ROADMAP MODEL

ICCT Roadmap model v2.3.0 documentation

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THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

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INTRODUCTION

The ICCT's Roadmap model is a global transportation emissions model covering all on-road vehicle activity in over 190 countries. The Roadmap model is intended to help policymakers worldwide to identify and understand trends in the transportation sector, assess emission impacts of different policy options, and frame plans to effectively reduce emissions of both greenhouse gases (GHGs) and local air pollutants. It is designed to allow transparent, customizable estimation of transportation emissions for a broad range of policy cases.

Making use of the ICCT's worldwide tracking of transportation policies, the model provides annual estimates of historical and future emissions under currently adopted policies out to 2050 for USA, and 2070 everywhere else. Roadmap estimates historical and projected well-to-wheel CO_2 emissions disaggregated by powertrain and fuel type as well as emissions of 15 local air pollutants. This version of the model includes six vehicle types and 11 powertrain and fuel combinations, as shown in Tables 1 and 2, respectively.

Table 1: *Roadmap vehicle types.*

Roadmap name	Vehicle category	Description
MC	MC	Two and three wheelers
PC	LDV	Passenger cars (GVW < 3.5 tonnes)
LCV	LDV	Light commercial vehicles (GVW < 3.5 tonnes)
Bus	HDV	Urban and coach buses (GVW ≥ 3.5 tonnes)
MDT	HDV	Medium-duty trucks (GVW 3.5-15 tonnes)
HDT	HDV	Heavy-duty trucks (GVW > 15 tonnes)

Table 2: *Roadmap powertrain types.*

Roadmap powertrain	Roadmap fuel	Description
ICE Diesel	Diesel	Internal combustion engines and conventional hybrids powered by diesel and biodiesel blends
ICE Gasoline	Gasoline	Internal combustion engines and conventional hybrids powered by gasoline and ethanol blends
ICE Biodiesel	Biodiesel	Pure biodiesel powertrains
ICE Ethanol	Ethanol	Pure ethanol powertrains
PHEV Diesel	Diesel, Electricity	Plug-in hybrid electric vehicles powered by diesel fuel and electricity
PHEV Gasoline	Gasoline, Electricity	Plug-in hybrid electric vehicles powered by gasoline fuel and electricity

ICE CNG	CNG	Internal combustion engines powered by compressed natural gas and biogas
ICE LNG	LNG	Internal combustion engines powered by liquefied natural gas
ICE LPG	LPG	Internal combustion engines powered by liquefied petroleum gas
BEV	Electricity	Battery electric vehicles
FCEV	Hydrogen	Fuel cell electric vehicles powered by hydrogen

Many of the default model inputs are sourced from the IEA Mobility Model (MoMo)'s January 2023 version. Additional country-specific data is included for key regions where available. Using sales inputs and calibrated survival curves, Roadmap's turnover module first compiles a detailed inventory of vehicle stock. Applying per-vehicle mileage rates and energy intensities, the model next calculates detailed energy consumption estimates. These, in turn, are a key input to the emissions calculations. This document describes the inputs and methods used in each major calculation step as well as some additional optional components available to users.

Acknowledgments

Roadmap was first developed in 2019 by Caleb Braun, Lingzhi Jin, and Josh Miller. Version 2.3 was developed in 2024 by Georgia Klein, Gabe Hillman Alvarez, and Arijit Sen.

SALES

Together with vehicle survival curves, annual vehicle sales are the main driver of vehicle stock within Roadmap. Default historical data on vehicle sales are sourced from country-specific data sources and from the MoMo database, which provides historical sales data for 45 regions, including 31 individual countries.

Historical sales

For countries within aggregate MoMo regions, new vehicle sales are disaggregated based on each country's share of energy consumption within the region. Energy balances are derived from IEA's World Energy Balances 2019 edition, which covers road transport energy consumption by fuel type from 1971-2018. Energy consumption estimates for 2019 and 2020 (the final historical year) are extended from 2018 by applying growth rates derived from MoMo's energy consumption. Multiplying each country's fuel consumption shares by the regional total sales volumes gives country-specific vehicle sales for each of the 11 powertrain types. Finally, the ratio of used imports to new vehicle sales in each MoMo region is used to split the total sales volumes into new vehicle sales and used imports.

Note that the World Energy Balances lack data on LNG and Hydrogen and as such, the total sales are assumed to be 0 unless otherwise specified by an alternative data source. LNG and CNG are grouped into a single category in the World Energy Balances, while the MoMo data only include CNG. Therefore, no ICE LNG specific vehicle sales or stock are present in the model at the time of writing, so this does not pose an issue. For hydrogen, historical and projected sales of FCEVs are specified independently.

Historical sales for several countries are updated using country-specific data. Table 3 shows these data sources, ordered by priority. If an ISO + Vehicle + CY combination appears multiple times, assume that the first source in the table is the final source.

Table 3: *Data sources for historical new vehicle sales. This table is ordered by priority, meaning that the top row of data takes precedence over all data below it.*

Source	Vehicles	Region / ISO	Data Type	Calendar Years
Atlas Public Policy	PC, LCV	USA	New Sales volumes, new sales shares by powertrain	2020-2022
National Automobile Dealers Association	HDT	USA	New Sales volumes, new sales shares by powertrain	2020-2022
Oak Ridge National Laboratory	MDT	USA	New Sales volumes, new sales shares by powertrain	2020-2022
MOVES3	All	USA	New sales volumes, new sales shares by powertrain	2000-2020
ZEDATA	PC, LCV	CHN	New sales volumes, new sales shares by powertrain	2020-2022
ZEDATA	Bus, MDT, HDT	CHN	New sales volumes, new sales shares by powertrain	2012-2022
ADK Automotive	Bus, MDT, HDT	BRA	New sales volumes	1971-2020

ICCT: NOM-044 delay analysis	Bus, MDT, HDT	MEX	New sales volumes	2000-2020
Mexican Automotive Industry Association (AMIA)	PC excluding passenger light trucks, LCV	MEX	New sales volumes, new sales shares by powertrain	2005-2022
IHS Europe	Bus, MDT, HDT	European Union aggregated and selected European countries (DEU, DNK, ESP, GBR, ITA, NLD, NOR, SWE)	New sales volumes, new sales shares by powertrain	2005-2022
IHS Global	Bus, MDT, HDT	CAN, USA	New sales volumes, new sales shares by powertrain	2020
Australian Infrastructure Statistics with the Federal Chamber of Automotive Industries 2022 sales data	PC, LCV	AUS	New sales volumes, new sales shares by powertrain	1997-2022
Statistics Canada Transportation Statistics	PC, LCV	CAN	New sales volumes, new sales shares by powertrain	2010-2022
EV Volumes	PC, LCV	ARE, BRA, CHL, COL, IDN, ISR, JPN, KOR, MEX, MYS, NZL, PHL, RUS, SAU, SGP, THA, TWN, UKR, USA, ZAF	New sales volumes, new sales shares by powertrain	2011-2022
ICCT's Pocketbook	PC, LCV	European Union, ISL, GBR, NOR, CHE, TUR	New sales volumes, new sales shares by powertrain	2001-2022
India Emissions Model and Segment Y/ for 2019-2022 data.	All	IND	New sales volumes, new sales	2000-2018

			shares by powertrain	
[ACEA](#)	Bus, MDT, HDT (PC / LCV available if not covered in Pocketbook)	European Union, ISL, GBR, NOR, CHE	New sales volumes	2000-2018 (MC), 2000-2019 (PC), 1997-2019 (LCV). Note: Pocketbook data takes priority wherever available. Note: 1980-2021 (Bus, MDT, HDT). Note: IHS data for HDV takes priority wherever available.
IEA ETP (Energy Technology Perspectives)	All	All	New sales growth rate from 2021 using ETP data wherever applicable.	2022
IEA's Mobility Model (MoMo)	All	All	All	1970-2021

Projected sales

New vehicle sales volumes are projected using compound annual growth rates (CAGRs) which have been calibrated based on projected vehicle activity growth rates. For EU countries, sales growth rates are calibrated such that modeled activity growth matches the EU Reference Scenario 2020's projected change in passenger transport activity and freight demand. For the USA, MOVES3 projected sales are used for the full range out to 2050 and similarly for India, the projected sales from the IEM BAU scenario are used. For the EU, the final growth rate is applied for all projected years. For the rest of the world, growth rates are derived by calibrating long-term sales growth rates to align model estimates of activity growth with MoMo's freight and passenger activity projections under the IEA's Stated Policy Scenario (STEPS) from 2020. The following equation is used to project new sales for each country (C) and vehicle type (V):

$$Sales_{C,V,y2} = Sales_{C,V,y1} \times \left(1 + CAGR_{C,V,G} \right)^{y2-y1}$$

Where:

- $y1$ = The first year of the growth period
- $y2$ = The second year of the growth period
- G = The growth period $y1$ to $y2$

The timeline may be broken into multiple growth periods (e.g., 2021-2030, 2030-2050, 2050-2070), but in all cases, the last year ($y2$) of the last growth period is the model end year (2070). The first year ($y1$) of the first growth period is 2022.

Used vehicle imports

Roadmap includes default data quantifying total imports of used vehicles and estimates their characteristics based on country-specific import policies. The top vehicle-importing regions are Africa (excluding South Africa), the Middle East (excluding Israel), Latin America (excluding Argentina, Brazil, and Chile), Japan, Russia, and New Zealand. It should be noted, however, that data on used vehicle flows is sparse and often lacks detail on vehicle types and final destinations. For example, a large quantity of used vehicles imported to the United Arab Emirates are quickly re-exported to African countries (UNEP, 2020) and as a result may be reported as imports to both the United Arab Emirates and the final destination. Roadmap accounts for used vehicle exports by adjusting vehicle survival rates.

To support flexibility in modeling used vehicle imports, Roadmap calculates how many used imports enter the fleet for each new vehicle sold using a ratio of used to new sales. Users can therefore provide the model with alternate data for new sales, used sales, or total sales individually without needing to adjust the other assumptions.

As per Ecologic (Ecologic, 2020), Intra-EU trade is largely from Western European countries such as Germany, France, Netherlands etc. to Eastern European countries such as Poland, Romania, and Bulgaria. EU countries are also allowed to export vehicles to select non-EU neighbors such as Serbia, Turkey, and Albania. Passenger cars are the most imported used vehicle. Most countries will consider the amount of air pollution that is generated by an imported vehicle when calculating their registration tax, and some countries such as Finland, Hungary, and Serbia outright ban the import of vehicles that do not adhere to certain EU pollution standards (generally at least Euro 3 for passenger vehicles, and Euro 5 for commercial vehicles).

The Ecologic report also estimates the volume of used vehicles imported by specific European countries in 2017. These volumes are used in conjunction with the new vehicle sales data from the model to obtain used/new sales shares for each country and vehicle type, which by default is assumed to be constant going into the future. Outside of Europe, the ratio of used to new sales from MoMo is utilized by default, except when UNEP 2015-2020 LDV trade flow data reports imports in regions where MoMo reports none. In those regions, the ratio of used LDV imports from UNEP to new LDV sales from MoMo is utilized for LDV instead.

The ages and emission control technologies of used vehicle imports are determined one of several ways:

1. Based on the maximum age limit set by some vehicle-importing countries
2. Based on the minimum Euro standard set by some vehicle-importing countries
3. Based on country-specific assumptions for the average age of used vehicle imports
4. Based on default ages applied to countries with no specific input data

In all cases, we assume the entry age is subject to an upper limit of 15 years for HDV, 10 years for LDV, and 3 years for all ZEVs. See the emission standards section for more details on determining the age of used vehicle imports.

Because vehicle imports are highly variable year to year, by default the model assumes that the future ratio of used imports to new vehicle sales is an average of the 5 most recent years of data. This share is assumed to remain constant for all projected years; however, users may provide alternate ratios to replace the default assumptions.

Although the total number of used imports is determined by scaling the number of new vehicle sales, the powertrain shares for used imports are calculated independently.

For LDV, the model uses the source shares of used imports (default shares obtained from UNEP LDV trade flow data) to extract the used powertrain shares in the importing countries from the new powertrain shares in the exporting countries at model year MY = CY – EntryAge. E.g., if used cars are entering at age five, their powertrain share is assumed to be that of new cars in their source country, five years ago. Both the source shares and resulting used powertrain shares defaults may be overwritten by user inputs.

For HDV, the default powertrain shares of used imports are taken directly from MoMo shares for the importing countries and conservatively forward filled, as little data exists on the trade flow patterns for these vehicles. Nonetheless, these can also be overwritten by the user.

STOCK TURNOVER

Roadmap keeps track of the age distribution of the fleet at every timestep based on new vehicle sales, the import age of used vehicles, and region- and vehicle-specific retirement rates. There are two methods used to estimate stock turnover: one is based on the fraction of vehicles surviving from the original sales year, and the other is based on the fraction of vehicles surviving from one year to the next. Detailed baseline stock by age is provided for four major markets: EU, USA, China, and India.

From-age-zero turnover

From-age-zero survival curves represent the fraction of vehicles surviving from the original sales year. These survival curves are modeled using Weibull distributions (see Hao et al. (2011) for more details).

These survival curves are defined as:

$$e^{-(x/\lambda)^k}$$

Where:

- x = Age of vehicle
- λ = Steepness parameter
- k = Shape parameter = 5

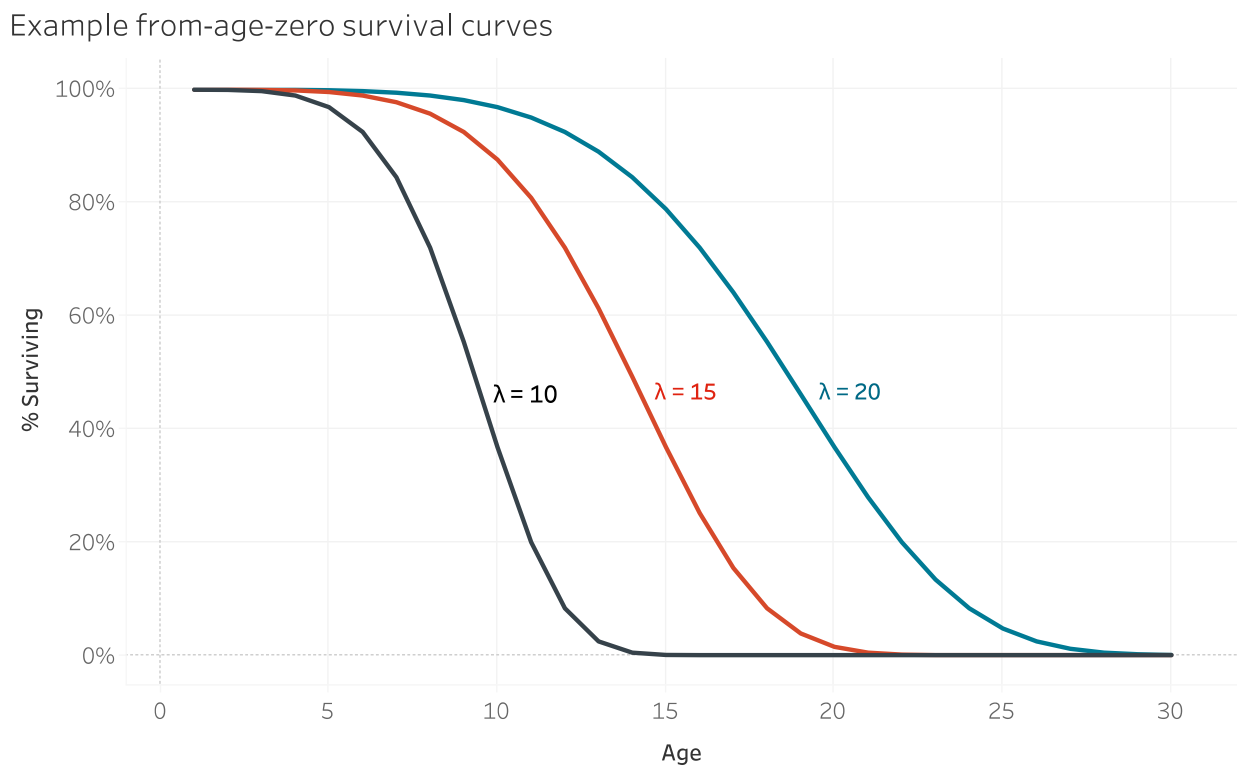

Figure 1: *Example from-age-zero survival curves.*

The steepness parameter is calibrated using historical stock and sales inventories. For most regions, the default from-age-zero survival curves are calibrated using stock and sales data from the MoMo database; however, some regions use more-detailed national fleet data for recent years. For each country (C) and vehicle type (V), the vehicle stock in a calendar year (CY) of a given model year (MY) is calculated:

$$Stock_{CY,MY} = Sales_{MY} \times Survival_{C,V}(CY - MY)$$

From-age-zero survival curves are applied by default to all countries for new sales as well as used vehicle imports. For used vehicles, these survival curves apply starting from when the vehicle enters the country.

Year-over-year turnover

The alternate method for estimating fleet turnover uses year-over-year survival curves. These curves represent the fraction of vehicles surviving from one year to the next. To be used effectively, a comprehensive inventory of the fleet broken down by age should be given for the base year. Unlike the from-age-zero survival curve method, used vehicles are actually treated as the age they are and not considered "new" when they enter a fleet. In this case, for each country (C) and vehicle type (V), the vehicle stock in a calendar year (CY) of a given model year (MY) is calculated:

$$Stock_{CY,MY} = Stock_{CY-1,MY} \times Survival_{C,V}(CY - MY)$$

In the case of age zero vehicles (CY = MY), sales are used instead of the previous year's stock:

$$Stock_{CY,MY} = Sales_{MY} \times Survival_{C,V}(0)$$

The year-over-year curves are applied by default to EU countries for new sales as well as used vehicle imports. This method is applied in order to accommodate detailed inputs on the starting age distribution of the vehicle stock and to model intra-EU vehicle trade.

Major Markets

The EU, USA, and India each have baseline stock by age and survival curves for stock turnover. China, on the other hand, has input stock by age *and* powertrain. Survival curves for China are calculated based on the average retirement age for each vehicle type. The EU data are derived from ACEA for PC and LCV in 2020 and from ACEM for MC in 2019. For HDVs (MDT, HDT, Bus), 2020 data are from an internal compilation of stock data from ACEA that is disaggregated by age using sales data from the IHS and IEA's Mobility Model. For the USA, the stock by age and survival curves data come from MOVES3 and for India, the same data are from IEM with additional inputs from transportation sector experts in the country. Lastly, the China stock by age and powertrain is derived from an internal meta analysis of data from CAAM and CATARC.

MILEAGE

Total vehicle-kilometers traveled (VKT) is calculated by multiplying the number of vehicles in the stock by the average annual mileage, based on the vehicle type and country. Historical per-vehicle mileages are input and calibrated to align model estimates of energy consumption with historical energy balances. Unless otherwise specified, annual mileages are assumed to remain constant in future years.

Mileage degradation

Optionally, an age-based mileage adjustment can be made which applies mileage degradation curves to the fleet. This does not significantly alter total VKT, but it shifts mileage to newer vehicles. Mileage degradation is regionally implemented for European Union, China and USA based on ICCT internal analysis except for USA – where the data is directly taken from MOVES. For every other region, global average mileage degradation factors are used.

Scrappage policies

Roadmap can also model the impacts of policies that are designed to shift activity from older, typically more polluting, vehicles to newer vehicles. Examples of such policies include scrappage and/or retrofit programs and low-emission zones. While these policies are likely to have effects on vehicle stock, these policies are currently only modeled as shifts in VKT among vehicle technologies as opposed to affecting the total level of VKT or vehicle stock. In other words, any scrappage of older vehicles (that would have traveled a certain amount of VKT) is treated as an equivalent increase in VKT by newer vehicles.

This module takes as an input the percent of VKT for each specified vehicle population (based on any of age, standard, vehicle type, fuel type) that should be reassigned to newer vehicles. Users can also specify the fuel type and model year of the vehicles that receive the shifted activity.

Passenger-freight activity

Alongside the calculation of vehicle activity, Roadmap calculates passenger-freight activity by multiplying load factors—defined as the number of passengers or amount of freight (in tonnes) a vehicle carries on average—by VKT. Passenger activity (passenger-km) is calculated for Bus, PC, and MC; while freight activity (tonne-km) is calculated for LCV, MDT, and HDT.

Default data for load factors come from IEA STEPS projections, though users can specify their own load factors for specific ISOs, vehicle types, and years. The calculation of passenger-freight activity is performed alongside other Roadmap calculations and does not impact vehicle stock, sales, or other quantities.

VEHICLE EFFICIENCY

Roadmap's default data on the energy intensities of new vehicles are derived from a combination of country-specific data sources, ICCT analyses, and historical data from the MoMo database. Vehicle- and powertrain-specific energy intensities by model year are sales-weighted and adjusted to reflect differences between on-road performance and test cycle values. USA energy intensity data are based on detailed energy consumption and vehicle mileage data from MOVES3. In countries that are not covered individually by available data sources or analysis, default energy intensities are based on the matching aggregate region in the MoMo database.

Energy intensities for each of the powertrain types are derived from the "Default AFV MPGGE (MPDGE) Relative Ratio" values found in the Argonne National Laboratory AFLEET Tool 2020. In order to match the more aggregated vehicle types in the Roadmap model, the vehicle types given in the AFLEET Tool are weighted in their respective Roadmap equivalents using their vehicle miles traveled. These weights are subsequently used to calculate the aggregated ratio for Roadmap vehicle types. The final energy intensity values for alternative powertrain types (everything but ICE Gasoline and ICE Diesel) are calculated using the ratio to the ICE value that is predominant for that vehicle type. This is ICE Gasoline for PC and MC and ICE Diesel for all other vehicle types. The equation below represents the calculation, where $[w_1, \ldots, w_n]$ represents all the weights of AFLEET vehicle types that compose a Roadmap vehicle type.

$$EI_{alternative} = \left(\sum_{i=w_1}^{w_n} \frac{i}{AFLEET\ Ratio} \right) \times EI_{ICE}$$

Users can adjust these energy intensity ratios for any combination of countries, vehicle types, and model years.

Projected new vehicle energy intensities are calculated based on user-specified inputs. By default, these inputs are specified as annualized rates of efficiency improvement by vehicle type for 16 world regions (defined in the model as RoadmapRegion); however, the user can supply detailed inputs for any combination of countries, vehicle types, fuel types, and calendar years. These inputs are intended to reflect changes in real-world fuel consumption (after applying on-road adjustment / CO_2 gap).

EMISSIONS

Emissions standards

On-road emissions are heavily dependent on the emissions control technologies of the vehicle fleet. The Roadmap model contains a frequently updated database of emission control regulations for at least 75 countries and the EU. Roadmap assumes that from the year a regulation takes effect onward, all new vehicles are sold with the required emission control technologies. (For more on how Roadmap accounts for tampered/degraded controls, see High emitters below.) Emission standards are classified based on their closest equivalents within the Euro emission standard categories.

The emission standards of imported vehicles are more difficult to determine. Many countries have policies that restrict old or dirty vehicles. The three cases included in Roadmap are:

1. A complete ban of used vehicle imports
2. Restrictions based on vehicle's age
3. Restrictions based on vehicle's standard

In case 1, the country cannot import used vehicles at all, so all vehicles follow the same emission standard timeline. In the other two cases, used imports are disaggregated by exporting country. In case 2, it is conservatively assumed that all imported vehicles are the maximum age allowed. The import year and import age are used to calculate the model year of the entering vehicles. The vehicle's model year is matched to the emission standard timeline of the *exporting* country.

In the third case the emission standard is restricted to the earliest standard in the exporting country that complies with the importing country's policies. This case can also be used to directly input the emission control levels assumed for imported used vehicles. Using the reverse process used in case 2, this standard is used to estimate the age of the entering vehicle. Similarly, it is conservatively assumed that all imported vehicles are the maximum age that still comply with the control standard.

In all cases, Roadmap assumes the emissions performance of used vehicle imports is equivalent to or worse than new vehicles.

Emission factors

Tailpipe emission factors are sourced from a combination of emission factor models, ICCT analyses, and other technical studies. Emission factors for vehicles certified to European-equivalent standards are based primarily on the European Environment Agency's European Monitoring and Evaluation Programme (EMEP), the Handbook Emission Factors for Road Transport (HBEFA), and ICCT adjustments. Emission factors for vehicles certified to US- and China-equivalent standards are sourced from EPA's MOtor Vehicle Emission Simulator (MOVES) with ICCT adjustments and ICCT's China model, respectively. Currently the Roadmap model does not estimate non-exhaust emissions such as brake and tire wear.

As both HBEFA and EMEP provide emission factors for a larger variety of vehicle types and weight classes than Roadmap, we first aggregate the emission factors to the Roadmap categories. The emission factors for 19 countries are aggregated with local, up-to-date stock inventories. HBEFA emission factors are used for buses and include a weighting of urban vs. intercity buses in addition to vehicle weight class. Emission factors for other vehicle types are sourced from EMEP, however the additional detail by weight class is only given for trucks. By default, other countries that follow the EU regulatory pathway use emission factors based on the average fleet composition from the EU countries with available data; however, users can supply any set of country-specific emission factors.

For the United States and Canada, vehicle emission factors are based on EPA's MOVES3 model. MOVES estimates diesel, gasoline, and natural gas emission factors for vehicles following the US standards. Rather than match the EPA's emission control naming standard and frequency (e.g. US 2007 and US 2010), Roadmap offers emission factors for all model years from 1990 to 2025 calculated using the emissions and energy consumption of available vehicle and fuel combinations. Newer heavy-duty vehicles in Mexico are assumed to be partially sourced from the USA and thus are assigned a weighted emission factor based on US and EU standards. China-specific emission factors are sourced from the ICCT's China model, which incorporates data from the Vehicle Emission Control Center and Tsinghua University.

Further adjustments were made to the PM and NOx emission factors certified to US and EU regulatory pathways based on real-world performance data, including remote sensing measurements, recent PEMS testing, and planned updates to MOVES. For NOx, the MOVES3-based emission factors for the US are adjusted to align with real-world emissions from The Real Urban Emissions Initiative (TRUE). Roadmap also supports additional speciation of $PM_{2.5}$ for all regions into components BC, OC, non-carbon organic matter, NO_3, NH_4, elemental metals, and unspeciated PM, based on Table C-1 and Table C-3 of MOVES 2014a.

For alternative fuels, such as Ethanol, Biodiesel, CNG, and LPG, the emission factors are taken from the sources listed above where available. For any missing combinations of emission standards and fuels, the emission factors are calculated based on available data for similar emission standards and fuels. For example, for a given vehicle type and standard, if emission factors are not available for China, but they are available for an equivalent standard and fuel type in Europe, then the missing data for China are imputed as follows. The ratio of the predominant ICE emission factor (for gasoline or diesel depending on vehicle type) and the alternative fuel emission factor for the equivalent Euro standard is used to calculate the unknown alternative fuel emission factor for China using its known ICE emission factor.

$$EF_{China,AltFuel} = \frac{EF_{Euro,AltFuel}}{EF_{Euro,ICE}} \times EF_{China,ICE}$$

The emission factors may also be optionally adjusted according to age using an emission deterioration profile. This option allows for vehicles to deteriorate over time and thus emit more as they age.

Emission deterioration

Roadmap can model emission deterioration (or improvement) by using age-specific multipliers for emission factors. Except for NOx emission factor multipliers in USA HDVs (which are based on ICCT analysis), emission deterioration is fixed to 1 for all ages for every other ISO and vehicle category, given Roadmap default emission standards. If deterioration is modelled, we expect the multiplier to be higher than 1 as the vehicle ages, meaning that the vehicle will produce more emissions than when it was brand new. Alternatively, for older vehicles – retrofits might be introduced at a certain age which would then reduce the emissions generated compared to earlier years. In this case the multiplier is less than 1.

Plug-in hybrid electric vehicles (PHEVs)

PHEVs are modeled partly as ICE vehicles and partly as electric. Based on internally-developed numbers for the share of PHEV activity using fossil fuel versus the share using electricity, PHEVs are first divided into their two modes. Each of the driving modes have separate energy intensities and emission factors, and thus the model reports energy consumption and emissions separately for both fuel types.

High emitters

Emission factors derived from the models above are based on typical operation of emission control technologies averaged over all driving conditions. In addition, Roadmap accounts for high emitters—vehicles whose emissions control systems are malfunctioning as a result of tampering, poor maintenance, or failure. These vehicles produce emissions that are substantially higher than typical vehicle operations. By default, high emitter effects are currently only considered for PM and NO_X emissions from diesel vehicles.

Roadmap includes estimates of the shares of high-emitting vehicles for eight countries, the EU, and the rest of the world, ranging from 0% for some vehicle types and regions up to 20% for others. These shares are based on region-specific estimates and general compliance and enforcement levels for PM and NO_X. An emissions multiplier is used for each control level to determine the emission factors of high-emitting vehicles relative to a typically functioning vehicle of the same type.

As tampering, malfunction, and poor maintenance affect emissions based on the vehicle's age, we follow EMFAC and MOVES's approach to estimate high emitters' emission deterioration. As shown in the figure below, this approach models a linear increase in emission rates from the end of the warranty period (the first dashed line) up to the defined useful life age (the second dashed line). Once the useful life age is reached, we assume a constant emission rate equal to the product of the emissions multiplier and the baseline emission factor. Roadmap derives both the warranty age and the useful life age from region-specific regulations and vehicle activity.

Mileage was converted to age based on region-specific data that show how quickly different types of vehicles accumulate miles. We use TRACCS data for the EU and activity data from VECC for China, which is also consistent with the estimate from Huo et al. (Huo et al., 2012). We use the same ages for the US as in MOVES. In addition, we distinguish warranty and useful life ages by control level. For example, China only starts to have warranty requirements in China VI, and more recent standards, for example, China VI, Euro VI and US2004+, require a longer useful life than earlier standards.

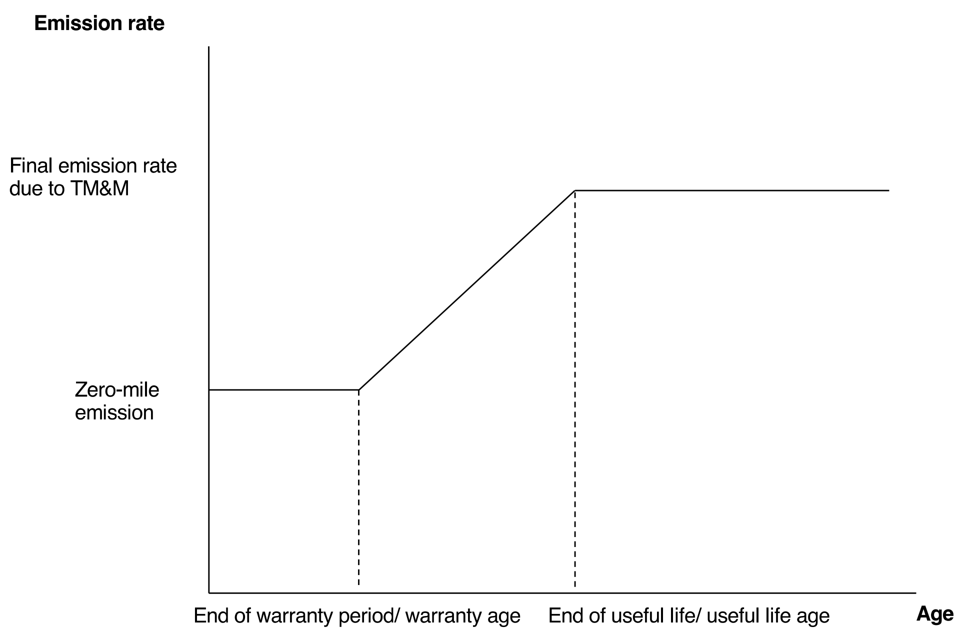

Figure 2: *Emission rate timeline by age, used to model mileage degradation.*

Qualitative depiction of the implementation of tampering, mal-maintenance, and malfunction (TM&M) age effects. Adapted from MOVES2014 technical report.

Sulfur effects

Fuel sulfur effects on sulfate (SO_4) and sulfur dioxide (SO_2) running emissions apply MOVES2014a methods (equations 9-1 and 9-3).

$$SO_2(g) = FC(g) \times [S](ppm) \times \frac{MW_{SO_2}}{MW_S} \times fSO_2 \times \left(\frac{10^6}{ppm}\right)$$

Where:

- $FC(g)$ = fuel consumption (grams)
- $[S](ppm)$ = fuel-sulfur level (ppm)
- $\frac{MW_{SO_2}}{MW_S}$ = the ratio of molecular weight of sulfur dioxide to sulfur = 2.0
- fSO_2 = Fraction of fuel sulfur that is converted to gaseous SO_2 emissions (1 - fraction converted to SO_4).

This equation simplifies to:

$$SO_2(g) = FC(g) \times SO_2\ EF\ (g/ppm) \times S(ppm)$$

where $SO_2 EF$ is the emission factor specific to HDVs and LDVs by emission control technology.

SO_4 emissions are calculated:

$$SO4_x = NonECPMB \times S_B \times \left[1 + F_B \times \left(\frac{x}{x_B} - 1\right)\right]$$

Where:

- $NonECPMB$ = the reference non-elemental carbon $PM_{2.5}$ emission rate
- S_B = the sulfate reference fraction
- x = the user-supplied fuel sulfur level
- x_B = the reference fuel sulfur level
- F_B = the percentage of sulfate originating from the fuel sulfur in the reference case
- $SO4_x$ = sulfate emissions at the user-supplied fuel sulfur level

The S_B, F_B, and x_B, parameters vary by vehicle type, model year group, and emission process.

Biodiesel effects on local air pollutants

Roadmap can also optionally model the impact of biodiesel blends on tank-to-wheel NO_X and PM emissions. Emission multipliers developed by the ICCT consider country-specific differences in feedstock, fuel sulfur level, and biodiesel blend level. Biodiesel effects on local air pollutants are only available for the United States, Indonesia, and Brazil; all other regions do not account for the combustion effects of biofuel blends.

Well-to-wheel GHG emissions of biofuels

The feedstock shares for regions in which this level of detail is provided are used to calculate an aggregate for the emissions in that region. Currently, detailed biofuel feedstock data are not available for every country, but a global default is used as an estimate. This default is calculated based on the share of production of various biofuels in the countries for which we have data. Biofuels are typically blended into a primary fuel type such as gasoline or diesel and as such, they will have a proportionate effect on total emissions based on this blend share. The remaining calculation of GHG emissions is derived from the other fuel in the blend. GHG emissions at the feedstock level may be optionally output by the model for countries in which the detail is provided.

GHG emissions

Roadmap reports emissions for three GHGs (CO_2, CH_4, and N_2O) as well as climate forcers BC, OC, and sulfate aerosols. By default, the model calculates tank-to-wheel (TTW), well-to-tank (WTT), and well-to-wheel (WTW) GHG emissions. Unlike other pollutants which depend on vehicle emission control technologies, CO_2 emissions are calculated based on energy consumption and fuel carbon intensity. Fuel GHG emission intensities are taken from a comprehensive ICCT life-cycle assessment which includes emissions from fuel extraction, refining, operation, and disposal (Bieker, 2021). They are reported on a 20-year and 100-year horizon, using the following GWP values in Table 4 (AR5 WG1 Chapter 8 Supplemental (8SM) Table 8.SM.17):

Table 4: *GWP values for calculating GHG emissions.*

Pollutant	GWP20	GWP100
CO_2	1	1
CH_4	83.9	28.5
N_2O	263.7	264.8
SO_2	-141.1	-38.4
BC	2421.1	658.6
OC	-244.1	-66.4

While combustion (TTW) emissions are typically globally consistent, upstream (WTT) emissions can vary significantly depending on the regional production processes. Roadmap considers the emission intensities of the feedstocks for biodiesel, biogas, ethanol, and hydrogen. The relative blend levels of biodiesel, biogas, and ethanol in diesel, CNG, and gasoline respectively are informed for a few countries by national biofuel blend targets. For other regions, the biofuel blend shares are calculated as the ratio of bio- to fossil-fuel consumption reported in the World Energy Balances.

Base year global inputs for the GHG intensity of electricity generation by power plant type are sourced from IPCC 2011. These are combined with the projected share of electricity generation by type from IEA's World Energy Outlook (WEO) 2022 Stated Policy Scenario (STEPS) for the USA, China, India, Japan, and the EU to obtain default aggregate CO_2 emission intensity values for electricity generation. The emission intensity for electricity generation in other regions is based on the same scenario, but instead uses only the aggregated value. Users may also choose to use the IEA's Announced Policy Scenario (APS), Net Zero Emissions Scenario (NZE), and the Sustainable Development Scenario (SDS) from 2021 for the aggregate emission intensity for electric generation. Finally, users may also specify other scenarios of generation shares (grid mix).

POLICIES AND SCENARIOS

The Roadmap model is designed to explore the implications of national and regional policies. Users can provide inputs defining alternate scenario pathways or updating baseline assumptions.

Scenario inputs

Scenarios can define the inputs shown in Table 5.

Table 5: *Descriptions of scenario inputs.*

Input	Description
Sales powertrain shares	Share of new vehicle sales by powertrain type
Sales used/new ratio	Ratio of used imports to new vehicle sales
Sales	Historical country-specific new vehicle sales
Sales growth rate	Compound annual growth rate of new vehicle sales
Survival curves	Vehicle survival rates by age
Average retirement age	Mean value, used when no detailed survival curves are available
Energy intensity	New vehicle energy intensity (absolute or relative to the baseline)
Fuel sulfur	Diesel and gasoline sulfur content by year
New vehicle standards	Emission standard timeline for new vehicles
Import restrictions	Age or standard-based restrictions on used vehicle imports
Import source	Share of used imports coming from different exporters
Import powertrain shares	Share of used imports by powertrain type
VKT per vehicle	Annual average activity by vehicle type
Mileage degradation	Scaling factors to alter VKT per vehicle by age
PHEV usage patterns	Share of PHEV activity in charge-depleting mode

Fleet renewal policies	Annual activity shifts by vehicle and technology which could represent low emission zones, retrofits, or scrappage policies
Emission factors	Emission factors by country, vehicle, powertrain, fuel, and control technology
Emission deterioration	Emission deterioration multipliers by country, vehicle, powertrain, fuel, age, and control technology
High emitter parameters	High emitter shares, emissions multipliers, warranty length and useful life ages
Biofuel blend shares	Annual biofuel blend shares for diesel, gasoline, or CNG
Feedstock shares	Biofuel feedstock shares
Fuel emission intensity	GHG and upstream air pollutant fuel emission intensities (excluding electricity)
Electricity grid mix	Grid mix by generation source
Electricity emission intensity	Electricity grid emission intensity by year per generation source (excluding transmission and distribution losses)
Transmission and distribution losses	Regional transmission and distribution (T&D) loss multipliers
Aggregate electricity emission intensity	Electric grid aggregate GHG intensity including T&D losses
Load factors	Passenger or freight load factors, in number of passengers or tonnes

Subregional policies

Roadmap’s default data inputs represent best estimates of each country’s total fleet of on-road vehicles. For some analyses, however, it can be useful to model the effects of policies implemented at a more granular level, such as states or provinces within a country. Roadmap can run analyses for any number of arbitrary subregions by using national fleet data, if appropriate downscaling factors are provided. When running in the subregion mode, all model results including vehicle stock, sales, activity, energy consumption, and emissions are output for each subregion.

In order to toggle the subregion mode, users must provide a mapping file indicating in which country/region (denoted by ISO alpha-3 code in the model) the subregion is located. Additionally, sales for all vehicle types must be provided for each subregion, either as a share of the regional total or as absolute numbers of vehicles. If data are only available for a subset of years, the model will extrapolate the subregional sales shares to cover all model years. Note that the specified subregions do not have to cover the entire country/region, in which case a subregion labeled “Other” is created to represent the missing share. Further downscaling factors are only required if modeling a subregion within a country/region that uses year-over-year survival curves, which requires downscaling factors for stock distribution by age. Subregional stock totals are also required if calibrating subregion-specific survival curves.

Besides the inputs used as downscaling factors, all other subregion inputs such as annual vehicle mileage, energy intensity, and emission factors are inferred from the larger region by default. The user may optionally provide subregional detail for any of the scenario input files that are supported by the model, except for total vehicle sales. As a subregion's total vehicle sales or share of national sales are used to define its baseline vehicle fleet as a subset of the national fleet, varying subregion sales as a scenario input is not supported.

Vehicle segmentation

Roadmap can be run for any of six vehicle types by default, including two- and three-wheelers (MC), passenger cars (PC), light commercial vehicles (LCV), urban and coach buses (Bus), medium-duty trucks (MDT), and heavy-duty trucks (HDT). These categories are intentionally broad, as there is little consistency in terms of classifications and data availability across all global regions. Many countries, however, do have greater detail on vehicle segments. In these cases, Roadmap can accept additional data on how to segment the larger categories and run with a greater level of detail.

Vehicle segmentation inputs are very similar to subregional inputs, described above. To toggle the segmentation mode, users must provide a mapping file of segments to Roadmap vehicle types, as well as indicate in which countries/regions (denoted by ISO alpha-3 code) the mapping applies. Different levels of segmentation can be applied for different ISOs. As with subregions, detailed sales must also be provided for each segment, either as a share of the Roadmap vehicle type total or as absolute numbers of vehicles. An example of a basic segment map is provided in Table 6.

Table 6: *Example segment map.*

ISO	Vehicle	Segment
USA	Bus	Urban
USA	Bus	Coach

With detailed vehicle segments, it is highly recommended to provide scenario inputs for key characteristics of each segment. Many segments are typically defined by gross vehicle weight or activity patterns which make it unrealistic to assume variables like energy intensity and mileage would be the same as the broader vehicle category. All supported scenario inputs can be specified at the segment level.

The Roadmap model data pipeline also provides the option to output MOVES3 model inputs by vehicle segment. In this case, the user must define their configuration to utilize these data.

Combining Subregions and Segments

Roadmap has the capability to run scenarios that use both subregional and segmented data. In this case, users must include mapping and sales files for subregions and segments separately. Default data is disaggregated first using subregional downscaling factors, then by segments. It is important to note that inputs for both levels of disaggregation must not both be totals, as this can lead to conflicting values. When defining further scenario inputs, it is required to provide the full level of detail in each input file; that is, the inputs should include detail for both subregion and vehicle segments.