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World Energy Projection System Plus (WEPS+): Transportation Module

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1. Introduction

Purpose of this report

The Transportation Sector Model (generally referred to as the International Transportation Energy Demand Determinants model, or ITEDD) of the World Energy Projection System Plus (WEPS+) is a computer-based energy demand modeling system of the world's transportation sector at a regional level. This report describes the version of ITEDD that was used to produce the transportation sector projections published in the *International Energy Outlook 2019* (IEO2019). ITEDD is one of many components of the WEPS+ energy modeling system, but ITEDD can also be run as a separate, individual model. The WEPS+ is a modular system, consisting of a number of separate energy models that are joined together through the overall system model to communicate and work with each other. These models are each developed independently but are designed with well-defined protocols for system communication and interactivity. The WEPS+ modeling system uses a common and shared database (the *restart file*) that allows all the models to communicate with each other when they are run in sequence over a number of iterations. The overall WEPS+ uses an iterative solution technique that allows for convergence of consumption and price to a simultaneous equilibrium solution.

This report documents the objectives, analytical approach, and development of ITEDD. It also catalogues and describes critical assumptions, computational methodology, parameter estimation techniques, and model source code. This document serves three purposes. First, it is a reference document providing a detailed description for model analysts, users, and the public. Second, it meets the legal requirement of the U.S. Energy Information Administration (EIA) to provide adequate documentation in support of its models (Public Law 93-275, section 57.b.1). Third, it facilitates continuity in model development by providing documentation from which energy analysts can undertake and analyze their own model enhancements, data updates, and parameter refinements for future projects.

Model summary

The WEPS+ ITEDD for the IEO2019 projects the amount of energy that is consumed in providing passenger and freight transportation services. This projection includes personal household on-road transportation in light-duty vehicles, which is projected by ITEDD rather than by the residential consumption model. This projection also includes fuel consumed by natural gas pipelines and small amounts of lubricants and waxes. The model projects transportation consumption for 10 energy sources in each of the 16 WEPS+ regions to 2050. Underlying the consumption projections are projections of energy service demand and energy efficiency by travel mode. Service demand is measured in passenger-miles for passenger services and in ton-miles for freight services. The energy efficiency is measured as the passenger-kilometers per British thermal unit (Btu, a measure of energy consumption) for passenger services except for light-duty vehicles, where miles per gallon (mpg) is used. Efficiencies are reported in ton-miles per Btu for freight services.

ITEDD categorizes transportation services for passengers and freight in four modes: road, rail, water, and air. These modes are also disaggregated into submodes (Table 1. Transportation submodes included in the ITEDD model). ITEDD projects service demand by fuel and service based on multiple demand determinants. Service demand fuel shares are projected for most modes. The service energy efficiency projections by service and fuel are endogenous to the model. Total consumption by fuel and service is a function of demand and efficiency.

Table 1. Transportation submodes included in the ITEDD Model

Transportation modes	Transportation submodes
1. Road	1a. Light-duty vehicles: private, commercial
	1b. Two- and three-wheel vehicles
	1c. Buses
	1d. Heavy freight trucks
	1e. Medium-duty trucks
	1e. Light-duty trucks
2. Rail	2a. Passenger
	2b. Freight coal (placeholder)
	2c. Freight other (currently, *all* freight rail)
3. Water	3a. Domestic
	3b. International
4. Air	4a. Passenger air (currently, *all* air)
	4b. Freight air (placeholder)

ITEDD obtains macroeconomic and price projections from the WEPS+ *restart file*. These projections have been previously calculated in the WEPS+ macroeconomic model and by various transformation and supply models. The transportation model projects transportation energy consumption for a variety of energy sources and outputs them to the restart file for other models to use.

Model archival citation

This documentation refers to the WEPS+ ITEDD as archived for IEO2019.

Model contact

John Maples
U.S. Energy Information Administration
Transportation Energy Consumption & Efficiency Analysis Team
EI-32/Forrestal Building
U.S. Department of Energy
1000 Independence Avenue SW
Washington, DC 20585
Telephone: (202) 586-1757
Email: John.Maples@eia.gov

Organization of this report

Chapter 2 of this report discusses the purpose of ITEDD, the objectives and the analytical issues it addresses, the general types of activities and relationships it embodies, the primary input and output variables, and the relationship of the model to the other models in WEPS+. Chapter 3 of the report describes the rationale behind the ITEDD design, providing insights into further assumptions used in the model. Chapter 4 describes the model structure in more detail and includes flowcharts, variables, and equations.

The appendixes to this report provide supporting documentation for input data and parameter files. Appendix A provides the model abstract. Appendix B lists and defines the input data used to generate parameter estimates and endogenous projections, along with relevant outputs. Appendix C is a bibliography of reference materials used in the model development process. Appendix D discusses input data sources and data quality.

2. Model Purpose

Model objectives

The WEPS+ International Transportation Energy Demand Determinants model (ITEDD) has three primary objectives. First, the model generates disaggregated projections of energy demand in the transportation sector for the period of 2016 through 2050 by fuel type, international region, mode/submode, and service category. Second, the model is an analysis tool that can be used to assess the impact of policies and other changes in transportation modes through their service demands and service intensities. Third, as an integral component of WEPS+, the model provides consumption inputs to the various transformation and supply models of WEPS+ and contributes to the calculation of the overall energy supply and demand balance. The consumption inputs are also used by the Greenhouse Gases Model to calculate energy-related carbon dioxide emissions. ITEDD calculates energy consumption for transportation as the product of two underlying components: energy service demand and energy efficiency.

As part of WEPS+, ITEDD provides projections for the 16 WEPS+ world regions. These regions consist of countries and country groupings within the broad divide of Organization for Economic Cooperation and Development (OECD) and non-OECD countries. The 16 regions are shown in Table 2. Regional coverage of the World Energy Projection System Plus Model.

Table 2. Regional coverage of the World Energy Projection System Plus Model

OECD regions	Non-OECD regions
United States	Russia
Canada	Other Non-OECD Europe and Eurasia
Mexico/Chile	China
OECD Europe	India
Japan	Other Non-OECD Asia
Australia/New Zealand	Middle East
South Korea	Africa
	Brazil
	Other Central and South America

Model inputs and outputs

Inputs

As part of WEPS+, ITEDD uses macroeconomic and price projections that are input from the WEPS+ restart file. These projections are calculated before the execution of ITEDD in the WEPS+ Macroeconomic Model and are calculated by various transformation and supply models (see Table 3. WEPS+ models that provide input to ITEDD through the restart file).

Table 3. WEPS+ models that provide input to ITEDD through the restart file

Transportation Model input	Source
Gross domestic product	Macroeconomic Model
Population	Macroeconomic Model
Industrial output by commodity type	Macroeconomic Model
U.S. disposable income	Macroeconomic Model
Merchandise exports	Macroeconomic Model
Transportation motor gasoline retail price	Refinery Model
Transportation distillate (diesel) retail price	Refinery Model
Transportation residual retail price	Refinery Model
Transportation liquefied petroleum gas retail price	Refinery Model
Transportation jet fuel retail price	Refinery Model
Transportation natural gas retail price	Natural Gas Model
Transportation coal retail price	Coal Model
Transportation electricity retail price	World Electricity Model
Transportation hydrogen retail price	Natural Gas Model

A number of exogenous data series are also imported into ITEDD from the three input files shown in Table 4. Major exogenous ITEDD Model input data series.

Table 4. Major exogenous ITEDD Model input data series

Source input file	Model input
TranBase.xml	Coefficients and historical data for passenger travel demand forecast
	Coefficients and historical data for passenger light-duty vehicles
	Coefficients and historical data for passenger two- and three-wheel vehicles, buses, and rail
	Coefficients and historical data for freight (light, medium, and heavy trucks, rail, and domestic marine)
	Coefficients and historical data for international marine freight
	Historical on-road vehicle sales for 1980–2016
	Historical on-road vehicle stock for 1980–2016
	Historical vehicle-kilometers traveled per light-duty vehicle for 1980–2016
	Historical fuel efficiency for on-road vehicles 1980–2016
TranBXML.xml	Region names
	Fuel names
	Service names
TranMisc.xml	Switches for reporting, calibration to *Short-Term Energy Outlook* (STEO) projections
Trnair.xml	Coefficients and historical data for air travel

Outputs

As part of WEPS+, ITEDD projects energy consumption for 10 energy sources that are mapped to the 13 fuel types used by the rest of WEPS+ and writes these projections to the WEPS+ restart file for use by the other models. Table 5 presents a list of these energy source outputs and the models that access them.

Table 5. ITEDD Model outputs and the WEPS+ models that use them

Transportation Model output	Destination
Motor gasoline consumption	Petroleum and Refinery Models
Distillate (diesel) consumption	Petroleum and Refinery Models
Residual consumption	Petroleum and Refinery Models
Liquefied petroleum gas consumption	Petroleum and Refinery Models
Jet fuel consumption	Petroleum and Refinery Models
Sequestered petroleum consumption	Petroleum and Refinery Models
Other petroleum consumption	Petroleum and Refinery Models
Natural gas consumption	Natural Gas Model
Coal consumption	Coal Model
Electricity consumption	World Electricity Model
Ethanol (E85) consumption	Petroleum and Refinery Models
Other biofuels consumption	Petroleum and Refinery Models
Hydrogen consumption	Natural Gas Model

In the course of computing the overall demand projections, ITEDD also projects a variety of the components of demand—at a high level of detail—for each of the WEPS+ regions. Table 6 provides a summary of these output data series.

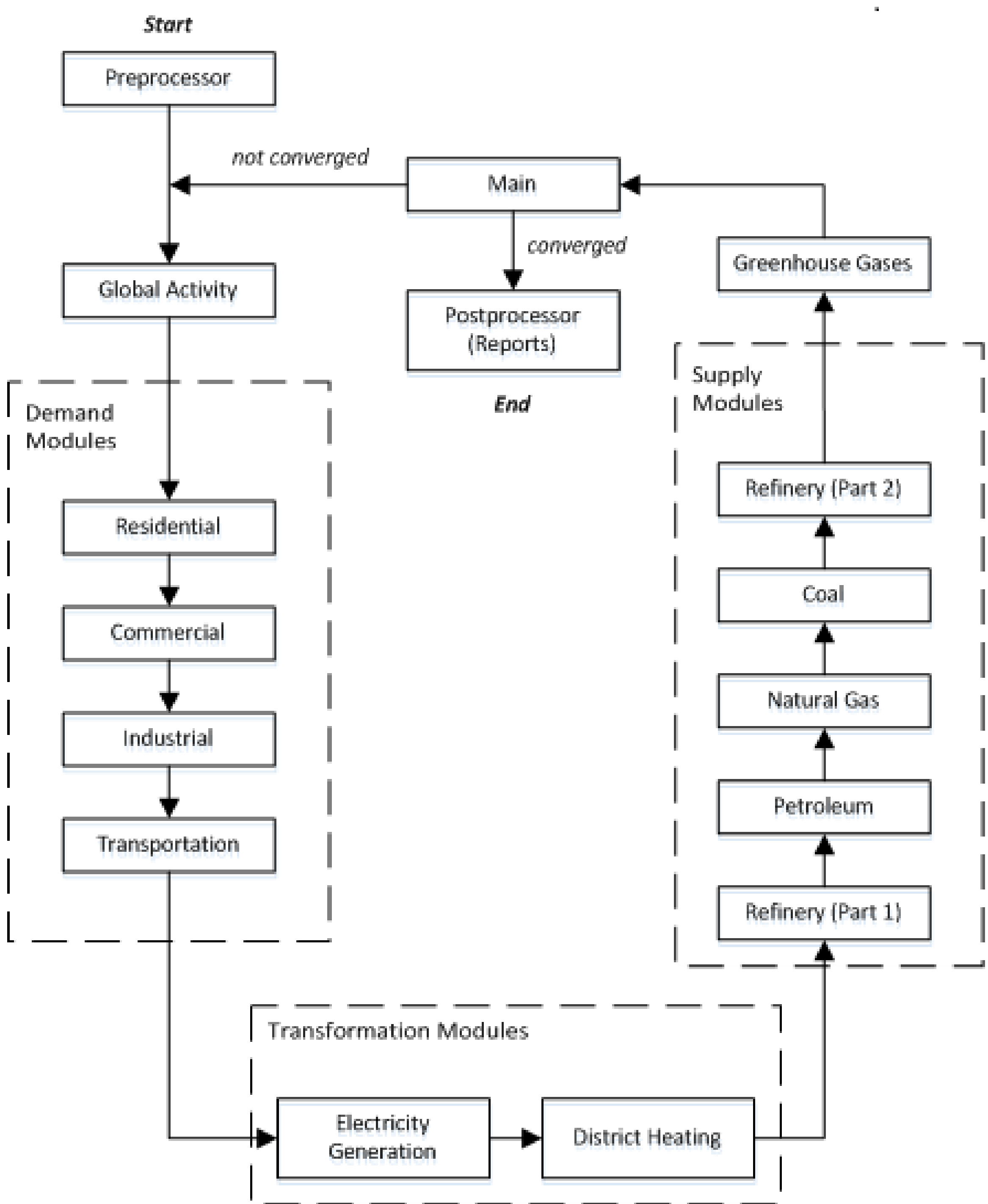
Table 6. Detailed ITEDD output data series by passenger and freight categories

Category	Model output
Passenger	Service demand in passenger-miles by submode, fuel, and region
	Energy efficiency in passenger-miles per British thermal unit (Btu) by submode (except light-duty vehicle, or LDV), fuel, and region
	LDV sales and stocks by technology type, new LDV fuel economy, average LDV fuel economy
Freight	Service demand in ton-miles by submode, fuel, and region
	Energy efficiency in ton-miles per Btu by submode, fuel, and region

Relationship to other models

ITEDD is an integral component of WEPS+ and depends on other models in the system for some of its key inputs (Figure 1. World Energy Projection System Plus (WEPS+) Model sequence). In turn, ITEDD provides projections of transportation energy consumption, on which other models in the system depend (see Figure 1. World Energy Projection System Plus (WEPS+) Model sequence). A summary description of the models, flows, and mechanics of WEPS+ used for the *International Energy Outlook 2019* (IEO2019) report is available in a separate *Overview* document.

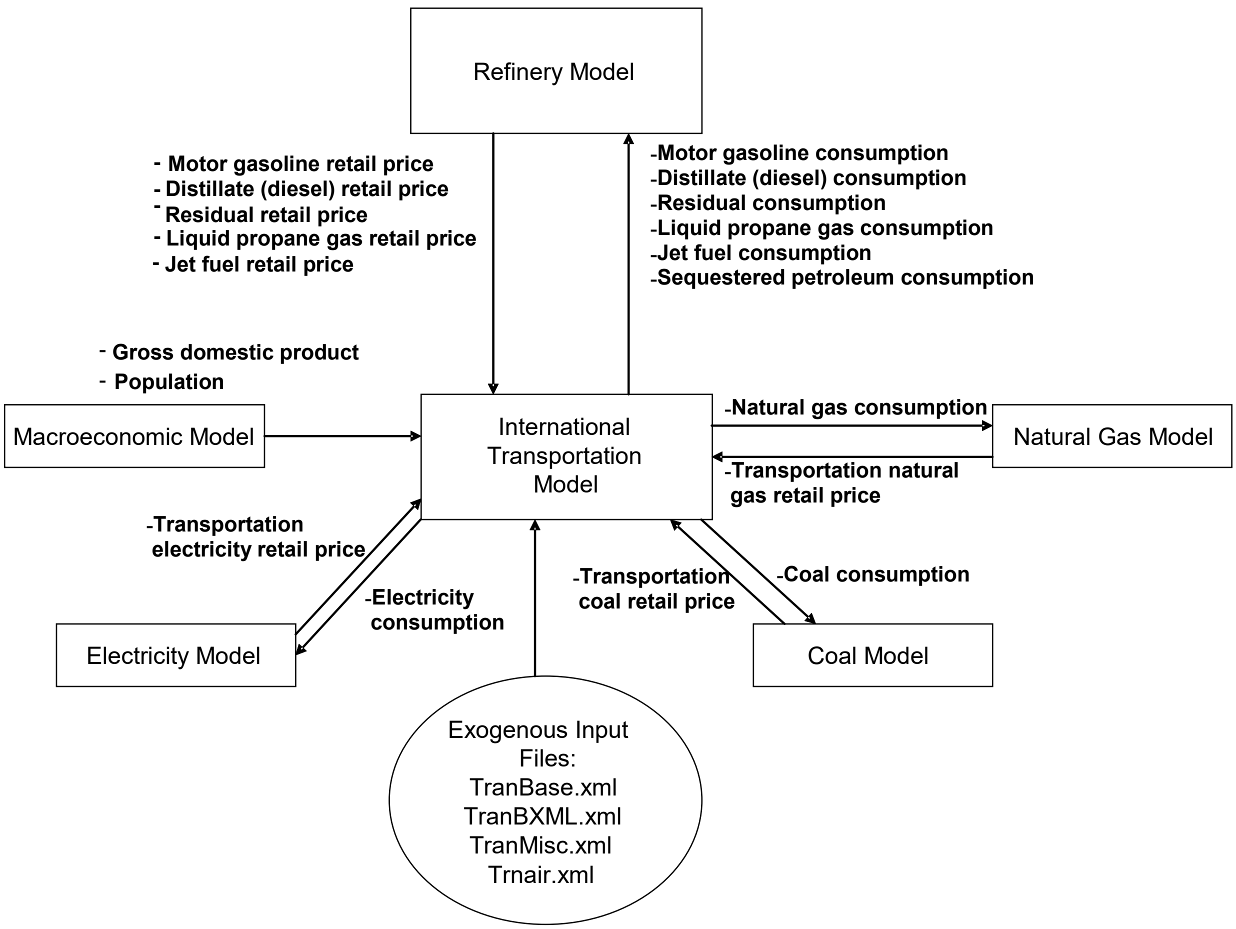
Figure 1. World Energy Projection System Plus (WEPS+) Model sequence



Through the WEPS+ restart file, ITEDD receives gross domestic product (GDP) and population projections from the Global Activity Model, as well as a variety of transportation retail price projections from various supply models (Figure 2. Relationship between the ITEDD Model and other WEPS+ models). In turn, ITEDD provides consumption projections, through the system, back to the supply models.

Although ITEDD is an integral part of WEPS+, it can also be easily run as a stand-alone model outside of the system. In stand-alone mode, ITEDD uses macroeconomic and price projection inputs from the WEPS+ restart file created in a previous full-system run.

Figure 2. Relationship between the ITEDD Model and other WEPS+ models



3. Model Rationale

Theoretical approach

The International Transportation Energy Demand Determinants (ITEDD) Model provides a framework for projecting the energy consumed by global travel services. Toward that purpose, ITEDD looks at energy consumption as the product of two underlying components:

- Energy service demand (the amount of travel provided)
- Energy efficiency

In addition, a vintage stock model is used for light-duty vehicles. For most of the passenger modes and submodes, service demand is measured as passenger-kilometers, and the energy efficiency is measured as either passenger-kilometers per Btu or Btu per vehicle-kilometer. In the latter case, as for two- and three-wheel vehicles and buses, a passenger load factor is used to convert passenger-kilometers to vehicle-kilometers. For light-duty vehicles, the model calculates both the demand for travel in terms of passenger-kilometers and expected travel based on the stock of vehicles. Fuel economy is projected for new vehicles, and the average fuel economy of the stock is calculated based on data on the remaining stock from previous years. For freight modes and submodes, the service demand is measured as ton-miles, and the energy efficiency is measured as miles per gallon converted to Btu per ton-mile using load factor assumptions. ITEDD then estimates transportation energy consumption as a function of the service demand and the energy efficiency.

ITEDD projects annual transportation energy consumption for each of the 16 WEPS+ regions to 2050. To enhance readability, much of the discussion in this report omits the reference to regions and projection years. ITEDD categorizes transportation services for passengers and freight in four modes: road, rail, water, and air (Table 7. Transportation services in the ITEDD Model). Pipeline natural gas is part of the transportation sector, but projections of pipeline natural gas are included in the WEPS+ Natural Gas Model and not in ITEDD. ITEDD currently considers 10 transportation services, although the structure includes two additional categories—one for air freight and one for coal rail freight—that could be incorporated should additional data become available.

Table 7. Transportation services in the ITEDD Model

<table>
<tr><th>Mode</th><th>Units</th><th>Road</th><th>Rail</th><th>Air</th><th>Water</th></tr>
<tr><td rowspan="3">Passenger service</td><td rowspan="3">Passenger-miles</td><td>Light-duty vehicle (car, sport utility vehicle)</td><td rowspan="3">Generic</td><td rowspan="6">Domestic and international</td><td rowspan="3"></td></tr>
<tr><td>Two- and three-wheel vehicle</td></tr>
<tr><td>Bus</td></tr>
<tr><td rowspan="3">Freight service</td><td rowspan="3">Ton-miles</td><td>Heavy-duty truck</td><td rowspan="3">Generic</td><td>Domestic</td></tr>
<tr><td>Medium-duty truck</td><td rowspan="2">International</td></tr>
<tr><td>Light-duty truck</td></tr>
</table>

Model assumptions

As noted above, ITEDD projects the amount of travel provided and energy efficiency of that travel. This projection reflects the overall assumption that the total amount of energy consumed by transportation services is determined by the total amount of service provided (passenger-miles or ton-miles) along with the average efficiency of the service.

Light-duty vehicle consumption is treated differently than the other modes because a stock model is used to track the average efficiency of vehicles over time as a function of the fuel economy of new vehicle purchases each year. Passenger travel is projected and converted to vehicle-kilometers using an explicit load factor.

ITEDD assumes that changes in total service demand for both passenger and freight services are related to multiple demand determinants: changes in economic activity (measured by gross domestic product [GDP], industrial outputs, and/or population), energy prices, and many other drivers. The measure of economic activity varies by service and region, as described in subsequent sections.

Although the words *demand* and *consumption* are often used interchangeably, they refer to different but related concepts. Demand is the behavioral result of real-life conditions of income and prices, but it can often be partly unrealized because of other constraints. Consumption is the amount of the demand that is realized. A consumer, for example, may demand one level of passenger-kilometers given the level of income and fuel prices, but because the roads are heavily congested and/or full of potholes, the consumer may actually use less. In this document, the terms *demand* and *consumption* are interchangeable, but the concept of *unmet demand* is used as warranted.

4. Model Structure

Structural overview

The main purpose of the International Transportation Energy Demand Determinants (ITEDD) Model is to estimate annual transportation sector energy consumption by region, service, and fuel type to 2050. The transportation energy consumption calculations are based on travel demand and fuel efficiency estimates. Consumption is estimated for each of the 16 WEPS+ regions for 10 different services and 13 energy sources.

The basic structure of the ITEDD model is illustrated in Figure 3, located at the end of this Structural Overview section. A call from the WEPS+ interface to ITEDD initiates importation of the supporting information needed (such as energy prices and macroeconomic variables) to complete the projection calculations. The model then executes the Tran subroutine, the major component of the model, which calls a series of subroutines that perform all submodule computations. The Tran subroutine then exports all projections to the restart file for use by other WEPS+ models.

The first step of the Tran subroutine is to call the Tinput subroutine. Tinput imports data from three exogenous data sources, the TranMisc.xml, TranBXML.xml, and TranBase.xml data files. TranMisc.xml contains various switches (for reporting; for *Short-Term Energy Outlook*, or STEO, calibration; and for other routine functions). TranBXML.xml includes basic model identifiers (such as region names, fuel names, service names) as well as indexes that are used throughout the computations to map services with transport modes (road, air, rail, and water) and purposes (passenger and freight). TranBase.xml includes the following:

- Coefficients for passenger travel demand projection
- Coefficients for passenger light-duty vehicles (LDVs)
- Coefficients for passenger two- and three-wheel vehicles, buses, and rail
- Coefficients for freight (light, medium, and heavy trucks, rail, and domestic marine)
- Coefficients for international marine freight
- Historical vehicle sales, stocks, vehicle-kilometers traveled per vehicle, and fuel efficiency for 1980–2016

Many of the exogenous data elements provided in TranBase.xml are only provided in five-year increments. The Tinput subroutine therefore converts these data, after importation, to annual data series by interpolating between years to 2050.

After the Tinput subroutine has executed, the Tran subroutine calls the Tranair Submodule (passenger air), Passmdl (passenger LDV, two- and three-wheel vehicles, buses, and rail), Freightmdl (freight truck, rail, and domestic marine), IntlMarinemdl (International Marine Submodule), and Pass_Fr_Submodule (sums consumption and writes a report) subroutines.

Several computations are made using the historical data series to prepare the data for the projection calculations. For each WEPS+ region in each historical year, the Tran subroutine performs the following preliminary calculations:

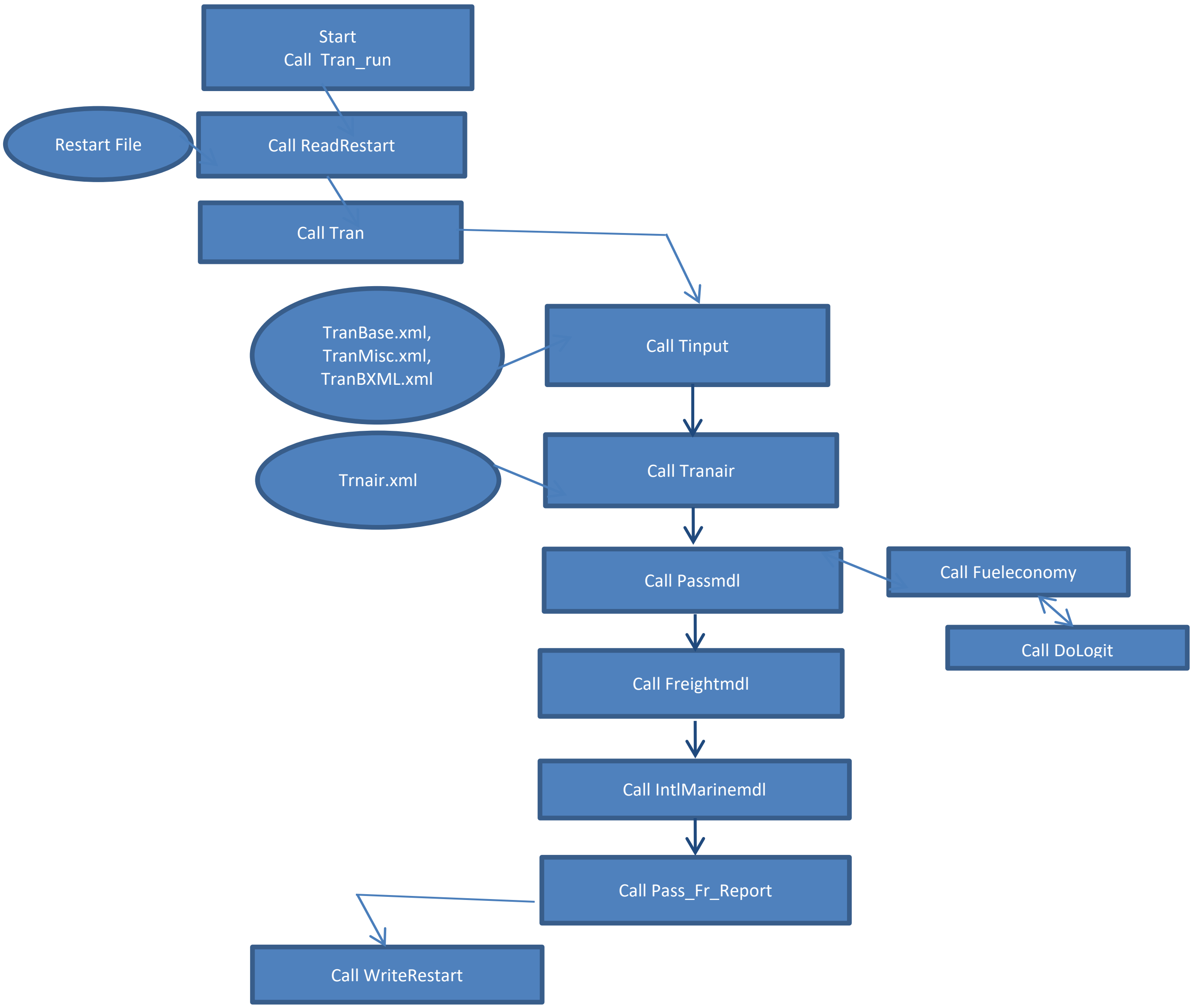
- Adjusts historical price data by adding any carbon price increment to the fuel prices provided through the restart file

- Aggregates the historical residual, sequestered petroleum, and *other* petroleum consumption estimates and determines their historical shares
- Subtracts pipeline natural gas from total transportation natural gas use
- Calculates historical shares for the 10 major fuels

Once the historical data series are ready, the Tran subroutine calls other subroutines to project passenger and freight energy consumption by region, fuel, and service. Finally, the Tran subroutine calculates total liquids consumption by region and calibrates the projections to regional STEO projections through 2021.

The Tran subroutine generates several output files and returns to the main ITEDD routine, which then executes the WriteRestart subroutine. The WriteRestart subroutine provides projections to the restart file for use by other WEPS+ models. These output data series include projections of regional transportation energy use by fuel.

Figure 3. Flowchart for the ITEDD Model



Organization of ITEDD

The ITEDD Model of WEPS+ projects energy used for passenger and freight transportation services. For each of the 16 WEPS+ regions, ITEDD projects annual transportation energy consumption through 2050 for 10 energy sources that are mapped to the 13 fuel types used by the rest of WEPS+.

Fuel types

Table 8 shows how the 10 ITEDD fuels are mapped to the 13 WEPS+ fuels. Table 8 is followed by a discussion on how heavy oil, pipeline natural gas, and renewable fuels are modeled in ITEDD.

Table 8. Fuels in the ITEDD Model

WEPS+ fuels	ITEDD fuel type	ITEDD fuels
1	Motor gasoline	1
2	Diesel	2
3	Residual oil	4
4	Liquefied petroleum gas	5
5	Jet fuel	3
6	Sequestered oil	4
7	Other residual	4
8	Natural gas	8
9	Coal	6
10	Electricity	7
11	Ethanol	9
12	Other biofuels	9
13	Hydrogen	10

Heavy oil

One of the consumption categories in ITEDD is a petroleum category for heavy oil. Although modeled as a single category, heavy oil actually consists of residual oil, sequestered petroleum, and other petroleum. The total consumption estimates for heavy oil are allocated to the various components based on their initial base year shares. In addition, residual oil used in marine vessels is assumed to be a blend of residual and distillate oils.

Pipeline natural gas

In the *International Energy Outlook* (IEO) analysis, the reporting of transportation energy consumption includes projections of pipeline natural gas. The consumption of pipeline natural gas is projected elsewhere in WEPS+ (in the Natural Gas Model) and then added to the transportation natural gas totals in ITEDD. Because ITEDD does not project pipeline natural gas endogenously, it is necessary to subtract out the pipeline natural gas from the historical data at the beginning, run the model, and then add it back in at the end.

Renewable fuels

ITEDD does not include a projection of renewable fuels such as ethanol (E85) and biodiesel that are blended with petroleum products. This blending is represented in the refinery model of WEPS+. ITEDD does include vehicles that use hydrogen as a transportation fuel.

Parameters / index definitions

ITEDD provides a framework for projecting both the amount of travel provided and the energy consumed in providing travel services. For the sake of readability, much of the discussion in this report omits the reference to regions and projection years. ITEDD categorizes passenger and freight transportation services into four modes: road, rail, water, and air. As shown in Table 9, the modes are further disaggregated into a total of 12 transportation services (2 of which are no longer used).

Table 9. Services (*s*) in the ITEDD Model

Service type index	Service grouping	Mode	Service type
1	Passenger	Road	Light-duty vehicle
2	Passenger	Road	Two- or three-wheel vehicle
3	Passenger	Road	Bus
4	Passenger	Rail	Rail
5	Passenger/Freight	Air	Air
6	Freight	Road	Heavy truck
7	Freight	Road	Light and medium duty trucks
8	*Freight*	*N/A*	*Not used*
9	Freight	Rail	Rail
10	Freight	Water	Domestic maritime
11	Freight	Water	International maritime
12	*Freight*	*N/A*	*Not used*

Services in ITEDD are measured in units of passenger-miles for each of the passenger services and in ton-miles for each of the freight services. Other main dimensions of variables in ITEDD appear in Tables 10 and 11.

Table 10. Vehicle ownership types (*w*) in the ITEDD Model

Vehicle ownership type index	Vehicle ownership type
1	Private
2	Commercial
3	Total

Table 11. Light-duty vehicle (LDV) technology types *(t)* in the ITEDD Model

LDV technology	Map to fuel(s)
ICE [a] or hybrid gasoline	Gasoline(1)
ICE or hybrid diesel	Diesel(2)
ICE natural gas	Natural gas(8)
ICE liquefied petroleum gas (LPG)	LPG(5)
ICE or hybrid other	Other(9)
Electric	Electricity(7)
Hydrogen fuel cell	Hydrogen(10)
Plug-in hybrid	Gasoline(1) and electricity(7)

[a] Internal combustion engine

Figure 3, shown earlier in this section, illustrates the primary subroutines and the order of execution. ITEDD first calls the Tranair subroutine to calculate passenger air travel. The Tranair Submodule is from the National Energy Modeling System (NEMS) and has been modified to work independently of the rest of NEMS, to transfer the WEPS+ 16-region data (for gross domestic product, or GDP, and population) to 13 Tranair regions, and then to allocate the 13-region Tranair consumption projections to the 16 WEPS+ regions.

The Passmdl subroutine is called next to calculate energy consumption for LDVs, two- and three-wheel vehicles, buses, and passenger rail. This subroutine calculates passenger travel demand by these four services, based on income, population, employment, oil prices, and externally derived saturation coefficients. It also generates an initial estimate of vehicle-kilometers traveled (VKT) for LDVs, two- and three-wheel vehicles, and buses using assumed load factors.

LDV stocks are projected using GDP per capita and externally derived saturation coefficients. LDV sales are computed by applying survival rates to previous-year stocks. Total sales are sales that are necessary to replace retiring vehicles plus those used to satisfy new demands. Vehicle sales are then allocated to vehicle types using a logit function and the attributes of each vehicle type. Vehicle sales by type are tracked by vintage with the newest vintage each year being vehicles sold in that year. The Fueleconomy and DoLogit subroutines are called to estimate the new fuel economy (mpg) and market shares among new vehicle types.

VKT from LDV stocks provides a check on the projected LDV share of vehicle-kilometers traveled from the passenger travel demand forecast. The final LDV VKT used to compute fuel consumption is based on the minimum of the stock-based VKT or shared passenger-kilometers traveled (PKT) converted to VKT. The average VKT per vehicle (converted to miles) is divided by the fuel economy (converted to Btu/mile) to yield fuel consumption.

The Freightmdl subroutine calculates consumption for light, medium, and heavy trucks; freight rail; and domestic marine. This subroutine first projects ton-miles of freight demand by these services and then applies fuel efficiency estimates to generate energy consumption.

The IntlMarinemdl subroutine calculates energy consumption for international marine freight transportation, based on ton-miles projected and fuel efficiency projections.

The Pass_Fr_Report subroutine collects the fuel consumption estimates across services and passes the results by fuel to the rest of WEPS+.

For each model iteration, ITEDD imports the following information from the WEPS+ shared restart file:

- Projected fuel prices (all years and all regions)
- Macroeconomic and demographic drivers
- Historical transportation energy consumption levels

After making its calculations, ITEDD outputs the resulting transportation fuel consumption projections, by region and year, to the restart file for use by other WEPS+ models. Within ITEDD, transportation fuel consumption values are projected at levels that are more disaggregate than the levels sent to the restart files.

Projections of transportation energy components

ITEDD projects annual transportation travel (in passenger-kilometers or ton-miles), fuel economy, and consumption, for each fuel and submode (service), in each of the 16 WEPS+ regions through 2050.

Hereafter, the following parameters/indexes used in ITEDD are defined as:

y = year
r = region
s = service
w = ownership
t = LDV technology
i = vintage
cm = commodity

Passenger LDVs, two- and three-wheel vehicles, buses, rail submodule

The ITEDD passenger submodule estimates travel demand (in passenger-kilometers) for four services—light-duty vehicles (LDVs), two- and three-wheel vehicles, buses, and rail. Provisional demand by service (vehicle-kilometers traveled, or VKT) is calculated using assumed load factors. For LDVs, a vehicle stock submodule also generates vehicle-kilometers traveled. LDV passenger-kilometers computed from vehicle stocks provide a check on the provisional LDV passenger-kilometers. The anticipated kilometers traveled per vehicle is based on the average kilometers per vehicle by vintage and any price or policy effects. The final LDV VKT used to compute fuel consumption is based on the minimum of the stock-based VKT and provisional VKT. If the provisional VKT is larger, a portion of the *unmet* demand is allocated to bus or rail. Fuel economy and shares by technology type are also computed for LDVs, while exogenous assumptions regarding fuel economy and fuel shares are used for two- and three-wheel vehicles, buses, and rail. Fuel consumption is estimated as a function of travel demand and efficiency.

Travel demand budget—passenger

An estimate of passenger-kilometers traveled per capita for each service is generated in two steps. First, the model uses externally derived saturation coefficients and GDP per capita as economic drivers. Then an adjustment is computed using additional external coefficients, employment, and oil prices. The adjusted passenger-kilometers per capita are then added together (except for LDVs, where it is proportionally allocated based on exogenous factors).

First Step

$$PkmperCapA_{s,r,y} = maxpkm_{s,r} - \left[\frac{1}{maxpkm_{s,r} - minpkm_{s,r}} + e^{\left(constant1_{s,r} + \left(shape_{s,r} \times \frac{GDP\_P_{r,y}}{constant3_{s,r}}\right)\right)}\right]^{-1}$$

where

$PkmperCapA_{s,r,y}$ = passenger-kilometers traveled per capita by service s in region r during year y;
$maxpkm_{s,r}$ = maximum travel demand constant used in PKT calculation by service s in region r;
$minpkm_{s,r}$ = minimum travel demand constant used in PKT calculation by service s in region r;
$GDP\_P_{r,y}$ = GDP per capita in region r during year y;
$constant1_{s,r}$ = travel demand constant used in PKT calculation by service s in region r;
$constant3_{s,r}$ = travel demand GDP sensitivity constant used in PKT calculation by service s in region r; and
$shape_{s,r}$ = travel demand S-curve shape coefficient in region r.

Second Step

If bus, rail, two- or three-wheel vehicle,

$$PkmperCapB_{s,r,y} = e^{\left(constant2_{r,s} + \left(EmpCoef_{r,s} \times \ln\left(Employment_{r,y}\right)\right) + \left(OilCoef_{r,s} \times \ln\left(WPTPPrc_{y}\right)\right)\right)} - 1$$

$$PkmperCap_{s,r,y} = PkmperCapA_{s,r,y} + PkmperCapB_{s,r,y}$$

where

$PkmperCapB_{s,r,y}$ = passenger-kilometers traveled per capita by service s in region r during year y – second step;
$PkmperCap_{s,r,y}$ = total passenger-kilometers traveled per capita by service s in region r during year y;
$Employment_{r,y}$ = employment in region r during year y;
$WPTPPrc_{r,y}$ = world oil price in region r during year y;
$constant2_{s,r}$ = travel demand constant used in non-LDV PKT equation by service s in region r;
$EmpCoef_{r,s}$ = LDV travel demand employment coefficient by service s in region r; and
$OilCoef_{r,s}$ = LDV travel demand oil price coefficient by service s in region r.

If LDV,

$$
\begin{aligned}
PkmperCapB_{s,r,y} \\
&= TR2\_int_{s,r} + \left(TR2\_gdp1_{s,r} \times \ln\left(GDP\_p_{r,y}\right)\right) \\
&+ \left(\mathrm{TR2\_wop}_{s,r} \times \ln\left(WPTPPrc_y\right)\right) + \left(TR2\_gdp2_{s,r} \times \left(\ln\left(GDP\_p_{r,y}\right)\right)^2\right) \\
&+ \left(TR2\_time_{s,r} \times Time_y\right) + \left(TR2\_time2_{s,r} \times \left(Time_y\right)^2\right) + TR2\_yShift_{s,r}
\end{aligned}
$$

$$
PkmperCap_{s,r,y} = \left(TR2\_inc_{s,r} \times PkmperCapA_{s,r,y}\right) + \left(TR2\_reg_{s,r} \times PkmperCapB_{s,r,y}\right)
$$

where

$PkmperCapA_{s,r,y}$ = passenger-kilometers traveled per capita by service s in region r during year y – first step;
$PkmperCapB_{s,r,y}$ = passenger-kilometers traveled per capita by service s in region r during year y – second step;
$PkmperCap_{s,r,y}$ = total passenger-kilometers traveled per capita by service s in region r during year y;
$GDP\_P_{r,y}$ = GDP per capita in region r during year y;
$WPTPPrc_{r,y}$ = world oil price in region r during year y;
$Time_y$ = LDV travel demand time constant during year y;
$TR2\_int_{s,r}$ = travel demand constant by service s in region r;
$TR2\_gdp1_{s,r}$ = Coefficient for GDP per capita by service s in region r;
$TR2\_gdp2_{s,r}$ = Coefficient for GDP per capita squared by service s in region r;
$TR2\_time_{s,r}$ = Coefficient for time by service s in region r;
$TR2\_time2_{s,r}$ = Coefficient for time squared by service s in region r;
$TR2\_wop_{s,r}$ = Coefficient for world oil price by service s in region r;
$TR2\_yShift_{s,r}$ = LDV travel demand y-intercept shift constant by service s in region r;
$TR2\_inc_{s,r}$ = percentage of $PkmperCapA$ to use in $PkmperCap$, by service s in region r; and
$TR2\_reg_{s,r}$ = percentage of $PkmperCapB$ to use in $PkmperCap$, by service s in region r.

Total passenger-kilometers traveled (PKT) is then calculated.

$$
PKT\_ByServ_{s,r,y} = PkmperCap_{s,r,y} \times TPop_{r,y}
$$

where

$PKT\_ByServ_{s,r,y}$ = passenger-kilometers traveled by service s in region r during year y;
$TPop_{r,y}$ = total population in region r during year y.

An initial (provisional) vehicle-kilometers traveled (VKT) is calculated by dividing the estimated PKT by an assumed load factor.

$$
VKT_{s,r,y} = \frac{PKT\_ByServ_{s,r,y}}{LF\_Pass_{s,r,y}}
$$

where

$VKT_{s,r,y}$ = vehicle-kilometers traveled by service s in region r during year y;
$LF\_Pass_{s,r,y}$ = load factor by service s in region r during year y.

LDV stocks and sales

LDV stocks per capita are projected using Gompertz curves to relate vehicle ownership and income, as developed in Dargay et al. (2007).[1] The saturation parameters are derived externally, and the economic driver is GDP per capita. Once the total stock is estimated, it is divided into personal vehicles (index=1) and commercial vehicles (index=2) using a user-specified share factor.

$$
\begin{aligned}
&Vstockpercap_{r,y,3} \\
&\qquad = \left(St\_Dmd\_2_r \times theta \times e^{\left(St\_Dmd\_3_r \times e^{(St\_Dmd\_4_r \times GDP\_P_{r,y})}\right)}\right) \\
&\qquad + \left((1 - theta) \times Vstockpercap_{r,y-1,3}\right)
\end{aligned}
$$

$$Vstockpercap_{r,y,1} = Vstockpercap_{r,y,3} \times HLDVStockP_{r,y}$$

$$Vstockpercap_{r,y,2} = Vstockpercap_{r,y,3} \times (1 - HLDVStockP_{r,y})$$

where

$Vstockpercap_{r,y,w}$ = LDV stocks per capita in region r during year y for ownership w;
$St\_Dmd\_2_r$ = vehicle stock per capita maximum car ownership (saturation level) in region r;
$St\_Dmd\_3_r$ = vehicle stock per capita shape factor (x-axis displacement), negative value;
$St\_Dmd\_4_r$ = vehicle stock per capita GDP shape factor (growth rate), negative value;
$theta$ = vehicle stock per capita speed of adjustment parameter;
GDP_P = GDP per capita; and
$HLDVStockP_{r,y}$ = Percentage of stock that is privately owned, in region r during year y.

LDV stock is then calculated by multiplying by population.

$$Vstock_{r,y,w} = Vstockpercap_{r,y,w} \times TPop_{r,y}$$

where

$Vstock_{r,y,w}$ = LDV stock in region r during year y for ownership w.

The model's projected stocks for 2016 are then calibrated to the 2016 IEA (International Energy Agency) Mobility Model for the Transport Model (MoMo) data. This calibration factor is applied to projected stocks in future years.

[1] Dargay, Joyce, Dermot Gately, and Martin Sommer, "Vehicle Ownership and Income Growth, Worldwide: 1960-2030," *The Energy Journal*, Vol. 28, No. 4 (2007), p. 150.

$$Diff = HLDVstock\_vt_{r,2016,w} - Vstock_{r,2016,w}$$

$$Vstock\_B_{r,y,w} = Vstock_{r,y,w} + Diff$$

where

$Diff$ = difference between calculated value and historical value;
$HLDVstock\_vt_{r,y,w}$ = historical LDV stock technology type in region r during year y by vehicle ownership type w; and
$Vstock\_B_{r,y,w}$ = LDV stock calibrated to 2016 IEA MoMo data in region r during year y by vehicle ownership type w.

Survival curves are calculated for use in stock vintaging. Assumptions about vehicle survival rates are taken from Huo and Wang (2012).[2]

$$Scurve_{r,y,w} = e^{\left[-1 \times \left(\frac{y+bcoef_r}{Tcoef_r}\right)^{bcoef_r}\right]}$$

where

$Scurve_{r,y,w}$ = cumulative survival curve in region r during year y by vehicle ownership type w;
$bcoef_r$ = vehicle stock per capita GDP shape factor (growth rate), negative value in region r; and
$Tcoef_r$ = parameter associated with vehicle life in region r.

Annual survival curves by vintage are then created.

$$SurvCurv_{r,i,y,w} = \frac{e^{\left[-1 \times \left(\frac{y+bcoef_r}{Tcoef_r}\right)^{bcoef_r}\right]}}{e^{\left[-1 \times \left(\frac{y-1+bcoef_r}{Tcoef_r}\right)^{bcoef_r}\right]}}$$

where

$SurvCurv_{r,i,y,w}$ = survival curve during year *y* for vintage i in region r by vehicle ownership type w.

The Huo and Wang paper provides parameters for $bcoef_r$ and $Tcoef_r$ for four major regions: China, United States, Europe, and Japan. Chinese vehicles have much shorter lifetimes than vehicles in other regions. In their scenarios, Huo and Wang allow the China vehicle scrappage rate to evolve over time to values from another region. This flexibility has been included in ITEDD as well, where each of the WEPS+ regions has been mapped to these four region coefficients with an initial year and final year. Commercial

[2] Huo, Hong and Michael Wang, "Modeling Future Vehicle Sales and Stock in China," *Energy Policy*, Vol. 43 (April 2012), p. 23.

light-duty vehicles are assumed to have scrappage curves with a similar functional form but different parameters.

The next step is to set up the initial 2016 LDV stock by age vintage using historical vehicle sales. First, the survival curves are applied to calculate the expected surviving stock in 2016, $SumVSales$.

$$SumVSales_{r,2016,w} = HLDVSales\_vt_{r,2016,w} + \sum_{y=1980}^{2015} (HLDVSales\_vt_{r,y,w} \times Scurve_{r,y,w})$$

where

$SumVSales_{r,2016,w}$ = sum of vintage sales in region r during year 2016 by vehicle ownership type w;
$HLDVSales\_vt_{r,y,w}$ = historical sales of LDV stock by vintage vt in region r during year y by vehicle ownership type w; and
$Scurve_{r,y,w}$ = survival curve in region r during year y by vehicle ownership type w.

A multiplicative calibration factor is computed and applied to historical sales so that surviving sales will sum to the 2016 stock.

$$Bnch_{r,2010,w} = \frac{VStock\_B_{r,2016,w} - HLDVSales\_vt_{r,2016,w}}{SumVSales_{r,y,w} - HLDVSales\_vt_{r,2016,w}}$$

$$VSales\_B_{r,y,w} = HLDVSales\_vt_{r,y,w} \times Bnch_{r,2016,w} \quad \text{for } y\text{=1980 to 2015}$$

where

$Bnch_{r,2016,w}$ = 2016 calibrated value for historical sales in region r by vehicle ownership w; and
$VSales\_B_{r,y,w}$ = sales calibrated to 2016 IEA MoMo sales in region r during year y by vehicle ownership type w.

Surviving stock by vintage is calculated for each year based on the survival rate vehicles from previous year sales.

$$Stock_{i,r,y,w} = VSales\_B_{i-1,y-1,w} \times SurvCurve_{r,i-1,y,w}$$

$$SurvStock_{r,y,w} = \sum_{i=1}^{25} Stock_{i,r,y,w}$$

where

$Stock_{i,r,y,w}$ = stock by vintage i during year y in region r by vehicle ownership type w; and
$SurvStock_{r,y,w}$ = surviving stock in region r during year y by vehicle ownership type w.

Benchmarked stock is calculated for 2016 so that the benchmarked stock equals the actual stock.

$$Bench\_Stock_{r,2016,w} = \frac{VStock\_B_{r,y,w}}{\sum_{i=1}^{25} Stock_{i,r,y,w}}$$

$$Stock_{i,r,2010,w} = Stock_{i,r,2016,w} * Bench\_Stock_{r,2016,w}$$

where

$Bench\_Stock_{r,2016,w}$ = 2016 calibrated value for historical stock in region r by vehicle ownership w

Next, vehicle sales are projected (2016–2050) as total stock minus surviving stock or, in other words, sales necessary to replace retiring vehicles plus those used to satisfy new demands.

$$VSales\_B_{r,y,w} = Vstock\_B_{r,y,w} - SurvStock_{r,y,w}$$

As described below in the LDV Fuel Economy section, vehicle sales are shared to vehicle types using a logit function and the attributes of each vehicle type. Vehicle sales by type are tracked by vintage with the newest vintage each year being vehicles sold in that year.

LDV-vehicle-kilometer traveled

Next, average annual distance traveled per vehicle (kilometers) is calculated. Travel per personal vehicle is assumed to decline as vehicle ownership increases in developing regions. For commercial vehicles, the travel per vehicle is assumed to be constant.

$$New\_Aadtpv_{r,y,1} = \left(VKTCon_r \times \left(Vstockpercap_{r,y,1} \times 1000\right)^{VKTExp_r}\right) \times 1000$$

$$New\_Aadtpv_{r,y,2} = Aadtpv\_c_r$$

$$New\_Aadtpv_{r,y,3} = (New\_Aadtpv_{r,y,1} \times HLDVStockP_{r,y}) + \left(New\_Aadtpv_{r,y,2} \times \left(1 - HLDVStockP_{r,y}\right)\right)$$

where

$New\_Aadtpv_{r,y,w}$ = projected average annual distance traveled per vehicle (kilometers) for ownership type w in region r during year y;
$VKTCon_r$ = vehicle-kilometers traveled constant in region r;
$VKTExp_r$ = vehicle-kilometers traveled coefficient in region r; and
$Aadtpv\_c_r$ = annual average distance traveled per commercial vehicle (kilometers) in 2016 in region r.

Then provisional LDV VKT from stocks is calculated.

$$VKT\_LDV_{r,y,3} = New\_Aadtpv_{r,y,3} \times \frac{VStock\_B_{r,y,3}}{1000}$$

where

$VKT\_LDV_{r,y,w}$ = vehicle-kilometers traveled per vehicle from stock model for ownership type w in region r during year y.

The projected LDV travel is compared with the provisional VKT estimated previously. The difference is unmet demand (a positive number means there is unmet demand, where passenger travel demand for LDV is greater than LDV demand estimated based on stock).

$$Unmet_{r,y,3} = VKT_{1,r,y} - VKT\_LDV_{r,y,3}$$

$$Unmetpct_{r,y,3} = \frac{Unmet_{r,y,3}}{VKT_{1,r,y}}$$

$$VKTFINAL_{r,y,3} = \min\left(VKT\_LDV_{r,y,3}, VKT_{1,r,y}\right)$$

where

$Unmet_{r,y,3}$ = unmet demand (vehicle-kilometers) for both passenger and commercial vehicle ownership types w in region r during year y;
$VKT_{s,r,y}$ = vehicle-kilometers traveled by service s in region r during year y;
$Unmetpct_{r,y,3}$ = percentage of unmet demand for both passenger and commercial vehicle types w in region r during year y; and
$VKTFINAL_{r,y,3}$ = final vehicle-kilometers traveled per vehicle for both passenger and commercial vehicle types w in region r during year y.

A portion of the unmet travel demand from LDVs is then allocated to bus and rail travel demand, based on the bus and rail proportion of travel demand (service 3 = Bus, service 4 = Rail).

$$\begin{aligned} PKT\_ByServ_{s,r,y} & \\ &= PKT\_ByServ_{s,r,y} \\ &+ min\left(\left(\frac{PKT\_ByServ_{s,r,y}}{(PKT\_ByServ_{3,r,y} + PKT\_ByServ_{4,r,y})}\right.\right. \\ &\left.\left.\times Unmet_{r,y,3} \times Lf\_Pass_{1,r,y}\right), \left(allocate\_unmet_{r,y} \times PKT\_ByServ_{3,r,y}\right)\right) \end{aligned}$$

where

$PKT\_ByServ_{s,r,y}$ = passenger-kilometers traveled by service s in region r during year y;
$Lf\_Pass_{1,r,y}$ = load factor for LDVs in region r during year y; and
$Allocate\_unmet_{r,y}$ = exogenous factor to allocate unmet demand to bus or rail in region r during year y.

LDV fuel economy and fuel shares

ITEDD contains seven light-duty vehicle technology types: gasoline, diesel, natural gas, liquefied petroleum gas (LPG), battery electric, hydrogen, and plug-in hybrid electric vehicles (PHEVs). Conventional hybrids are treated as vehicles with fuel economy improvements within gasoline and diesel vehicles rather than as separate vehicle types. No vehicle type explicitly uses biofuels because biofuels are represented only as a fuel blending component in the supply side of WEPS+.

The new fuel economy and market shares among vehicle types are related elements. First, fuel economy is projected for each vehicle technology type. Then, using the previous year's market shares among vehicle types, the average fuel economy is computed and compared with the fuel economy standard, if any. If the standard is not met, additional fuel economy is added to the various vehicle types, and a pricing adjustment is made among vehicle types that will yield the desired standard.

Because compressed natural gas (CNG) and LPG vehicles are likely to remain small portions of the global vehicle market and their engines are similar to gasoline engines, EIA assumes that manufacturers will produce essentially the same vehicle for these fuels with the same fuel economy. Therefore, the fuel economy of CNG and LPG vehicle types is simply set equal to that of gasoline rather than being independently computed based on those two fuel prices.

Electric vehicles have few cost-effective fuel economy opportunities because they are already very efficient, but they are likely to experience cost declines over time as the battery technology improves. These battery cost reductions are a user input that leads to a reduction over time in the base electric price and the price for PHEV20s (plug-in hybrid electric vehicles with a 20 mile all electric range).

Consumers are assumed to minimize their total LDV transport costs, which include the vehicle price and the present value of lifetime fuel costs. Vehicle fuel economy curves for gasoline and diesel vehicles were developed based on the NEMS LDV model. These curves show a linear relationship between the incremental vehicle price and incremental mpg. As a result, the incremental cost minimization is represented by setting the following derivative to zero.

$$\frac{d}{dMPG}\left((CCoef_{t,r} \times MPGB4_{w,t}) + \left(\frac{P_{t,r,y} \times LFM_w}{MPGB4_{w,t}}\right)\right) = 0$$

For each vehicle type, incremental cost minimization solves to

$$MPGB4_{r,y,w,t} = \left(\frac{P_{t,r,y} \times LFM_w}{CCoef_{t,r}}\right)^{0.5}$$

where

$MPGB4_{r,y,w,t}$ = optimal mpg where the lifetime fuel and vehicle costs are minimized for year y in region r by vehicle ownership w and technology type t;
$P_{t,r,y}$ = vehicle price ($) for year y in region r by technology type t;
LFM_w = lifetime fuel costs by ownership type w; and
$CCoef_{t,r}$ = fuel economy curve coefficient in region r by technology type t.

The next step is to compute the average mpg across all vehicle types to determine whether fuel economy standards (if any) are met. The weighted average uses the vehicle technology market shares from the previous year as a starting point. If the average mpg is below the standard, then the fuel economy is raised for all vehicle types until the standard is met by increasing the marginal cost (dollars per gallon per mile [$/gpm]) of the vehicles with the lowest marginal costs to the marginal costs of the next most expensive until the standard is met. This process assumes that vehicle manufacturers try to minimize the cost of compliance.

$$MC\_GPM\_target_{r,y,w,t} = CCoef_{t,r} \times \left(MPGB4_{r,y,w,t}\right)^2$$

$$MPGAF_{r,y,w,t} = Max\left(\left(\frac{MC\_GPM\_target_{r,y,w,t}}{CCoef_{t,r}}\right)^{0.5}, MPGbase_{t,r}\right)$$

$$MPGFinal_{r,y,w,t} = MPGAF_{r,y,w,t}$$

$$MC\_GPM\_Final_{r,y,w,t} = CCoef_{t,r} \times \left(MPGAF_{r,y,w,t}\right)^2$$

where

$MC\_GPM\_target_{r,y,w,t}$ = target marginal cost ($/gpm) for year y in region r by vehicle ownership w and technology type t;
$MPGAF_{r,y,w,t}$ = fuel efficiency (mpg) for year y in region r by vehicle ownership w and technology type t;
$MPGbase_{t,r}$ = mpg base by technology type t and region r – first leg of curve;
$MPGFinal_{r,y,w,t}$ = final fuel efficiency (mpg) after checking to meet standard, for year y in region r by vehicle ownership w and technology type t; and
$MC\_GPM\_Final_{r,y,w,t}$ = final marginal costs ($/gpm) after checking to meet standard for year y in region r by vehicle ownership w and technology type t.

Another method of raising overall fuel economy is increasing the market share of vehicles with high fuel economy while decreasing the market share of vehicles with low fuel economy, such as would result from a shift from gasoline internal combustion engines (ICE) to diesel engines or plug-in hybrids and electric vehicles. Manufacturers might accomplish this shift by adjusting vehicle prices to change the relative attractiveness to consumers. The optimal strategy would be that of providing incentives and disincentives based on the same marginal cost of compliance. This strategy adjusts retail vehicle prices by the amount each vehicle type is determined to be above or below the standard times the marginal cost. The net adjustments will be close to zero. A parameter is included that allows the user to scale the price adjustment by a factor of zero to one; in other words, to exclude this effect, include some fraction of this effect, or include it fully. Early tests suggested that a full inclusion might change the market shares more than desired, so the factor ($VehAdj_r$) is currently set at 50%**.**

$$GPM\_P_{r,y,w,t} = \frac{1}{MpgAF_{r,y,w,t}}$$

$$GMP\_S_{r,y} = \frac{1}{Standard_{r,y}}$$

$$Diff\_S_{r,y,w,t} = GPM\_P_{r,y,w,t} - GPM\_S_{r,y}$$

$$VehprAdj_{r,y,w,t} = Diff\_S_{r,y,w,t} \times MC\_GPM\_Final_{r,y,w,t} \times VehAdj_r$$

where

$GPM\_P_{r,y,w,t}$ = gallon per mile (gpm) (inverse of mpg) in region r during year y by vehicle ownership w and technology type t;
$GMP\_S_{r,y}$ = gpm of fuel economy standard in region r during year y;

$Diff\_S_{r,y,w,t}$ = difference between average fuel economy and standard (gpm) in region r during year y by vehicle ownership w and technology type t;
$VehprAdj_{r,y,w,t}$ = \$/gpm price adjustment in region r during year y by vehicle ownership w and technology type t;
$Standard_{r,y}$ = fuel economy standard (mpg) in region r during year y; and
$VehAdj_r$ = percentage of costs from this share adjustment by region.

The market shares for the vehicle types are projected using a multinomial logit function similar to the one in the LDV submodule of NEMS, although with a smaller set of attributes: vehicle price, fuel cost per mile, make-and-model availability, fuel availability, and a constant. The fuel cost per mile takes into account fuel price and the vehicle fuel economy. The make-and-model availability (MMA) represents the concept that new vehicle technologies (such as plug-in hybrids) are initially offered in limited car models and therefore provide consumers with less choice across other attributes. As a result, the market share will be more limited when the vehicles are first introduced. As a vehicle type gains market share, the MMA increases.

$$Utility\_v_{r,y,w,t} = Coef\_veh_r \times (VehCstNew_{w,t} + VehprAdj_{r,y,w,t})$$

$$Utility\_f_{r,y,w,t} = Coef\_ful_r \times FcstpMile_{y,w,t}$$

$$Utility\_m_{r,y,w,t} = Coef\_mma \times \ln(MMA\_At2_{w,t,,r,y})$$

$$Utility\_fa_{r,y,w,t} = Coef\_fa1 \times e^{coef\_fa2 \times Favail_{r,y,w,t}}$$

$$Utility\_tot_{r,y,w,t} = Utility\_v_{r,y,w,t} + Utility\_f_{r,y,w,t} + Utility\_m_{r,y,w,t} + Utility\_fa_{r,y,w,t} + MPGCon_{t,r}$$

where

$Utility\_v_{r,y,w,t}$ = utility of vehicle price in region r during year y by vehicle ownership w and technology type t;
$Utility\_f_{r,y,w,t}$ = utility of fuel price in region r during year y by vehicle ownership w and technology type t;
$Utility\_m_{r,y,w,t}$ = utility of MMA in region r during year y by vehicle ownership w and technology type t;
$Utility\_fa_{r,y,w,t}$ = utility of fuel availability in region r during year y by vehicle ownership w and technology type t;
$Utility\_tot_{r,y,w,t}$ = total utility in region r during year y by vehicle ownership w and technology type t;
$VehCstNew_{w,t}$ = vehicle price in region r during year y by vehicle ownership w and technology type t;
$FcstpMile_{w,t}$ = fuel costs per mile by vehicle ownership w and technology type t;
$MMA\_At2_{w,t,r,y}$ = make and model availability attribute by vehicle ownership w and technology type t in region r during year y;

$Favail_{r,y,w,t}$ = fuel availability region r during year y by vehicle ownership w and technology type t;
$Coef\_veh_{r,y}$ = coefficient for vehicle price in region r during year y;
$Coef\_ful_r$ = coefficient for cost of driving in region r;
$Coef\_mma$ = coefficient for make and model availability;
$Coef\_fa1$ = coefficient 1 for fuel availability;
$Coef\_fa2$ = coefficient 2 for fuel availability; and
$MPGCon_{t,r,y}$ = constant for mpg calculation by technology type t in region r during year y.

The market shares are calculated using a logit function.

$$Utility\_\_exp_{r,y,w,t} = e^{Utility\_\_tot_{r,y,w,t}}$$

$$LDVShare\_T_{r,y,w,t} = \frac{Utility\_exp_{r,y,w,t}}{= \sum_t Utility\_\_exp_{r,y,w,t}}$$

where

$Utility\_\_exp_{r,y,w,t}$ = exponential of total utility in region r during year y by vehicle ownership w and technology type t; and
$LDVShare\_T_{r,y,w,t}$ = market share of LDV sales in region r during year y by vehicle ownership w and technology type t.

After the market shares have been computed, the average fuel economy is recomputed with the adjusted mpg to meet the standard. If the shares have changed significantly, the resulting average may overshoot the efficiency standard. Therefore, a small iterative loop repeats the fuel economy calculation using the new market shares and then recomputes the market shares until the average is within the desired tolerance (usually only one or two additional passes).

One final step prevents the projected LDV technology shares from changing too much annually (user-defined limit is currently set at 3%). If a technology's increase in market share is greater than the user-defined limit, the overage is allocated to other technologies that were not up against their limits.

Sales, stock, efficiency calculations by LDV technology

Results from the Fuel Economy subroutine are shares ($LDVShare\_T_{r,y,w,t}$) of new LDVs and fuel economy ($MPGFinal_{r,y,w,t}$) for new LDVs. These shares are applied to total sales to determine sales by LDV technology.

$$Sales\_ByTech_{r,y,w,t} = LDVShare\_\_T_{r,y,w,t} \times VSales\_\_B_{r,y,w}$$

where

$SalesByTech_{r,y,w,t}$ = sales in region r during year y by vehicle ownership w and technology type t.

Mpg by LDV technology ($MPGFinal_{r,y,w,t}$) of the new sales is stored into a new variable ($HFEFF_{r,y,1,w,t}$) that holds the fuel economy of vehicles by age vintage by technology and ownership type.

$$HFEFF_{r,y,1,w,t} = MpgFinal_{r,y,w,t}$$

where

$HFEFF_{r,y,1,w,t}$ = fuel economy in region r during year y by technology type t and by vintage (where 1 is new).

The vehicle market shares and fuel economies are applied to new vehicle sales each year. Values from survival curves are applied to projections of existing stock, and new sales are added to calculate total stock by technology type.

$$XStockT_{r,i,y,w,t} = (Sales\_ByTech_{r,y,w,t} \times SurvCurve_{r,i-1,y-1,w})$$

$$XSurvStockT_{r,y,w,t} = \sum_{i=1}^{25} XStockT_{r,i,y,w,t}$$

where

$XStockT_{r,i,y,w,t}$ = surviving stock in region r by vintage i during year y by vehicle ownership w and technology type t; and

$XSurvStockT_{r,y,w,t}$ = surviving stock in region r during year y by vehicle ownership w and technology type t.

Total stock can then be calculated from the surviving stock.

$$Stock\_Det_{r,y,w,t} = \sum_{i=1}^{25} XStockT_{r,i,y,w,t}$$

where

$Stock\_Det_{r,y,w,t}$ = total stock in region r during year y by vehicle ownership w and technology type t.

Vehicle travel varies by vehicle vintage, and total VMT by age is calculated for use in computing the stock average fuel economy and fuel consumption.

$$VMTAge_{r,y,w,i} = NEW\_Aadtvp_{r,y,w} \times VKTRatio_{r,i,w}$$

where

$VMTAge_{r,y,w,i}$ = vehicle travel in region r during year y by vehicle ownership w by vintage i; *and*

$VKTRatio_{r,i,w}$ = VKT ratios by age in region r by vintage i and vehicle ownership w.

Average fuel efficiency of the surviving stock by technology type is calculated as a function of the VMT and the fuel economy by vintage. The fuel economy is adjusted to represent an on-road efficiency that is lower than the rated efficiency.

$$XFEFF_{r,i,y,w,t} = HFEFF_{r,y,1,w,t}$$

$$XEFFAvg_{r,y,w,t} = \frac{\sum_{i=1}^{25}\left(XstockT_{r,i,y,w,t} \times VMTAge_{r,y,w,i}\right)}{\sum_{i=1}^{25}\left(\frac{XstockT_{r,i,y,w,t} \times VMTAge_{r,y,w,i}}{XFEFF_{r,i,y,w,t} \times CDF_{y-i+1}}\right)}$$

where

$XFEFF_{r,i,y,w,t}$ = fuel economy (mpg) in region r by vintage i during year y by vehicle ownership w and technology type t;

$XEFFAvg_{r,y,w,t}$ = average fuel economy (mpg) in region r during year y by vehicle ownership w and technology type t; and

CDF_{y-i+1} = fuel economy on-road degradation factor during year y by vintage i.

In many regions, VKT varies significantly between gasoline and diesel vehicles. To account for that effect on fuel consumption, the average VKT shares for privately owned vehicles are adjusted by technology using the 2016 historical VKT by vehicle type. Commercial VKT shares by technology are assumed to be proportional to commercial stock shares.

$$Mult_r = \frac{HMileage_{r,2016,1,1,2}}{HMileage_{r,2016,1,1,1}}$$

$$Stock\_Det_{r,y,1,9} = \sum_{t=1}^{ntechs} Stock\_Det_{r,y,1,t}$$

$$Stock\_Det_{r,y,1,10} = \sum_{1}^{ntechs\ (except\ 2)} Stock\_Det_{r,y,1,t}$$

If diesel,

$$VKTperVehbyTech_{r,y,1,t} = \left[\frac{(New\_AADTPV_{r,y,1} \times Stock\_Det_{r,y,1,9})}{Stock\_Det_{r,y,1,2} \times Mult_r + Stock\_Det_{r,y,1,10})}\right]$$

If not diesel,

$$VKTperVehbyTech_{r,y,1,t} = Mult_r \times \left[\frac{(New\_AADTPV_{r,y,1} \times Stock\_Det_{r,y,1,9})}{(Stock\_Det_{r,y,1,2} \times Mult_r + Stock\_Det_{r,y,1,10})}\right]$$

$$LDVsh\_vt_{r,y,1,t} = \frac{(VKTperVehbyTech_{r,y,1,t} \times Stock\_Det_{r,y,1,9})}{\sum_{1}^{ntechs} (VKTperVehbyTech_{r,y,1,t} \times Stock\_Det_{r,y,1,t})}$$

where

$Mult_r$ = ratio of diesel to motor gasoline mileage per vehicle (kilometers) in region r;

$HMileage_{r,y,s,w,t}$ = IEA MoMo LDV mileage in region r during year y by service s by vehicle ownership w and technology type t;

$VKTperVehbyTech_{r,y,1,t}$ = vehicle-kilometers traveled in region r during year y by vehicle ownership w by vehicle technology type t; and

$LDVsh\_vt_{r,y,1,t}$ = share of LDV vehicle travel in region r during year y by vehicle ownership w by vehicle technology type t.

LDV fuel consumption

As described above, stock is tracked by vintage. The average stock fuel economy for each vehicle type is multiplied by the stock of that type and average VKT per vehicle to yield fuel consumption. With the exception of PHEVs, each vehicle type is mapped to the type of fuel used in the powertrain for that vehicle. For PHEVs, electric and gasoline shares of VKT are used to split total consumption into the two fuels.

For LDVs

$$Passcons_{r,y,f,1} = \frac{\frac{VKTFINAL_{r,y,w}}{ConvKmMi} \times LDVSh\_vt_{r,y,w,t} \times Split}{\left(\frac{(XEFFAvg_{r,y,w} \times 42)}{(Convfac_f * 1000)}\right)}$$

where

$Passcons_{r,y,f,s}$ = passenger consumption in region r during year y by service s and ITEDD fuel type (Btu);
$ConvKmMi$ = conversion factor for kilometers to miles;
$Split$ = proportion of plug-in hybrid vehicle miles fueled by electricity; and
$Convfac_f$ = heat content (British thermal units per barrel) by fuel type f.

Fuel consumption for other passenger modes

Vehicle sales and stocks are not tracked for the other passenger modes of two- and three-wheel vehicles, buses, and rail. The total VKT per mode is multiplied by exogenously specified fuel shares and average fuel economy to project fuel consumption, except for rail where passenger-kilometers traveled is used. The fuel economy is specified in joules per kilometer (either vehicle or passenger) and is converted to Btu in the consumption equations.

Two- and three-wheel vehicles

$$Passcons_{r,y,f,2} = \frac{VKT_{2,r,y} \times Share\_2_{r,y} \times Eff\_2_{r,y}}{1.0551}$$

Buses

$$Passcons_{r,y,f,3} = \frac{VKT_{3,r,y} \times Share\_3_{r,y} \times Eff\_3_{r,y}}{1.0551}$$

Rail

$$Passcons_{r,y,f,4} = \frac{PKT\_ByServ_{r,r,y} \times Share\_RL\_P_{r,y} \times Eff\_4_{r,y}}{1.0551}$$

where

$Eff\_2_{r,y}$ = efficiency in petajoules per vehicle-kilometer (PJ/veh km) for two- and three-wheel vehicles in region r during year y;
$Eff\_3_{r,y}$ = efficiency in petajoules per vehicle-kilometer (PJ/veh km) for buses in region r during year y;

$Eff\_4_{r,y}$ = efficiency in petajoules per passenger-kilometer (PJ/pkm) for rail in region r during year y;
$Share\_2_{f,r,y}$ = share by fuel type f for two- and three-wheel vehicles in region r during year y;
$Share\_3_{f,r,y}$ = share by fuel type f for buses in region r during year y; and
$Share\_RL\_P_{f,r,y}$ = share by fuel type f for rail in region r during year.

Air submodule

ITEDD uses the same global air submodule as the one developed for NEMS. The Tranair Submodule from NEMS has been modified to work independently of the rest of NEMS, to transfer the WEPS+ 16-region data (for GDP and population) to 13 Tranair regions, and then to share the 13-region Tranair consumption results out to the 16 WEPS+ regions. For simplicity, the total Tranair jet fuel consumption for freight and passenger travel is assigned to the WEPS+ passenger air travel energy consumption. The following is a simplified representation of the model sharing out the data from the Tranair submodule ($Airout_{y,j}$) that is at the 13 regions to the WEPS+ ($Passcons_{r,y,f,s}$) variable that is at the WEPS+ 16 regions.

$$PassCons_{k,y,3,5} = WepsShr\_Tranair_k \times Airout_{y,j}$$

where

k = 16 IEO regions;
j = 13 Tranair regions;
$WepsShr\_Tranair_k$ = regional share factor (13 Tranair regions to 16 WEPS+ regions); and
$Airout_{y,j}$ = consumption by 13 Tranair regions (Btu).

Freight truck, rail, domestic marine submodule

Heavy-duty vehicle, rail, and domestic marine freight energy consumption is a function of travel demand, expressed in ton-miles, and energy efficiency. Historical ton-miles are available from the OECD/World Bank for Organization for Economic Cooperation and Development (OECD) countries and Russia, China, and India, and they are estimated from IEA MoMo for the remaining ITEDD regions. Projections of ton-miles are a function of the growth in industrial output by commodity. Historical efficiencies are estimated from IEA MoMo. Projections of efficiencies are based on exogenous assumptions.

Projection of ton-miles

The model starts by projecting ton-miles for truck, rail, and domestic marine by nine industrial output commodities, which are listed in Table 12. The projections incorporate user-defined assumptions about switching between modes. Projections by commodity are then summed for ton-miles by mode.

Table 12. Commodities (*cm*) in the ITEDD Model

Commodity number	Industry/commodity type
1	Chemicals
2	Iron and steel
3	Food
4	Paper
5	Refinery (petroleum products)
6	Non-metallic minerals
7	Other industrial
8	Agriculture
9	Extraction

Ton-mile projections by commodity for truck, rail, and domestic marine are calculated first.

$$TonMiles\_X\_CM_{cm,r,y} = TonMiles\_X\_CM_{cm,r,2012} \times \frac{Tmpmacgo\_PPP_{cm,r,y}}{Tmpmacgo\_PPP_{cm,r,2016}} \times MSwitch\_X\_CM_{cm,r,y}$$

where

$TonMiles\_X\_CM_{cm,r,y}$ = ton-miles by commodity cm in region r during year y by mode (X), where X = T for trucks, R for rail, DM for domestic marine;

$Tmpmacgo\_PPP_{cm,r,y}$ = industrial output by commodity cm in region r during year y; and

$MSwitch\_X\_CM_{cm,r,y}$ = mode switch fraction by commodity cm in region r during year y.

Ton-mile projections are summed across commodities for truck, rail, and domestic marine.

$$Truck\_TonMiles_{r,y} = \sum_{cm=1}^{9} TonMiles\_T\_CM_{cm,r,y}$$

$$FMode\_TonMiles_{r,y,4} = \sum_{cm=1}^{9} TonMiles\_R\_CM_{cm,r,y}$$

$$FMode\_TonMiles_{r,y,5} = \sum_{cm=1}^{9} TonMiles\_DM\_CM_{cm,r,y}$$

where

$Truck\_TonMiles_{r,y}$ = ton-miles for trucks in region r during year y; and

$FMode\_TonMiles_{r,y,4}$, $FMode\_TonMiles_{r,y,5}$ = ton-miles by mode (4 = rail, 5= domestic marine) in region r during year y.

Projections for light, medium, and heavy trucks are calculated next. Shares of heavy-duty trucks are calculated based on GDP per capita and user-defined coefficients. Non–heavy-duty truck shares are estimated based on their previous year ton-mile proportions.

Shares for projection years are then calculated.

$$Share\_HT_{r,y} = Min\left(0.9, \left(Coef\_A_r \times \ln\left(\frac{TGDP_{r,y}}{Tpop_{r,y}} \times 1000\right) - Coef\_B_r\right)\right)$$

$$Share\_MT_{r,y} = \left(1 - Share\_HT_{r,y}\right) \times \frac{FMode\_TonMiles_{r,y-1,2}}{(FMode\_TonMiles_{r,y-1,2} + FMode\_TonMiles_{r,y-1,1})}$$

$$Share\_LT_{r,y} = \left(1 - Share\_HT_{r,y}\right) \times \frac{FMode\_TonMiles_{r,y-1,1}}{(FMode_{TonMiles_{r,y-1,2}} + FMode_{TonMiles_{r,y-1,1}})}$$

where

$Share\_XX_{r,y}$ = shares by truck size (XX) where XX = LT for light trucks, MT for medium trucks, HT for heavy trucks in region r during year y; and

$Coef\_A_r$, $Coef\_B_r$ = coefficients determining heavy truck percentage share of ton-miles in region r.

Ton-miles by light, medium, and heavy trucks for projection years are then calculated.

$$FMode\_TonMiles_{r,y,x} = Truck\_TonMiles_{r,y} \times Share\_XX_{r,y}$$

where

$Share\_XX_{r,y}$ = shares by truck size (XX) where XX = LT for light trucks, MT for medium trucks, HT for heavy trucks in region r for year y; and

$FMode\_TonMiles_{r,y,x}$ = ton-miles by mode in region r during year y where x = 1 for light trucks, 2 for medium trucks, 3 for heavy trucks.

Fuel shares

Shares by fuel for rail transportation

The projections of the natural gas share of rail are based on the three-year running average growth in the difference between diesel and natural gas fuel prices and annual growth in GDP per capita. The electric share is held constant over time in all regions except China and India. In China and India, the natural gas share is held constant over time. The diesel share is calculated as one minus the natural gas and electric shares.

All regions except China and India

$$Share\_R\_Fuel_{ng,r,y} = Max(\,Share\_R_{ng,r,y-1} + \left(Share\_R_{ds,r,y-1} \times \left(Growth_{1,r,y} \times Coef\_R\,\right)\right),0)$$

$$Share\_R\_Fuel_{el,r,y} = Share\_R\_Fuel_{el,r,y-1}$$

China and India

$$Share\_R\_Fuel_{ng,r,y} = Share\_R\_Fuel_{ng,r,y-1}$$

$$Share\_R\_Fuel_{el,r,y} = Max(\,Share\_R_{el,r,y-1} + \left(Share\_R_{ds,r,y-1} \times \left(Growth_{1,r,y} \times Coef\_R\,\right)\right),0)$$

All regions

$$Share\_R\_Fuel_{ds,r,y} = 1 - Share\_R\_Fuel_{el,r,y} - Share\_R\_Fuel_{ng,r,y}$$

where

$Share\_R\_Fuel_{f,r,y}$ = shares by fuel for rail transportation by fuel f in region r during year y;
$Growth_{1,r,y}$ = three-year average growth rate in region r during year y for the difference between diesel and natural gas prices times the change in GDP per capita from the previous year; and
$Coef\_R$ = diesel–natural gas fuel price difference elasticity for rail transportation in region r during year y where ng = natural gas, el = electric, ds = diesel.

Shares by fuel for domestic marine transportation

The projections of the natural gas share for domestic marine transportation are also based on the three-year running average growth in the difference between diesel and natural gas fuel prices and annual growth in GDP per capita. The residual share is set as the residual share in 2016 minus the natural gas shares for this year, but the residual share is not allowed to become negative. The diesel share is calculated as the remaining share, that is, one minus the natural gas and residual shares.

$$\begin{aligned} Share\_DM\_Fuel_{ng,r,y} &\\ &= Max\Big(Share\_DM_{ng,r,y-1} \\ &+ \Big((Share\_DM_{ds,r,y-1} + Share\_DM_{rs,r,y-1}) \\ &\times \left(Growth_{1,r,y} \times Coef\_DM\right)\Big), Share\_DM\_Fuel_{ng,r,2016}\Big) \end{aligned}$$

$$Share\_DM\_Fuel_{rs,r,y} = Max(Share\_DM_{rs,r,2016} - Share\_DM_{ng,r,y}\ ,0)$$

$$Share\_DM\_Fuel_{ds,r,y} = 1 - Share\_DM\_Fuel_{rs,r,y} - Share\_DM\_Fuel_{ng,r,y}$$

where

$Share\_DM\_Fuel_{f,r,y}$ = shares by fuel for domestic marine transportation in region *r* for year *y* by fuel *f*; and
$Coef\_DM$ = diesel–natural gas fuel price difference elasticity for domestic marine transportation in region *r* for year *y where* ng = natural gas, rs = residual fuel, ds = diesel.

Shares by fuel for truck transportation

The projections of the natural gas consumption shares for light trucks, medium trucks, and heavy trucks are based on the three-year running average growth in the difference between diesel and natural gas fuel prices and annual growth in GDP per capita. For each size class, the natural gas share is then subtracted from the 2016 motor gasoline share to compute the current-year motor gasoline share. The LPG share is held constant over time. The diesel share is calculated as one minus the natural gas, motor gasoline, and LPG shares.

$$GW\_share\_ng_{XX,r,y} = \left(pval_{XX,r,y} + \frac{qval_{XX,r,y}}{mval_{XX,r,y}} \times Share\_ng_{XX,r,y-1}\right) \times \left(mval_{XX,r,y} - Share\_ng_{XX,r,y}\right)$$

$$Share\_ng_{XX,r,y} = Share\_ng_{XX,r,y-1} + GW\_share\_ng_{XX,r,y}$$

$$Share\_XX\_Fuel_{ng,r,y} = Share\_ng_{XX,r,y}$$

$$Share\_XX\_Fuel_{mg,r,y} = Max(Share\_XX_{mg,r,2012} - Share\_XX_{ng,r,y}, 0)$$

$$Share\_XX\_Fuel_{lpg,r,y} = Share\_XX\_Fuel_{lpg,r,y-1}$$

$$Share\_XX\_Fuel_{ds,r,y} = 1 - Share\_XX\_Fuel_{mg,r,y} - Share\_XX\_Fuel_{lpg,r,y} - Share\_XX\_Fuel_{ng,r,y}$$

where

$GW\_share\_ng_{XX,r,y}$ = the growth rate of the share of natural gas by truck size XX in region r during year y by fuel f where XX = LT for light trucks, MT for medium trucks, HT for heavy trucks;

$pval_{XX,r,y}$ = minimum value of the natural gas share by truck size XX in region r during year y;

$qval_{XX,r,y}$ = variable for policy and GDP per capita growth by truck size XX in region r during year y;

$mval_{XX,r,y}$ = variable for natural gas and diesel price ratio by truck size XX in region r during year y;

$Share\_ng_{XX,r,y}$ = the share of natural gas by truck size XX in region r during year y; and

$Share\_XX\_Fuel_{f,r,y}$ = shares by fuel by truck size (XX) transportation in region r during year y by fuel f where ng = natural gas, mg = motor gasoline, lpg = LPG, ds = diesel.

Truck load factors

Load factors for trucks are projected based on GDP per capita and user-defined coefficients, and they are limited to being no lower than the projected U.S. load factors that are user-specified.

$$LoadFactor\_XX_{r,y} = Max\left(\left(LXX\_CoefA_r \times \ln\left(\frac{TGPD_{r,y}}{TPop_{r,y}}\right) \times 1000\right) + LXX\_CoefB_r, LoadFactor\_XX_{US,y}\right)$$

where

$LoadFactor\_XX_{r,y}$ = load factor by truck size (XX) in region r during year y where XX = LT for light trucks, MT for medium trucks, HT for heavy trucks;

US = U.S. region;

LXX_CoefA_r = coefficient for truck load factors by truck size (XX) in region r where XX = LT for light trucks, MT for medium trucks, HT for heavy trucks;

$TGDP_{r,y}$ = gross domestic product (GDP) in region r during year y;

$TPop_{r,y}$ = population in region r during year y; and

LXX_CoefB_r = constant coefficient for truck load factors in region r where XX = LT for light trucks, MT for medium trucks, HT for heavy trucks.

Efficiencies

For each truck size, the change in average mpg is projected using assumed improvement factors relative to projected U.S. mpg improvement values to reflect the amount of U.S.-driven fuel economy improvement that applies to the region.

$$MPG\_XX_{f,r,y} = MPG\_XX_{f,r,y-1} \times \left(1 + Max\left(\frac{MPG\_XX_{f,US,y} - MPG\_XX_{f,US,y-1}}{MPG\_XX_{f2,US,y-1}} \times Imp\_XX_{f_r}, 0\right)\right)$$

where

$MPG\_XX_{f,r,y}$ = fuel economy (mpg) by truck type (XX) in region *r* during year *y* by fuel *f* where XX = LT for light trucks, MT for medium trucks, HT for heavy trucks; and

$Imp\_XX\_f_r$ = exogenous improvement factors by truck type (XX) and fuel type f in region r.

These truck efficiencies are adjusted based on changes in fuel price and are converted from mpg to Btu/ton-mile based on load factors and assumed price elasticity coefficients and fuel price growth.

$$EFF\_XX_{r,y} = \left(1 - \left(Coeff\_XX \times Avg\_f_y\right)\right) \times \left(\frac{1}{MPG\_XX_{f,r,y)}} \times LoadFactor\_XX_{r,y} \times ENCNT\_XX\_F\right)$$

where

$EFF\_XX_{r,y}$ = fuel economy (Btu/ton-mile) by truck size (XX) in region r during year y by fuel f where XX = LT for light trucks, MT for medium trucks, HT for heavy trucks;

Avg_f_y = three-year running average fuel price growth during year y by fuel (f) where f= D for diesel, MG for motor gasoline, LPG for liquefied petroleum gas, CNG for compressed natural gas;

$ENCNT\_XX\_F$ = energy content of fuel by truck size (XX) and fuel (F); and
$Coeff\_XX$ = diesel to natural gas fuel price difference elasticity.

Efficiencies for rail and domestic marine are user specified by year and region.

Energy consumption

Energy consumption by fuel for light, medium, and heavy trucks; for rail; and for domestic marine is then calculated as the product of ton-miles, efficiencies, and fuel shares.

$$FreightCons_{r,y,f,s} = FMode\_TonMiles_{r,y,s} \times Share\_XX\_Fuel_{f,r,y} \times \frac{EFF\_XX_{f,r,y}}{1000}$$

where

$FreightCons_{r,y,f,s}$ = freight consumption (Btu) by mode in region r during year y by fuel f by service s, where s = 1 for light trucks, 2 for medium trucks, 3 for heavy trucks, 4 for rail, 5 for domestic marine; and
$FMode\_TonMiles_{r,y,s}$ = ton-miles in region r during year y by service s, where s = 1 for light trucks, 2 for medium trucks, 3 for heavy trucks, 4 for rail, 5 for domestic marine.

International marine model

International marine energy consumption is a function of travel demand, in this case measured in nautical ton-miles, and the efficiency of that travel demand movement. Total historical ton-mile data were developed from various editions of the United Nations Conference on Trade and Development (UNCTAD) Review of Maritime Transport. International trade volume estimates (in thousand U.S. dollars) are taken from UNCTAD International Trade Statistics. These value data (exports plus imports) are used to share out total global ton-mile data into regions by commodity. Ton-mile projections are a function of growth in commodities produced. The historical efficiency of these ton-mile movements is taken from the International Maritime Organization (IMO) Second IMO GHG Study 2009. Projections of efficiencies are a function of the growth in the world oil price.

The methodology to determine commodity movement is as follows:

(1) EIA uses UN trade data (U.S. dollars by commodity and region) that were used to create the historical ton-mile shares; EIA notes which countries/regions were net importers and which were net exporters during the past five years.
(2) For regions that are exporters, EIA calculates the five-year average (2012–2016) share of exports (10-year exponential moving average for petroleum product as a result of recent market changes).
(3) For regions that are importers, EIA calculates the growth rate in consumption by energy commodity (coal, LPG, natural gas, petroleum product) by year in the projection period.
(4) EIA applies fixed exporter shares (2) to the importer growth (3) and adds to previous year's exporter ton-mile value.

The following provides a detailed description of these calculations.

First, energy consumption is summed across all sectors for each fuel type (LPG, coal, natural gas, and petroleum products) for use in energy commodity growth-rate calculations.

$$QLGAS_{r,y} = (QLGRS_{r,y} + QLGCM_{r,y} + QLGIN_{r,y} + QLGTR_{r,y})/1000$$

where

$QLGAS$ = LPG consumption in Btu in region r during year y;
$QLGRS$ = LPG consumption in the residential sector in region r during year y;
$QLGCM$ = LPG consumption in the commercial sector in region r during year y;
$QLGIN$ = LPG consumption in the industrial sector in region r during year y; and
$QLGTR$ = LPG consumption in the transportation sector in region r during year y.

$$QCLAS_{r,y} = (QCLRS_{r,y} + QCLCM_{r,y} + QCLIN_{r,y} + QCLTR_{r,y} + QCLPG_{r,y} + QCLDH_{r,y})/1000$$

where

$QCLAS$ = coal consumption in Btu in region r during year y;
$QCLRS$ = coal consumption in the residential sector in region r during year y;
$QCLCM$ = coal consumption in the commercial sector in region r during year y;
$QCLIN$ = coal consumption in the industrial sector in region r during year y;
$QCLTR$ = coal consumption in the transportation sector in region r during year y;
$QCLPG$ = coal consumption in the power generation sector in region r during year y; and
$QCLDH$ = coal consumption in the district heating sector in region r during year y.

$$QNGAS_{r,y} = (QNGRS_{r,y} + QNGCM_{r,y} + QNGIN_{r,y} + QNGTR_{r,y} + QNGPG_{r,y} + QNGDH_{r,y})/1000$$

where

$QNGAS$ = natural gas consumption in Btu in region r during year y;
$QNGRS$ = natural gas consumption in the residential sector in region r during year y;
$QNGCM$ = natural gas consumption in the commercial sector in region r during year y;
$QNGIN$ = natural gas consumption in the industrial sector in region r during year y;
$QNGTR$ = natural gas consumption in the transportation sector in region r during year y;
$QNGPG$ = natural gas consumption in the power generation sector in region r during year y; and
$QNGDH$ = natural gas consumption in the district heating sector in region r during year y.

$$QPPAS_{r,y} = (QDSRS_{r,y} + QDSCM_{r,y} + QDSIN_{r,y} + QDSTR_{r,y} + QDSPG_{r,y} + QDSDH_{r,y} + QMGCM_{r,y} + QMGIN_{r,y} + QMGTR_{r,y} + QRSCM_{r,y} + QRSIN_{r,y} + QRSTR_{r,y} + QRSPG_{r,y} + QRSDH_{r,y} + QKSRS_{r,y} + QKSCM_{r,y} + QKSIN_{r,y} + QPCIN_{r,y} + QJFTR_{r,y} + QSPIN_{r,y} + QSPTR_{r,y} + QOPIN_{r,y} + QOPTR_{r,y})/1000$$

where

$QPPAS$ = petroleum products consumption in Btu in region r during year y;
$QDSRS$ = distillate consumption in the residential sector in region r during year y;
$QDSCM$ = distillate oil consumption in the commercial sector in region r during year y;
$QDSIN$ = distillate oil consumption in the industrial sector in region r during year y;
$QDSTR$ = distillate oil consumption in the transportation sector in region r during year y;
$QDSPG$ = distillate oil consumption in the power generation sector in region r during year y;
$QDSDH$ = distillate oil consumption in the district heating sector in region r during year y;
$QMGCM$ = motor gasoline consumption in the commercial sector in region r for year y;
$QMGIN$ = motor gasoline consumption in the industrial sector in region r during year y;
$QMGTR$ = motor gasoline consumption in the transportation sector in region r during year y;
$QRSCM$ = residual fuel consumption in the commercial sector in region r during year y;
$QRSIN$ = residual fuel consumption in the industrial sector in region r during year y;
$QRSTR$ = residual fuel consumption in the transportation sector in region r during year y;
$QRSPG$ = residual fuel consumption in the power generation sector in region r during year y;
$QRSDH$ = residual fuel consumption in the district heating sector in region r during year y;
$QKSRS$ = kerosene consumption in the residential sector in region r during year y;
$QKSCM$ = kerosene consumption in the commercial sector in region r during year y;
$QKSIN$ = kerosene consumption in the industrial sector in region r during year y;
$QPCIN$ = petroleum coke consumption in the industrial sector in region r during year y;
$QJFTR$ = jet fuel consumption in the transportation sector in region r during year y;
$QSPIN$ = sequestered petroleum consumption in the industrial sector in region r during year y;
$QSPTR$ = sequestered petroleum consumption in the transportation sector in region r during year y;
$QOPIN$ = other petroleum (including feedstocks) in the industrial sector in region r during year y; and
$QOPTR$ = other petroleum (including feedstocks) in the transportation sector in region r during year y.

Next, historical ton-miles are loaded into the ton-mile variable used for ton-miles for all years.

$$TonMiles_{cm,r,y} = HTonMiles_{cm,y,r}$$

where

$TonMiles_{cm,r,y}$ = ton-miles for commodity cm in region r during year y; and
$HTonMiles_{cm,y,r}$ = historical ton-miles for commodity cm in region r during year y.

Growth rates are calculated for world oil price, for industrial gross output, and for the four fuel consumption categories above.

$$AvgBWOP_y = (WPTPPrc_y \times alpha) + \left(avgBWOP_{y-1} \times (1 - alpha)\right)$$

$$Growem_{7,r,y} = \frac{AvgBWOP_y - AvgBWOP_{y-1}}{AvgBWOP_{y-1}}$$

$$Growem_{1,r,y} = 1 + \frac{Summacgo_{r,y} - Summacgo_{r,y-1}}{Summacgo_{r,y-1}}$$

$$Growem_{x,r,y} = 1 + \frac{QXXAS_{r,y} - QXXAS_{r,y-1}}{QXXAS_{r,y-1}}$$

where

$AvgBWOP_y$ = 10-year exponential moving average world oil price during year y;
$alpha$ = 10-year exponential moving average coefficient;
$Growem_{x,r,y}$ = consumption growth rate by fuel type x where x=1 for gross output, x=2 or 3 for petroleum, x=4 for coal, x=5 for liquid gas, x=6 for natural gas, x=7 for world oil price in region r during year y; and
$Summacgo_{r,y}$ = sum of industrial gross output in region r during year y (across industries 1–11, 20, 21 excluding 4, which is energy commodities).

$TonMiles_{cm,r,y}$ growth is then projected by commodity. For importers, ton-mile growth is a function of the growth in that commodity's consumption. For exporters, the three- or five-year average share of exports is used.

For importers,

$$TonMiles_{cm,r,y} = TonMiles_{cm,r,y-1} \times Growem_{cm,r,y}$$

$$SumtonMiles_{cm,y} = \sum_{r=1}^{6} TonMiles_{cm,r,y}$$

For exporters,

$$TonMiles_{cm,r,y} = \left(\left(SumTonMiles_{cm,y} - SumTonMiles_{cm,y-1} \right) \times Share\_Marine_{cm,r} \right) + TonMiles_{cm,r,y-1}$$

where

$SumtonMiles_{cm,y}$ = sum of ton-miles across commodities cm during year y; and
$Share\_Marine_{cm,r}$ = exogenous, historical shares of commodities cm by region r.

Historical efficiencies are loaded into the variable used.

$$Eff\_M_{cm,r,y} = Htm\_Eff_{r,y,cm}$$

where

$Htm\_Eff_{r,y,cm}$ = exogenous historical efficiency for commodity cm in region r during year y; and
$Eff\_M_{cm,r,y}$ = efficiency (Btu/ton-mile) for commodity cm in region r during year y.

Next, efficiency is projected as the product of an exogenously specified efficiency and a price elasticity effect based on the change in the 10-year exponential moving average world oil price. If the consumption growth rate of oil price is negative, the efficiency is held at the previous year's level.

$$Eff\_M_{cm,r,y} = Ptm\_Eff_{y,cm} \times \left(1 - \left(Growem_{7,r,y} \times Felas\right)\right)$$

where

$Felas$ = exogenous elasticity factor; and
$Ptm\_Eff_{y,cm}$ = exogenous efficiency by commodity cm during year y.

Ton-mile shares by fuel are calculated.

$$Share\_M_{RS,r,y} = FuelShare\_RS_{y,r}$$
$$Share\_M_{NG,r,y} = FuelShare\_NG_{y,r}$$
$$Share\_M_{DS,r,y} = 1 - Share\_M_{RS,r,y} - Share\_M_{NG,r,y}$$

where

$FuelShare\_RS_{y,r}$ = exogenous residual fuel share in region r during year y;
$FuelShare\_NG_{y,r}$ = exogenous natural gas share in region r during year y; and
$Share\_M_{f,r,y}$ = shares by fuel f in region r during year y.

International marine total heavy oil consumption is calculated by commodity transported, then summed across commodities.

$$MCons_{f,r,y} = \sum_{cm=1}^{6} \frac{TonMiles_{cm,r,y} \times Eff\_M_{cm,r,y}}{1000}$$

where

$MCons_{f,r,y}$ = consumption across commodities (Btu) in region r during year y for fuel f.

This international marine consumption is then allocated to residual and diesel using the fuel shares.

$$FreightCons_{r,y,f,6} = MCons_{7,r,y} \times Share\_M_{f,r,y}$$

Total fuel consumption

Total fuel consumption is summed across all passenger and freight services, and the indexes are converted from ITEDD fuel type indexes to WEPS+ fuel type indexes. The following is a simplified representation of the model sharing out the data from ITEDD ($PassCons_{r,y,f2,s}$ and $FreightCons_{r,y,f2,s}$) variables that are at the 10 ITEDD fuel types to the WEPS+ ($TrnQtyA_{r,y,f,s}$) variable that is at the WEPS+ 13 fuel types.

$$TrnQtyA_{r,y,f,s} = \sum_{s=1}^{11} (PassCons_{r,y,f2,s} + FreightCons_{r,y,f2,s}) \times Share$$

where

$TrnQtyA_{r,y,f,s}$ = consumption in region r during year y for fuel f and service s (Btu); and
$Share$ = share factor to convert from ITEDD fuel types to WEPS+ fuel types.

Appendix A. Model Abstract

Model name:

Transportation Sector Model of the World Energy Projection System Plus; also International Transportation Model

Model acronym:

ITEDD

Model description:

The Transportation Sector Model (generally referred to as the International Transportation Energy Demand Determinants, or ITEDD, Model) of the World Energy Projection System Plus (WEPS+) is a computer-based energy demand modeling system of the world transportation sector at a regional level. For the *International Energy Outlook 2019* (IEO2019), ITEDD projects the amount of energy that is consumed to provide passenger and freight transportation services. This projection includes personal household on-road transportation in light-duty vehicles, which is counted here rather than in the residential sector. This projection also includes fuel consumed by natural gas pipelines and small amounts of lubricants and waxes. The model projects transportation consumption for 13 energy sources in each of the 16 WEPS+ regions during the projection period to 2050. ITEDD projects energy service demand and energy efficiency by travel mode.

ITEDD categorizes transportation services for passengers and freight in four modes: road, rail, water, and air. These modes are also disaggregated into submodes. ITEDD projects service demand by fuel and service based on multiple demand determinants. Service demand fuel shares are projected for most modes. The service energy efficiency projections by service and fuel are endogenous to the model. Total consumption by fuel and service is a function of demand and efficiency.

Model purpose:

As a component of the WEPS+ integrated modeling system, ITEDD generates long-term projections of transportation sector energy consumption. As part of the system, the model provides consumption inputs for a variety of the other models. The model provides a tool for analysis of international transportation energy within the WEPS+ system and can be run independently as a stand-alone model.

Most recent model update:

April 2019.

Part of another model:

World Energy Projection System Plus (WEPS+).

Model interfaces:

The Transportation Model receives inputs from the Macroeconomic Model, Refinery Model, World Electricity Model, Natural Gas Model, and Coal Model. It provides outputs to the Refinery Model, World Electricity Model, Petroleum Model, Natural Gas Model, and Coal Model. These inputs and outputs are provided through the shared interface file of WEPS+.

Official model representative:

John Maples
U.S. Energy Information Administration
Transportation Energy Consumption & Efficiency Analysis Team
EI-32/Forrestal Building
U.S. Department of Energy
1000 Independence Avenue SW
Washington, DC 20585
Telephone: (202) 586-1757
E-mail: John.Maples@eia.gov

Documentation:

U.S. Energy Information Administration, U.S. Department of Energy, *World Energy Projection System Plus: Transportation Model*, DOE/EIA-M072(2020) (Washington, DC, February 2020).

Archive information:

The model is archived as part of the World Energy Projection System Plus archive of the runs used to generate the *International Energy Outlook 2019, DOE/EIA-0484 (September 2019)*.

Energy system described:

International transportation sector energy consumption.

Coverage:

- Geographic: 16 WEPS+ regions: United States, Canada, Mexico, OECD Europe, Japan, Australia/New Zealand, South Korea, Russia, Other Non-OECD Europe and Eurasia, China, India, Other Non-OECD Asia, Middle East, Africa, Brazil, and Other Central and South America.
- Mode: road, rail, air, water.
- Time Unit/Frequency: annual, 2016 through 2050.

Modeling features:

The Transportation Model projects energy service demand (a measure of use) and service intensity (measured as an energy efficiency) for the overall stock of vehicles. The model looks at these measures for both passenger and freight services over a variety of modes and submodes, including

- Light-duty vehicle
- Two- and three-wheel vehicle
- Bus
- Heavy truck
- Other truck
- Freight rail
- Passenger rail
- Air
- Domestic water

- International water

In addition, a vintage stock model is used for light-duty vehicles that tracks fuel economy of the vehicle stock and projects fuel economy for new vehicles.

DOE input sources:

U.S. Energy Information Administration, International Energy Statistics Database (data as of April 2019).

U.S. Energy Information Administration, *Short-Term Energy Outlook* (STEO), Washington, DC, (April 2019 release).

Non-DOE input sources:

International Energy Agency (IEA), *Energy Balances of OECD Countries*, Paris, 2018.

International Energy Agency (IEA), *Energy Balances of Non-OECD Countries*, Paris, 2018.

Oxford Economics Global Energy Model (February 2019).

Oxford Economics Industrial Model (February 2019).

Independent expert reviews:

None.

Computing environment:

Hardware/Operating System: Basic PC with Windows XP (or other Windows OS).

Language/Software Used: Python and Fortran 90/95 (Currently using Compaq Visual Fortran), not required at runtime.

Run Time/Storage: Stand-alone model with one iteration running in about 3–4 seconds. CPU memory is minimal, and inputs/executable/outputs require less than 20MB storage.

Special Features: None.

Appendix B. Input Data and Variable Descriptions

The following variables represent data input from the file TranBase.xml.

Classification: Input variable.

$AADTPV\_C_r$:	Annual distance traveled per vehicle (km) for commercial vehicles, read in as $AADTPV\_Comm_r$
$Allocate\_unmet_{r,y}$:	Exogenous factor to allocate unmet demand to bus or rail
$bcoef_r$:	Survival curve coefficient β
CDF_y:	Degradation factor
$coef_{t,r}$:	Fuel economy curve coefficient—first leg of curve
$Coef\_A_r$:	Coefficient determining heavy-truck percentage share of ton-miles
$Coef\_B_r$:	Coefficient determining heavy-truck percentage share of ton-miles
$Coef\_DM_r$:	Diesel–natural gas fuel price difference elasticity for domestic marine
$Coef\_fa1$:	Coefficient for fuel availability
$Coef\_fa2$:	Coefficient for fuel availability
$Coef\_ful_r$	Coefficient for cost of driving
$Coef\_mma$:	Coefficient for make and model availability
$Coef\_R_r$:	Diesel–natural gas fuel price difference elasticity for rail transportation
$Coef\_veh_r$:	Coefficient for vehicle price
$Constant1_{s,r}$:	Travel demand constant used in PKT calculation—first equation
$Constant2_{s,r}$:	Travel demand constant used in PKT calculation—first equation
$Constant3_{s,r}$:	Travel demand constant used in PKT calculation—first equation
$Convfac_f$:	Heat content (British thermal units per barrel)
$ConvKmMi$:	Conversion factor for kilometers to miles
$Discrte_r$:	Discount rate
$EFF\_2_{r,y}$:	Efficiency in petajoules per vehicle-kilometer for two- and three-wheel vehicles
$EFF\_3_{r,y}$:	Efficiency in petajoules per vehicle-kilometer for buses
$EFF\_4_{r,y}$:	Efficiency in petajoules per vehicle-kilometer for rail
$EFF\_DM_{r,y}$:	Domestic marine efficiency (Btu/ton-mile)
$EFF\_R_{r,y}$:	Rail efficiency (Btu/ton-mile)

$EFF\_Standard_{r,y}$:	New vehicle efficiency standard
$Empcoef_{m,r}$:	Employment coefficient used in PKT calculation—first equation
$ENCNT\_H\_CNG$:	Energy content—heavy trucks—CNG (Btu/ton-mile)
$ENCNT\_H\_D$:	Energy content—heavy trucks—diesel (Btu/ton-mile)
$ENCNT\_H\_LPG$:	Energy content—heavy trucks—LPG (Btu/ton-mile)
$ENCNT\_H\_MG$:	Energy content—heavy trucks—motor gasoline (Btu/ton-mile)
$ENCNT\_L\_CNG$:	Energy content—light trucks—CNG (Btu/ton-mile)
$ENCNT\_L\_D$:	Energy content—light trucks—diesel (Btu/ton-mile)
$ENCNT\_L\_LPG$:	Energy content—light trucks—LPG (Btu/ton-mile)
$ENCNT\_L\_MG$:	Energy content—light trucks—motor gasoline (Btu/ton-mile)
$ENCNT\_M\_CNG$:	Energy content—medium trucks—CNG (Btu/ton-mile)
$ENCNT\_M\_D$:	Energy content—medium trucks—diesel (Btu/ton-mile)
$ENCNT\_M\_LPG$:	Energy content—medium trucks—LPG (Btu/ton-mile)
$ENCNT\_M\_MG$:	Energy content—medium trucks—motor gasoline (Btu/ton-mile)
$FcstPmile_{w,t}$:	Fuel costs per mile
$Felas$:	Exogenous fuel price elasticity—international marine
$FuelShare\_NG_{y,r}$:	Exogenous natural gas fuel oil share—international marine
$FuelShare\_RS_{y,r}$:	Exogenous residual fuel oil share—international marine
$HTM\_EFF_{y,cm}$:	Exogenous historical efficiency—international marine (Btu/ton-miles)
$HtonMiles_{y,r,cm}$:	Historical ton-miles—international marine (ton-miles)
$IMP\_H\_CNG_r$:	Exogenous improvement factor—heavy trucks—CNG
$IMP\_H\_D_r$:	Exogenous improvement factor—heavy duty trucks—diesel
$IMP\_H\_LPG_r$:	Exogenous improvement factor—heavy duty trucks—LPG
$IMP\_H\_MG_r$:	Exogenous improvement t factor—heavy duty trucks—motor gasoline
$IMP\_L\_CNG_r$:	Exogenous improvement factor—light duty trucks—CNG
$IMP\_L\_D_r$:	Exogenous improvement factor—light duty trucks—diesel
$IMP\_L\_LPG_r$:	Exogenous improvement t factor—light duty trucks—LPG
$IMP\_L\_MG_r$:	Exogenous improvement factor—light duty trucks—motor gasoline
$IMP\_M\_CNG_r$:	Exogenous improvement factor—medium trucks—CNG
$IMP\_M\_D_r$:	Exogenous improvement factor—medium trucks—diesel
$IMP\_M\_LPG_r$:	Exogenous improvement factor—medium trucks—LPG

$IMP\_M\_MG_r$:	Exogenous improvement factor—medium trucks—motor gasoline
$LF\_PASS_{s,r,y}$:	Load factor by service for LDVs
LFH_CoefA_r:	Coefficient for heavy-truck load factors
LFH_CoefB_r:	Constant for heavy-truck load factors
LFL_CoefA_r:	Coefficient for light-truck load factors
LFL_CoefB_r:	Constant for light-truck load factors
LFM_CoefA_r:	Coefficient for medium-truck load factors
LFM_CoefB_r:	Constant for medium-truck load factors
$Maxpkm_{s,r}$:	Maximum travel demand constant used in PKT calculation—first equation
$MILEAGE_{r,y,t}$:	Light-vehicle mileage from MoMo (kilometers)
$Minpkm_{s,r}$:	Minimum travel demand constant used in PKT calculation—first equation
$MMA\_At2_{t,r}$:	Make and model availability attribute
$MPG\_H\_CNG_{y,r}$:	Miles per gallon—heavy trucks—CNG (mpg)
$MPG\_H\_CNG\_us_{y,r}$:	Miles per gallon—heavy trucks—U.S. CNG (mpg)
$MPG\_H\_D_{y,r}$:	Miles per gallon—heavy trucks—diesel (mpg)
$MPG\_H\_D\_us_{y,r}$:	Miles per gallon—heavy trucks—U.S. diesel (mpg)
$MPG\_H\_LPG_{y,r}$:	Miles per gallon—heavy trucks—LPG (mpg)
$MPG\_H\_LPG\_US_{y,r}$:	Miles per gallon—heavy trucks—U.S. LPG (mpg)
$MPG\_H\_MG_{y,r}$:	Miles per gallon—heavy trucks—motor gasoline (mpg)
$MPG\_H\_MG\_us_{y,r}$:	Miles per gallon—heavy trucks—U.S. motor gasoline (mpg)
$MPG\_L\_CNG_{y,r}$:	Miles per gallon—light trucks—CNG (mpg)
$MPG\_L\_CNG\_us_{y,r}$:	Miles per gallon—light trucks—U.S. CNG (mpg)
$MPG\_L\_D_{y,r}$:	Miles per gallon—light trucks—diesel (mpg)
$MPG\_L\_D\_us_{y,r}$:	Miles per gallon—light trucks—U.S. diesel (mpg)
$MPG\_L\_LPG_{y,r}$:	Miles per gallon—light trucks—LPG (mpg)
$MPG\_L\_LPG\_us_{y,r}$:	Miles per gallon—light trucks—U.S. LPG (mpg)
$MPG\_L\_MG_{y,r}$:	Miles per gallon—light trucks—motor gasoline (mpg)
$MPG\_L\_MG\_us_{y,r}$:	Miles per gallon—light trucks—U.S. motor gasoline (mpg)
$MPG\_M\_CNG_{y,r}$:	Miles per gallon—medium trucks—CNG (mpg)

$MPG\_M\_CNG\_us_{y,r}$:	Miles per gallon—medium trucks—U.S. CNG (mpg)
$MPG\_M\_D_{y,r}$:	Miles per gallon—medium trucks—diesel (mpg)
$MPG\_M\_D\_us_{y,r}$:	Miles per gallon—medium trucks—U.S. diesel (mpg)
$MPG\_M\_LPG_{y,r}$:	Miles per gallon—medium trucks—LPG (mpg)
$MPG\_M\_LPG\_us_{y,r}$:	Miles per gallon—medium trucks—U.S. LPG (mpg)
$MPG\_M\_MG_{y,r}$:	Miles per gallon—medium trucks—motor gasoline (mpg)
$MPG\_M\_MG\_us_{y,r}$:	Miles per gallon—medium trucks—U.S. motor gasoline (mpg)
$MPGbase_{t.r}$:	Miles per gallon base—first leg of curve
$MPGcon_{t,r}$:	Constant for mpg calculation
$MSwitch\_DM_{cm,r}$:	Mode switch maximum share allocated to domestic marine from truck
$MSwitch\_R_{cm,r}$:	Mode switch maximum share allocated to rail from truck
$MSwitch\_T_{cm,r}$:	Mode switch maximum share allocated away from truck to rail
$Oilcoef_{m,r}$:	Oil coefficient used in PKT calculation—first equation
$Pbackyrs_r$:	Payback period (number of years)
$PTM\_EFF_{y,cm}$:	Exogenous efficiency by commodity—international marine (Btu/ton-mile)
$SALES_{r,y,t}$:	LDV sales from MoMo
$Shape_{s,r}$:	Travel demand S-shape coefficient used in PKT calculation—first equation
$Share_r$:	Share factor to convert ITEDD fuel types to WEPS+ fuel types
$SHARE\_2_{t,r,y}$:	Share by fuel—two- and three-wheel vehicles
$SHARE\_3_{t,r,y}$:	Share by fuel—buses
$Share\_marine_{cm,r}$:	Share by commodity—international marine
$SHARE\_RL\_P_{r,y}$:	Passenger rail—diesel share
$Split$:	Proportion of plug-in hybrid vehicle miles fueled by electricity
$St\_dmd\_2_r$:	Vehicle stock per capita maximum car ownership (in other words, saturation) in region r, read in as Darg_2
$St\_dmd\_3_r$:	Vehicle stock per capita shape factor (in other words, x-axis displacement), negative value, read in as Darg_3
$St\_dmd\_4_r$:	Vehicle stock per capita GDP shape factor (in other words, this factor determines growth rate), negative value, read in as Darg_4
$Standard_r$:	Fuel economy standard (mpg)

$STOCK_{r,y,t}$: LDV stock from MoMo

$tcoef_r$: Survival curve coefficient T

$Theta$: Vehicle stock per capita speed of adjustment parameter

$Time_y$: LDV travel demand time constant

$TR2\_gdp1_{s,r}$: Travel demand GDP per capita coefficient

$TR2\_gdp2_{s,r}$: Travel demand GDP per capita squared coefficient

$TR2\_inc_{s,r}$: Percentage of PkmperCapA used in PkmperCap calculation

$TR2\_int_{s,r}$: Travel demand constant

$TR2\_reg_{s,r}$: Percentage of PkmperCapB used in PkmperCap calculation

$TR2\_time_{s,r}$: Travel demand time coefficient

$TR2\_time2_{s,r}$: Travel demand time squared coefficient

$TR\_wop_{s,r}$: Travel demand world oil price coefficient

$TR2\_yShift_{s,r}$: LDV travel demand y-intercept shift constant

$VehAdj_r$: Percentage of costs from manufacturers' pricing behavior algorithm to use

$VEHCOST_{t,r}$: Base vehicle cost ($)

$VKTCON$: Vehicle-kilometers traveled constant

$VKTEXP$: Vehicle-kilometers traveled coefficient

$Vktratio_{r,i,w}$: VKT ratios by age for LDVs

$Wepshr\_Tranair_r$: Regional share factor (13 Tranair regions to 16 WEPS+ regions)

The following variables represent data input from the restart file.

Classification: Input variable from Macroeconomic Model, Refinery Model, and demand models.

$Employment_{r,y}$: Employment

$GDP\_PPP_{r,y}$: Regional GDP expressed in purchasing power parity by year (note r = 17 is total world GDP)

$Pop_{r,y}$ Regional population by year (note: r = 17 is total world population)

$TmpMacGo\_PPP_{r,y}$: Industrial output by commodity

$QCLCM_{r,y}$: Coal consumption in the commercial sector by region and year

$QCLDH_{r,y}$: Coal consumption in the district heating sector by region and year

$QCLIN_{r,y}$: Coal consumption in the industrial sector by region and year

$QCLPG_{r,y}$: Coal consumption in the power sector by region and year

$QCLRS_{r,y}$: Coal consumption in the residential sector by region and year

$QCLTR_{r,y}$: Coal consumption in the transportation sector by region and year

$QDSCM_{r,y}$: Distillate fuel consumption in the commercial sector by region and year

$QDSDH_{r,y}$: Distillate fuel consumption in the district heating sector by region and year

$QDSIN_{r,y}$: Distillate fuel consumption in the industrial sector by region and year

$QDSPG_{r,y}$: Distillate fuel consumption in the power sector by region and year

$QDSRS_{r,y}$: Distillate fuel consumption in the residential sector by region and year

$QDSTR_{r,y}$: Distillate fuel consumption in the transportation sector by region and year

$QMGCM_{r,y}$: Motor gasoline consumption in the commercial sector by region and year

$QMGIN_{r,y}$: Motor gasoline consumption in the industrial sector by region and year

$QMGTR_{r,y}$: Motor gasoline consumption in the transportation sector by region and year

$QNGCM_{r,y}$: Natural gas consumption in the commercial sector by region and year

$QNGDH_{r,y}$: Natural gas consumption in the district heating sector by region and year

$QNGIN_{r,y}$: Natural gas consumption in the industrial sector by region and year

$QNGPG_{r,y}$: Natural gas consumption in the power sector by region and year

$QNGRS_{r,y}$: Natural gas consumption in the residential sector by region and year

$QNGTR_{r,y}$: Natural gas consumption in the transportation sector by region and year

$QRSCM_{r,y}$: Residual fuel consumption in the commercial sector by region and year

$QRSDH_{r,y}$: Residual fuel consumption in the district heating sector by region and year

$QRSIN_{r,y}$: Residual fuel consumption in the industrial sector by region and year

$QRPGR_{r,y}$: Residual fuel consumption in the power sector by region and year

$QRSTR_{r,y}$: Residual fuel consumption in the transportation sector by region and year

$QLGCM_{r,y}$: Liquefied petroleum gas consumption in the residential sector by region and year

$QLGTR_{r,y}$:	Liquefied petroleum gas consumption in the commercial sector by region and year
$QLGIN_{r,y}$:	Liquefied petroleum gas consumption in the industrial sector by region and year
$QLGTR_{r,y}$:	Liquefied petroleum gas consumption in the transportation sector by region and year
$QJFTR_{r,y}$:	Jet fuel consumption in the transportation sector by region and year
$QKSRS_{r,y}$:	Kerosene consumption in the residential sector by region and year
$QKSCM_{r,y}$:	Kerosene consumption in the commercial sector by region and year
$QKSIN_{r,y}$:	Kerosene consumption in the industrial sector by region and year
$QPCIN_{r,y}$:	Petroleum coke consumption in the industrial sector by region and year
$QSPTIN_{r,y}$:	Sequestered petroleum fuel consumption in the industrial sector by region and year
$QSPTR_{r,y}$:	Sequestered petroleum fuel consumption in the transportation sector by region and year
$QOPIN_{r,y}$:	Other petroleum consumption in the industrial sector by region and year
$QOPTR_{r,y}$:	Other petroleum consumption in the transportation sector by region and year
$QELTR_{r,y}$:	Electricity consumption in the transportation sector by region and year
$QETTR_{r,y}$:	Ethanol (E85) consumption in the transportation sector by region and year
$QOBTR_{r,y}$:	Biofuels (excluding ethanol) consumption in the transportation sector by region and year
$QHYTR_{r,y}$:	Hydrogen fuel consumption in the transportation sector by region and year
$WPTPRC_{r,y}$:	World oil price

The following variables represent data elements calculated in the subroutine Tran.

Classification: Computed variable.

$Airout_{y,r}$:	Consumption by 13 Tranair regions (Btu)
$Alpha$:	10-year exponential moving average coefficient
$AvgBWPOP_y$:	10-year exponential moving average of world oil price

Avg_F_y:	Three-year running average fuel price growth
$Bench\_Stock_{r,y,w}$:	2010 calibrated value for historical stocks
$Bnch$:	2016 calibrated value for historical sales
$Diff$:	Difference between calculated value and historical value
$Diff\_S_{w,t}$	Difference between average fuel economy and standard ($/gpm)
$EFF\_HT_{r,y}$:	Fuel economy (Btu/ton-mile)—heavy trucks
$EFF\_LT_{r,y}$:	Fuel economy (Btu/ton-mile)—light trucks
$EFF\_MT_{r,y}$:	Fuel economy (Btu/ton-mile)—medium trucks
$EFF\_M_{cm,r,y}$:	Efficiency for international marine
$Favail_{r,y,w,t}$:	Fuel availability
$Fmode\_TonMiles_{r,y,s}$:	Ton-miles by mode
$FreightCons_{r,y,f,s}$:	Freight consumption (Btu) by service and fuel
$GDP\_P_{r,y}$:	GDP per capita
$GPM\_P_{r,y,w,t}$:	Gallon per mile (inverse of mpg) of average fuel economy
$GPM\_S_{r,y,w,t}$:	$/gpm of fuel economy standard
$Growem_{x,r,y}$:	Growth rates for consumption
$HLDVStockP_{r,y}$:	Percentage of stock that is privately owned
$HLDVStock\_vt_{r,y,w}$:	Historical LDV stock by technology type
$HLDVSales\_vt_{r,y,w}$:	Historical sales of LDV stock by technology type
$HMileage_{r,y,1,w,t}$:	IEA MoMo mileage
$HFEFF_{r,y,1,w,t}$:	Fuel economy by LDV technology and ownership
$LDVShare\_T_{r,y,w,t}$:	Market share of LDV sales
$LDVsh\_vt_{r,y,w,t}$:	Share of LDV vehicle travel
LFM_w:	Lifetime fuel costs
$LoadFactor\_HT_{r,y}$:	Load factor for heavy trucks
$LoadFactor\_LT_{r,y}$:	Load factor for light trucks
$LoadFactor\_MT_{r,y}$:	Load factor for medium trucks
$MPG\_HT_{f,r,y}$:	Fuel economy (mpg)—heavy trucks
$MPG\_LT_{f,r,y}$:	Fuel economy (mpg)—light trucks
$MPG\_MT_{f,r,y}$:	Fuel economy (mpg)—medium trucks

$MC\_GPM\_target_{r,y,w,t}$: Target marginal costs ($/gpm)

$MC\_GPM\_Final_{r,y,w,t}$: Final marginal costs ($/gpm) after checking to meet standard

$MCons_{y,r,y}$: Consumption across commodities—international marine

$MPGB4_{r,y,w,t}$: Optimal mpg where the lifetime fuel and vehicle costs are minimized

$MPGAF_{r,y,w,t}$: Fuel efficiency (mpg)

$MPGFinal_{r,y,w,t}$: Final fuel efficiency (mpg) after checking to meet standard

$Mult_r$: Ratio of diesel to gasoline mileage per vehicle (kilometers)

$Mval_{XX,r,y}$: Variable for natural gas and diesel price ratio by truck size XX in region r during year y

$New\_Aadtpv_{r,y,w}$: Projected average annual distance traveled per vehicle

P_r: Vehicle price

$PassCons_{r,y,f,s}$: Passenger consumption by service and ITEDD fuel type

$PkmperCapA_{s,r,y}$: Passenger-kilometers traveled per capita for first step

$PkmperCapB_{s,r,y}$: Passenger-kilometers traveled per capita for second step

$PkmperCap_{s,r,y}$: Passenger-kilometers traveled per capita

$Pkt\_ByServ_{s,r,y}$: Passenger-kilometers traveled

$Pval_{XX,r,y}$: Minimum value of the natural gas share by truck size XX in region r during year y

$QCLAS_{r,y}$: Coal consumption (Btu)

$QLGAS_{r,y}$: LPG consumption (Btu)

$QNGAS_{r,y}$: Natural gas consumption (Btu)

$QPPAS_{r,y}$: Petroleum products consumption (Btu)

$Qval_{XX,r,y}$: variable for policy and GDP per capita growth by truck size XX in region r during year y

$SalesbyTech_{r,y,w,t}$: Sales by LDV technology and ownership

$Scurve_{r,y,w}$: Cumulative survival curve

$Share\_HT_{r,y}$: Shares of heavy truck

$Share\_LT_{r,y}$: Shares of light truck

$Share\_MT_{r,y}$: Shares of medium truck

$Share\_NG_{XX,r,y}$: Share of natural gas by truck size XX in region r during year y

$Share\_HT\_Fuel_{f,r,y}$: Shares of heavy truck by fuel

$Share\_M_{f,r,y}$:	Fuel share—international marine
$Share\_MT\_Fuel_{f,r,y}$:	Shares of medium truck by fuel
$Share\_LT\_Fuel_{f,r,y}$:	Shares of light truck by fuel
$Share\_R\_Fuel_{f,r,y}$:	Shares by fuel of rail transportation
$Share\_DM\_Fuel_{f,r,y}$:	Shares of domestic marine by fuel
$Summacgo_{r,y}$:	Sum of industrial gross output
$SumTonMiles_{c,y}$:	Sum of ton-miles across commodities for international marine
$SumVSales_{r,y,w}$:	Sum of vintage sales
$Stock_{t,y,w}$:	LDV stock
$Stock\_Det_{r,y,w,t}$:	Stock by technology and ownership type
$SurvCurv_{r,i,y,w}$:	Survival curve
$SurvStock_{r,y,w}$:	Surviving stock
$TonMiles_{cm,r,y}$:	Ton-miles by commodity for international marine
$TonMiles\_T\_CM_{c,r,y}$:	Ton-miles by commodity by mode for trucks
$TonMiles\_R\_CM_{c,r,y}$:	Ton-miles by commodity by mode for rail
$TonMiles\_DM\_CM_{c,r,y}$:	Ton-miles by commodity by mode for domestic marine
$Tpop_{r,y}$:	Population
$TrnQtyA_{f,r,y}$:	Transportation consumption by fuel, region, and year
$Truck\_TonMiles_{r,y}$:	Ton-miles for trucks
$Unmet_{r,y,w}$:	Unmet demand (vehicle-kilometers)
$Unmetpct_{r,y,w}$:	Percentage of unmet demand
$Utility\_v_{r,y,w,t}$:	Utility of vehicle price by technology and ownership types
$Utility\_\exp_{r,y,w,t}$:	Exponential of total utility price
$Utility\_f_{r,y,w,t}$:	Utility of fuel price by technology and ownership types
$Utility\_fa_{r,y,w,t}$:	Utility of fuel availability by technology and ownership types
$Utility\_m_{r,y,w,t}$:	Utility of MMA by technology and ownership types
$Utility\_tot_{r,y,w,t}$:	Total utility by technology and ownership types
$VehprcAdj_{w,t}$:	\$/gpm price adjustment by technology and ownership types
$VehCstNew_{w,t}$:	Vehicle price
$VKT_{s,r,y}$:	Vehicle-kilometers traveled

$VKT\_LDV_{r,y,w}$:	Vehicle-kilometers traveled per vehicle from stock model
$VKTperVehbyTech_{r,y,1,t}$:	Vehicle-kilometers traveled by technology and ownership types
$VKTFinal_{r,y,w}$:	Final vehicle-kilometers traveled per vehicle
$VMTAge_{r,y,w,i}$:	Vehicle travel by vintage by technology and ownership types
$Vsales\_B_{r,y,w}$:	Sales calibrated to IEA MoMo sales
$Vstock_{r,y,w}$:	LDV stock
$Vstockpercap_{r,y,w}$:	LDV stocks per capita
$Vstock\_B_{r,y,w}$:	LDV stock calibrated to 2016 IEA MoMo data
$XEFFAvg_{r,y,w,t}$:	Average fuel economy of stock by technology type and ownership
$XFEFF_{r,y,w,t}$:	Fuel economy
$XStockT_{r,i,y,w,t}$:	Surviving stock by LDV technology and ownership and vintage
$XSurvStockT_{r,y,w,t}$:	Surviving stock by LDV technology type and ownership

Appendix C. References

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Appendix D. Data Quality

Introduction

The WEPS+ International Transportation Model (International Transportation Energy Demand Determinants, or ITEDD) develops projections of world transportation energy use by service (light-duty vehicles, two- and three-wheel vehicles, buses, heavy-duty trucks, other trucks, passenger rail, freight rail, domestic water, international water, and air) and fuel (motor gasoline, distillate fuel, residual fuel, liquefied petroleum gas, jet fuel, other petroleum, ethanol, other biofuels, hydrogen fuel, sequestered petroleum, natural gas, coal, and electricity) for 16 regions of the world. These projections are based on the data elements described in Appendix B of this report. In Chapter 4, Model Structure, the documentation details transformations, estimation methodologies, and inputs required to implement the model algorithms. The quality of the principal sources of input data is discussed here in Appendix D. Information regarding the quality of parameter estimates and user inputs is provided where available.

Sources and quality of input data

Sources of input data

- *STEO*—Short-term liquid fuel consumption is provided by region from EIA's *Short-Term Energy Outlook.*
- *International Energy Statistics Database*—The U.S. Energy Information Administration provides historical data on international electricity capacity, generation, and consumption by fuel type from 1984 through 2017. These data are used as the historical basis for all regional projections that appear in the *IEO2017*. Although the numbers are continually updated, WEPS+ used a *snap shot* of the database as it existed March 2017 as the source of its international data.
- *International Energy Agency*—The by-end-use-sector, by-product historical data are available from the OECD and non-OECD balances and statistics database by country on the subscription site www.iea.org. These data are benchmarked to the historical aggregate energy consumption data provided in the U.S. Energy Information Administration's international statistical database.
- *National Energy Modeling System (NEMS)*—ITEDD uses the NEMS air submodule, which is an international air model, for its estimates of jet fuel consumption.
- *Leidos*—Historical stock, sales, vehicle-kilometers traveled, and fuel efficiency for vehicles derived from the IEA Mobility Model (MoMo) for the Transport Model. The database given, through email, to John Maples, DOE/EIA, from Delma J. Bratvold, Leidos, on July 1, 2014.
- *International Maritime Organization*, Second IMO GHG Study 2009.
- *United Nations Conference on Trade and Development*, Review of Maritime Transport 2013.
- *World Bank*, Organization for Economic Cooperation and Development (OECD) statistics.

Data quality verification

As a part of the input and editing procedure, an extensive program of edits and verifications was used, including the following:

- Checks on world and U.S. consumption of liquid fuel and price, based on previous values, responses, and regional and technical knowledge
- Consistency checks
- Technical edits to detect and correct errors and extreme variability