30%	15%	8%
Ch	International	88%	89%	62%	31%	16%	8%
NE	International	84%	94%	66%	33%	17%	8%
SE	International	84%	94%	66%	33%	17%	8%
SW	International	76%	85%	60%	30%	15%	7%
Oc	International	86%	96%	67%	34%	17%	8%

Data source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* Reference case

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

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 2012 Commodity Flow Survey (CFS).[33] 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 13). The flowchart for the Freight Transportation Submodule further described in a report prepared for EIA by IHS Markit, Inc.[34]

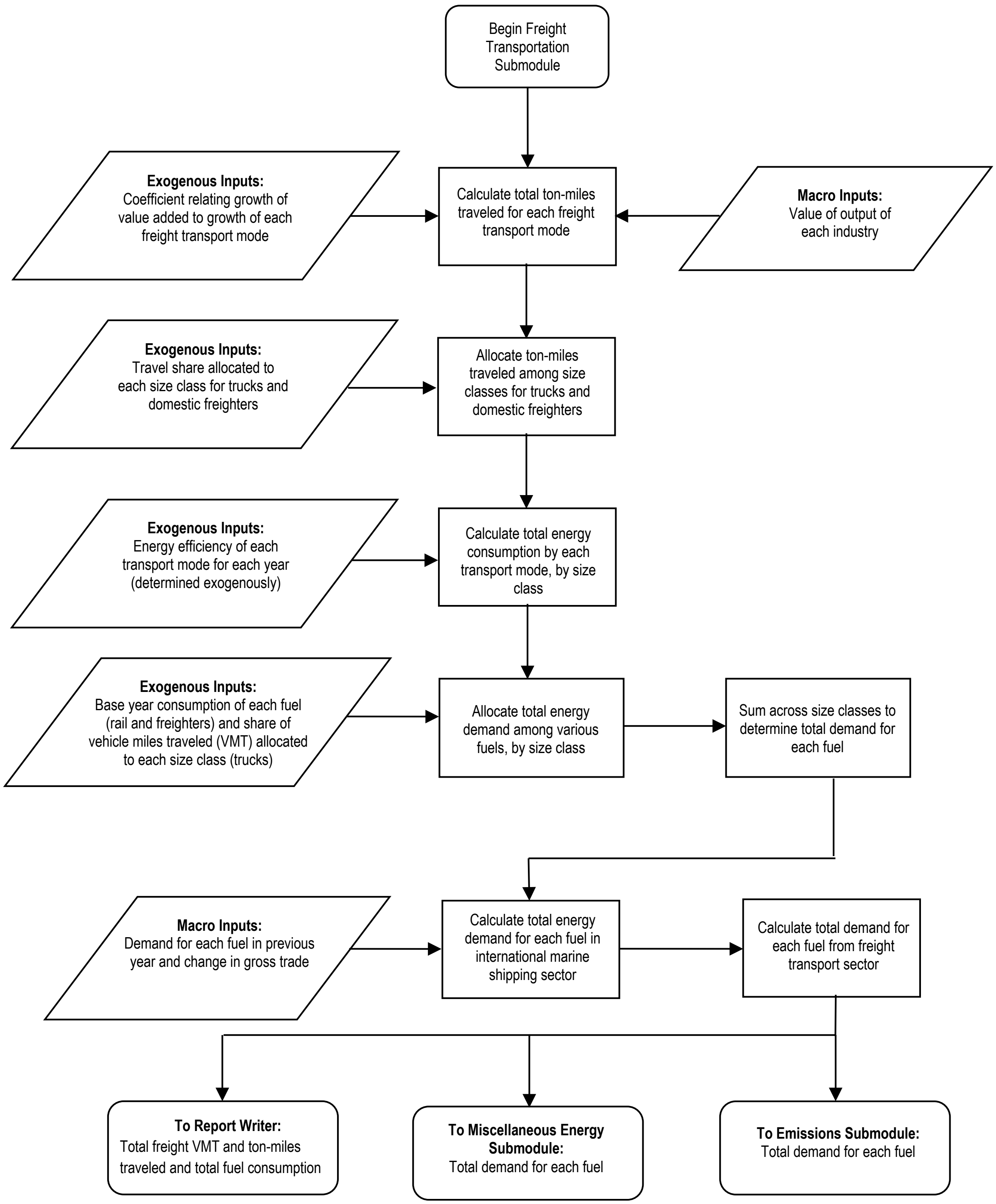
Freight Truck Stock Adjustment Component (FTSAC)

The FTSAC 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 FTSAC 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 come from the TDM.

[33] 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.

[34] IHS Global, Inc., NEMS Freight Transportation Module Improvement Study (June 20, 2014).

Figure 13. Freight Transportation Submodule of the Transportation Sector Demand Module (TDM), National Energy Modeling System (NEMS)



Data source: U.S. Energy Information Administration
Note: The Emissions Submodule is currently inactive.

- In each of 12 industrial sectors, the FTSAC projects the consumption of:
- Diesel
- Motor gasoline
- LPG
- CNG/LNG
- Flex-fuel
- Electricity
- Hydrogen accounted for by freight trucks

Throughout each submodule, 34 truck vintages, 19 truck market classes, 14 fuel-efficiency standard market subclasses and 2 fleet types are tracked, each having its own average fuel economy and number of miles driven per year (Table 7). The results, reported in four truck market classes, are defined as follows:

- Class 2b includes trucks 8,501 to 10,000 GVWR
- Class 3 includes trucks 10,001 to 14,000 pounds GVWR
- Classes 4 through 6 include trucks 14,001 to 26,000 pounds
- Classes 7 and 8 include trucks more than 26,000 pounds[35]

The 14 fuel-efficiency 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; 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 (Figure 14).

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.

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

Table 7. Freight truck vehicle fuel-efficiency market subclass category for the Transportation Demand Module, National Energy Modeling System

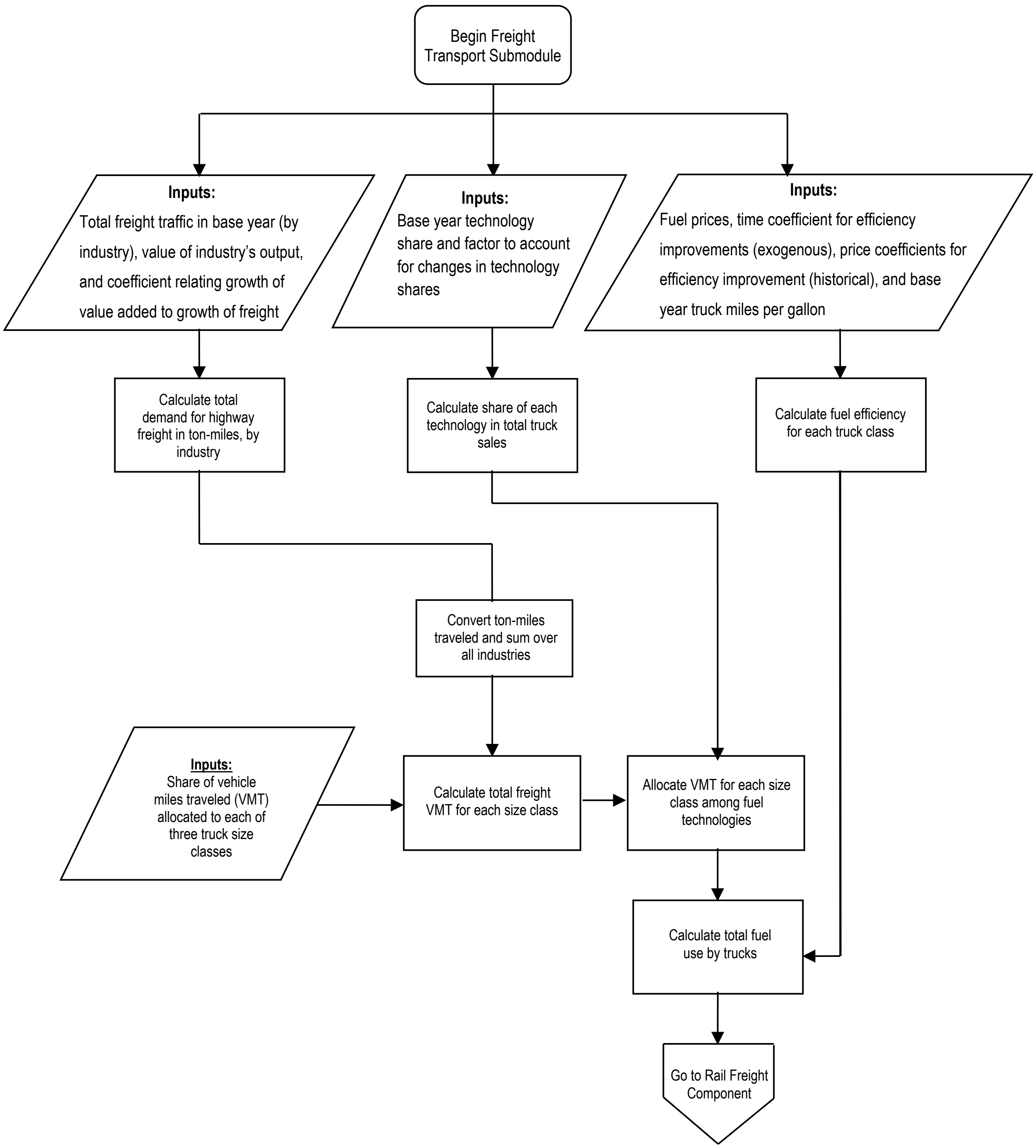
	Reporting	Fuel efficiency standard market		
Vehicle category	**size class**	**size class**	**subclasses**	**Roof[1]**
1	2b	2b	2b–3 pickup and van	-
2	2b	2b	2b–5 vocational	-
3	3	3	2b–3 pickup and van	-
4	3	3	2b–5 vocational	-
5	4–6	4	2b–5 vocational	-
6	4–6	5	2b–5 vocational	-
7	4–6	6	6–7 vocational	-
8	7–8	7	6–7 vocational	-
9	7–8	7	Tractor—day cab	Low
10	7–8	7	Tractor—day cab	Mid
11	7–8	7	Tractor—day cab	High
12	7–8	8	8 vocational	-
13	7–8	8	Tractor—day cab	Low
14	7–8	8	Tractor—day cab	Mid
15	7–8	8	Tractor—day cab	High
16	7–8	8	Tractor—sleeper cab	Low
17	7–8	8	Tractor—sleeper cab	Mid
18	7–8	8	Tractor—sleeper cab	High
19	7–8	8	Heavy-haul	-

Data source: U.S. Energy Information Administration
[1]Applies to Class 7 and Class 8 day and sleeper cabs only.

Estimate new truck fuel economies

The first step in the FTSAC is to determine the characteristics of the incoming class of truck purchases. Estimates of new commercial light, light, medium-heavy, and heavy truck fuel economies are generated endogenously and depend on the market penetration of specific fuel-saving technologies determined by consumer preference or regulatory requirements.

Figure 14. Highway Freight Component of the Transportation Sector Demand Module (TDM), National Energy Modeling System (NEMS)



Data source: U.S. Energy Information Administration

Future technologies are adapted from the joint EPA and NHTSA Final Rulemaking to establish greenhouse gas emissions standards and fuel efficiency standards for medium- and heavy-duty engines and vehicles.[36] A second more stringent phase (Phase 2) took effect in 2021.[37] 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 for diesel, gasoline, LPG, CNG/LNG, flexfuel, electric, PHEV diesel, PHEV gasoline, and hydrogen fuel cell trucks.

The first step in the component is to calculate the fuel trigger price at which the technology becomes economically viable:

$$TRIGGERPRICE\_pX_{itech,icafe19,ifuel} = \frac{TECHCOST_{itech,isc19}}{\sum_{IP=1}^{PAYBACK_{icafe,itech}} \left\{ \frac{TEMP\_BTU\_pX_{isc19,ifuel} * \left(\frac{ANNVMT\_19_{icafe19,ip,ifuel}}{ANNVMT\_19_{icafe19,1,ifuel}} \right) * TECHEFF\_pX_{itech,icafe19,ifuel}}{(1+DISCRTXG)^{ip}} \right\}}, \quad \textbf{(182)}$$

where

$TRIGGER\_PRICE\_pX_{itech,icafe19,ifuel}$ = fuel trigger price at which a technology, *itech*, becomes economically viable in phase X where X = 1 for phase 1 and x = 2 for phase 2 of the heavy duty vehicle fuel economy and greenhouse gas emission standard;

$PAYBACK_{icafe,itech}$ = payback period for a given technology and market class, in years (model increases PAYBACK to ensure compliance with minimum fuel efficiency 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 VMT by vintage by 19 size classes;

$TECHEFF\_pX_{itech,icafe19,ifuel}$ = incremental fuel economy improvement;

[36] U.S. Environmental Protection Agency and National Highway Traffic Safety Administration, "Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles; Final Rule," *Federal Register*, Vol. 76, No. 179 (September 15, 2011), pp. 57106–57513.

[37] 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), pp. 57106–57513

DISCRTXG = discount rate;

ip = index for payback periods;

itech = freight truck technologies;

icafe19 = 19 market classes;

ifuel = index referring to powertrain type, where 1 = diesel, 2 = gasoline, 3 = LPG, 4 =CNG/LNG, 5 = flexfuel, 6 = electric, 7 = PHEV diesel, 8 = PHEV gasoline, and 9 = hydrogen fuel cell; and

isc19 = map from 4 reporting size classes to 19 market classes.

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 three years.

The next step in the component is to calculate the average fuel price over the previous three years

$$Avg\_Fuel\_\$_{year,ifuel} = \frac{PRICE_{year,ifuel}+PRICE_{year-1,ifuel}+PRICE_{year-2,ifuel}}{3}, \quad \textbf{(183)}$$

where

$Avg\_Fuel\_\$_{year,ifuel}$ = average price of fuel over three year, in dollars per million British thermal units; and

$PRICE_{year,ifuel}$ = price of each fuel, in dollars per thousand British thermal units.

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

$$PREFF\_pX_{itech,icafe19,ifuel} = 1 + TECHVAR_{itech,isc19} * \left(\frac{Avg\_fuel\_\$_{ifuel,year}}{TRIGGERPRICE\_pX_{itech,icafe19,ifuel}} - 1\right), \quad \textbf{(184)}$$

where

$PREFF\_pX_{itech,icafe19,ifuel}$ = effect of fuel price on market penetration rates for each freight technology in either phase 1 or phase 2 of the standards;

$TECHVAR_{itech,isc19}$ = 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%; and

year = model year.

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

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

$$P_{year} = TECHSHARE\_pX_{itech,isc19} + \left(TECHMAX_{(itech,isc19)} - TECHBASE\_pX_{itech,icafe19,ifuel}\right) * \left(\frac{1}{1+e^{-\frac{TECHPENYR\_pX_{year,itech,icafe19,ifuel} - TECHMID_{itech,isc19}}{TECHSHAPE_{itech,isc19}}}}\right), \tag{185}$$

where

P_{year} = market penetration by year;

$TECHSHARE\_pX_{itech,isc19}$ = $TECHSHR\_pX_{year-1,itech,icafe19,ifuel}$ if the technology penetration is less than the base year technology penetration or $TECHBASE\_pX_{itech,icafe19,ifuel}$ if the technology is greater than or equal to the base share penetration;

$TECHSHR\_pX_{year-1,itech,icafe19,ifuel}$ = market share of fuel-saving technology, by market size class and fuel type in Phase 1 and Phase 2;

$TECHBASE\_pX_{itech,icafe19,ifuel}$ = base year market penetration parameter;

$TECHMAX_{itech,isc19}$ = maximum market penetration parameter;

$TECHMID_{itech,isc19}$ = parameter for existing technologies;

$TECHPENYR\_pX_{year,itech,icafe19,ifuel}$ = year that a technology becomes available for Phase 1 or Phase 2 of the fuel efficiency and greenhouse gas (GHG) heavy-duty vehicle (HDV) standards; and

$TECHSHAPE_{itech,isc19}$ = 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

$$TECHSHR\_pX_{year,itech,icafe19,ifuel} = PREFF\_pX_{itech,icafe19,ifuel} * P_{year} \; . \tag{186}$$

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

$$TECHSHR\_pX_{year,itech,icafe19,ifuel} = TECHSHR\_pX_{year-1,itech,icafe19,ifuel} * PREFF\_pX_{itech,icafe19,ifuel}. \tag{187}$$

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

$$TECHSHR\_pX_{year,itech,icafe19,ifuel} = TECHSHR\_pX_{year,itech,icafe19,ifuel} * (1 - ADVSHR) , \quad (188)$$

where

ADVSHR = superseding effect, equal to the market share of the superseding technology.

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

$$MPGEFF\_pX_{ifuel,icafe19} = \prod_{itech=1}^{TechpX} \left(1 - TECHEFF\_pX_{itech,icafe19,ifuel} * TECHADJSHR\_px_{year,itech,icafe19,ifuel}\right), \quad (189)$$

where

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

TechpX = the number of technologies in Phase 1 and Phase 2, that is 37 and 83, respectively; and

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

Fuel economy of new vintage, AGE = 1, freight trucks by market class can finally be determined as

$$NEW\_MPG\_19_{year,ifuel,icafe19} = \frac{BASE\_MPG\_pX_{ifuel,icafe19}}{MPGEFF\_pX_{ifuel,icafe19}} , \quad (190)$$

where

$NEW\_MPG\_19_{year,ifuel,icafe19}$ = new truck fuel economy by 19 size classes; and

$BASE\_MPG\_pX_{ifuel,icafe19}$ = fuel economy of new freight trucks with no fuel-saving technologies.

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 nine powertrain types:

- Diesel
- Gasoline
- LPG
- CNG/LNG

- Flex-fuel
- Electric
- PHEV diesel
- PHEV gasoline
- Hydrogen fuel cell

Market penetration of alternative fuel freight trucks is more likely to be driven by legislative or regulatory action than by economic cost or benefit consideration. For this reason, separate trends are incorporated for fleet vehicles, which are assumed to be more likely targets of future legislation, and non-fleet vehicles. The fuel technology 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. The user specifies the market share that alternative fuel trucks are likely to achieve if they have no cost advantage over conventional technologies. The inherent sensitivity of each fuel technology to the cost of driving is also specified exogenously. The latter parameter represents the commercial potential of each fuel technology beyond what is required by government and serves to modify the exogenous trend based on relative fuel prices and fuel economies. Additional user-specified parameters include the year in which the market penetration curves are initiated and the length of the market penetration cycle.

Market share AFVs

The first step in this process is to calculate the fuel cost for new trucks of each market class and fuel type that is defined as

$$FCOST\_regn_{ifuel,iregn,icafe19,year} = \frac{Avg\_Fuel\_\$\_regn_{ifuel,iregn}}{NEW\_MPG\_19_{year,ifuel,icafe19}} * HRATE_{isc19,ifuel}, \tag{191}$$

where

$FCOST\_regn_{ifuel,iregn,icafe19,year}$ = fuel cost of driving a truck by fuel type in dollar per mile;

$Avg\_Fuel\_\$\_regn_{ifuel,iregn}$ = average price of fuel over three-year period, in dollars per million British thermal units;

$HRATE_{isc19,ifuel}$ = heat rate of fuel, in million British thermal units per gallon; and

iregn = index for census divisions.

The fuel cost of driving diesel trucks (Frt_Fuel=1) relative to LPG and CNG/LNG vehicles is then calculated as

$$DCOST = 1 - \left(\frac{FCOST\_regn_{ifuel,iregn,icafe19,year}}{FCOST\_regn_{fuel=1,iregn,icafe19,year}} - 1\right) * PRAFDFXG_{isc19,ifuel}, \tag{192}$$

where

DCOST = fuel cost per mile of diesel relative to AFVs;

PRAFDFXG$_{isc19,ifuel}$ = parameter representing inherent variation in AFV market share as a result of a difference in fuel prices; and

ifuel = fuel type (1 = diesel, 3 = LPG, 4 = CNG/LNG, 5 = flex-fuel, 6 = electric, 7 = PHEV diesel, 8 = PHEV gasoline, and 9 = hydrogen fuel cell).

The market penetration curve parameters are determined during a user-specified trigger year in the following equations

$$SLOPE = \frac{\ln(0.01)}{0.5 * CYAFVXG_{isc19,iifuel,iflt}}, \quad \textbf{(193)}$$

where

SLOPE = logistic market penetration curve parameter;

CYAFVXG$_{isc19,jfuel,iflt}$ = logistic market penetration curve parameter representing number of years until maximum market penetration; and

Iflt = index for fleet vehicles: 1 for non-fleet vehicles and 2 for fleet vehicles.

$$MIDYR = TRGSHXG_{icafe19,ifuel,iflt} + \left(0.5 * CYAFVXG_{isc19,ifuel,iflt}\right), \quad \textbf{(194)}$$

where

MIDYR = logistic market penetration curve parameter representing *halfway point* to maximum market penetration; and

TRGSHXG$_{icafe19,jfuel,iflt}$ = year in which each alternative fuel begins to increase in market share because of EPACT1992 or other factors.

After the market penetration of alternative fuel trucks has been triggered, the AFV market trend is determined through a logistic function as follows

$$MPATH\_regn_{icafe19,ifuel,iflt,year,iregn} = DCOST * \left(BFSHXG_{isc19,ifuel,iflt} + \left(\frac{EFSHXG_{isc19,ifuel,iflt} - BFSHXG_{isc19,ifuel,iflt}}{1 + e^{SLOPE*curcalyr-MIDYR}}\right)\right), \quad \textbf{(195)}$$

where

MPATH_regn$_{icafe19,ifuel,iflt,year,iregn}$ = baseline market penetration;

BFSHXG$_{isc19,jfuel,iflt}$ = base year (2010) market share;

EFSHXG$_{isc19,jfuel,iflt}$ = maximum market share; and curcalyr = current model year.

The market share of alternative fuel trucks is assumed to never be less than the previous year's level in each sector. The final projected AFV market share used in the model is therefore defined as the maximum of the historical base year share and the projected share

$$FUEL\_SHR\_regn_{year,icafe19,ifuel,iflt,iregn} = \max\left[BFSHXG_{isc19,ifuel,iflt}, MPATH\_regn_{icafe19,ifuel,iflt,iregn}\right], \qquad \textbf{(196)}$$

$FUEL\_SHR\_regn_{year,icafe19,jfuel,iflt,iregn}$ = market share of CNG freight trucks by region.

a) Economic market share of CNG and LNG

Subroutine *TRUCK_STOCK* performs the first step in projecting the market share of CNG and LNG freight trucks. This calculation is done by fleet, size class, VMT group, and region. VMT group, *ivmt,* is divided into 11 separate vehicle-miles-traveled categories.

First, calculate the annual fuel savings of CNG/LNG trucks as compared with diesel trucks

$$ANN\_\$\_SAVINGS\_CNG\_regn_{ivmt,iflt,icafe19,iregn} = VMT\_VEH_{ivmt,iflt,isc19} * \left(FCOST\_regn_{fuel=1,iregn} - FCOST\_regn_{fuel=4,iregn}\right)$$

(197)

where

$ANN\_\$\_SAVINGS\_CNG\_regn_{ivmt,iflt,icafe19,iregn}$ = annual fuel savings for CNG/LNG vehicles compared with diesel or gasoline vehicles;

$VMT\_VEH_{ivmt,iflt,isc19}$= VMT per vehicle by fleet, non-fleet, size class, and VMT group; and

fuel = fuel type (1 = diesel for size classes 5–8; 2 = gasoline for size classes 2b–4; 4 = CNG/LNG).

Next, calculate the net value of these fuel savings in the projection year

$$NPV\_ADS\_regn_{ivmt,iflt,icafe19,year,iregn} = \frac{ANN\_\$\_SAVINGS\_CNG\_regn_{ivmt,iflt,icafe19,iregn}}{(1+DISCRTXG)^{year}},$$

(198)

where

$NPV\_ADS\_regn_{ivmt,iflt,icafe19,year,iregn}$ = net present value of the fuel savings from using CNG/LNG; and

year = payback year spans from one to four years.

The share of vehicles by VMT group, fleet or non-fleet, and size class for the year is then weighted by a payback share distribution that accounts for the average payback periods demanded by freight truck owners andoperators

$$BUY\_CNG\_regn_{ivmt,iflt,icafe19,year,iregn} = PBACK\_SHR_{year} * VEH\_SHR_{ivmt,iflt,isc19}\ , \tag{199}$$

where

$BUY\_CNG\_regn_{ivmt,iflt,icafe19,year,iregn}$ = share of CNG vehicles brought by fleet, size class, and region;

$PBACK\_SHR_{year}$ = distribution of payback periods by owner/operators; and

$VEH\_SHR_{ivmt,iflt,isc19}$ = percent share of vehicle fleet and size class.

Positive purchase decisions, *BUY_CNG*, by fleet, size class, and VMT group occur if the incremental cost of CNG/LNG vehicles ($17,000 for Classes 2b and 3, $40,000 for Classes 4 to 6, and $60,000 for Classes 7 to 8) is less than the net present value of fuel savings, *NPV_ADS*.

The shares of CNG vehicles purchased by fleet and by size class are then calculated as

$$\begin{aligned} &Fuel\_Shr\_regn_{year,icafe19,ifuel=4l=4,iflt,iregn} \\ &\quad = Fuel\_Shr\_regn_{year,icafe19,ifuel=4=4,iflt,iregn} \\ &\quad + \left(\sum_{year=1}^{4} buy\_cng\_regn_{ivmt,iflt,icafe19,year,iregn} \right. \\ &\quad \left. * MPATH\_regn_{icafe19,ifuel=4,iflt,year,iregn} \right), \end{aligned} \tag{200}$$

The market share variable *FUEL_SHR_regn* is then used in the following subroutine to calculate final market share for CNG trucks.

Market share of diesel trucks

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

$$\begin{aligned} &MPATH\_regn_{icafe19,iifuel,iflt,iyear,iregn} \\ &\quad = BFSHXG_{isc19,ifuel,iflt} + \left(EFSHXG_{isc19,ifuel,iflt} - BFSHXG_{isc19,ifuel,iflt}\right) \\ &\quad * \left(1 - e^{CSTDXG_{isc19,iflt} + CSTDVXG_{isc19,iflt} * curcalyr}\right), \end{aligned} \tag{201}$$

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

$$Fuel\_Shr\_regn_{year,icafe19,ifuel=2,iflt,iregn} = \max\left[0, 1 - \sum_{ifuel=1,3-9} Fuel\_Shr\_regn_{year,icafe19,ifuel,iflt,iregn}\right]. \quad (202)$$

Determine composition of existing 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. Scrappage rates are applied to the previous year's truck population estimates

$$TRK\_19\_regn_{year,icafe19,iage,ifuel,iflt,iregn} = TRK\_19\_regn_{year-1,icafe19,iage-1,ifuel,iflt,iregn} * \left(1 - SCRAP\_RATE_{isc,iage-1,ifuel}\right), \quad (203)$$

where

$TRK\_19\_regn_{year,icafe19,iage,ifuel,iflt,iregn}$ = existing stock of trucks aggregated by vehicle weight class *(isc);*

$SCRAP\_RATE_{isc,iage,ifuel}$ = factor representing the proportion of trucks of each vintage that are scrapped each year; and

iage = index for vintage of vehicle from 234; 1 implies new vehicle.

The new estimate for the number of existing trucks is simply the existing population (after scrappage) minus fleet transfers

$$TRK\_19\_regn_{year,icafe19,iage,ifule,iflt,iregn} = TRK\_19\_regn_{year,icafe19,iafe,ifuel,iflt,iregn} - \left(TFFXGRT_{isc,iage} * TRK\_19\_regn_{year,icafe19,iage,ifuel,iflt=2,iregn}\right),$$

and

$$TRK\_19\_regn_{year,icafe19,iage,ifuel,iflt,iregn} = TRK\_19\_regn_{year,icafe19,iage,ifuel,iflt,iregn} + \left(TFFXGRT_{isc,iage} * TRK\_19\_regn_{year,icafe19,iage,ifuel,iflt=2,iregn}\right), \quad (204)$$

$TFFXGRT_{isc,iage}$ = Percentage of trucks of each vintage to be transferred from fleets to non-fleets.

Calculate purchases of new trucks

New truck purchases are based on Classes 2b and 3 truck sales and on the Macroeconomic Activity Module's projection of Classes 4 through 8 truck sales that is split between truck Classes 4 to 6 and Classes 7 to 8, as defined at the beginning of this section

$$NEWTRUCKS\_regn_{year,isc=1,iflt=iflt=3,iregn=11} = MC\_VEHICLES_{(isc=3,year)} * 1000000,$$

$$NEWTRUCKS\_regn_{year,isc=2,iflt=3,iregn=11} = NEWCLS46_{year} * MC\_SUVTHAM_{year} * 1000000,$$

$$NEWTRUCKS\_regn_{year,isc=3,iflt=3,iregn=11} = \left(1 - NEWCLS46_{year}\right) * MC\_SUVTHAM_{year} * 1000000,$$

$$NEWTRUCKS\_regn_{year,isc=4,iflt=3,iregn=11} = \left(MC\_VEHICLES_{isc=1,year} + MC\_VEHICLES_{isc=2,year} - TEMPCLS12A_{year}\right) * 1000000\ ,\ ,$$

(205)

where

$NEWTRUCKS\_regn_{year,isc,iflt,iregn}$ = national new truck sales where isc = 1 for Class 3, isc = 2 for Classes 46, isc = 3 for Classes 7–8, and isc = 4 for Class 2b;

$MC\_VEHICLES_{isc,year}$ = sales of Class 1–3 trucks from the Macroeconomic Activity Module;

$NEWCLS46_{year}$ = truck Classes 4–6 share of total truck sales;

$MC\_SUVTHAM_{year}$ = total new truck sales for Classes 4–8, from the Macroeconomic Activity Module;

$TEMPCLS12A_{year}$ = the total of Class 1–2 trucks that are considered light-duty vehicles; and

iregn = 11 = total of all census divisions.

The next step is to calculate the new truck sales, *iage* = 1,

$$\begin{aligned} TRK\_19\_regn_{year,icafe19,iage=1,ifuel,iflt=2,iregn} &= NEWTRUCKS\_regn_{year,isc,iflt=3,iregn} * FLEETSHR_{isc} \\ &* REGN\_SHARE_{year-1,iage=1,iflt,iregn} * Fuel\_Shr\_regn_{year,icafe19,ifuel,iflt,iregn} \\ &* sc\_share_{icafe19,iflt,iregn} \end{aligned}$$

$$\begin{aligned} TRK\_19\_regn_{year,icafe19,iage=1,ifuel,iflt=1,iregn} &= NEWTRUCKS\_regn_{year,isc,iflt=3,iregn} * (1 - FLEETSHR_{isc}) \\ &* REGN\_SHARE_{year-1,iage=1,iflt,iregn} * Fuel\_Shr\_regn_{year,icafe19,ifuel,iflt,iregn} \\ &* sc\_share_{icafe19,iflt,iregn} \end{aligned}$$

(206)

where

$FLEETSHR_{isc}$ = percentage of HDV in fleet use by size class;

$REGN\_SHARE_{year,iage,iflt,iregn}$ = regional share of new truck sales from previous model year by fleet;

$Fuel\_Shr\_regn_{year,icafe19,ifuel,iflt,iregn}$ = fuel shares for new trucks by size class, fleet/non-fleet, region; and

$sc\_share_{icafe19,iflt,iregn}$ = share of new trucks by size class.

Calculate fuel consumption

The next stage of the component takes the total miles driven by trucks of each market class, fuel type, and age and divides by fuel economy to determine fuel consumption.

The aggregate VMT growth by economic sector, *SEC*, is estimated. The model calculates the VMT growth rate using a ratio between current year and previous year total truck ton-miles. This VMT growth rate is then applied to the previous year truck VMT, by census division and industrial sector, to calculate truck VMT

$$TVMT_{year,iregn,isec} = TVMT_{year-1,isec,iregn,isec} * \left(\frac{TTONMI_{year,iregn,isec}}{TTONMI_{year-1,iregn,isec}}\right), \tag{207}$$

where

$TVMT_{year,iregn,isec}$ = freight truck vehicle miles traveled, by industrial sector and census division;

$TTONMI_{year,iregn,isec}$ = freight truck ton-miles by industrial sector and census division ; and

isec = index of economic sectors.

The model then calculates the adjustment VMT per truck

$$VMTADJR_{year} = \frac{\sum_{iregn=1}^{9}\sum_{isec=1}^{10} TVMT_{year,iregn,isec}}{\sum_{isc,iage,ifuel,ivoc} ANNVMT_{(isc,iage,ifuel,ivoc)} * TRK\_19\_regn_{year,icafe19,iage,ifuel,iflt,regn=11}}, \tag{208}$$

where

$VMTADJR_{year}$ = aggregate VMT adjustment factor;

$ANNVMT_{isc,iage,ifuel,ivoc}$ = base year VMT per truck by freight reporting classes; and

ivoc = index for vocational vehicles where 1 = non-vocational and 2 = vocational.

The model applies the VMT adjustment to obtain VMT across all sectors

$$VMTFLTR_{year,isc,iage,ifuel,iflt,iregn} = ANNVMT_{isc,iage,ifuel,ivoc} * VMTADJR * TRK\_19\_regn_{year,icafe19,iage,ifuel,iflt,iregn=11} * VMTSHRR_{year,iregn} ,$$

(209)

where

VMTFLTR$_{year,isc,iage,ifuel,iflt,iregn}$ = HDV VMT; and

VMTSHRR$_{year,iregn}$ = regional share of VMT.

Fuel consumption in gasoline- or diesel-gallons equivalent[38] is calculated by dividing VMT by on-road fuel economy

$$FUELDMDR_{year,isc,ifuel,iflt,iregn} = \sum_{iage=1}^{34} (1 - VMTFLTR\_CAV\_SHR) * \frac{VMTFLTR_{year,isc,iage,ifuel,iflt,iregn}}{HDV_{MPG_{year,isc,iage,ifuel}}} + VMTFLTR\_CAV\_SHR * \frac{VMTFLTR_{year,isc,iage,ifuel,iflt,iregn}}{\frac{HDV\_MPG_{year,isc,iage,ifuel}}{1 - HDV\_MPG\_CAV\_ADJ}}$$

(210)

where

FUELDMDR$_{year,isc,ifuel,iflt,iregn}$ = total freight truck fuel consumption by market class and fuel type, in gasoline- or diesel-gallons equivalent;

HDV_MPG$_{year,isc,iage,ifuel}$ = fuel economy of freight trucks, by year, market class, fuel, and vintage;

VMTFLTR_CAV_SHR = share of platoon-eligible freight truck VMT, *VMT_CAV_ELIG*, that is driven in platoons; and

HDV_MPG_CAV_ADJ = operational energy savings from platooning, not including fuel economy improvement.

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

$$FUELBTUR_{isc,ifuel,iflt,iregn} = FUELDMDR_{isc,ifuel,iflt,iregn} * HRATE_{isc,ifuel} * PCT\_VMT_{ifuel,ifuel7,iregn} ,$$

(211)

[38] 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.

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.

Rail Freight Component

Rail projections simplify the freight truck approach, in that only one class of freight rail and vehicle technology is considered (Figure 15). 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, transfer coal ton-miles traveled (*COAL_TMT*) within NEMS as follows

$$COAL\_TMT_{year} = TTONMILE_{year}, \tag{212}$$

where

$COAL\_TMT_{year}$ = ton-miles traveled for coal in a given year; and

$TTONMILE_{year}$ = billion ton-miles by railroad for coal by coal summed over regions, from the Coal Market Module.

Then, project the growth of coal rail freight ton-miles by census division

$$RPROJ\_CTONMI_{year,iregn} = RPROJ\_CTONMI_{year-1,iregn} * \left(1 + \left[\frac{COAL\_TMT_{year} - COAL\_TMT_{year-1}}{COAL\_TMT_{year-1}}\right]\right), \tag{213}$$

Next, project the growth of non-coal rail freight ton-miles by census division and industrial sector

$$RPROJ\_NCTONMI_{year,iregn,isic} = \left(\frac{TSIC_{iregn,isic,year}}{1000}\right) * RTM\_OUTPUT_{iregn,isic}, \tag{214}$$

where

$RPROJ\_NCTONMI_{year,iregn,isic}$ = ton-miles traveled for non-coal in a given year;

$RTM\_OUTPUT_{iregn,isic}$ = 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

$$RTMTT_{year,iregn} = \sum_{iregn=1}^{9} \sum_{isic=1}^{16} RPROJ\_NCTONMI_{year,iregn,isic} + \sum_{REG=1}^{9} RPROJ\_CTONMI_{year,iregn},$$

(215)

Energy consumption is then estimated using the projected rail energy efficiency

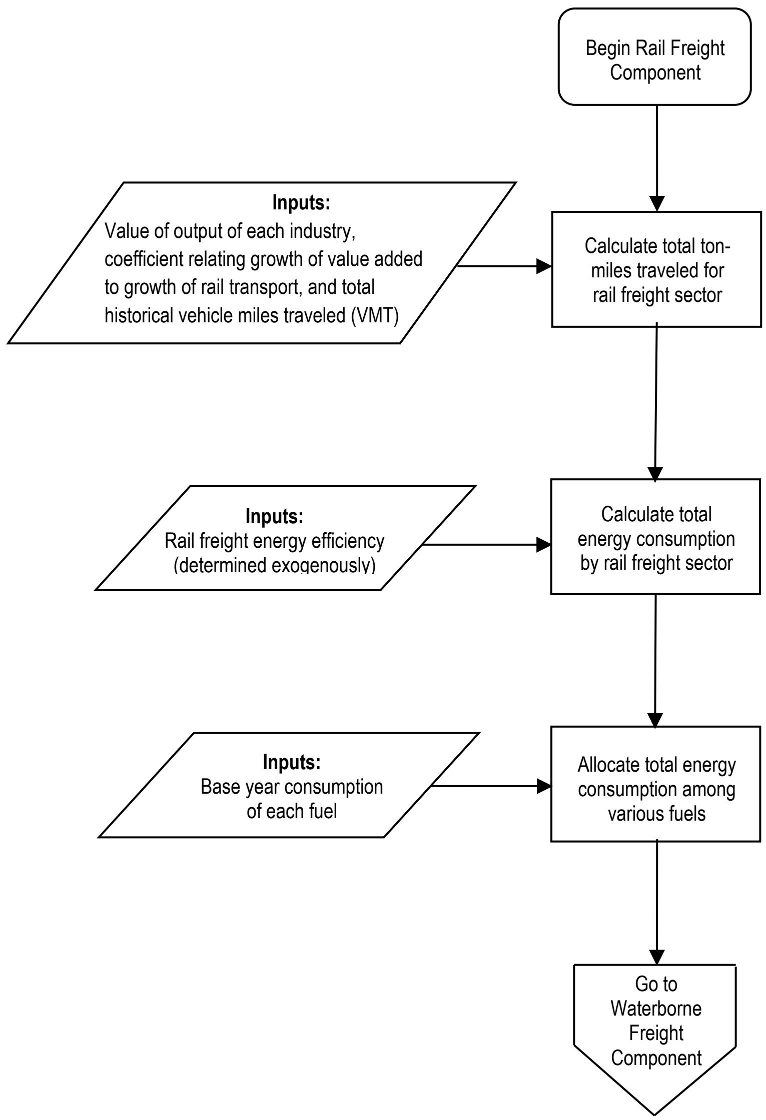
$$TQFRAILT_{year,iregn} = RTMTT_{year,iregn} * FREFF_{year}, \tag{216}$$

where

$TQFRAILT_{year,iregn}$ = total energy consumption by freight trains; and

$FREFF_{year}$ = freight rail energy efficiency.

Figure 15. Rail Freight Component for the Transportation Sector Demand Module (TDM), National Energy Modeling System (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

$$NPV\_LNG_{year} = \frac{ANN\_FUEL\_SAVINGS_{PAYBK=1}}{1+DISCRT} + \frac{ANN\_FUEL\_SAVINGS_{PAYBK}}{1+DISCRT^{PAYBK}}, \tag{217}$$

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 is then allocated to each region by

$$TQRAILR_{Rail\_Fuel,iregn,year} = TQFRAILR_{iregn,year} * RAIL\_FUEL\_SHR_{Rail\_Fuel,year}, \tag{218}$$

where

$TQRAILR_{Rail\_Fuel,iregn,year}$ = total regional fuel consumption for each technology; and

$RAIL\_FUEL\_SHR_{Rail\_Fuel,year}$ = share of rail freight fuel consumption, by fuel.

Waterborne Freight Component

Two classes of waterborne freight transportation are considered in this component: domestic marine traffic and freighters conducting foreign trade (Figure 16). 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

$$STMTT_{iregn,year} = \sum_{isic=1}^{16} TSIC_{iregn,isic.year} * DSTM_{OUTPUT\,iregn,isic} * \left(1 + ANN_{DECLINE\,year}\right), \tag{219}$$

where

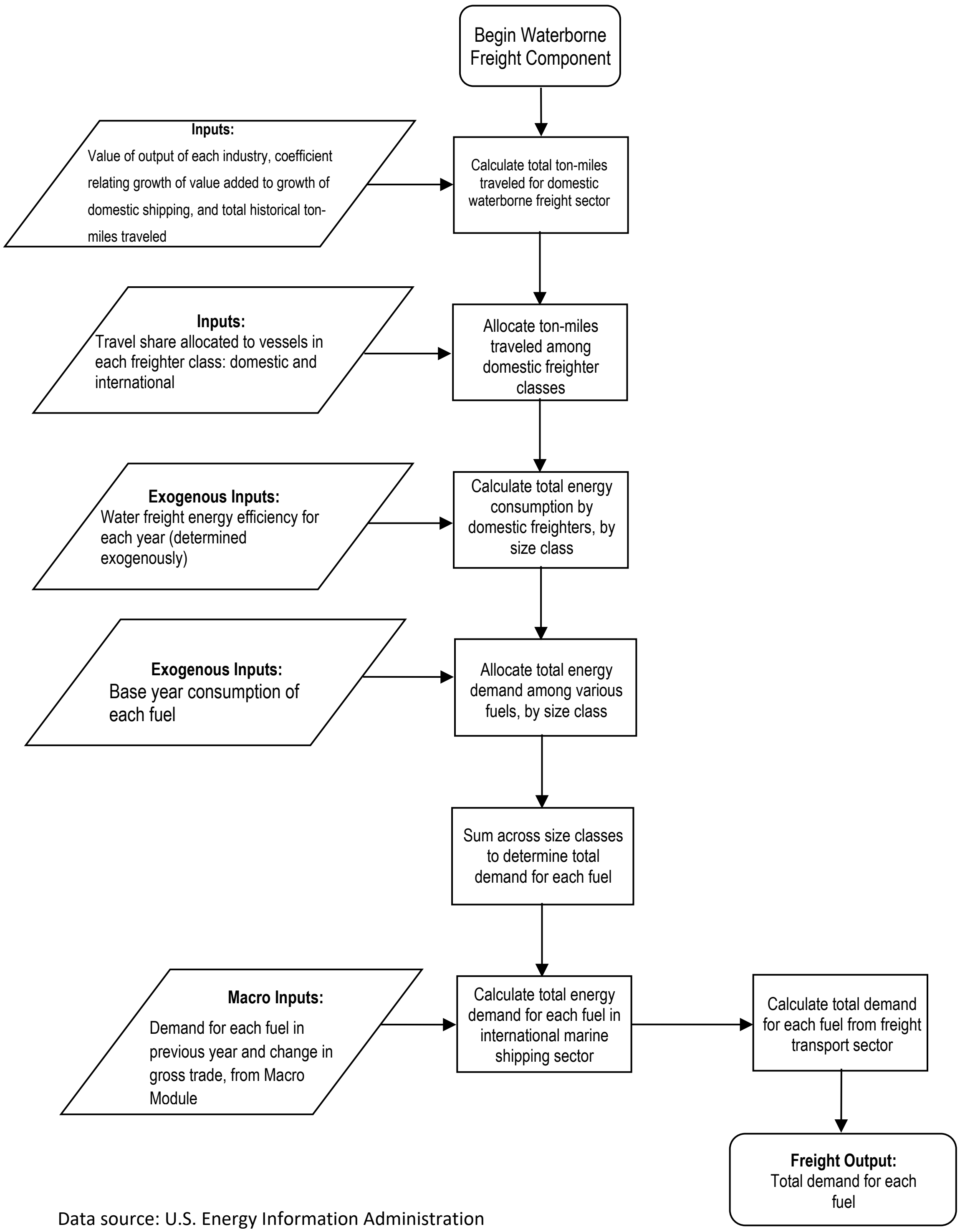
$STMTT_{iregn,year}$ = total ton-miles of waterborne freight by census division in year, *Year*;

$TSIC_{iregn,isic,year}$ = 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 16.Waterborne Freight Component for the Transportation Sector Demand Module (TDM), National Energy Modeling System (NEMS)



Data source: U.S. Energy Information Administration

Energy use is subsequently estimated, using average energy efficiency

$$TQDSHIPT_{year,iregn} = STMTT_{year,iregn} * DSEFF_{year} \text{ ,} \tag{220}$$

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

$$TQDSHIPR_{Ship\_Fuel,iregn,year} = TQDSHIPT_{iregn,year} * DOMSHIP\_FUEL\_SHR_{Ship\_Fuel,year}, \tag{221}$$

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[39] 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

$$ISFDT_{year} = ISFDT_{year-1} + 0.5 * ISFDT_{year-1} * INTS\_B * \left[\frac{GROSST_{year}}{GROSST_{year-1}} - 1\right], \tag{222}$$

where

$ISFDT_{year}$ = total international shipping energy demand in year *Year*;

INTS_B = for frozen technology case = 0.4, for high technology case = 0.6; and

$GROSST_{year}$ = value of gross trade (imports and exports), from the Macroeconomic Activity Module.

[39] Oak Ridge National Laboratory, *Transportation Energy Data Book Edition 28*, June 2009.

Total energy demand is then allocated among the four fuels by the following

$$ISFD_{Ship\_Fuel,year} = ISFDT_{year} * INTSHIP\_FUEL\_SHR_{Ship\_Fuel,year}, \quad \textbf{(223)}$$

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

$$TQISHIPR_{Ship\_Fuel,iregn,year} = ISFD_{Ship\_Fuel,year} * SEDSHRXX_{iregn,year}, \quad \textbf{(224)}$$

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

$$FUELCONS_{2012,class,iregn} = TRANSITFUELCONS_{2012,class,iregn} + AUXFUELCONS_{2012,class,iregn}, \quad \textbf{(225)}$$

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

$$ECAFUELCONS_{iregn,year} = \sum_{class}\Big(FUELCONS_{2012,class,iregn} * MAX[0,1-(year-2012) * FLEETTO_{class}] * FUELCONS_{2012,class,iregn} * \{1 - MAX[0,1-(year-2012) * FLEETTO_{class}]\} * [1 - EFFINC_{class}]^{0.5*(year-2012)} * GEEFFECTS_{class,year}\Big), \quad \textbf{(226)}$$

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

$$FLTPROF_{mftype,iregn,year} = \frac{P_{mftype}^{alpha} * beta_{mftype}}{\sum_{mftype} P_{mftype}^{alpha} * beta_{mftype}}, \quad \textbf{(227)}$$

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 17). 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 18). The fractional change in the military budget is first calculated as follows

$$MILTARGR_{year} = \frac{MC\_GFMLR_{year}}{MC\_GFMLR_{year-1}}, \quad \textbf{(228)}$$

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

$$MFD_{Mil\_Fuel,year} = MFD_{Mil\_Fuel,year-1} * MILTARGR_{year}, \quad \textbf{(229)}$$

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

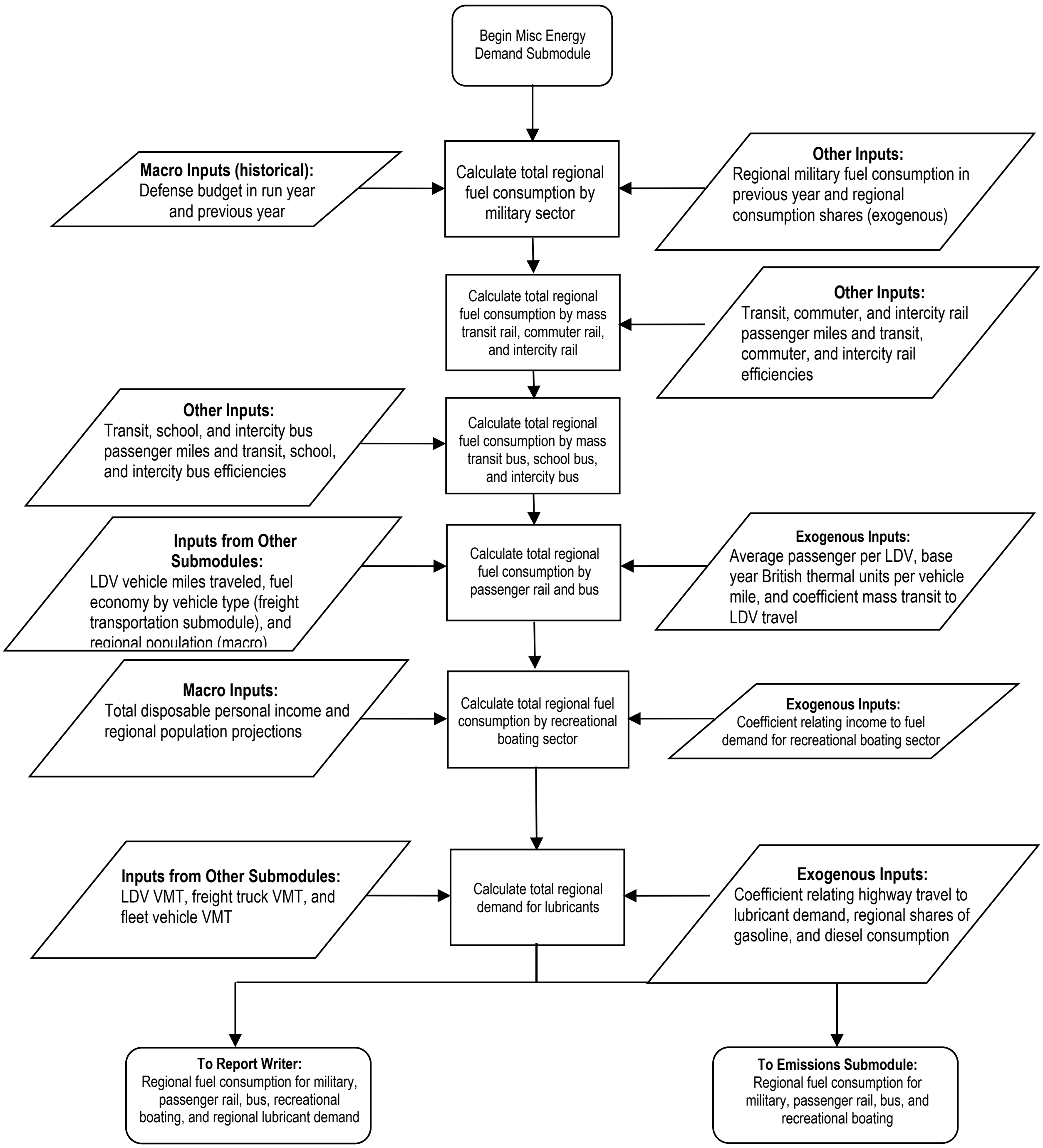
$$QMILTR_{Mil\_Fuel,iregn,year} = MFD_{Mil\_Fuel,year} * MILTRSHR_{Mil\_Fuel,iregn,year}, \quad \textbf{(230)}$$

where

QMILTR$_{Mil_Fuel,iregn,year}$ = regional fuel consumption, by fuel type, in Btu; and

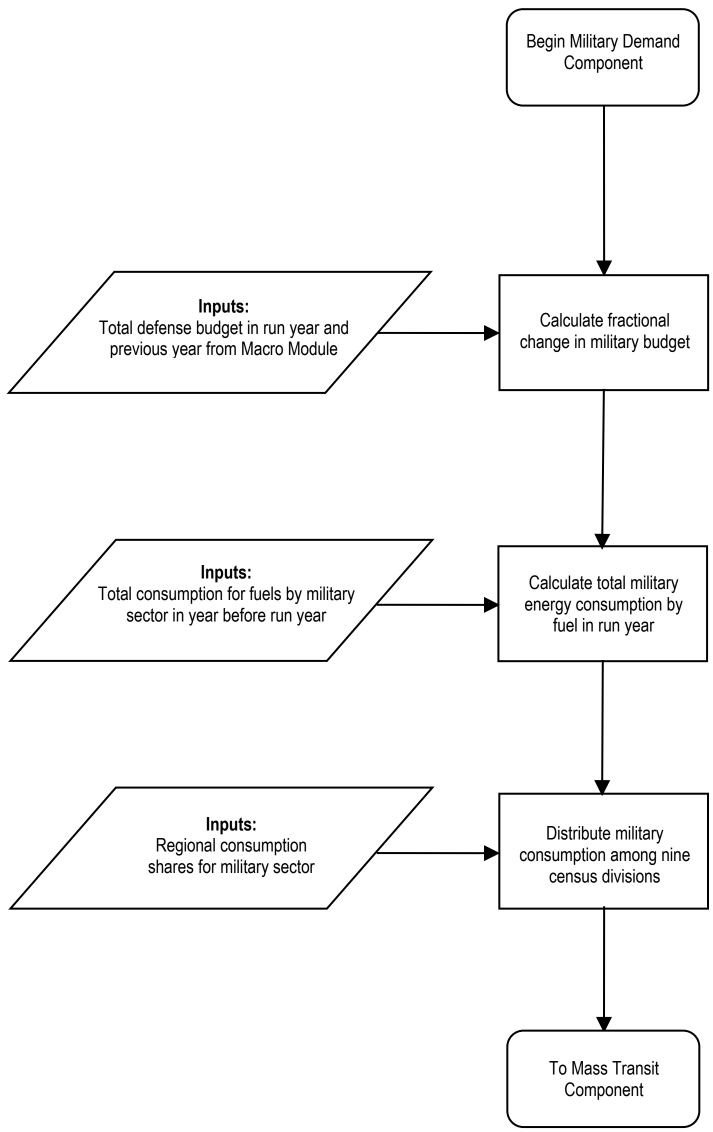
MILTRSHR$_{Mil_Fuel,iregn,year}$ = regional consumption shares, from 1991 data, held constant.

Figure 17. Miscellaneous Energy Demand Submodule for the Transportation Sector Demand Module (TDM), National Energy Modeling System (NEMS)



Data source: U.S. Energy Information Administration
Note: The Emissions Submodule is currently inactive.

Figure 18. Military Demand Component in the Transportation Demand Module, National Energy Modeling System



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 19). 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

$$QMTRR_{ifuel,iregn,year} = TRED_{iregn,year} + CREDE_{iregn,year} + IREDER_{iregn,year} \ , \qquad \textbf{(231)}$$

where

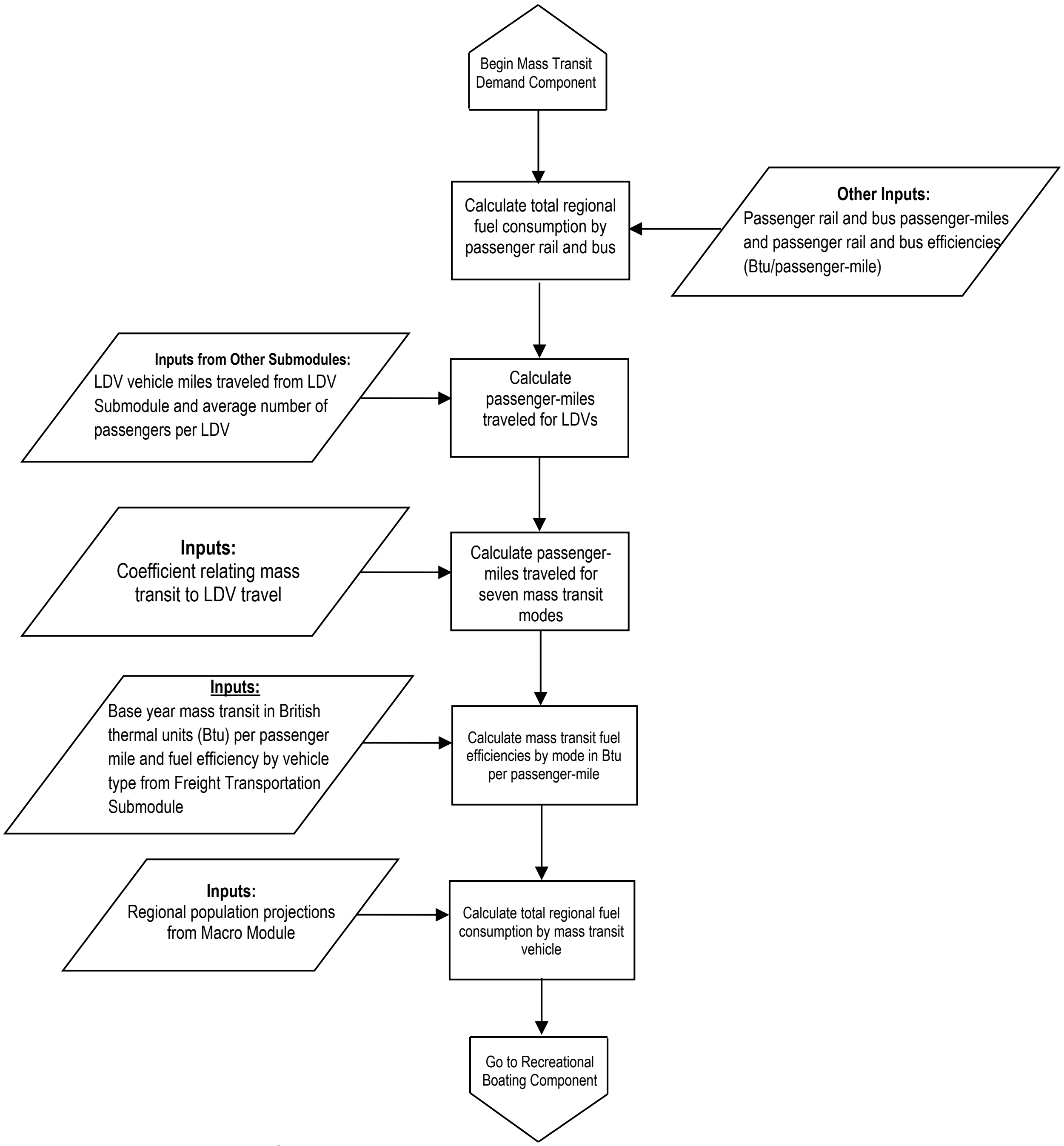
$QMTRR_{ifuel,iregn,year}$ = passenger rail energy demand by fuel by census division;

$TRED_{iregn,year}$ = 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 19. Mass Transit Demand Component for the Transportation Sector Demand Module (TDM), National Energy Modeling System (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, IM=1

$$TMPMT_{iregn,year} = TBPMTPC_{iregn,yearn} * MC_{NP16A_{NP16A_{iregn},n}iregn,year}, \quad \textbf{(232)}$$

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;

MC_NP16A$_{iregn,year}$ = U.S. population age 16 and older from the Macroeconomic Activity Module; 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 and rail. Mass transit efficiencies, in Btu per passenger-mile, are calculated as

$$TBBTUPM_{iregn,year} = TBBTUPM_{iregn,year-1} * TBSYSEFF_{iregn} * 1 - \left(\left(1 - \left(\frac{TRFTMPG_{year-1}}{TRFTMPG_{year}}\right) * TBFSHR_{iregn,ifuel=diesel,year}\right)\right) * 1 + \left(\left(TBFSHR_{iregn,ifuel=CNG,year} - TBFSHR_{iregn,ifuel=CNG,year-1}\right) * 0.25\right), \quad \textbf{(233)}$$

where

TBBTUPM$_{iregn,year}$ = Btu per passenger-mile for the transit bus mode;

TRFTMPG$_{year}$ = freight mpg, by vehicle type, from the Freight Transportation Module;

TBSYSEFF$_{iregn}$ = bus system efficiency for the transit bus mode, in Btu per passenger; and

TBFSHR$_{iregn,ifuel,year}$ = projected fuel share for transit buses, by fuel type.

Total fuel consumption is calculated and distributed among regions according to their populations based on the following

$$QMTBR_{im,ifuel,iregn,year} = TBPMT_{iregn,year} * TBBTUPM_{iregn,year} * TBFSHR_{iregn,ifuel,year}, \quad \textbf{(234)}$$

where

QMTBR$_{im,ifuel,iregn,year}$ = regional consumption of fuel, by mode.

The following equations describe the bus segment of the model for intercity and school buses

$$TMOD_{im,year} = TMPASMIL_{im} * MC\_NP_{year}, \quad \textbf{(235)}$$

where

$TMOD_{im,year}$ = passenger-miles traveled, by mode;

$TMPASMIL_{im}$ = passenger-miles per capita, by bus mode;

MC_NP_{year} = U.S. population from the Macroeconomic Activity Module (adult population for intercity, child population for school); and

im = index of transportation mode: 1 = Intercity bus, 2 = School bus.

Fuel efficiencies, in Btu per vehicle mile, are obtained from the Freight Transportation Submodule for buses and rail and mass transit efficiencies, in Btu per passenger-mile, are calculated as

$$TMEFF_{im,year} = TMEFF_{im,year-1} * BUSSYSEF_{im} * 1 \\ -\left(\left(1-\left(\frac{TRFTMPG_{year-1}}{TRFTMPG_{year}}\right) * QMODFSHR_{im,ifuel=diesel,year}\right)\right) * 1 \\ + \left(\left(QMODFSHR_{im,ifuel=CNG,year} - QMODFSHR_{im,ifuel=CNG,year-1}\right) * 0.25\right)$$

(236)

where

$TMEFF_{im,year}$ = Btu per passenger-mile, by mass transit mode; and

$BUSSYSEF_{im}$ = bus system efficiency by mode, in Btu per passenger.

Total fuel consumption is calculated and distributed among regions according to their population shares

$$QMTRBR_{IM,ifuel,iregn,year} = TMOD_{IM,year} * TMEFF_{IM,year} * \frac{MC\_NP_{iregn,year}}{\sum_{iregn=1}^{9} MC\_NP_{iregn,year}} * \\ QMODFSHR_{IM,ifuel,iregn}, \tag{237}$$

where

$MC\_NP_{iregn,iyearyear}$ = regional population projections, from the Macroeconomic Activity Module; and

$QMODFSHR_{IM,ifuel,iregn}$ = projected fuel share for intercity and school buses, by fuel type

Recreational Boating Demand Component

The growth in fuel use by recreational boats is related to the growth in disposable personal income. 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 20). The following equations describe the model used

$$RBEDPC_{ifuel,year} = X1_{ifuel} + X2_{ifuel} * \log\left(INC00\$NPT_{iregn,year}\right) + X3_{ifuel} * PRICE04_{iregn,year}, \tag{238}$$

where

$RBEDPC_{ifuel,year}$ = recreational boating fuel consumption per capita in year, *Year*, fuel (where 1= Gasoline and 2 = Diesel);

$X1_{ifuel}$ = energy demand constant term for the above fuel types;

$X2_{ifuel}$ = energy demand log of income for the above fuel types;$X3_{ifuel}$ = energy demand fuel cost in 2004 dollars for the above fuel types;

$INC00\$NPT_{year}$ = per capita income in 2000 dollars; and

$PRICE04_{ifuel}$ = fuel price in 2004 dollars for the above fuel types.

This value is then used to estimate the national recreational boating fuel consumption for each year with the following equation

$$RECFD_{ifuel,year} = RBEDPC_{ifuel,year-1} * \sum_{iregn=1}^{9} MC\_NP_{iregn,year}, \quad \textbf{(239)}$$

where

$RECFD_{ifuel,year}$ = national recreational fuel consumption in year, Year, Fuel (where 1=Gasoline and 2 = Diesel).

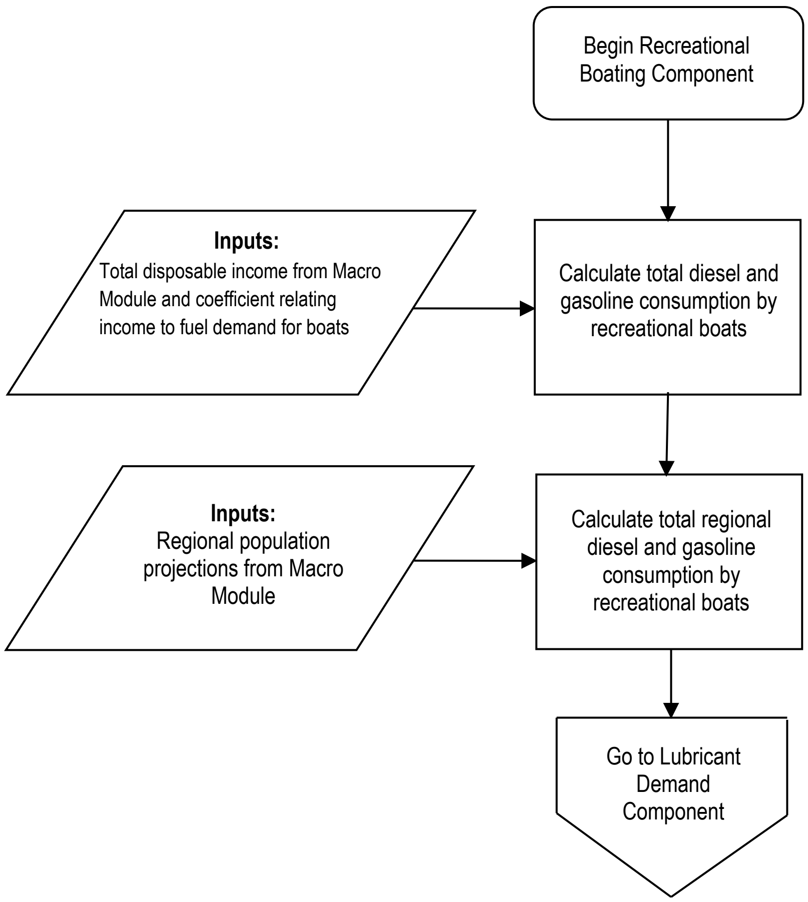
Following this step, the regional consumption is calculated according to population, as for mass transit

$$QRECR_{ifuel,iregn,year} = RECFD_{ifuel,year} * \frac{MC\_NP_{iregn,year}}{\sum_{iregn=1}^{9} MC\_NP_{iregn,year}}, \quad \textbf{(240)}$$

where

$QRECR_{ifuel,iregn,year}$ = regional fuel consumption by recreational boats in Year, Fuel (where 1=Gasoline and 2=Diesel).

Figure 20. Recreational Boating Demand Component for the Transportation Sector Demand Module (TDM), National Energy Modeling System (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 (VMT) is first determined as

$$HYWAY_{year} = \sum VMTHH_{year} + FTVMT_{year} + \sum FLTVMT_{year}, \tag{241}$$

where

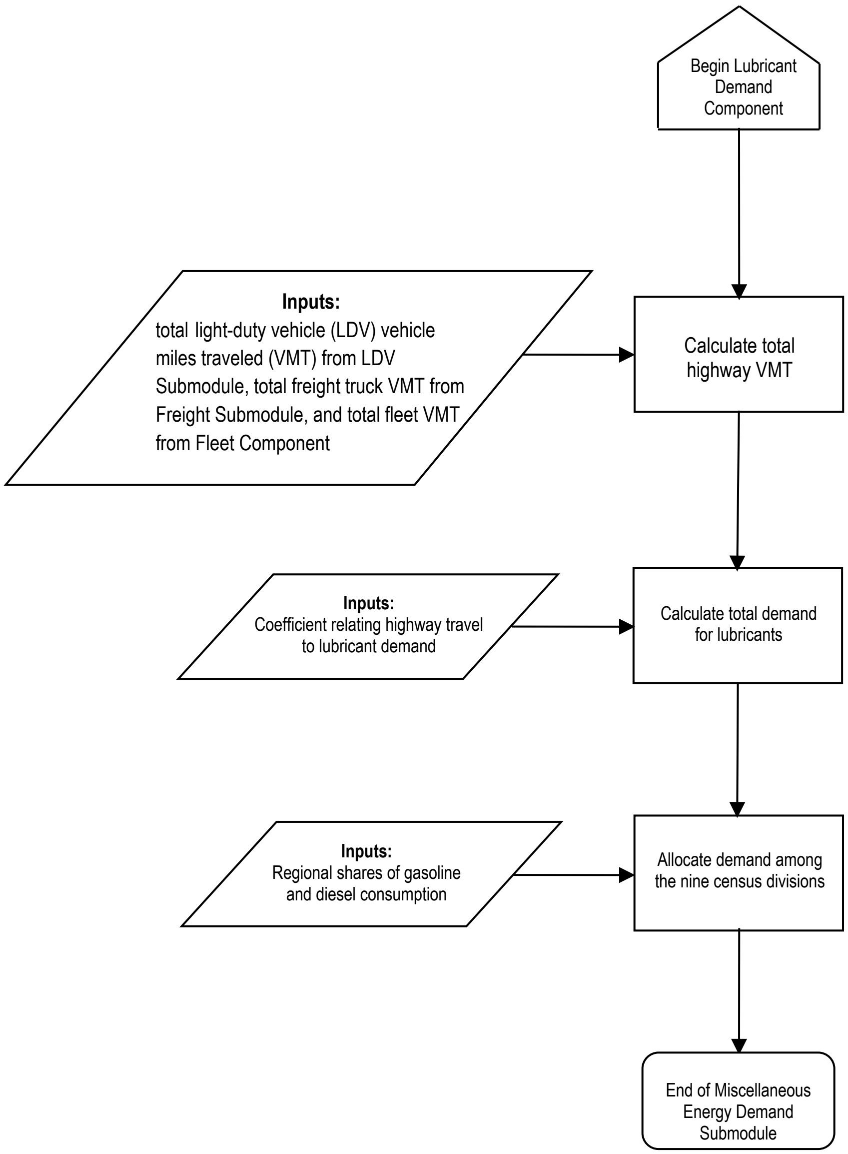
$HYWAY_{iyear}$ = total highway VMT;

$VMTHH_{year}$ = total household light-duty VMT;

$FTVMT_{year}$ = total freight truck VMT, from the Freight Transportation Submodule; and

$FLTVMT_{year}$ = total fleet vehicle VMT, from the LDV Fleet Component.

Figure 21. Lubricant Demand Component for the Transportation Sector Demand Module (TDM), National Energy Modeling System (NEMS)



Data source: U.S. Energy Information Administration

Lubricant demand is then estimated based on the following

$$LUBFD_{year} = LUBFD_{year-1} * \left[\frac{HYWAY_{year}}{HYWAY_{year-1}}\right]^{BETALUB}, \quad \textbf{(242)}$$

where

LUBFD$_{year}$ = total demand for lubricants in year, *Year*; and

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

$$QLUBR_{iregn,year} = LUBFD_{year} * \left[\frac{(\sum VMTHH_{year})*SHRMG_{iregn,year}+(\sum FTVMT_{year})*SHRMG_{iregn,year}+FTVMT_{year}*SHRDS_{iregn,year}}{HYWAY_{year}}\right], \quad \textbf{(243)}$$

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)

Model acronym
TRAN

Description
The TDM is part of the 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:

- Light-Duty Vehicles (including light-duty fleet vehicles, light-duty stock, and commercial light trucks)
- Air Travel
- Freight Transportation (truck, rail, and marine)
- 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.

Most recent model update
November 2019 Model Interfaces

Receives inputs from four modules:

- Electricity Market Module
- Liquid Fuels Market Module
- Natural Gas Transmission and Distribution Module
- Macroeconomic Activity

Documentation
Model Documentation Report: Transportation Sector Demand Module of the National Energy Modeling System, DOE/EIA-M070 (2022), May 2022.

Energy system described
Domestic transportation sector as well as international aviation and marine energy consumption.

Coverage

- 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
- Time unit/frequency: annual, 1995 through 2050
- Products: motor gasoline, aviation gasoline, diesel (distillate), residual oil, electricity, jet fuel, LPG, CNG, LNG, methanol, ethanol, hydrogen, lubricants, and pipeline fuel
- 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.

Status of evaluation efforts by sponsor:

None.

DOE input sources:

- State Energy Data (SEDS), June 2021
- Short-Term Energy Outlook, November 2021
- Macroeconomic Activity Module Inputs: new vehicle sales, economic and demographic indicators, and defense spending
- NEMS supply models: fuel prices

Non-DOE input sources:

- National Energy Accounts
- U.S. Department of Transportation, Bureau of Transportation Statistics: Air Carrier Summary Data, various years

- Jet Information Services Inc., World Jet Inventory: Year-End, various years.
- Federal Highway Administration, Highway Statistics Series, various years.
- Oak Ridge National Laboratory, Transportation Energy Data Book, various years.
- Department of Commerce, Bureau of the Census, Vehicle Inventory and Use Survey 2002, December 2004.
- U.S. Environmental Protection Agency, Engines and Vehicles Compliance Information System, various years.
- U.S. Environmental Protection Agency and National Highway Traffic Safety Administration, The Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule for Models Years 2021-2026 Passenger Cars and Light Trucks, April 2020.
- IHS Markit Polk, National Vehicle Population Profile, various years.
- IHS Markit Polk, Trucking Industry Profile, various years.
- Federal Highway Administration , Freight Analysis Framework, 2015
- Federal Transit Administration, National Transit Database, various years

Appendix B. Acronyms

Acronym
AEO2022: *Annual Energy Outlook 2022*
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
FCV: fuel cell vehicle
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 Figure 22. The figure shows 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, in the order presented in Figure 22, 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, rail, and marine), and Miscellaneous Energy Demand.

Called by: NEMS Main Module; Emissions Module

Calls: TRANLBLS; READWK1; TMAC; NEWLDV; TMPGNEW; TFLTVMTS; TSMOD; TMPGSTK; TCURB; TFLTMPGS; TFLTCONS; TRANFRT; TVMT; TMPGAG;TCOMMCL_TRK; TRAIL; TSHIP; TAIRT; TAIREFF; TMISC; TCONS; TINTEG; TBENCHMARK; TEMISS;TREPORT; TOUTPUT

Equations: 1-243

SUBROUTINE: READLDV

Description: Reads the spreadsheet input file trnldvx.xlsx.

Called by: TRAN

Calls: None

Equations: None

SUBROUTINE: READSTOCK

Description: Reads the spreadsheet input file trnstockx.xlsx.

Called by: TRAN

Calls: None

Equations: None

SUBROUTINE: TMAC

Description: This subroutine reassigns MACRO data to TRAN subroutine local variables.

Called by: TRAN

Calls: None

Equations: None

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

Calls: None

Equations: None

SUBROUTINE: TMPGNEW

Description: This subroutine starts the fuel economy module, AFV module, and loads data inputs. After completion, the average price of vehicles is computed.

Called by: TRAN

Calls: READNHTSA ; READHIST; AFVADJ; FEMCALC; CGSHARE; TREG; TLDV; CAFECALC; CAFETEST

Equations: 1-138

SUBROUTINE: READNHTSA

Description: This subroutine reads the NHTSA calibration data file trnnhtsax.xlsx.

Called by: TMPGNEW

Calls: None

Equations: None

SUBROUTINE: READHIST

Description: This subroutine reads new light-duty vehicle sales data for 1990 through the year the MTCC base year from the historical data file (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 historic ATV offsets to report writer variables. AFVADJ is called to calibrate current year ATV attributes using current year gasoline data.

Called by: TMPGNEW

Calls: AFVADJ

Equations: None

SUBROUTINE: AFVADJ

Description: This subroutine establishes alternative fuel vehicle (AFV) characteristics relative to conventional gasoline. AFVADJ is an initialization subroutine and calculates the price, weight, fuel economy, and horsepower for the AFVs for all historical years through the base year in the MTCC. Most of these values 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. Sixteen vehicle and fuel types are represented: conventional gasoline, turbo direct-injection diesel, flex-fuel ethanol, dedicated ethanol, dedicated CNG, dedicated LPG, CNG bi-fuel, LNG bi-fuel, LPG bi-fuel, dedicated electric, diesel electric hybrid, plug-in gasoline electric hybrids, gasoline electric hybrid, methanol fuel cell, and hydrogen fuel cell.

Called by: TMPGNEW; READHIST

Calls: EVCALC; HEVCALC; PHEV20CALC; PHEV50CALC; FCCALC

Equations: 1–75

SUBROUTINE: FEMCALC

Description: This subroutine determines the cost-effective market shares of technologies for each vehicle class. 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. Electric hybrid and plug-in hybrid vehicles have an additional price adjustment to account for battery cost. The adjustment is based on the adjusted cost for a midsize gasoline car and is scaled in accordance with the ratio of the weight of the gasoline version of the current vehicle to the weight of a midsize gasoline car. Additional learning curve adjustments are based on the learning curves of NiMH and lithium ion batteries. Consumer performance demand is adjusted downward as the horsepower-to-weight ratio increases so that performance gains cannot continue indefinitely. 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; PHEV20CALC; PHEV50CALC; FCCALC; FEMRANGE; CALIBNHTSA;

Equations: 1–138

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 TRNLDV.XML 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. This subroutine starts the Fuel Economy Model, AFV Model, and loads data inputs. After completion, the average price of vehicles is computed.

Called by: TRAN

Calls: None

Equations: None

SUBROUTINE: EVCALC

Description: This subroutine calculates battery costs and related quantities for electric vehicles. It applies learning curves to battery price, aggregates battery price based on NiMH and lithium ion market share, and adds to vehicle price. This subroutine also calculates vehicle weight as a function of battery weight, market share, and vehicle fuel economy as a function of vehicle weight.

Called by: FEMCALC

Calls: None

Equations: 1–138

SUBROUTINE: HEVCALC

Description: This subroutine calculates battery costs and related quantities for hybrid electric vehicles. It applies learning curves to battery prices, aggregates battery price based on NiMH and lithium ion market share, and adds to vehicle price. This subroutine also calculates vehicle weight as a function of battery weight and market share, as well as vehicle fuel economy as a function of vehicle weight.

Called by: FEMCALC

Calls: None

Equations: 1–138

SUBROUTINE: LIONCOSTCALC

Description: This subroutine calculates lithium ion battery cost ($/kWh) for PHEVs, EVs, and HAV systems for the four phases of the cost curve: the Revolutionary, Mature, and High-Volume phases. Lithium-ion capacity additions are calculated, and then the battery costs are calculated.

Called by: AFVADJ

Calls: None

Equation: 36

SUBROUTINE: PHEV20CALC

Description: This subroutine calculates battery costs and related quantities for plug-in hybrid electric vehicles with 35 miles or less all-electric range. It applies learning curves to battery prices, aggregates battery price based on NiMH and lithium ion market share, and adds to vehicle price. This subroutine also calculates vehicle weight as a function of battery weight and market share, as well as vehicle fuel economy as a function of vehicle weight.

Called by: FEMCALC

Calls: None

Equations: 1–138

SUBROUTINE: PHEV50CALC

Description: This subroutine calculates battery costs and related quantities for PHEV with more than 35 miles all-electric range. It applies learning curves to battery prices, aggregates battery price based on NiMH and lithium ion market share, and adds to vehicle price. This subroutine also calculates vehicle weight as a function of battery weight and market share, as well as vehicle fuel economy as a function of vehicle weight.

Called by: FEMCALC

Calls: None

Equations: 1–138

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 at 1.75 times cost plus a $1,500 amortization cost. 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

Calls: None

Equations: 1–138

SUBROUTINE: CALIBNHTSA

Description: This subroutine calibrates factors that are based on historical NHTSA data through the last available data year. All ATV calibration factors are set to equal corresponding gasoline vehicle calibration factors to preserve the differential relationships between gasoline vehicles and ATVs.

Called by: FEMCALC

Calls: None

Equations: None

SUBROUTINE: FEMRANGE

Description: This subroutine calculates vehicle range estimates.

Called by: FEMCALC

Calls: None

Equations: 1–138

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 historic 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

Calls: None

Equations: 1–138

SUBROUTINE: TREG

Description: This subroutine estimates the regional values for fuel demand, fuel cost, VMT demand, VMT shares, and sales of non-fleet vehicles. It calculates regional shares of fuel, regional income, regional driving demand, regional VMT shares, and regional sales of non-fleet cars and light trucks.

Called by: TMPGNEW

Calls: None

Equations: 1–138

SUBROUTINE: TLDV

Description: This subroutine initiates the vehicle choice routine.

Called by: TMPGNEW

Calls: TATTRIB; TALT2; TALT2X; TFLTSTKS; TLEGIS

Equations: 1–138

SUBROUTINE: TATTRIB

Description: This subroutine adjusts the LDV attributes such as mpg, price, range, and horsepower so they can be used throughout the model. The LDV attributes for gasoline are calculated in the subroutine CGSHARE. This subroutine determines vehicle price of ATVs to reflect differing price structures depending on whether they are in low- or high-volume production. As production moves from low to high volume, prices will decline. It estimates the ATV production volume price point using BASE year price differentials, constrained at both ends by high- and low-production volume prices (in other words, price can never drop lower than the high-volume production price or rise higher than the low-volume production price). It then combines domestic and import ATV attributes. The routine assumes the same domestic versus import sales shares as gasoline to provide for an equitable comparison of attributes across vehicle types. It bypasses the EPACT routine when PSPR equals zero to ensure that *non-allowable* vehicle classes do not end up with negative prices. All non-zero prices should be larger than the maximum credit, so an abort switch is activated in any other instance where the vehicle price goes negative.

Called by: TLDV

Calls: FLEXSHR

Equations: 1–138

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

Calls: None

Equations: 1–138

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 historic ratio of vehicle stock per refueling station. It regionalizes the predicted stations by regional vehicle sales and estimates fuel availability.

Called by: TLDV

Calls: None

Equations: 1–138

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

Equations: 1–138

SUBROUTINE: TALT314

Description: This subroutine calculates fuel cost, vehicle range, and fuel availability for ethanol flex-fuel vehicles.

Called by: TALT2X

Calls: None

Equations: 1–138

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

Calls: None

Equations: 1–138

SUBROUTINE: TALT316

Description: This subroutine calculates fuel cost, vehicle range, and fuel availability for LPG bi-fuel vehicles.

Called by: TALT2X

Calls: None

Equations: 1–138

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 combines federal and state EPACT regulations (EPACTREG) into one government mandate for both by averaging based on stocks from each. This subroutine can also adjust vehicle sales and market shares to reflect legislative mandates on sales of Zero Emission Vehicles (ZEV), including Transitional Zero Emission Vehicles (TZEV) and Advanced Technology Partial Zero Emission Vehicles (ATPZEV). Participating states include California, Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, and Vermont. 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: TLDV

Calls: None

Equations: 1–147

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: TLDV

Calls: None

Equations: 1–147

SUBROUTINE: CAFECALC

Description: This subroutine combines fuel economies from all vehicles and checks if the combined car and light truck mpg is greater than the CAFE standard.

Called by: TMPGNEW

Calls: None

Equations: 1–147

SUBROUTINE: CAFETEST

Description: This subroutine ensures that CAFE standards are met by increasing the sales of hybrid (gasoline and diesel) and diesel cars and light trucks.

Called by: TMPGNEW

Calls: None

Equations: 1–138

SUBROUTINE: TFLTVMTS

Description: This subroutine calculates VMT for fleets.

Called by: TRAN

Calls: None

Equations: 1–147

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

Calls: None

Equations: 1–147

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 AFVs 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

Calls: None

Equations: 1–147

SUBROUTINE: TCURB

Description: This subroutine calculates the stock average weight (by vintage) of cars and light trucks.

Called by: TRAN

Calls: None

Equations: 1–147

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

Calls: None

Equations: 1–147

SUBROUTINE: TFLTCONS

Description: This subroutine calculates fuel consumption of fleet vehicles by region.

Called by: TRAN

Calls: None

Equations: 1–138

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

Calls: None

Equations: None

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. It summarizes Economic Output into 12 Sectors: 1) chemicals, rubber, and plastic, 2) primary metals, 3) processed food, 4) paper products, 5) petroleum products, 6) stone, clay, glass, and concrete, 7) metal durables, 8) other manufacturing, 9) agriculture, 10) mining, 11) utility, and 12) government.

Called by: TRANFRT

Calls: CFREAD

Equations: 182-211

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

Calls: None

Equations: 182-211

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

Calls: None

Equations: None

SUBROUTINE: WR_FSHFLT

Description: This subroutine calculates fuel shares of the entire truck stock, excluding new trucks, for comparison with the fuel shares assigned in subroutine TRUCK_NEW.

Called by: TRUCK_STOCK

Calls: None

Equations: 182-211

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

Calls: FAC

Equations: 182-211

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. This subroutine summarizes personal and fleet light-duty vehicle sales and mpg by technology. It combines fleet and non-fleet cars and fleet and non-fleet light trucks and calculates total sales. Sales shares for each technology within cars and light trucks are calculated and summed. A harmonically averaged new car and light truck mpg is calculated separately. It also calculates fleet average stock car and light truck mpg, fleet average stock vehicle mpg, and fuel economy and sales separately for personal and fleet vehicles.

Called by: TRANFRT

Calls: None

Equations: 1–243

SUBROUTINE: TRUCK_NEW

Description: This subroutine determines the trigger price at which each technology is considered viable. For all emission technologies, the trigger price is set negative so it will penetrate. This subroutine implements fuel-saving technologies that include various technologies that are adopted when commercially available and cost-effective. It sets a market penetration price sensitivity factor and applies penetration criteria such as: 1) technology availability, 2) technology applicability to the fuel or market class, and 3) economical trigger price or price required by regulation. It subtracts the effects of technologies being superseded by more advanced technologies. It calculates combined market share of the chosen technology and more advanced technologies that are competing with it. It then reduces market share of next less advanced technology because of the penetration of competing higher technologies. In other words, the market share of a less-advanced technology is assumed to apply to that part of the market not yet taken by the more-advanced technologies. It determines combined mpg improvement of fuel-saving technologies by weighting each technology's improvement by its market share. In the frozen technology scenario (which assumes that regulated efficiency changes as a result of changes in emission standards), technology adoption is stopped after 2010. This subroutine implements the market penetration equation: s-shaped logistical equation to estimate market penetration over time. It outputs the market penetration fraction.

Called by: TRANFRT

Calls: None

Equations: 1–243

SUBROUTINE: TRUCK_STOCK

Description: This subroutine estimates new vehicle sales, stocks, and fuel economy. This subroutine determines the share of each fuel for new truck sales. The results of this subroutine can be altered by 1) changing the trigger year, 2) changing the slope, or 3) altering the base year or end year share. Cost of diesel per mile relative to other fuels is considered to derive a logistic penetration curve parameter. This subroutine returns SLOPE and Mid-Point on Logistic penetration curve. This subroutine determines the market share of CNG freight trucks purchased by fleet, size, and VMT groups. Purchase decisions are estimated by calculating the net present value of annual fuel savings as compared with diesel trucks, weighted by a payback share distribution. This subroutine calculates total personal light vehicle VMT. It calculates cost of driving per mile, unadjusted VMT per licensed driver, total VMT for light-duty vehicles, VMT for personal travel, and VMT by technology.

Called by: TRANFRT

Calls: WR_FSHFLT

Equations: 1–243

SUBROUTINE: TRAIL

Description: This subroutine calculates energy consumption by rail by region and fractional change in fuel efficiency.

Called by: TRAN

Calls: None

Equations: 212–218

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

Calls: None

Equations: 219-227

SUBROUTINE: TRANAIR

Description: This subroutine calls the air freight subroutines TAIRT and TAIREFF.

Called by: TRAN

Calls: TAIRT; TAIREFF

Equations: 148-181

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

Calls: None

Equations: 148–156

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

Calls: None

Equations: 157-158

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

Calls: None

Equations: 228–243

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

Calls: None

Equations: 1–147

SUBROUTINE: TINTEG

Description: This subroutine calculates total transportation energy consumption by fuel type for all modes.

Called by: TRAN

Calls: None

Equations: 1–243

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

Calls: None

Equations: 1–243

SUBROUTINE: TEMISS

Description: This subroutine calculates vehicle emissions by the three criteria pollutants: hydrocarbons, carbon monoxide, and nitrous oxides. This routine sums up total VMT across market classes, reads emission factors in grams per mile, and initializes emissions variables. It aggregates emissions by age (or vintage) for the model's report writer by converting the weight of emissions in grams to million metric tons.

Called by: TRAN

Calls: TRANFRT

Equations: 1–243

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

Calls: None

Equations: None

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

Calls: None

Equations: 120

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

Equations: 121

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

Equations: 122–1254

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

Calls: None

Equations: 1–243

FUNCTION: HARMONIC_MEAN

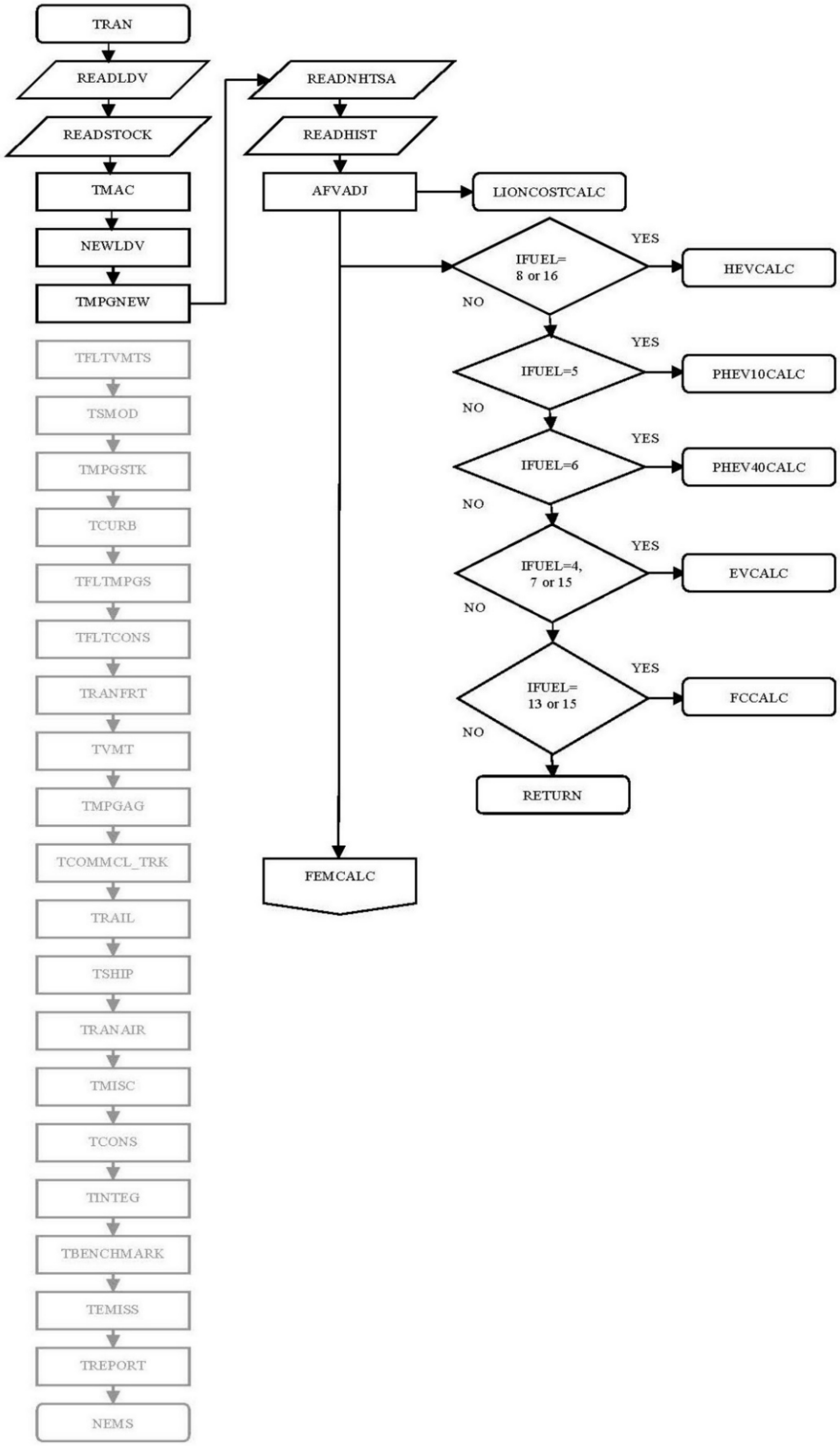
Description: This function computes a harmonic mean, used for averaging fuel economy measured in miles per gallon. The calculation essentially takes the reciprocal of mpg, or efficiency, and computes the quantity-weighted average and then converts the result back to miles per gallon by taking the reciprocal.

Called by: TRANFRT; TRUCK_STOCK; TFRTRPT

Calls: None

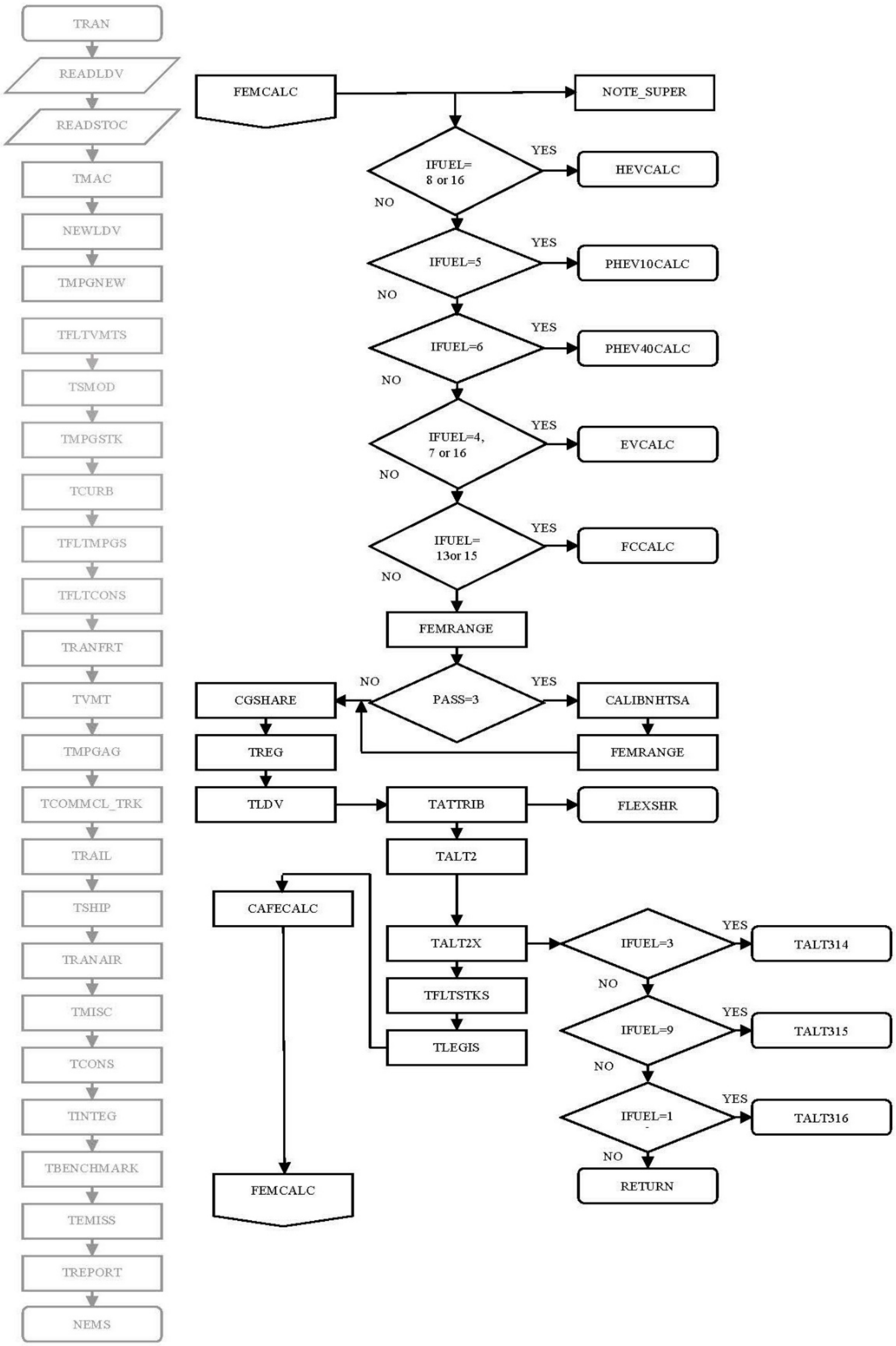
Equations: 182-211

Figure 22. Flowchart of calls made by TRAN subroutine of the Transportation Sector Demand Module (TDM), National Energy Modeling System (NEMS)



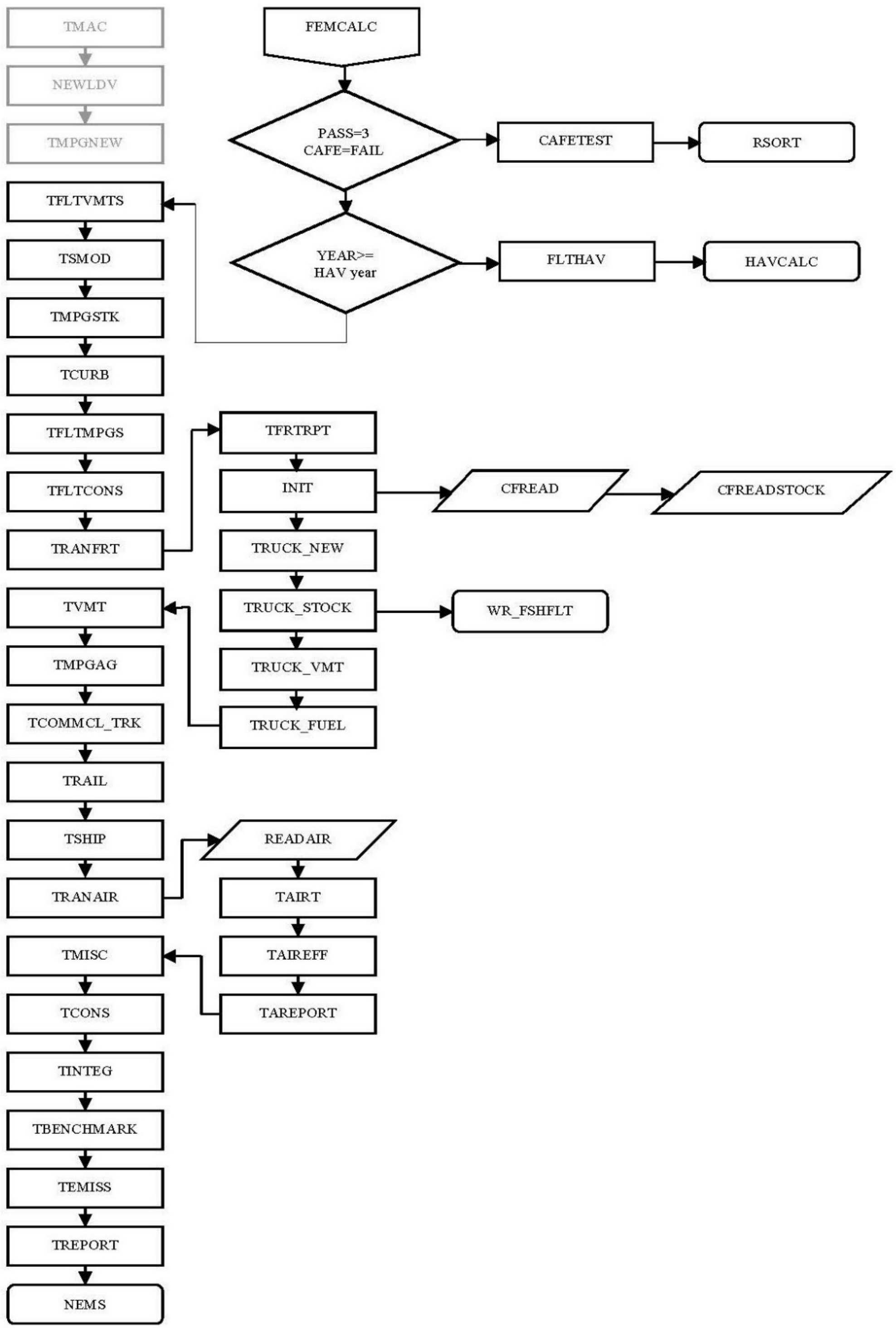
Source: U.S. Energy Information Administration

Figure 22. Flowchart of calls made by TRAN subroutine of the Transportation Sector Demand Module (TDM), National Energy Modeling System (NEMS)



Source: U.S. Energy Information Administration

Figure 22. Flowchart of calls made by TRAN subroutine of the Transportation Sector Demand Module (TDM), National Energy Modeling System (NEMS)



Source: U.S. Energy Information Administration

Appendix D. Input and Output Variables in Transportation Model

Variable name	Variable description
Transportation specific macro variables	
INC00$16	Disposable income per capita for population 16+ (2000$)
INC00$NPT	Disposable income per capita (thousands of 2000$)
INC90$NP	Disposable income per capita (1990 $)—fuel economy component
MC_GFMLR	Federal government purchases—defense
MC_SUVTHAM	Total new truck sales for Classes 4–8, from the Macroeconomic Activity Module
NEWCARS	New car sales
NEWCLS12A	New light truck sales, Classes 1–2a
TMC_PGDP	GDP deflator
Global definitions	
ACCL	Vehicle acceleration—0 to 60 mph
ACTUAL_MKT	Technology market share = MKT_PEN
AFVADJFE	ATV fuel economy differential
AFVADJHP	ATV horsepower differential
AFVADJPR	ATV price differential (1/2 low volume car/truck,3/4 High volume car/truck)
AFVADJPRH	ATV high volume price differential
AFVADJRN	ATV range differential
AFVADJWT	ATV weight differential
AHPCAR	Average car horsepower
APSHR44	Percentage of total light-duty vehicles sales by technology type
APSHR55	Absolute regional market shares of adjusted vehicle sales
ATPZEV	Total (percentage) mandated natural gas, hybrid and methanol/natural gas fuel cell vehicles
AVSALES	Total adjusted vehicle sales
AVSALEST	Total regional adjusted vehicle sales by market class
AWTCAR	Average car weight
AWTTRUCK	Average light truck weight
BatPackSize	Battery capacity (kWh) by powertrain
BatPackWgt	Battery weight (lbs) by powertrain
BETAFA2	ATV NMLM level 2, fuel availability 1
BRCOST25	Battery replacement cost—currently set to zero
CAFE_STAND	CAFE standards
CDCARSHR	Share of total cars by region
CDFREG	Car fuel efficiency degradation factor
CDLTSHR	Share of total light trucks by region
CDFRFG	Car fuel efficiency degradation factor
CFCoefA, CFCoefA2,CFCoefB, CFCoefB2, CFCoefC, CFCoefC2, CFCoefD, CFCoefD2	Coefficients to determine size class market share
CLASS_SHARE	Vehicle class market shares (within vehicle groups)
CMPGSTK	Car fuel economy
CMPGT	Car stock mpg
CMPGT_IT	Average fuel efficiency of cars by powertrain

Variable name	Variable description
COSTEF_FUEL	Cost effectiveness of mpg improvement of a subsystem technology
COSTEF_PERF	Cost effectiveness of performance improvement of a subsystem technology
cumul_lidar_prod	Cumulative LiDAR system production (L4a, L4b, and L5 variants)
CURRENT	FEM attribute index value for the current year
DEL_COSTABS	Absolute incremental change in cost ($)
DEL_COSTWGT	Relative incremental change in cost (dollars per pound [$/lb])
DEL_FE	Incremental fractional change in fuel economy
DEL_HP	Incremental fractional change in horsepower
DEL_WGTABS	Absolute incremental change in weight (lb)
DEL_WGTWGT	Relative incremental change in weight (lb/base vehicle lb)
DELTA_MKT	Incremental increase in subsystem technology market share
DISCOUNT	Discount rate
DOMCAR = 1	Vehicle group index value for a domestic car
ElecSysIncCost	Cost of on-board electricity systems and storage by powertrain
EV_DOD	EV battery depth of discharge (percentage)
FAVAIL	Fuel availability by technology, region, year
FAVL	Fuel availability index relative to gasoline
FIRST_HAV_YEAR	First year of market availability for each HAV level
FIRST_LIDAR_YEAR	First year available for low- and high-speed LiDAR
FLCOST	Fuel cost per mile
FLT	Fleet indexes
FLTCARSHR	Fleet car sales shares by technology
FLTCRAT	Fraction of total car sales attributed to fleets
FLTCSHR	Fraction of fleet cars purchased by a given fleet type
FLTECH	Vehicle purchases by fleet type and technology
FLTECHSAL	Fleet sales by size, technology, and fleet type
FLTFCLDVBT	Regional fuel consumption by fleet vehicles, by technology
FLTLDVC	Fuel consumption by technology, vehicle, and fleet type
FLTLDVSHR	Percentage of fleet vehicles by fleet type and size
FLTMPG	New fleet vehicle fuel efficiency, by fleet type and vehicle technology type
FLTMPGTOT	Overall fuel efficiency of new fleet cars and light trucks
FLTSAL	Sales to fleets by vehicle and fleet type
FLTSSHR	Percentage of fleet vehicles by fleet type, size class, and vehicle type
FLT_STOCK	Fleet stock, by fleet type, technology, and vintage
FLTTOTMPG	Total fleet mpg
FLTTRAT	Fraction of total truck sales attributed to fleets
FLTTRKSHR	Fleet light truck sales shares by technology
FLTTSHR	Fraction of fleet trucks purchased by a given fleet type
FLTVMTECH	Fleet VMT by technology, vehicle type, and fleet type
FLTVMTHAV	Benchmarked fleet VMT (billion miles)
FLTVMTYR	Annual miles of travel per fleet vehicle
FPMpg	CAFE by size class
FPMpgGrp	CAFE by manufacturer
FPRICE	Fuel price by region
FPrint	Vehicle footprint value
FUELCELL	Incremental fuel cell cost

Variable name	Variable description
FuelCell$kW	Fuel cell cost ($/kW)
FUELSAVE	Expected fuel savings of advanced subsystem technology
GAS	Vehicle fueling configuration index value for gasoline
HAV_battery_kWh	HAV system battery energy capacity (kWh)
hav_init_cost	Initial cost of HAV system ($)
hav_newtech_lag	Lag term for phase out of new technology limits
hav_newtech_lim	Time-dependent HAV technology new technology limit
hav_oper_limit	Disutility of operational domain limits for HAV levels 4a and 4b
hav_sys_cost	Cost of HAV system ($)
HAV_sys_lrn	Time-based HAV system learning curve
HFUEL	Home refueling
HP	Vehicle class base horsepower
LEARN_COST_MULTIPLIER	Technology learning curve parameters
LDVSTK	Vehicle stock, by engine technology fuel type, 1 ... 16, using above mapping
Li_ion_Cost	Lithium ion battery cost ($/kWh)
LIDAR_COEF_A	LiDAR production cost curve coefficient
LIDAR_COEF_B	LiDAR production cost curve coefficient
LiDAR_cost	Cost of LIDAR system ($)
LIDAR_PROD_THRSH	Cumulative production phase thresholds for LiDAR systems
LIDAR_RND_PROD	LiDAR R&D production, 1995–2050
LTDFRFG	Degradation factor for light trucks
LTSHRR	Light truck market shares by class
LTSTK	Light-duty vehicle light truck stock by fuel type and vintage
LTSTKREGN	Light-duty vehicle light truck stock by fuel type, vintage, and region
LUBFD	Transportation lubricant demand
LUGG	Vehicle luggage space
LVMT	Average miles driven by each vintage of light truck
MAINT	Vehicle maintenance cost
MAINTCAR	Car maintenance cost by technology, market class
MAINTTRK	Truck maintenance cost by technology, market class
MANDMKSH	Mandatory engineering note parameters
MAT_A	Cumulative Li-ion materials initial cost parameter
MAT_B	Cumulative Li-ion materials learning rate parameter
MAT_LR	Cumulative Li-ion materials learning rate
MAX_SHARE	Maximum technology market share = MMAX
MAXAGE	Vintage 25 for light-duty vehicles
MFD	Total military use by fuel type
MKT_FUEL	Subsystem technology market share based on efficiency cost effectiveness
MKT_MAX	Technology market share cap
MKT_PEN	Technology market share
MKT_PENF	Technology penetration aggregated over class
MKT_PERF	Subsystem technology market share based on performance cost effectiveness
MMAVAIL	ATV make/model availability
MMAX	Maximum technology market share = MKT_MAX
MPG	New car fuel economy, by size class

Variable name	Variable description
MPGC	New car fuel economy, by engine technology fuel type
MPGFLT	Average fuel efficiency for all light-duty vehicles
MPGFLTSTK	Light-duty fleet vehicle stock fuel economy
MPGT	New light truck fuel economy, by engine technology fuel type
N	Trans variable for curcalyr
NCS	New car sales, by market class and region
NCSTECH	Regional car sales by fuel type
NCSTSC	Car sales by class
NHTSALYR	Last year of NHTSA data
NiMH_Cost	Nickel metal hydride battery cost ($/kWh)
NLTECH	Regional light truck sales by fuel type
NLTS	New light truck sales, by market class and region
NLTSTSC	Light truck sales by class
NUM_SUP	Engineering note counters
NUMTECH	Actual number of input technologies
NVSALES	Total new LDV sales by size class
NVS7SC	Non-fleet, non-commercial sales
OLDFSTK	Old fleet stocks of given types and vintages, transferred to the private sector
OLDFSTKT	Total transferred vehicles from fleets to households
PACK_A	Cumulative Li-ion battery pack initial cost parameter
PACK_B	Cumulative Li-ion battery pack learning rate parameter
PACK_LR	Cumulative Li-ion battery pack learning rate
PASSHRR	Car market shares by class
PASSTK	Light-duty vehicle car stock by fuel type and vintage
PASSTKREGN	Light-duty vehicle car stock by fuel type, vintage, and region
PAYBACK	Payback period
PERFCAP	Vehicle class performance cap
PERFFACT	Vehicle class base performance factor
PERGRP	Manufacture share of sales by size class
PHASESHR	Fraction of total mandatory share by year
PHEV_DOD	PHEV battery depth of discharge
PRICE	Vehicle class base price (low volume)
PRICE_EX	Expected fuel price used in cost effectiveness calculation
PRICEHI	Vehicle class base price (high volume)
PSLOPE	Expected rate of change in future fuel price
PSPR	Average vehicle price
RANGE	Vehicle driving range
RATIO_LN	Used to determine size class shares
REG_COST	CAFE non-compliance fine
REGCOST	CAFE fine
REQ_MKT	Required market share—see engineering notes
REQUIRES	Required engineering note parameters
RSHR	Regional share of total VMT
SALESHR	Car and light truck sales shares by group
SCMPG	On-road stock mpg household cars
SIGN	Positive or negative indicator
SSURV25	Survival rate of cars and light trucks by vintage

Variable name	Variable description
STA_RAT	Refuel stations per vehicle stock
STKCAR	Total stock of non-fleet cars
STKTR	Total stock of non-fleet light trucks
STMPG	On-road stock mpg household light trucks
SUPERSEDES	Supersedes engineering note parameters
SURVFLT	Survival rate of given vintage, light duty fleet vehicles
SYNERGY	Synergy engineering note parameters
SYNR_DEL	Synergy engineering note parameters
TANKSIZE	Vehicle class base fuel tank size
TAXI_DATA_FEE	Monthly data fee for sensor data collection and transfer
TAXI_DISC_R	Discount rate applied for fleet capital investment
TAXI_IDLE_GPH	Fuel consumption per hour during taxi idling
TAXI_IDLE_HRS	Idle hours per month per taxi
TAXI_INSURE	Taxi monthly insurance cost
TAXI_LIVE_FRAC	Fraction of revenue generating miles
TAXI_MAINT_COST	Fixed monthly maintenance cost per taxi vehicle
TAXI_MAINT_MI	Per mile maintenance cost
TAXI_MI_ANN	Average annual mileage per taxi for investment decisions
TAXI_MI_LIFE	Expected taxi lifetime mileage for investment decisions
TAXI_NEWTECH_PD	Parameter for new technology limit phase-out curve
TAXI_NEWTECH_R	Parameter for new technology limit phase-out curve
TAXI_REV_COEF	Taxi lifetime present value (PV) revenue coefficient (per $1,000)
TAXI_REV_PERMI	Revenue per mile, per taxi vehicle
TAXI_SALARY	Taxi driver annual compensation
TAXI_SHIFTS	Average shifts per taxi per day
TECHCOST	First cost of subsystem technology—cost adjustments (economies of scale, etc.) made to this value
TECHNCS	Total new car sales, by engine technology fuel type
TECHNLT	Total new light truck sales, by engine technology fuel type
TFLTECHSTK	Total stock, by technology and fleet type
TMPASMIL	Passenger miles per capita by bus type
TMPGT	Light truck stock mpg
TMPGT_IT	Average fuel efficiency of light trucks by powertrain
TOT_MKT	Total market share of subsystem technology
TOTMICT	Total miles driven by cars
TOTMITT	Total miles driven by light trucks
TTLZEV	Total (percentage) mandated ZEV sales
TTMPGSTK	Truck fuel economy
USEDCAP	Fraction of vehicle class performance cap used
VAL_PERF	Value of performance improvement to consumer
VALUEPERF	Vehicle class base performance value
VMT	Annual VMT by vintage
VRNG	Vehicle range
VSPLDV	Light-duty vehicle shares of each of the 16 vehicle technologies
VT	Vehicle type, car and light truck
WEIGHT	Vehicle class base curb weight
WGT	Light-duty vehicle weight
X21	ATV NMLM level 2, vehicle price

Variable name	Variable description
X210	ATV calibration coefficients
X211	ATV calibration coefficients'
X212	ATV calibration coefficients
X22	ATV NMLM level 2, fuel cost
X23	ATV NMLM level 2, range
X24	ATV NMLM level 2, battery replacement
X25	ATV NMLM level 2, acceleration
X26	ATV NMLM level 2, EV home refueling
X27	ATV NMLM level 2, maintenance cost
X28	ATV NMLM level 2, luggage space
X29	ATV NMLM level 2, make/model availability
X31	ATV NMLM level 3, multi-fuel generation cost
ZEV	Total (percentage) mandated electric vehicles
ZFCV	Total (percentage) mandated hydrogen fuel cell vehicles
LDV Submodule	
LDV Stock Accounting Component	
PVMT	Car VMT per vintage
LDV VMT Stock Component	
COSTMI	Fuel cost of driving one mile (2004 cents per gallon)
EMP_RATE	Employment rate
LICDRIVER	Licensed drivers by region, gender, and age cohorts
VMTHH	Total household LDV VMT
VMTEER	Sum of regional VMT
VMTLD	VMT per licensed driver
VMTLDR	Regional vehicle miles traveled per licensed driver
New LDV	
CARSHRT	Non-normalized projected car share
Air Demand Submodule	
Aircraft Travel Demand	
ASM	Demand for available seat-miles, by aircraft body type, domestic/international, and region
BELLY_RPM_EQ	Air cargo demand filled by passenger aircraft belly capacity, converted to RPMs
BETA1_RPM	Gdp per capita elasticity of RPM per capita by region;
BETA1_RTM	Gdp coefficient for RTM by region
CARGOAC_RTM_DMD	Total payload demand for dedicated cargo aircraft by aircraft body type, region
GDP_PC	$WLD\_GDP_{iwreg,year}$ / $WLD\_POP_{iwreg,year}$
INTERCEPT_RPM	Intercept per capita RPM by region
INTERCEPT_RTM	Intercept RTM by region
LOAD_FACTOR	Exogenous load factor by aircraft type and region
PASS_WEIGHT	Average weight per passenger

Variable name	Variable description
PASSAC_RPM_DMD	Total payload demand for passenger aircraft by aircraft body type, region
PCT_BELLY_PLOAD	Percent of passenger aircraft payload that is freight
PCT_BELLY_FRT	Percent of total freight that is belly freight
RPM	Revenue passenger-miles by region, aircraft type
RPMT	Total RPMs by region
RPMT_PC	RPM per capita travel by region
RTM	Total revenue ton-miles, by region
RTM_TYP	Revenue ton-miles by region, by aircraft type
SHR_RTM	Distribution of RTMs by aircraft type, region
SHR_RPM_BODY	Distribution of RPMs by aircraft type by region
Aircraft Efficiency	
AIR_MGMT_ADJ	Additional distance flown (percent) due to flight routing, procedural separation rules, and weather
ASMPG_AVG_AGE	Fully-loaded passenger aircraft ASM per gallon, by region, body type, and domestic/international
ASMPG_NEW_TYP	Active aircraft sales seat-miles per gallon by body type
ASMPG_STK_TYP	Active aircraft stock seat-miles per gallon by body type
ASMPG_VINT	Fully-loaded passenger aircraft ASM per gallon, by region, vintage, body type, and domestic/international, in 2020
GPTMX_PASS_VINT	Fully-loaded passenger aircraft fuel consumption per ton-mile, by region, vintage, and body type, in 2020. X={D: Domestic, I:International}
RPMPG	Fuel economy of passenger aircraft
Aircraft Stocks	
CARGOAC_NEEDED	Aircraft supply deficit needed to meet dedicated cargo RTM demand
PASSAC_NEEDED	Aircraft supply deficit needed to meet passenger travel demand
STKCARGO_ACTIVE	Stock of surviving dedicated cargo aircraft by aircraft type, region, and given age
STKPASS_ACTIVE	Stock of surviving passenger aircraft by aircraft type, region, age
SURVAC	Survival rate of aircraft of a given age
Freight Transportation Submodule	
Rail Freight Model	
DISCRT	Discount rate applied by freight railroads
FREFF	Freight rail efficiency (1,000 Btu/ton-mile)
PAYBK	Payback period demanded by freight railroads
RAIL_FUEL_SHR	Historic rail fuel shares
RTM_OUTPUT	Freight rail ton-miles per dollar industrial output
RTMTT	Freight rail travel (billion ton-miles)
TQFRAILT	Total energy demand
Waterborne Freight Component	
Domestic Waterborne	
ANN_DECLINE	Annual rate of ton-mile per dollar output decline
DOMSHIP_FUEL_SHR	Domestic shipping fuel share

Variable name	Variable description
DSEFF	Domestic marine vessel efficiency
DSTM_OUTPUT	Domestic marine ton-miles per dollar industrial output
STMTT	Domestic marine travel (billion ton-miles)
International Waterborne	
GROSST	Gross tons shipped
INTSHIP_FUEL_SHR	International shipping fuel share
ISFD	Energy demand by fuel type (1-diesel, 2-residual,3-CNG,4-LNG)
ISFDT	Total international shipping energy demand in year
TQISHIPR	Regional energy demand by fuel type
Miscellaneous Energy Demand Submodule	
Transit Rail Submodule	
TR_CAV_ADJ	Transit rail HAV adjustment factor to account for HAV taxi impact on transit rail travel demand
TRED	Transit rail energy demand by census division
Commuter Rail Submodule	
CR_CAV_ADJ	Commuter rail HAV adjustment factor to account for HAV taxi impact on commuter rail travel demand
CREDE	Commuter rail electricity demand by census division
Intercity Rail Submodule	
IREDER	Intercity rail electricity demand by census division
Bus Mass Transit	
BUSSYSEF	Bus system efficiency by mode, in Btu per passenger
QMODFSHR	Bus fuel shares
TB_CAV_ADJ	Transit bus HAV adjustment factor to account for HAV taxi impact on transit bus travel demand
TMEFF	Bus efficiency (Btu/passenger mile)
TMOD	Bus passenger miles
Recreational Boating Demand Component	
RBEDPC	Energy demand per capita by fuel type
RECFD	Energy demand by fuel type (gasoline, diesel)
Miscellaneous Transportation Energy Variables	
QLUBR	Lubricant energy demand by region
QMILTR	Military energy demand by fuel by region
QMTBR	Bus energy demand by fuel by region
QMTRR	Passenger rail energy demand by fuel by region
QRECR	Recreational boat energy demand by region
Car light truck sales shares	
CARSHARE	Projected car share of LDV sales

Variable name	Variable description
DUMM	Car share dummy
Variables in TRANFRT Submodule	
AGE	Number of vintages for truck stocks 1–34
CAFE19	Number of truck classes with CAFE breakout for Classes 7–8 tractors
CUR	Current year subscript (= 2)
CURCALYR	Current model year
FLT	Fleet vehicles: 1—non-fleet, 2—fleet
FUEL	Number of powertrain types: 1—diesel, 2—gasoline, 3—LPG, 4—CNG/LNG, 5—flex-fuel, 6—electric, 7—PHEV diesel, 8—PHEV gasoline, 9—hydrogen fuel cell
LAG	Lag year subscript (= 1)
SC	Number of truck market Classes: 1—Medium Light, Class 3, 2—Medium Heavy, Classes 4–6, 3—Heavy, Classes 7–8, 4—commercial light truck, class 2b
SEC	Number of industrial sectors
TECH	Technologies available in Phase 1 of the heavy-duty CAFE and greenhouse gas emission standards
TECHP2	Technologies available in Phase 2 of the heavy-duty CAFE and greenhouse gas emission standards
VOC	Vocational truck: 1—non-vocational, 2—vocational
Subscripts	
IAGE	Index for vintage
IAGR	Index for population age group
IATV	Index for alternative fuel vehicle powertrain types (subset of ildv)
ICAFE19	Index for size classes for fuel consumption standard
ICL	Index for vehicle market/size class
IFLEET	Index for fleet
IFUEL	Index for light-duty vehicle highway fuel type (8)
IFUEL11	Index for SEDS fuel type (11)
IGP	Index for passenger vehicle manufacturing group
IGVW	Index for vehicle weight classes: 1—blank, 2—class 2b, 3—class 3, 4—class 4, 5—class 5, 6—class 6, 7—class 7, 8—class 8
ILDV	Index for vehicle powertrain type
IMF	Index for gender (1 = male, 2 = female)
IOWN	Index for vehicle owner type: 1—household, 2—business, 3—government, 4—utility, 5—taxi)
IP	Index for payback periods
IREGN	Index for census divisions
ISC	Index for aggregated vehicle weight class
ISEC	Index for industrial sector
ITC	Index for light duty vehicle technology type (88 technologies)
ITECH	Index for technology
ITR	Index for NEMS iteration
IVOC	Index for vocation
IVTYP	Index for passenger vehicle type (1 = car, 2 = light truck)
IWREG	Index for world regions (13)
IYR	Index for year

Variable name	Variable description
Mapping	
ISC19	Map 19 CAFE classes back to 4 size classes (SC)
Variables	
ADVSHR	Superseding effect, equal to the market share of the superseding technology
ANN_$_SAVINGS_CNG_regn	Annual fuel savings for CNG/LNG vehicles compared with diesel or gasoline vehicles
ANNVMT	Average annual VMT per vehicle by four reporting classes
ANNVMT_19	Average VMT by vintage by 19 size classes
AVG_FUEL_$	Average price of fuel over three years
AVG_FUEL_$_REGN	Average price of fuel over three years by region
BASEMPG_p1, BASEMPG_p2	Fuel economy of new freight trucks with no fuel-saving technologies for Phase 1 and Phase 2 of the HDV CAFE and GHG standards, respectively
BFSHXG	Base year (2010) market share of each fuel
BUY_CNG_regn	Share of CNG vehicles brought by fleet, size class, and region
CSTDVXG	Market penetration curve parameter for diesel
CSTDXG	Market penetration curve parameter for diesel
CYAFVXG	Logistic market penetration curve parameter
DCOST	Fuel cost per mile of diesel relative to alternative fuel vehicles
DISCRTXG	Discount rate
EFSHXG	Final market share of each fuel
FCOST_regn	Fuel cost of driving a truck by fuel type in dollars per mile
FLEETSHR	Percentage of HDV in fleet use by size class
FUEL_SHR_regn	Fuel shares for new trucks by size class, fleet/non-fleet by region
FUELBTUR	Total truck fuel consumption in trillion Btu by region
FUELDMDR	Freight truck fuel consumption by region
HDV_MPG	Fuel economy size class, vintage, and fuel in mpg miles/cubic CNG
HRATE	Heat rate by fuel type
MIDYR	Logistic market penetration curve parameter representing *halfway point* to maximum market penetration
MPGEFF_p1, MPGEFF_p2	Total effect of all fuel-saving technology on new truck fuel efficiency for Phase 1 and Phase 2 of the HDC CAFE and GHG standards, respectively
NEW_MPG_19	New truck fuel economy by 19 size classes
NEWCLS46	Share of truck sales in Class 4–8 that are Class 4–6, by year
NEWTRUCKS_regn	Sales of new trucks by market class, region, and fleet/non-fleet plus total
NPV_ADS_regn	Net present value of the fuel savings from using CNG/LNG
P	Market penetration by year
PAYBACK	Payback period for each technology by CAFE size class and fuel
PRAFDFXG	Parameter: variation in AFV market share because of different fuel prices
PREFF_p1, PREFF_P2	Market penetration price sensitivity multiplier for Phase 1 and Phase 2 of the HDC CAFE and GHG standards, respectively
SCRAP_RATE	Truck scrappage rate
SLOPE	Logistic market penetration curve parameter
TECHADJSHR_p1, TECHADJSHR_p2	Difference between the current tech share and the base tech share for Phase 1 and Phase 2 of the HDC CAFE and GHG standards, respectively

Variable name	Variable description
TECHBASE_p1, TECHBASE_p2	Base year market penetration parameter for Phase 1 and Phase 2 of the HDC CAFE and GHG standards, respectively
TECHEFF_p1, TECHEFF_p2	Percentage improvement in fuel economy by technology for Phase 1 and Phase 2 of the HDC CAFE and GHG standards, respectively
TECHMAX, TECHMAX_p2	Maximum market share for Phase 1 and Phase 2 of the HDC CAFE and GHG standards, respectively
TECHMID, TECHMID_p2	Number of years to 50% penetration for Phase 1 and Phase 2 of the HDC CAFE and GHG standards, respectively
TECHPENYR_p1, TECHPENYR_p2	Year that a technology becomes available for Phase 1 and Phase 2 of the HDC CAFE and GHG standards, respectively
TECHSHAPE, TECHSHAPE_p2	Market penetration shape constant for Phase 1 and Phase 2 of the HDC CAFE and GHG standards, respectively
TECHSHARE_p1, TECHSHARE_p2	TECHSHR_pX if the technology penetration is less than the base year technology penetration or TECHBASE_pX if the technology is greater than or equal to the base share penetration for Phase 1 and Phase 2 of the HDC CAFE and GHG standards, respectively
TECHSHR_p1, TECHSHR_p2	Market share of fuel-saving technology, by market size class and fuel type in Phase 1 and Phase 2 of the HDC CAFE and GHG standards, respectively
TECHVAR	Fuel price sensitivity parameter
TEMP_BTU_p1, TEMP_BTU_p2	Average annual truck fuel usage for Phase 1 and Phase 2 of the HDC CAFE and GHG standards, respectively
TEMPCLS12A	The total of Class 1–2 trucks that are considered light-duty vehicles
TFFXGRT	Exogenous percentage of trucks/vintage transferred from fleet to non-fleet
TRGSHXG	Logistics parameter: halfway to maximum market penetration
TRIGGER_PRICE_p1, TRIGGER_PRICE_P2	Trigger price when technology becomes economical
TRK_19_regn	Existing stock of trucks by 19 size classes and regions
TTONMI	Freight truck ton-miles by industrial sector and census division
TVMT	Freight truck vehicle miles traveled, by industrial sector and census division
VEH_SHR	Percentage share of vehicle fleet and size class
VMT_VEH	VMT per vehicle by fleet and size class for Phase 1 and Phase 2 of the HDC CAFE and GHG standards, respectively
VMTADJR	Aggregate VMT adjustment factor
VMTFLTR	HDV VMT

Appendix E. Bibliography

The TDM is documented along with a series of other NEMS model documentation reports at www.eia.doe.gov/reports/. Most of the references in the Bibliography refer to the model documentation reports and their publication numbers or other EIA reports that provide data inputs to the model. The references listed below are available (or will soon be available) and reflect changes incorporated for AEO2022.

Annual Energy Outlook 2022, DOE/EIA-0383(2022) (February 2022).