



# Global Transportation Roadmap

## Model Documentation and User Guide

### ICCT Roadmap Model Version 1-0

December 2012

The International Council on Clean Transportation is an independent nonprofit organization founded to provide high-quality research and analysis to governments in the world's largest vehicle markets. Our mission is to improve the environmental performance and energy efficiency of road, marine, and air transportation in order to benefit public health and mitigate climate change. For more information on our Global Roadmap, please visit [www.theicct.org/transportation-roadmap](http://www.theicct.org/transportation-roadmap).

## SUMMARY

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The ICCT's Global Transportation Roadmap model is a tool 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.

The Roadmap model estimates changes in actual transportation activity by country and region based on changes in forecasts of population, Gross Domestic Product (GDP), and relative fuel prices. Country estimates of future transportation activity are then split by mode using dynamic mode share assumptions to calculate GHG and local air pollutant emissions. Results are summarized on an output tab, which enables comparisons between cases, modes, and countries, and a country dashboard tab, which tabulates numerous estimates for any selected country/region.

This document describes the scope, structure, and functionality of the Roadmap model, which is a spreadsheet tool developed in Microsoft Excel. The report begins with an introduction to the model scope and structure, which is designed to equip the user to modify policy parameters, customize model outputs, and interpret results appropriately. The report continues with a documentation of the seven major modules that make up the spreadsheet tool. This second section is designed to allow interested users to better understand the model inputs, calculations, assumptions, and data sources.

Throughout the documentation, the following symbols are used to denote warnings, tips, and calculations.



Warning.



Tip.



Calculation.

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## 1. MODEL SCOPE AND STRUCTURE

The Roadmap model estimates total transportation activity, mode shares and emissions from 2000 to 2050 in five-year increments, including Well-to-Wheel (WTW) emissions of GHGs and local air pollutants from on-road vehicles, locomotives, aircraft, and marine vessels. The following table describes the specific modes, geographic regions, forecast years, pollutants, vehicle technologies, fuel types, and cases covered by the Roadmap model.

**TABLE 1. MODEL SCOPE**

| Category             | Items  |
|----------------------|--|
| Transportation modes | <b>Light Duty Vehicles</b> (LDVs, including SUVs), <b>buses</b> , <b>2-wheelers (2Ws)</b> , <b>3-wheelers (3Ws)</b> , <b>Light Heavy Duty Trucks</b> (LHDTs) (typically 8,500 – 14,000 lbs GVWR), <b>Medium HDTs</b> (MHDTs) (14,001 – 33,000 lbs GVWR), <b>Heavy HDTs</b> (HHDTs) (>33,000 lbs GVWR), <b>passenger rail</b> , <b>freight rail</b> , <b>aviation</b> (passenger only), and <b>marine</b> (freight only).   |
| Geographic regions   | The geographical focus is on the <b>11 countries/regions</b> with greatest annual new vehicle sales: United States, EU-27 (27 member states included in the European Union), China, India, Japan, Brazil, South Korea, Mexico, Canada, Australia, and Russia. The model also considers <b>five broader regions</b> : Latin America-31, non-EU Europe, Asia-Pacific-40, Africa, and the Middle East.  |
| Time horizon         | <b>2000 to 2050</b> in 5-year increments.  |
| Pollutants           | <b>GHG emissions</b> (CO <sub>2</sub> , CH <sub>4</sub> , and N <sub>2</sub> O) and <b>local air pollutants</b> (NO <sub>x</sub> , PM <sub>10</sub> , PM <sub>2.5</sub> , CO, BC, and SO <sub>2</sub> ). The Roadmap's calculations of emissions of GHGs and local air pollutants incorporate the fuel lifecycle, including the refining, processing, distribution and combustion of fuels. The Roadmap does not assess lifecycle emissions from vehicle manufacturing, distribution or end-of-life, or the transportation infrastructure lifecycle. |
| Vehicle technologies | <b>On-road vehicles</b> : conventional (internal combustion engine), hybrid, plug-in hybrid, fuel cell, and battery electric vehicles.<br><b>Locomotives</b> : diesel-electric, and electric.<br><b>Aircraft and marine vessels</b> : conventional engines only.   |
| Fuel types           | Gasoline, diesel (conventional, low-sulfur), ethanol (grain, sugarcane, cellulosic), biodiesel (oil-based, lingo-cellulosic), CNG, LPG, hydrogen, electricity, jet fuel, and residual fuel.  |
| Cases                | The model can handle two cases at a time:<br><b>Base case</b> : considers the effects of adopted policies, but does not consider additional technological improvements or policy changes;<br><b>Trajectory case</b> : accounts for changes in policies and technologies to achieve emission reductions.  |

The Roadmap model is built around two cases. The **base case** includes all adopted, enforceable, and finalized policies but assumes no further improvement beyond what is mandated in terms of vehicle fuel efficiency, penetration of electric drive vehicles, or biofuels. Trends in vehicle activity and mode share are maintained based on forecasted socio-demographic parameters. Users may adjust assumptions in the base case as better data become available, or update this case as new policies are finalized. The **trajectory case** is intended to be customized by the user and



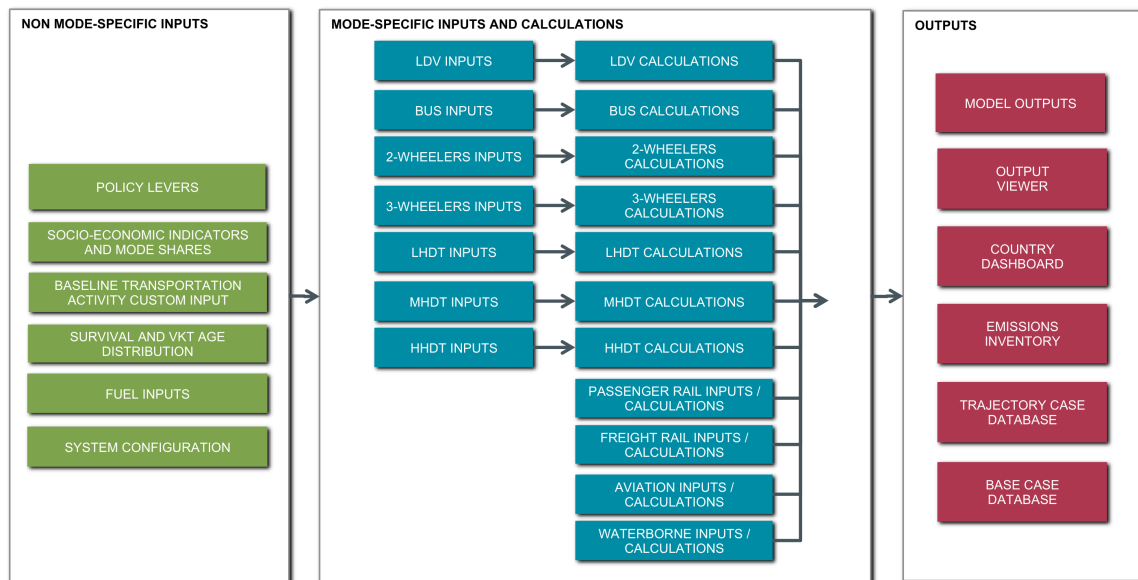
compared against the base case to evaluate the effects of additional policies on transportation emissions.



In the public version of the model, the assumptions in the trajectory case are equal to those in the base case. In the future, the ICCT will issue data inputs associated with different policy cases.

FIGURE 1 presents an overview of the tabs included in the Roadmap model. Tabs are categorized by general inputs, mode-specific inputs and calculations, and outputs.

**FIGURE 1. MODEL ORGANIZATION**



The Roadmap model can be used to generate policy-relevant results to varying degrees of breadth and detail. Thus, the relative ease or complexity of deriving usable outputs depends on the nature of the policy question. The following table provides an overview of the customizable inputs present in each model tab shown in the previous figure.

- Tabs with “Low” complexity allow the user to adjust data-validated cells and typically involve pre-defined tabulations and charts.
- Tabs with “Medium” complexity allow the user to adjust input assumptions by editing input tables—however some of these cells contain formulas that may be lost when modified.
- Tabs with “High” complexity allow advanced users to edit the equation parameters on which transportation activity and emissions estimates are based—users should be very careful when editing these tabs, since the calculations of other modules hinge on these values and equations.

**TABLE 2. MODEL STRUCTURE**

| Tab                | Description   | User inputs   | Complexity |
|--------------------|---|---|------------|
| Intro              | Summarizes the scope of the model and provides a general overview of the model structure and calculation methods. It also provides a colored legend that defines the purpose of cell and text colors.   | None.   | —          |
| Outputs            | <u>Model Outputs</u> : enables comparisons of model outputs between cases, modes, and regions.  | Select whether to include each of eight policy levers. View output charts by region, case, pollutant, and mode.   | Low        |
| Inputs             | <u>Policy Levers</u> : includes <b>customizable</b> assumptions about how fuel economy, transport activity, market penetration of electric vehicles, fuel carbon content, etc. vary from the base case. | Primary tab for adjusting trajectory case assumptions. These are activated by setting the relevant levers in the “Outputs” tab to “TRUE”.   | Low        |
| Output Viewer      | Enables flexible comparisons of input and output parameters.  | View outputs by region, case, and mode for a wide variety of parameters.  | Low        |
| Country Data       | Summarizes total and mode-specific activity, energy, and emission projections for a specified country/region.   | Outputs only. View tabulated results for a selected region by pollutant, mode, and units.   | —          |
| Baseline VKT Input | <u>Baseline Transportation Activity Custom Input</u> : offers alternative method of forecasting transportation activity   | Input mode-specific annualized activity growth rates to replace projections based on socio-economic indicators.   | Medium     |
| Socio              | <u>Socio-economic Indicators and Mode Shares</u> : estimates future transportation activity and mode shares based on Gross Domestic Product (GDP), population, and relative fuel prices.                | Edit forecasts of population, Purchasing Power Parity (PPP) GDP growth rates, and relative fuel prices, by region. <b>Intermediate outputs</b> : predicted vehicles/capita, passenger and freight activity and mode share projections ( <b>base</b> and <b>trajectory</b> ).  | High       |
| Fuel               | <u>Fuel Inputs</u> : includes fuel-related assumptions and inputs on fuel blends, sulfur content, and emission factors are outlined in this tab.  | Adjust <b>base case</b> assumptions by region and forecast year. Gasoline and diesel blends, plug-in hybrid electricity share, fuel sulfur content, fuel-based WWT and TTW emission factors, user factors.  | Medium     |
| Mode-specific tabs | Input and calculation tabs for each mode (LDV, Bus, 2W, 3W, LHDT, MHDT, HHDT, Passenger Rail, Freight Rail, Aviation, Marine).  | <u>Inputs</u> : edit historic vehicle stock (2000-2010), historic vehicle sales (2000-2010), load factors, annual distance/vehicle, share of VKT in urban areas, share of annual sales by fuel/engine technology, fuel consumption by engine technology, emission factors, introduction of emissions standards by year and region, share of vehicle activity by fuel/engine technology in 2000, in-use fuel consumption adjustment by specific fuel efficiency. | Medium     |
| Config             | <u>System Configuration</u> : contains the various lists used in the model, unit conversions, and Global Warming Potential (GWP) assumptions.   | Adjust GWP or Particulate Matter Conversion.  | —          |
| Survival           | <u>Survival and VKT Age Distribution</u> : accounts for gradual retirement in vehicle populations. The resulting survival rates are factored into the Mode Specific tabs                                | Modify shape of “survival” curves to adjust rates of vehicle fleet turnover.  | High       |

|  |  |  |  |
|--|--|--|--|
|  | to calculate fleet average emissions factors and fuel economies. |  |  |
|--|--|--|--|

## 2. OUTPUT TABS

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The model is designed to allow the general user to activate and adjust policy levers, and view the impacts on emissions using only the “Inputs,” “Outputs,” and “Country Data” tabs; however the model is open to additional modification. In general, **trajectory** case parameters can be easily modified using the “Inputs” tab, whereas **base case** parameters and underlying data and assumptions should be modified in the appropriate **Input** tab (e.g., Socio, Fuel, LDV Inputs, etc.).

### 2.A. OUTPUTS

#### Select Region

Users can customize results shown on the “Outputs” tab to focus on any of the eleven largest vehicle markets or one of five regional aggregations. The default section, “Global,” shows outputs for all countries and regions in the model scope.

#### Policy Lever Control Panel

An important element of the “Outputs” tab is the “Policy Lever Control Panel.” Here users can **include or exclude policy levers from the trajectory case** and compare the resulting forecast to the base case. Several levers apply to all modes, including Low Carbon Fuels, Grid Decarbonization, Mode Shift, Activity Reduction, and Fuel Sulfur Effects. The remaining three levers can be activated for specific modes: these include Vehicle Fuel Economy, Electric Drive Vehicles, and Emission Standards. For a given mode, marking a lever “TRUE” will activate the corresponding trajectory case values in the “Inputs” tab.



To include the impacts of specific policies, users need to input policies in the “Inputs” tab and set the corresponding lever to “TRUE” in the “Outputs” tab. Marking a policy lever “FALSE” deactivates that policy for all regions and ignores any user values in the corresponding trajectory case inputs. For example, if the “Vehicle fuel economy” lever is deactivated for LDVs, the model will still apply the fuel economy improvements to LDVs specified in the **base case** (reflecting the standards already in effect) but ignore any additional improvements specified in the **trajectory case**.

**FIGURE 2. POLICY LEVER CONTROL PANEL**

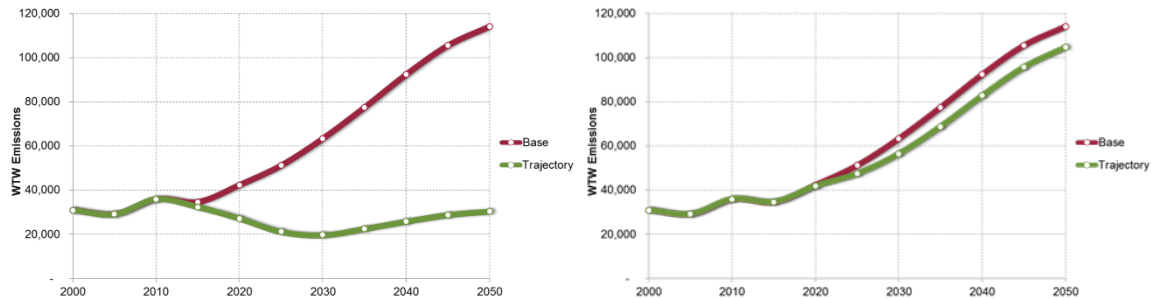
| LEVER                    | All  | LDV  | HDT  | Other on-road | Rail | Aviation | Marine |
|--------------------------|------|------|------|---------------|------|----------|--------|
| Vehicle Fuel Economy     |      | TRUE | TRUE | TRUE          | TRUE | TRUE     | TRUE   |
| Low Carbon Fuels         | TRUE |      |      |               |      |          |        |
| Electric Drive Vehicles  |      | TRUE | TRUE | TRUE          | TRUE |          |        |
| Grid Decarbonization     | TRUE |      |      |               |      |          |        |
| Mode Shift               | TRUE |      |      |               |      |          |        |
| Activity Reduction / MBM | TRUE |      |      |               |      | TRUE     | TRUE   |
| Emission Standards       |      | TRUE | TRUE | TRUE          | TRUE | TRUE     | TRUE   |
| Low Sulfur Fuels         | TRUE |      |      |               |      |          |        |

The Policy Lever Control Panel can be especially useful for conducting sensitivity analyses of policy levers. For example, a user might specify a region and compare the base and trajectory emissions of a particular pollutant in the chart immediately below the control panel. Then, the user could deactivate “Emission Standards” to see the marginal effect—in this case, what trajectory emissions would be if emissions standards did not change from the base case but other policy levers improved relative to the base case.



Use the Policy Lever Control Panel to conduct sensitivity analyses of policies for a specified region and pollutant.

**FIGURE 3. SAMPLE COMPARISON OF EMISSIONS FORECASTS – EMISSIONS STANDARDS MARKED “TRUE” VS. “FALSE”**



#### “Outputs” charts

1. Trajectory and base case emissions
2. Country emissions by mode
3. Passenger activity by mode
4. Freight activity by mode
5. Vehicle stock and sales
6. Share of vehicle sales by engine technology
7. New fleet fuel efficiency
8. Fuel consumption and savings
9. Fuel consumption by mode in 2010
10. Fuel consumption by mode
11. Emissions standards timeline
12. Performance metrics
13. Emissions relative to the year 2000

#### Output Charts

Charts of key parameters are included in the “Outputs” tab. Users should be aware that some charts are not applicable to every mode and pollutant. Thus, some mode and pollutant selections will expectedly cause certain charts and support tables to be blank.

*Example: “Vehicle stock and sales” and “New fleet fuel efficiency” apply only to on-road modes. Therefore, these charts should be blank if the user selects passenger or freight rail,*

*aviation, or marine modes.*

### **Support Tables**

The last section in the “Outputs” tab contains support tables, which compile values for calculated TTW vehicle efficiencies from the rest of the model and convert these into the units specified the “Outputs” charts. Other tables in this section perform similar functions, compiling calculations of average fuel carbon content, transport carbon intensity, and passenger and freight activity.



Grayed-out tables should not be deleted, since calculations depend on the values in these tables to produce model results.

### **2.B. COUNTRY DATA**

#### **“Country data” tabulations**

1. Socio-economic indicators and mode share
2. On-road activity and fuel efficiency
3. Rail activity and energy intensity
4. Fuel inputs
5. Vehicle emission standards
6. TTW energy consumption
7. TTW emissions by mode

The “Country data” tab provides a comprehensive, tabulated summary of model inputs and outputs for a specified region/country. It excludes marine emissions and activity, since these are estimated only at the global level. This sheet tabulates numerous parameters to allow side-by-side comparisons between

the trajectory and base case. As such, it is a good place to review input and output assumptions for a specific country, though these assumptions should only be edited using the corresponding input tabs. The parameters are organized in seven broad categories. As in the “Outputs” tab, users may need to adjust the specified mode or pollutant in order to show certain support tables.

### 3. POLICY INPUTS

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The underlying input assumptions behind the levers in the “Outputs” tab can be edited in the “Inputs” tab. The grayed out tables to the right of the policy inputs are activated by the selections made in the policy lever control panel and directly linked to the rest of the calculations in the model. Once active, each grayed out table draws upon the related trajectory or base assumptions (for the calculations). The following section describes how to edit the assumptions of each policy lever.

#### 3.A. ON-ROAD VEHICLE FUEL ECONOMY (PASSENGER VEHICLE/FREIGHT TRUCK)

For inputs corresponding to the “Passenger Vehicle/Freight Truck Fuel Economy” policy lever, the input tables for the trajectory and base case for each mode are editable and displayed side-by-side. For each case, the user may enter fuel economy standards for new vehicles by region and year. These values should reflect the average **test cycle efficiency** for new ICE and non-plug-in hybrid vehicles. For LDV, the fuel economy values represent average fuel consumption for new ICE vehicles, including gasoline, diesel, non-plug-in hybrids, CNG and LPG. Inputs for other modes should be entered separately for gasoline and diesel vehicles. Assumptions about the difference between test cycle and in-use efficiency can be edited in the mode-specific tabs. The test cycle efficiency for new electric drive vehicles is assumed to improve at roughly half the rate of ICEs—the rationale for this assumption is that electric drive vehicles are already substantially more efficient than ICEs, which indicates that there is less potential for further efficiency improvements. Users may specify one of six different units for the fuel economy standards of a given region: MJ/km, L/100km, km/L, mpg, gCO<sub>2</sub>/km, or gCO<sub>2</sub>/mi. The support tables to the right of these input columns convert all fuel economy inputs to MJ/km and display the equivalent annual percent improvement.

Fuel economy/consumption for new on-road vehicles should be entered in absolute units according to the chosen input unit.



For the purposes of annual improvements, each 5-year time period is denoted by the last year in that period. That is, annual improvements in “2050” apply to the period 2046-2050.

#### 3.b. RAIL, AVIATION AND MARINE EFFICIENCY

Similar to on-road vehicle fuel economy, the input tables for “Rail, Aviation & Marine Efficiency” policy levers are editable and displayed by trajectory and base case. For rail and aviation, annual efficiency improvements can be adjusted by region and projected year. The improvements represent the annualized rate of reduction in fuel consumption for each mode. For rail, improvements apply to the diesel share of energy only. At present, marine improvements can be entered only at the global level.

Efficiency improvements to rail, aviation, and marine modes should be entered in the form of annual percentage rates.

#### 3.c. LOW CARBON FUELS

This section allows adjustments in both regulatory treatments and also fuel blend shifts. For biofuels, WTT CO<sub>2</sub> emission factors differ substantially by regulatory agency. Four sets of

regulatory estimates are pre-loaded in the Roadmap, which are RFS2, CARB, EU (no iLUC) and EU (with iLUC). By default, the Roadmap assumes no emission benefits from biofuels; however, users can choose which set of regulatory estimates to use in the model. Additionally, for a given biofuel, users can decide whether to include TTW biofuel offset. Default values set all TTW CO<sub>2</sub> emissions of biofuels equal to zero by setting the option to “Yes”.

For conventional fossil fuels, WTT CO<sub>2</sub> emission factors are calculated as a weighted average depending on the global share of conventional and various unconventional fossil fuel sources. By default, EIA forecasts are used. Users can adjust these values in both base and trajectory cases.

#### Fuel blend increase

1. Gasoline to ethanol (starch)
2. Gasoline to ethanol (sugar)
3. Gasoline to ethanol (cellulosic)
4. Diesel to biodiesel (oil-based)
5. Diesel to biodiesel (cellulosic/waste-oil)

The share of the corresponding biofuel in the fuel blend is shown to the right of each input table. The dropdown menu can be used to toggle between the base and the trajectory case. As in the other “Inputs” tab sections, fuel carbon content input parameters only change the trajectory case relative to the base case. Users

who wish to edit the base case fuel blend assumptions may do so from the “Fuel” tab.

*Example: if the base case blend for a given region and time period is 95% gasoline and 5% sugarcane ethanol, entering “10%” in the corresponding input field would shift 10% from gasoline to sugarcane ethanol, and result in a blend of 85% gasoline and 15% sugarcane ethanol in the trajectory case.*

### 3.d. LOW SULFUR FUELS

The Roadmap models the effects of diesel fuel sulfur content on emissions of PM and SO<sub>2</sub> from all types of modes. In general, high levels of sulfur in fuel inhibit the function of emission control devices and result in higher emissions for each level of emissions control. Policies that reduce the sulfur content of diesel can be entered in the trajectory case.

### 3.e. ELECTRIC DRIVE VEHICLES

This section allows users to adjust the electric drive vehicle share of annual light-duty vehicle sales in the trajectory case, in terms of percentage-point increase from the base case. Increases in the share of electric drive vehicles for other on-road modes can be entered in the mode-specific input tabs.

#### Electric vehicle sales

1. Gasoline plug-in hybrid
2. Diesel plug-in hybrid
3. Fuel cell
4. Electric

To the right of each input table, users can toggle the dropdown menu to view the annual share of new vehicle sales of the corresponding electric drive vehicle type for the base or trajectory case. Percentage-point increases over the base case need to be entered for each period of interest: specifying an improvement for a single time period will not affect sales in future time periods.

*Example: if fuel cell vehicles were to make up 5% of all new vehicle sales in 2045 and 10% in 2050 in the base case, entering “5%” in the input cell for 2045 and “5%” in 2050 would result in fuel cells making up 10% of new vehicle sales in 2045 and 15% in 2050 in the trajectory case.*

### 3.f. GRID DECARBONIZATION

In this section, users can input reductions in the overall carbon intensity of electricity, in terms from percent reduction from the base case. The table to the right of the input parameters shows the resulting country-specific WTT emission factors for electricity in gCO<sub>2</sub>/MJ. As with other tables in the “Inputs” tab, users may toggle between the base and trajectory case. A simplifying assumption applies the same percent reductions in carbon intensity across all pollutants and regions—this assumption models the general effect of increasing the mix of renewable electricity in the grid and thus reducing local air pollutants along with GHGs. Country- and pollutant-specific WTT emission factors for electricity can be entered in the “Fuels” tab, though doing so will override the percent reductions specified in this policy lever.



Reductions in electricity carbon intensity should be entered as positive values between zero and 100 percent. Cells exceeding these limits will display red fill.

### 3.g. MODE SHIFT

#### Mode shifts

1. LDV to bus
2. LDV to rail
3. LDV to 2-wheelers
4. LDV to 3-wheelers
5. LDV to walk/bike
6. HHDT to rail

Users can specify percentage transportation activity shifts from high-carbon modes (light duty vehicles and heavy HDTs) to lower-carbon alternative modes (public transit, freight rail, and non-motorized transportation (NMT)) in the trajectory case. Six possible mode shifts can be adjusted using the “Inputs” tab. In general, the emissions reductions from mode shifts are a function of the difference in emissions per unit of activity (gCO<sub>2</sub>/pkm or gCO<sub>2</sub>/tkm) times the volume of activity shifted. Corresponding levels of activity shifted (billion PKM/TKM) are shown in the tables on the right according to

the input percentages. These values provide an indication of the level of transit, freight rail, or NMT investment that would be required to offset the reduction in LDV or HHDT activity. For users who want to model constant absolute shifts in activity after a certain model year, table tools are available on the right to help calculate the corresponding percentage over time. These tables estimate the input mode shifts that would need to be entered to model a constant shift in activity despite changes in overall activity.

*Example: entering “3%” in 2015 for Mexico in the “LDV to Bus” table would reduce LDV passenger activity by 3%, convert it to PKM, and add that same number of PKM to bus activity in 2015. If the same PKM values are expected to be shifted after 2015 constantly, select the year as 2015 from the dropdown menu in the table on the right (column AF), then copy the calculated percentages shift for future years into the corresponding mode shift input fields.*



Only positive values between zero and 100% may be entered (reverse mode shifts from low-impact modes to LDVs, etc. cannot be input). The box above the upper righthand corner of each parameter table will read “Error” if user inputs result in any mode having a share greater than 100% or less than zero. Reductions in one year do not carry over for future years.

### 3.h. TRAVEL DEMAND MANAGEMENT

The Roadmap provides users flexibility to decrease or slow the growth of transportation activity by reducing activity or trip length in trajectory case. By entering the activity reduction percentages for LDV and trucks, users can decrease the PKM/TKM needs by specific region and model year. In



addition, average trip length in urban areas can be adjusted for LDV, 2W and 3W. Higher percentages reflect increases in density of urban areas and thus shorter trip lengths. This factor is in addition to reductions in total passenger activity.

Trajectory case activity starts out as equal to baseline activity. Then, it is adjusted by reductions in activity and mode shifts (implemented simultaneously), followed by reductions in urban trip length where available.



Only positive values between zero and 100% can be entered. Reductions in one year do not affect future years.

### 3.I. AVIATION MARKET-BASED MEASURES

This section models the effects of Market-Based Measures (MBMs) on demand for aviation. Users can adjust the percentage reduction in activity for both cases.



Values applied in the baseline case should also be entered for the trajectory case. Only positive values between zero and 100% can be entered. Reductions in one year do not affect future years. By default, the estimated in-sector reductions in aviation activity are included for the EU ETS.

### 3.J. LOAD FACTORS

This section provides users to option to adjust load factors in units of percent increase from the base case for LDV, buses, or heavy-duty trucks. Load factors are used to estimate vehicle activity from transportation activity, which represent the average number of passengers per vehicle, or payload for freight vehicles. Corresponding values are shown to the right of each input table. These can be customized via dropdown menus to show either the initial value for base case or the user-adjusted value for trajectory case. Increases in load factors could be driven by either improved congestion management policies or logistics. For trucks, resulting load factors apply to all light, medium and heavy heavy-duty trucks.

### 3.K. IN-USE FUEL EFFICIENCY

Reductions/increases in in-use fuel consumption can be adjusted for on-road vehicle activity in urban areas. Users can either improve efficiency in the trajectory case or worsen the efficiency in the base case. This section is applies adjustments consistently across all on-road modes, including heavy-duty trucks, and to all ICE vehicles (excluding fuel cell and electric vehicles). Improvements in in-use fuel efficiency in urban areas could be driven by congestion relief strategies, such as congestion pricing, cordon pricing, VKT fees, carpooling incentives, and parking pricing. Here users can specify trajectory case improvements to the average efficiency of on-road vehicles in units of percent improvement over the base case. Similarly, users can worsen efficiency in the base case, which could result from increasing congestion due to VKT growth in the absence of adequate congestion relief strategies.

The following table compares the effects of a sample change in “improvement in in-use fuel efficiency” in the trajectory case versus “degradation of in-use fuel efficiency” in the base case. Total fuel consumption for a given mode as a result of these policies is approximated by the equation:



$$(\text{Adjusted ICE fuel consumption}) = (\text{Unadjusted ICE fuel consumption}) * [1 - \% \Delta(\text{Vehicle efficiency in urban areas}) * (\text{Share of VKT in urban areas})]$$

**TABLE 3. COMPARISON OF IN-USE FUEL EFFICIENCY LEVERS — EXAMPLE**

|                    | Improvement in in-use fuel efficiency  | Degradation of in-use fuel efficiency  |
|--------------------|--|--|
| Case               | Trajectory   | Base   |
| Example scenario   | Congestion pricing improves (trajectory case) urban fuel economy in 2030 by 10%. | Unmitigated congestion degrades (base case) urban fuel economy in 2030 by 10%. |
| Urban fuel economy | Improves from 50 mpg to 55 mpg.  | Degrades from 50 mpg to 45 mpg.  |
| Input value        | "10%" in 2030  | "10%" in 2030  |



Note using this section assumes that improvements in in-use fuel efficiency are made only in trajectory case, while degradation in efficiency as a result of congestion occurs only in the base case. Using this section with some degree of precision would likely require more-refined assumptions on the share of HDT VKT in urban areas (by default assumed to be 50%).

## 4. INPUTS AND CALCULATIONS

The following sections explain the tabs that make up the spreadsheet tool, including relevant equations and calculation processes. The first part of each section focuses on the inputs, which can be edited to customize model results, and the second part of each section is designed to provide interested users with a better understanding of the model calculations, assumptions, and data sources. Similar to the organization within each section, the modules are ordered from “Low” to “High” complexity.

### 4.A. CALCULATIONS OVERVIEW

Generally, emissions are the product of transportation activity and emission factors.



In general, for each pollutant, country, and year, WTW emissions are equal to the sum of WTT emissions and TTW emissions:

$$WTW \text{ Emissions} = TTW \text{ Emissions} + WTT \text{ Emissions}$$

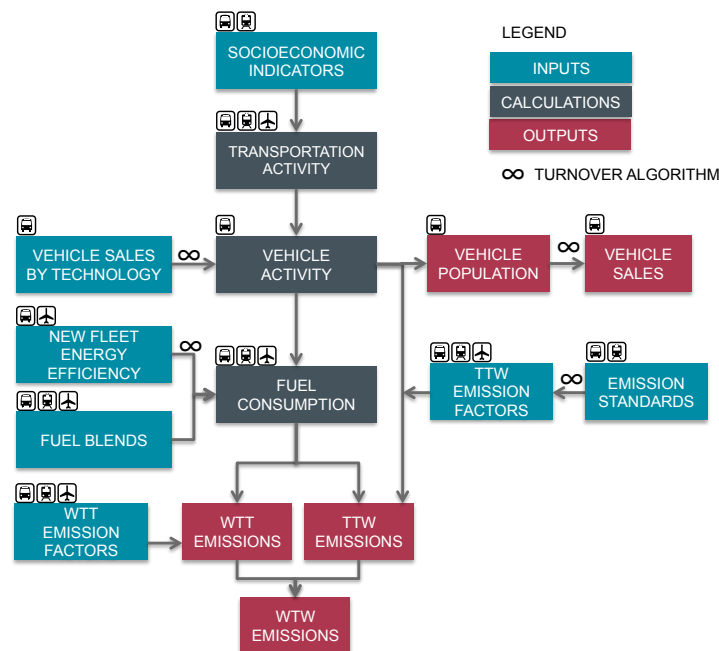
Where,

$$TTW \text{ Emissions} = \text{Transportation Activity} * \text{Emission Factors}$$

$$WTT \text{ Emissions} = \text{Energy Consumption} * \text{Emission Factors}$$

The following figure illustrates the simplified emissions calculation methods in the Roadmap model.

FIGURE 4. SIMPLIFIED EMISSION CALCULATION METHODS



Changes in land-based passenger and freight transportation activity are determined from changes in population, Gross Domestic Product (GDP), and relative fuel price forecasts. Aviation and marine activity are based on International Civil Aviation Organization (ICAO) and International Maritime Organization (IMO) projections. Vehicle activity (for on-road modes) is then determined from transportation activity and load factors. The breakdown of vehicle activity by

technology type is determined from vehicle sales and a turnover algorithm. Vehicle population and sales are calculated as model outputs, and can be used to validate and calibrate the model. Fuel consumption is the product of vehicle activity and average fleet energy efficiency (which is estimated from the new fleet efficiency and a turnover algorithm). The breakdown of fuel consumption by fuel type is determined from fuel blends.

TTW emissions of CO<sub>2</sub> are calculated as the product of fuel consumption (by fuel type) and carbon content of fuels, while TTW emissions of other pollutants are calculated as the product of TTW emission factors and either vehicle activity (for on-road modes) or transportation activity (for rail and aviation). Average TTW emission factors are based on vehicle emission standards and a turnover algorithm. WTT emissions of all pollutants are calculated as the product of fuel consumption (by fuel type) and emission factors. Emissions from marine vessels are estimated directly from IMO projections.

The specific methods to calculate transportation activity, energy consumption, and emission factors for different modes and pollutants are summarized in TABLE 4. More-detailed calculations are presented in subsequent sections.

**TABLE 4. EMISSIONS CALCULATIONS**

| Mode     | Pollutant                     | Transportation activity  | Emission factor*  |
|----------|-------------------------------|--|---|
| On-road  | TTW - CO <sub>2</sub>         | VKT is estimated from socio-economic indicators and used to calculate energy consumption, which is multiplied by emission factors to estimate emissions.<br><i>Energy consumption (MJ) = Vehicle efficiency (MJ/km) x VKT</i>  | g/MJ<br>Based on carbon content of fuels included in the mix. |
| On-road  | TTW - All but CO <sub>2</sub> | VKT is estimated from socio-economic indicators and used directly in the calculations of emissions.  | g/km<br>Based on vehicle emission standards.                  |
| Rail     | TTW - All                     | Passenger-km and ton-km are estimated from socio-economic indicators and used to calculate energy consumption, which is multiplied by emission factors to estimate emissions. <i>Energy<sub>passenger rail</sub> (MJ) = Locomotive efficiency (<math>\frac{MJ}{pass.km}</math>) x pass. km</i><br><i>Energy<sub>freight rail</sub> (MJ) = Locomotive efficiency (<math>\frac{MJ}{ton.km}</math>) x ton km.</i> | g/MJ  |
| Aviation | TTW - All                     | Revenue passenger-km is estimated from ICAO projections and used to calculate energy consumption, which is multiplied by emission factors to estimate emissions.<br><i>Energy consumption (MJ) =</i>   | g/MJ  |

|           |           |   |      |
|-----------|-----------|---|------|
|           |           | <i>Aircraft efficiency (RPK/MJ) x RPK.</i>                                |      |
| Marine    | TTW - All | N/A. Emissions are estimated directly from IMO emissions projections.     |      |
| All modes | WTT - All | Energy consumption (MJ) is used directly in the calculation of emissions. | g/MJ |

TTW: Tank to wheels; WTT: Well to tank.

\* The same emission factors were used for all regions. The model has a factor to differentiate emission factors by region, but currently this factor is set to 1.

#### 4.B. FUEL

The “Fuel” tab contains fuel-related assumptions and input parameters, including fuel blends for gasoline and diesel, sulfur content, fuel-based CO<sub>2</sub> emission factors, and WTT emission factors for both trajectory and base cases. The following table shows the base case assumptions, which can be edited in the “Fuel” tab.

**TABLE 5. FUEL INPUT PARAMETERS**

| Table                                       | Description  |
|---|--|
| Fuel blends (%)                             | Biofuel percentages blended into fuel for gasoline and diesel vehicles, including plug-in hybrids.   |
| Sulfur content (ppm)                        | Gasoline, conventional diesel, ultra-low sulfur diesel, CNG, LPG.  |
| Fuel-based emission factors                 | Based on energy content, fuel density, carbon content.   |
| WTT emission factors (g/MJ)                 | For each pollutant and fuel. Trajectory case is set equal to base case.  |
| User factors                                | For each fuel, by region and year. User factors adjust any discrepancies in WTT emission factors relative to U.S. 2010 values, which are set to 1. |
| WTT emission factors for electricity (g/MJ) | By region, pollutant, and year.  |

Changes to “Fuel Blends”, “Sulfur content (weighted average for diesel)” and “WTT Emission Factors for Electricity” in the trajectory case relative to the base case are intended to be edited using the “Inputs” tab. In addition, users may select “No benefits” from biofuels or one of several regulatory treatments; for conventional fuels, WTT emissions are based on the assumed share of unconventional fossil fuels.



Users should only edit input cells, which are denoted by blue text. Other cells contain intermediate calculations and outputs.

WTT emission factors for electricity were developed on a separate model, summarized in Appendix C.

#### 4.C. ON-ROAD

On-road modes include LDV, Bus, 2W, 3W, LHDT, MHDT, and HHDT. Each on-road mode has its own input and calculation tabs. This section describes how to edit input assumptions for these modes, followed by a more detailed discussion of the method for estimating emissions from on-road vehicles.



“Calc” tabs should not be edited, since they contain only intermediate calculations. Users may edit mode-specific inputs in the relevant “Input” tab.

#### On-Road Inputs

Table 6 shows the assumptions that can be edited in the on-road mode-specific “Input” tabs.

**TABLE 6. ON-ROAD MODE-SPECIFIC INPUT PARAMETERS**

| Table  | Description  |
|--|--|
| Stock and Sales  | Historic vehicle stock and sales. Base case can be edited here, and by default, trajectory case is set equal to base case.   |
| Load factor (passengers per vehicle) / Payload (metric tons per vehicle)                 | Fleetwide average. Base case can be edited here, though trajectory case inputs should be expressed in terms of percent change from the base case using the “Inputs” tab.   |
| Average annual distance traveled per vehicle (km)  | Used to calculate vehicle inventory from vehicle activity (VKT). Trajectory case is set equal to base case.  |
| Share of VKT in urban areas (%)  | Used to isolate the effects of congestion relief strategies and land-use policies to urban areas. For LDV, 2W, and 3W, reductions can be modeled in units of percentage in “Inputs” tab.   |
| Share of new vehicle sales by fuel/engine technology (%)                                 | Includes conventional, plug-in hybrid, CNG, LPG, fuel cell, electric. Base case can be edited here, while trajectory case inputs should be entered in terms of percentage-point change from the base case in the “Inputs” tab.   |
| Share of vehicle activity by fuel/engine technology in 2000                              | Includes conventional, plug-in hybrid, CNG, LPG, fuel cell, electric. Only year 2000 valued can be adjusted by users. Shares for subsequent years are calculated based on sales data. Gasoline ICE/hybrid shares are assumed to be 1 minus the other shares. Trajectory case is set equal to base case.  |
| Fuel consumption by fuel/engine technology (MJ/km) – fleet average vs. new fleet in 2000 | Includes fuel cell and electric vehicles. Year 2000 values can be adjusted by users. Values should represent the difference between fleet average fuel consumption and new vehicles sold in the year 2000. Fleet average fuel consumption by fuel/engine technology for subsequent years is calculated using sales, new vehicle efficiency, and turnover algorithms. |
| Annual VKT per vehicle by fuel/engine technology   | Used to differentiate distance per vehicle relative to gasoline ICE, e.g. battery electric vehicles are driven   |

|   |  |
|---|--|
|   | less on average than conventional vehicles   |
| Average fuel consumption (MJ) – new fleet | Includes in-use fuel consumption adjustment and average fuel consumption value for all engine technologies. The adjustments are set equal in base case and trajectory, which can be adjusted by users here. For average fuel consumption, adjustments are recommended to made in the “Inputs” tab. |
| Miscellaneous inputs                      | Includes fuel consumption differentials from diesel to gasoline and from LPG/CNG to gasoline, and the energy share of electric drive for plug-in hybrids.  |
| Emission factors (g/km)                   | Average fleet TTW emission factors by standard and pollutant, for gasoline, diesel, CNG, and LPG vehicles. Includes “country adjustment factors” which allow for differentiation of emission factors by country.   |
| Introduction of emission standards        | For gasoline and diesel vehicles, by introduction year and country. Allows for standards that phase in over several years.   |
| Fuel consumption differentials            | Ratio of fuel consumption of diesel (or CNG/LPG) vehicles relative to gasoline vehicles; used to convert composite efficiency for ICE vehicles into separate gasoline, diesel, CNG/LPG values. Only CNG/LPG differentials are explicit inputs for other on-road modes.                             |



The input years for emission standards are different from the 5-year time periods in the rest of the model, in that users can enter the specific year in which the standards are introduced.

## On-Road Methods

### On-Road Tabs (INPUT & CALC)

1. LDV
2. BUS
3. 2-WHEELERS
4. 3-WHEELERS
5. LHDT
6. MHDT
7. HHDT

The following figure illustrates the methodology used by the Roadmap model for on-road emissions calculations, which are the most complex calculations in the model. Historical land-based transportation activity (passenger-km and ton-km) and mode shares are taken from multiple data sources, and the projections of land-based transportation activity and mode share are estimated from socio-economic indicators (population, GDP and relative fuel prices). The main formula used for predictions of transportation activity and mode share is a Gompertz S-curve growth function that relates socio-economic indicators to activity and mode share. More

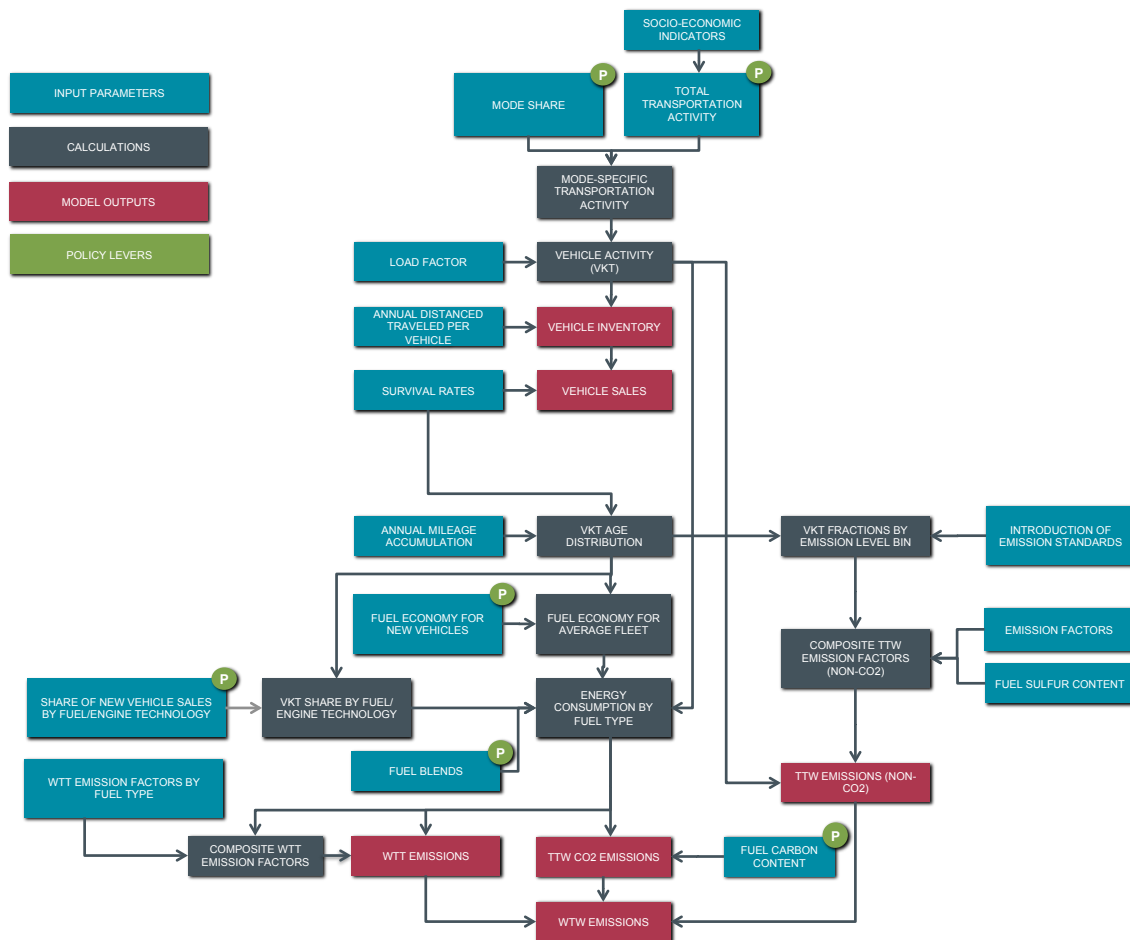
detailed information can be found in the sub-section “Socio-Economic”.

A load factor (passenger/vehicle or ton/vehicle) is used to convert transportation activity into vehicle activity (VKT). Vehicle inventory is calculated by considering an average annual distance traveled per vehicle. To derive annual vehicle sales, survival curves are developed using a Weibull distribution reliability function to estimate average vehicle retirement age for a given region and mode. Please refer to the next sub-section for further details on the survival curves and the turnover model.

Total energy consumption by fuel type is calculated as the product between vehicle activity, average VKT share by fuel/engine technology (e.g., gasoline conventional engines), and average vehicle fuel economy by fuel/engine technology. The model uses a turnover algorithm to estimate the average VKT share by fuel/engine technology (from new vehicle sales by fuel/engine technology) and the average vehicle fuel economy (from new vehicle fuel economy). Total energy consumption by fuel type is used to calculate TTW CO<sub>2</sub> emissions and Well-to-Tank (WTT) emissions for all pollutants. In both of these cases, emission factors are expressed in terms of gCO<sub>2</sub>/MJ.

TTW emissions of all pollutants except CO<sub>2</sub> are calculated based on emission factors (g/km) and VKT. A turnover model is used to determine the share of travel activity by vehicles in each emission standard category. These shares are used to estimate composite emission factors, which reflect average non-CO<sub>2</sub> emissions per km.

**FIGURE 5. ON-ROAD EMISSION CALCULATION METHODOLOGY**



The following section gives an overview of the calculations for emissions from Light Duty Vehicles. The calculations for the Bus, 2-wheeler, and 3-wheeler modes are identical. Calculations for LHDT, MHDT, and HHDT are computed in the same manner as well, except transportation activity is converted to VKT using load factors of tons/vehicle instead of passengers/vehicle.





For each pollutant, country, and year, WTW emissions from on-road vehicles are equal to the sum of WTT emissions and TTW emissions:

$$WTW \text{ Emissions} = TTW \text{ Emissions} + WTT \text{ Emissions}$$

For CO<sub>2</sub> and SO<sub>2</sub>, TTW emissions are calculated as follows:

$$TTW \text{ Emission (g)} = \sum Emission \text{ Factor}_{Fuel} \left( \frac{g}{MJ} \right) * Share \text{ of } Energy_{Fuel}(\%) * LDV \text{ Energy (MJ)}$$

Emission factors for CO<sub>2</sub> and SO<sub>2</sub> are based on the carbon and sulfur content of fuel, respectively. Emission factors for other pollutants are based on a weighted average of emission rates from vehicles in each emission standard category.

For local air pollutants, TTW emissions are calculated as follows:

$$TTW \text{ Emissions (g)} = \sum Emission \text{ Factor}_{vehicle \text{ fuel type}} \left( \frac{g}{km} \right) * Share \text{ of } VKT_{vehicle \text{ fuel type}}(\%) * LDV \text{ Activity (km)}$$

Note that electricity used by on-road vehicles generates zero TTW emissions; however it does generate WTT emissions, as specified in the “Fuel” tab. WTT emissions of each pollutant are equal to the sum of WTT emissions from each fuel:

$$WTT \text{ Emissions (g)} = \sum WTT \text{ Emission Factor}_{Fuel} \left( \frac{g}{MJ} \right) * Share \text{ of } Energy_{Fuel}(\%) * LDV \text{ Energy (MJ)}$$

Where LDV energy is defined as the product of energy intensity and activity:

$$LDV \text{ Energy (MJ)} = Energy \text{ Intensity} \left( \frac{MJ}{VKT} \right) * LDV \text{ Activity (VKT)}$$

LDV activity is derived from mode share and total passenger activity:

$$LDV \text{ Activity (VKT)} = Mode \text{ Share}_{LDV}(\%) * [Baseline \text{ Total Passenger Activity} + f(Population, GDP, Fuel \text{ Prices})]$$

#### 4.D. PASSENGER AND FREIGHT RAIL

Emissions from passenger and freight rail are estimated using a simplified version of the on-road method. The main difference is that the rail module does not use a turnover model to calculate average locomotive efficiency; rather, average locomotive efficiency, expressed in MJ/passenger-km and MJ/ton-km, is an input parameter to the model. The rail module does, however, use the turnover model to estimate the share of locomotives in each emissions category for local air pollutants. Both TTW and WTT emissions are calculated from energy consumption. Emission factors for all pollutants are expressed in g/MJ.

##### Rail Inputs

Inputs and calculations for non-road modes are included in a single tab per mode type, as opposed to in separate sheets. Rail inputs are similar to the on-road inputs, albeit simpler. Freight rail inputs are the same as passenger rail, except passenger-km are replaced with ton-km. The following table shows the assumptions which can be edited in the “Passenger Rail” and “Freight Rail” tabs.

**TABLE 7. RAIL INPUT PARAMETERS**

| Table   | Description  |
|---|--|
| Energy Intensity (MJ/passenger-km or MJ/ton-km) | Both load factors and locomotive efficiency influence this single input. Improvements, only applied on diesel share of energy, can be adjusted by users for both base and trajectory case in “Inputs” tab. |
| Diesel Share (%)                                | Diesel share of total energy consumed. The remaining share is assumed to be electricity.   |
| TTW Emission Factors for Average Fleet (g/MJ)   | Contains assumptions about average (TTW) local air pollutant emission factors for locomotives that meet certain tier standards.  |
| Country Adjustment Factor                       | Allows coefficients that adjust emissions factors for local air pollutants to be specified by country. Set to 1 by default.  |
| Emission Standards                              | By introduction year and country. Allows for standards that phase in over several years.   |

### **Rail Methods**

The following section explains the calculations for emissions from passenger rail. Freight rail is calculated in the same way, except transportation activity is measured by ton-km instead of passenger-km.



For each pollutant, country, and year, WTW emissions are equal to the sum of WTT emissions and TTW emissions:

$$WTW \text{ Emissions} = TTW \text{ Emissions} + WTT \text{ Emissions}$$

TTW CO<sub>2</sub> and SO<sub>2</sub> emissions are calculated according to carbon and sulfur content of fuels (entered in the “Fuel” tab) as follows:

$$TTW \text{ Emissions (g)} = \text{Emission Factor}_{\text{Diesel}} \left( \frac{\text{g}}{\text{MJ}} \right) * \text{Share of Energy}_{\text{Diesel}}(\%) * \text{Passenger Rail Energy (MJ)}$$

TTW emissions of other pollutants are calculated according to the fleet average emission factors for each emissions standard tier (shown near the top of the corresponding rail tab) as follows:

$$TTW \text{ Emissions (g)} = \sum_{\text{Uncontrolled}}^{\text{Tier 4}} TTW \text{ Diesel Emission Factor}_{\text{Tier}} \left( \frac{\text{g}}{\text{MJ}} \right) * \text{Diesel Share of Energy}_{\text{Tier}}(\%) * \text{Passenger Rail Energy (MJ)}$$

$$\text{Where: Diesel Share of Energy}_{\text{Tier}}(\%) = \text{VKT Fraction}_{\text{Tier}}(\%) * \text{Overall Diesel Share}(\%)$$

Note that electricity used for passenger rail generates zero TTW emissions. WTT emissions are calculated as follows:

$$WTT \text{ Emissions (g)} = [\text{WTT Emission Factor}_{\text{Diesel}} \left( \frac{\text{g}}{\text{MJ}} \right) * \text{Share of Energy}_{\text{Diesel}}(\%) + \text{WTT Emission Factor}_{\text{Elec}} \left( \frac{\text{g}}{\text{MJ}} \right) * (1 - \text{Share of Energy}_{\text{Diesel}}(\%))] * \text{Passenger Rail Energy (MJ)}$$

Where passenger rail energy is defined as the product of energy intensity and rail activity:

$$\text{Passenger Rail Energy (MJ)} = \text{Energy Intensity} \left( \frac{\text{MJ}}{\text{pass km}} \right) * \text{Passenger Rail Activity (pass km)}$$

Passenger rail activity is derived from mode share and total passenger activity:

$$\begin{aligned} \text{Passenger Rail Activity (pass km)} \\ = \text{Mode Share}_{\text{Passenger Rail}} (\%) * [\text{Baseline Total Passenger Activity (pass km)} \\ + f(\text{Population, GDP, Fuel Prices})] \end{aligned}$$

#### 4.E. AVIATION

Emissions from aviation are estimated similarly to on-road vehicles. As in the on-road module, TTW emission factors for local air pollutants are inputs in the aviation tab and are expressed in g/MJ. WTT emissions utilize emissions factors and country-specific user factors contained in the “Fuel” tab. This section describes how to edit input assumptions for aviation, followed by a more detailed discussion of the Roadmap’s method for estimating aviation emissions.

##### Aviation Inputs

The following table shows the inputs that can be edited in the “Aviation” tab.

**TABLE 8. AVIATION INPUT PARAMETERS**

| Table  | Description   |
|--|---|
| Energy efficiency for new aircraft (RPK/kg jet fuel) | Both base and trajectory case should be edited using “Inputs” tab.  |
| Biofuel blend (%)                                    | Oil-based and advanced, by country and year. CO <sub>2</sub> emissions from burning biofuels (TTW) are set to zero. |
| TTW emission factors (g/MJ)                          | All pollutants, by country and year. CO <sub>2</sub> factors based on jet fuel in “Fuel” tab.                       |

##### Aviation Methods

Aviation activity, expressed in revenue passenger-km, is determined from SAGE/AEDT projections assuming an unconstrained growth scenario (i.e., infrastructure growth parallels industry and demand growth).<sup>1</sup> Historical data are available for all regions considered in the Roadmap, but projections are only available at the global scale. Activity growth is allocated to regions based on GDP projections, assuming an elasticity of activity growth to GDP growth ratio of 1. The model uses a turnover algorithm to convert new aircraft efficiency to average aircraft efficiency, which is multiplied by passenger activity to determine energy consumption. Emissions of all pollutants, for both WTT and tank-to-“wing,” are calculated from energy consumption (all emission factors are expressed in g/MJ).

Looking at published bottom-up historical and projected inventories, SAGE/AEDT is used in a significant number of projects. SAGE/AEDT is a computer model used to predict aircraft fuel burn and emissions with capabilities to include all civilian commercial flights for a given year with

<sup>1</sup> System for Assessing Aviation’s Global Emission (SAGE) is now incorporated into the Aviation Environmental Design Tool (AEDT).

output for a single flight, airport, country, regional, or at global level. It is currently under development for public release by the U.S. Federal Aviation Administration (FAA), and is projected to be available in 2012. Although not yet publically accessible, processed inventories have already been published for multiple years.

SAGE/AEDT uses various emission, aircraft fleet, and operations data to model global flights and, in turn, emissions. This produces a database of raw fuel burn and emissions data for jet and turboprop aircraft in a relational format. The database can then be queried to produce processed fuel burn data and emissions. In addition to fuel burn, the specific data available are CO<sub>2</sub>, NO<sub>x</sub>, HC, CO, H<sub>2</sub>O and SO<sub>x</sub> emissions. Particulate matter is excluded due to the lack of a comprehensive scientific understanding regarding aircraft emissions. Further research and data are warranted prior to inclusion.

The nature of aircraft transportation creates a different set of pollution effects due to higher altitudes. In high altitudes, NO<sub>x</sub> becomes a greenhouse gas. It also has a stronger impact on the ozone layer in the upper atmosphere. The Roadmap model considers NO<sub>x</sub> as a criteria pollutant only, however, because of the current disagreement about the GWP values of high-altitude NO<sub>x</sub>.

The following section explains the Roadmap calculations for emissions from aviation.



For each pollutant, country, and year, WTW emissions from aviation are equal to the sum of WTT emissions and TTW emissions:

$$WTW \text{ Emissions} = TTW \text{ Emissions} + WTT \text{ Emissions}$$

TTW CO<sub>2</sub> emissions are calculated as follows:

$$TTW \text{ Emissions (g)} = \text{Emission Factor}_{jet \text{ fuel}} \left( \frac{g}{MJ} \right) * \text{Share of Energy}_{jet \text{ fuel}}(\%) * \text{Aviation Energy (MJ)}$$

Note that biofuels used for aviation are assumed to yield net zero CO<sub>2</sub> emissions. TTW local air pollutant emissions are based on composite emissions factors that include emissions from biofuels.

WTT emissions for each pollutant are equal to the sum of emissions from each fuel type:

$$WTT \text{ Emissions (g)} = \sum WTT \text{ Emission Factor}_{Fuel \text{ type}} \left( \frac{g}{MJ} \right) * \text{Share of Energy}_{Fuel \text{ type}}(\%) * \text{Aviation Energy (MJ)}$$

Where aviation energy is defined as the product of energy intensity and activity:

$$\text{Aviation Energy (MJ)} = \text{Energy Intensity} \left( \frac{MJ}{RPK} \right) * \text{Aviation Activity (RPK)}$$

Aviation activity starts with SAGE and ICAO data and adjusts these estimates for later time periods using mode share and total passenger activity estimates from the “Socio” tab:

$$\text{Aviation Activity (RPK)} = \text{Baseline Activity (SAGE, ICAO) (RPK)} + [\text{Mode Share}_{Aviation}(\%) * \Delta \text{Passenger Activity}]$$

The change in total passenger activity is a function of population, GDP, and fuel prices.

#### 4.F. MARINE

The process for estimating marine emissions is quite different than for other modes. Base case TTW marine emissions are adjusted from International Maritime Organization (IMO) projections, which are separated into “Lowerbound” and “Upperbound” estimates

##### **Marine Inputs**

There is no direct input available in this tab. However, users can adjust TTW emissions using emission reduction strategies in the “Inputs” tab. By default, the base case assumes that new ships in 2015, 2020 and 2025 will be 5%, 15% and 25% more efficient than 2010 as a result of the IMO’s Energy Efficiency Design Index (EEDI). In addition, users can enter assumptions for TTW emission reductions achieved through Market-Based Measures (MBMs).



Changing “Method” from the default “average” changes marine emissions estimates from the base case as well as the trajectory case.

##### **Marine Methods**

The Roadmap model relies on projections of emissions from the International Maritime Organization’s (IMO) 2009 GHG Study, whose data are considered as the best estimates for future marine emissions.<sup>2</sup> The report was compiled by experts in the industry and published by the Marine Environmental Protection Committee (MEPC) under the IMO. The report includes projections of CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>x</sub>, and PM emissions. The emission projections of other GHGs such as CH<sub>4</sub>, N<sub>2</sub>O, and black carbon are not assessed here because they are greatly outweighed (by a factor of 10,000 for CH<sub>4</sub> in 2020) by CO<sub>2</sub> emissions.

The IMO forecasts future fuel consumption and emissions in six different scenarios corresponding to those used by the IPCC. As our base case, we created a range of emissions, where the scenarios with the highest and lowest emissions represent the upper-bound (A1B) and lower-bound (B2) estimates. We assume no explicit regulatory policies or mandates to reduce CO<sub>2</sub> emissions from shipping, nor any fuel efficiency improvements. In the case of NO<sub>x</sub>, SO<sub>x</sub>, and PM, the revised MARPOL Annex VI standard is assumed to apply.

Marine emissions are reported on a global basis because the underlying data did not lend itself to a country disaggregation of emissions. We are in the process of developing such a disaggregation.

For NO<sub>x</sub>, SO<sub>x</sub>, and PM, other factors are considered besides just fuel consumption. Based on International Convention for the Prevention of Pollution From Ships (MARPOL 73/78), ships engines built after 2000 need to comply with Tier I standards. Tiers II and III, which will be introduced in 2011 and 2016, respectively, will reduce NO<sub>x</sub> emission levels. All of these approved regulations are included in the base case.

MARPOL 73/78 designated two sulfur emission control areas (SECA). One is the Baltic Sea SECA, which has been enforced as a SECA since May 19, 2006 and the other is the North Sea SECA, designated as such since November 22, 2007. Two additional areas, North America ECA

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<sup>2</sup> IMO (2009): Prevention of Air Pollution from Ships. Second IMO GHG Study 2009. Final Report Covering Phase 1 and Phase 2. MEPC 59/INF. 10. April 9, 2009.

and Caribbean ECA, will come into full effect to reduce SO<sub>x</sub>, NO<sub>x</sub>, and PM starting in 2016, corresponding to the Tier III rule. North America ECA covers 200 nautical miles from the coastlines of US and Canada, and the Caribbean ECA covers US territories in Caribbean. Currently the following caps in fuel sulfur content are:

**In SECAs:** 1% beginning in July 2010, and 0.1% in January 2015;

**Globally:** from January 2012, the global sulfur cap will be reduced from 4.5% to 3.5%. From January 2020, the global cap will be decreased to 0.5%.

IMO uses an activity-based approach to first estimate fuel consumption and then total emissions. With this approach, the fuel consumption is estimated for individual ship categories, including both the main engine(s) and auxiliary engine(s) in the estimate. The main engine (ME) fuel consumption of a ship category is estimated by multiplying the number of ships in each category with the average ME power to find the installed power (kW) by category. The annual power outtake (kW·h) is then estimated by multiplying the installed power with a category-specific estimate of the operating hours of the main engine and the average engine load factor. Finally, the fuel consumption is estimated by multiplying the power outtake with the specific value of fuel oil consumption that is applicable to the engines of the given category (g/kW·h).

This approach is different from the approach used in previous IMO work, which was based on the use of fuel statistics. Fuel statistics have their limitations with respect to coverage, consistency of reporting and accuracy in various parts of the world, presenting a risk of errors and under-reporting in fuel statistics. The difference between the fuel statistics and the activity-based estimate is about 30%.



The following table explains the calculation of emissions from marine vessels. The marine module uses its own simplified turnover module to model improvements in fuel efficiency over three time periods: 2015-19, 2020-24, and 2025-2050.

**TABLE 9. MARINE TAB STRUCTURE**

| Table  | Description   |
|--|---|
| TTW Emissions – From IMO                             | Contains lowerbound and upperbound emissions estimates from IMO, in million metric tons. Values in these tables reflect IMO estimates which have been stripped of projected efficiency gains. We then incorporate our own assumptions about efficiency gains.   |
| “Turnover” Module<br>(Lowerbound and Upperbound)     | <p>Computes share of vessels of each age, assuming no growth in fleet stock and constant turnover rates to maintain an average fleet age of 30 years. Each year, the oldest 1/30<sup>th</sup> of ships retire and are replaced one-for-one with ships of that model year. For each time period:</p> $\text{Share of vessels in each model year} = 1/30$ <p>If vessel age is between 0 and 30, and zero otherwise. The second part of the table sums fleet shares in each model year into four time periods, each with its own assumed average fleet efficiency.</p> |
| Growth in Fleet Stock<br>(Lowerbound and Upperbound) | <p>Growth in the fleet stock is assumed to be proportional to growth in emissions. For each time period after 2010:</p> $\text{Additional stock to fulfill new demand (\%)} = \%\Delta(\text{Emissions})$ <p>Adjusts share of vessels made in each time period, assuming that 100% of</p>   |

|  |  |
|--|--|
|  | additional stock consists of new vessels.  |
| Improvements   | Contains input assumptions about overall efficiency improvements for vessels manufactured in each time period: 2015-2019, 2020-24, and 2025-2050. Units are in terms of percent improvement from Pre-2015 average.   |
| TTW Emissions – Adjusted from IMO, Base case (Lowerbound and Upperbound) | <p>Adjusts IMO emissions estimates downward based on fleet age composition and efficiency improvements specified in previous table. These estimates are equivalent to the original IMO estimates if “improvements” are set to zero. Adjusted emissions are equal to the sum of adjusted emissions from each the four vessel time periods:</p> $Adjusted\ Emissions = IMO\ Emissions * \sum_{t=Pre-2015}^{2025-2050} (\% \text{ of fleet manufactured}_t) * (1 - \% \text{ improvement}_t)$ <p>Where <math>t</math> denotes the time period in which vessels were manufactured.</p> |
| TTW Emissions, Trajectory case (Lowerbound and Upperbound)               | <p>Adjusts base case TTW emissions downward based on “Total Average” efficiency improvements in “CO<sub>2</sub> Emission Savings” tables. For each time period:</p> $TTW\ Emissions_{Tra.} = TTW\ Emissions_{Ref.} * (1 - \% \text{ avg. savings})$ <p>Local air pollutants are multiplied by a conversion factor.</p>   |
| Emissions (Final)  | Equal to “Lowerbound”, “Upperbound”, or “Average” emissions as specified in “Method”.  |

#### 4.G. CONFIG

Many of the formulas and data validation selections in the model refer to a list of names or data contained in this sheet. These lists include the regions, modes, pollutants, fuel technologies, and fuel types covered by the model.



Users should not change the “Config” tab lists, since many formulas in the model would also need to be changed to make any improvement.

Other data contained in the config tab include unit conversions between English and S.I. units, Global Warming Potentials (GWP) of carbon dioxide, methane, nitrous oxide, and black carbon (all relative to CO<sub>2</sub>), and a conversion factor between PM10 and PM2.5. Users may be interested in adding a GWP value for black carbon (BC), since it is set to zero by default.

#### 4.H. SOCIO-ECONOMIC

The Roadmap model is designed to provide a consistent basis for forecasting transportation activity across time and geography. Globally-consistent country-specific socioeconomic forecasts are generally more readily available than corresponding transportation activity forecasts. While forecasts for a limited number of transportation parameters, such as new vehicle sales, are available *for some countries*, such forecasts are generally not sufficient to accurately define overall levels of activity in the absence of corresponding data on vehicle survival rates, per-vehicle VKT, etc., especially with regard to the influence that socioeconomic development may have on such parameters over time. For these reasons, it is preferable to utilize socioeconomic forecasts as the basis for estimating future changes in transportation activity.

The Roadmap model starts with historical data on transportation activity and adjusts activity levels over time according to predicted relationships between forecasted socioeconomic data (population, GDP, and fuel prices) and transportation activity. These relationships are developed through statistical analysis of historic socioeconomic and transportation activity data. The overall methodology can be summarized in four distinct steps:

1. Develop a historic time series database of socioeconomic and transportation activity data;
2. Derive socioeconomic and transportation activity relationships from this database using statistical analysis;
3. Develop forecasts for socioeconomic parameters which can be used to predict transportation activity;
4. Use socioeconomic forecasts to derive corresponding estimates of transportation activity.

The approach employed in the Roadmap model imposes important limits in the use of developed statistical relations. Such relations are essentially restricted to a nominal role, in which they are used only to forecast *changes* in transportation activity as opposed to *absolute* activity levels. In effect, the statistical relations are used to adjust country-specific data across time, rather than predict country-specific data directly. This process preserves important country-specific and regional distinctions that are not captured in the global statistical analyses used to derive the socioeconomic relationships. This does, however, impose an additional step in the development of transportation activity estimates, namely:

5. Develop baseline transportation activity estimates for each of the countries or regions included in the Roadmap model (*i.e.*, develop transportation activity measures for historic data years 2000-2010, upon which subsequent year estimates will be based).

It is important to note that marine vessel and aircraft activity is not part of this approach. Activity estimates for these transportation modes are developed independently, as documented earlier in this report. Ultimately, the projections of transportation activity are independent of the case utilized by the Roadmap model.



Socioeconomic forecasts of population, GDP, and fuel prices are the same for the base and trajectory case, and changes in transportation activity are estimated using these common socioeconomic forecasts. By utilizing this method to forecast transport activity,



we allow users to assess the impacts of policies which reduce the growth in transport activity that would be expected according to economic and population growth. Such policies can be entered using the “Activity reduction” section in the “Inputs” tab.

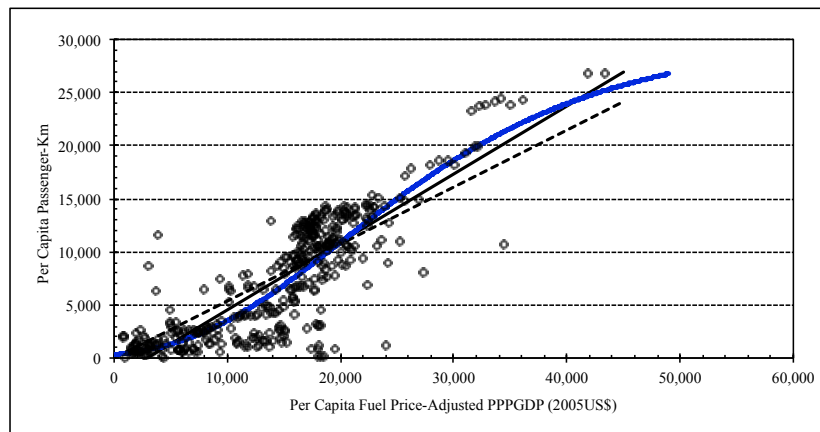
To develop relationships between forecasted socioeconomic data and transportation activity, a global database containing historic national-level estimates of transportation parameters (*e.g.*, VKT, fleet populations), socioeconomic data (*e.g.*, population, GDP), and geographic data (*e.g.*, land area, waterway extent) was developed using data obtained from the International Road Federation (IRF), the International Monetary Fund (IMF), and the U.S. government. Various parameters from this database were subjected to statistical regression analysis in an effort to develop predictive relationships between socioeconomic activity and transportation activity. While many of these analyses were ultimately discarded as not useful, a series of relationships was developed to estimate transportation activity for all transportation modes (except aircraft and ocean-going marine vessels).

Three socioeconomic parameters are used as the basis for all transportation activity forecasts: population, purchasing power parity gross domestic product (PPPGDP), and fuel price (expressed as a ratio to current year U.S. fuel prices). To maximize flexibility and force predictive maxima, all regression-based relationships were developed as best fit Gompertz functions (illustrated in FIGURE 6), taking the form of:<sup>3</sup>

$$\text{transportation parameter} = \text{UBL} \times e^{\left[ \text{IP} \times e^{(\text{GRP} \times \text{socioeconomic parameter})} \right]}$$

where: UBL is the upper bound regression limit,  
 IP is the regression parameter that determines the y-axis intercept, and  
 GRP is the regression parameter that determines the function rate of change.

**FIGURE 6. GOMPERTZ CURVE FOR PASSENGER ACTIVITY**



<sup>3</sup> A Gompertz function can generally be thought of as an “S” curve that starts at an asymptotic minimum value and rises up through an intermediate inflection point to an asymptotic maximum value. The flexibility of such a function derives from its ability to approximate not only S-shaped relationships, but also linear and exponential relationships (that are reflected as constrained portions of the larger S-shaped curve). Given this flexibility and the extensive data management required to undertake the documented statistical investigation, Gompertz functions were used without exception as the basic curve fitting criteria.

### **Passenger Activity**

For passenger activity, vehicle ownership rates (total vehicles per capita) are estimated on the basis of per capita PPPGDP using: UBL = 1, IP = -3.20579, and GRP =  $-5.4 \times 10^{-5}$  ( $r^2 = 0.59$ ,  $t_{IP} = -62$ ,  $t_{GRP} = -52$ , observations = 1,886). These vehicle ownership rates are used to estimate a secondary socioeconomic parameter, denoted as fuel price adjusted PPPGDP (FPA-PPPGDP), which is calculated as:

$$\text{FPA - PPPGDP} = [\text{PPPGDP} \times \text{maximum}(1 - \text{VPC}, 0)] + \left[ \frac{\text{PPPGDP}}{\text{Fuel Price Ratio}} \times \text{minimum}(\text{VPC}, 1) \right]$$

where: VPC is the estimated number of vehicles per capita (used as an estimate of the fraction of the population with transportation activity expenses affected by fuel prices, and Fuel Price Ratio is the local fuel price relative to the current year U.S. fuel price.

Total per capita transportation passenger activity is then estimated on the basis of FPA-PPPGDP using: UBL = 30,000 (km/year), IP = -4.55045, and GRP =  $-7.5 \times 10^{-5}$  ( $r^2 = 0.71$ ,  $t_{IP} = -39$ ,  $t_{GRP} = -32$ , observations = 403).

It is important to note several issues related to the development and use of these socioeconomic-based activity predictions. First, the underlying dataset includes time series data for as many as 201 country-level jurisdictions beginning in 1980 and running nominally through 2007. The IRF transportation dataset goes back further, to 1963, but the WEO economic dataset starts in 1980. There are a few data points for 2008, but these are not common. Second, most of the data are missing for any given analysis, so that the number of countries reflected in a regression analysis will be far fewer than 201 and will not include data for all years of the time series for those countries that are included. Third, the data are analyzed in the aggregate. This is generally necessary since the range of the independent socioeconomic regression parameter is not sufficient for individual countries or even individual geographic regions to allow transportation activity forecasts to be reliably developed for expected future socioeconomic conditions (in effect, significant extrapolation would be required if the dataset were not analyzed in the aggregate). In all cases, visual examination of the data on a regionally-specific basis was undertaken to ensure that no obvious geographic distinctions were overlooked.

To reiterate, regression-based transportation activity forecasts are used only to predict changes in country-specific activity. Country-specific activity estimates were developed independently of the regression analysis and are used for the 2000 and 2005 time periods (and other periods where available, including data for future years if the user wishes to “override” the socioeconomic-based forecasts). Activity forecasts for all years for which local activity data are not available are estimated by adjusting the local activity data for the last available data year by the change in predicted transportation activity over those same years. Doing so ensures that local deviations from global socioeconomic-transportation relations are maintained throughout the forecast period, greatly reducing regression correlation issues that might otherwise introduce significant local uncertainty into the activity estimation process.

Passenger activity estimates are disaggregated into road and rail shares. The road share of activity is estimated on the basis of FPA-PPPGDP using: UBL = 1, IP = -0.10112, and GRP =  $-1.8 \times 10^{-5}$  ( $r^2 = 0.01$ ,  $t_{IP} = -14$ ,  $t_{GRP} = -1.8$ , observations = 403). The passenger rail share of activity is simply one minus the road share. As indicated by the near-zero correlation coefficient of

the road share regression, there is a large degree of variation about this nominal relation across countries, but the regression coefficients are significant at the 93 percent confidence level. Given the near linear rate of change of the regression equation and the fact that associated regression predictions are used only to estimate relative changes in actual country-specific data, the nominal relationship appears reasonable for a first-cut approach.

The road share of passenger activity is further disaggregated into light-duty vehicles (passenger cars and light passenger trucks), motorcycles (and three wheelers), and bus shares using the following procedure. First, VKT for each of the three modes is estimated on the basis of FPA-PPPGDP. Second, assumed load factors are applied to the VKT estimates for each mode to convert VKT to total passenger activity estimates. Third, the passenger activity shares for each mode are estimated by dividing the mode-specific passenger activity estimate by the total passenger activity estimate for all three modes.

Two specific issues complicated the regression analysis performed to estimate VKT for the three road transportation modes. First, outlier data exerted undue influence in the analysis. That is not to say that outliers were not also present in the previously discussed data, but simply that the influence of such outliers was unacceptably high in the mode-specific VKT regressions due to the magnitude of associated deviation. Thus it was necessary to treat the outliers directly. Second, the VKT data appear to be bimodal for both motorcycles and buses. This is consistent with intuition given that both public (bus) and inexpensive (motorcycle) transport modes would be expected to be accessed first in developing societies with lower ranges of personal income. Following this trend, it is also expected that increases in VKT would occur in line with increases in GDP. However, as personal income continues to increase, less-public and more-expensive modes (such as cars and light trucks) become more popular. As VKT for light duty vehicles increases, public, cheaper alternatives (again, motorcycles and buses) begin to exhibit a dampened VKT trend. Regression analysis was performed over two distinct FPA-PPPGDP ranges to capture this effect.

A relatively simple and conservative procedure was utilized to identify and remove outliers from the VKT analysis datasets. First, the 20<sup>th</sup> and 80<sup>th</sup> percentile FPA-PPPGDP and per capita VKT data were calculated. A linear rate of change (slope) and implied zero FPA-PPPGDP VKT estimate (y-axis intercept) were calculated from these data. Minimum and maximum allowable deviations at the y-axis (zero FPA-PPPGDP) were established at the calculated y-axis intercept plus and minus two times the per-capita VKT range observed between the 20<sup>th</sup> and 80<sup>th</sup> percentiles. The minimum and maximum allowable deviations were expanded across the FPA-PPPGDP (x-axis) range using the slope calculated from the 20<sup>th</sup> and 80<sup>th</sup> percentile data, but increased by 50 percent to define the maximum data limit and decreased by 50 percent to define the minimum data limit (in effect creating an ever-increasing cone of “data acceptability” across the FPA-PPPGDP range. This process allows for substantial data variability and most certainly misses a substantial number of outliers. It does, however, remove those outliers that exert undue influence on nominal relations due to their inordinate deviation. In total, 9 outliers were removed from 757 passenger car data observations, 26 outliers were removed from 371 motorcycle (and three wheeler) observations, and 50 outliers were removed from 726 bus observations.

The following table shows the regression results for predicting changes in passenger activity based on measures of GDP, with the identified outliers removed. The parameter estimates are reported according to the following function, as described earlier:

$$\text{transportation parameter} = \text{UBL} \times e^{\left[ \text{IP} \times e^{(\text{GRP} \times \text{socioeconomic parameter})} \right]}$$

**TABLE 10. PASSENGER ACTIVITY REGRESSION RESULTS**

| Transportation parameter | Measure of GDP | Parameter estimates  | Model fit and number of observations  |
|--------------------------|----------------|--|---|
| Light-duty vehicle VKT   | FPA-PPPGDP     | $t.p. = 11,000 * e^{-4.28775 * e^{(-8 \times 10^{-5}) * \text{GDP}}}$  | $r^2 = 0.38$<br>$t_{IP} = -16$<br>$t_{GRP} = -12$<br>$n = 621$  |
| Motorcycle VKT           | FPA-PPPGDP     | For per-capita FPA-PPPGDP up to 22,705 (2005 \$US)<br>$t.p. = 2,000 * e^{-4.5927 * e^{(-2.5 \times 10^{-5}) * \text{GDP}}}$<br>For per-capita FPA-PPPGDP > 22,705 (2005 \$US)<br>$t.p. = 4,000 * e^{-1.92273 * e^{(2.36 \times 10^{-5}) * \text{GDP}}}$  | First equation:<br>$r^2 = 0.21$<br>$t_{IP} = -38$ ; $t_{GRP} = -9.1$<br>$n = 311$<br>Second equation:<br>$r^2 = 0.18$<br>$t_{IP} = -2.3$ ; $t_{GRP} = -2.6$<br>$n = 34$ |
| Bus VKT <sup>4</sup>     | FPA-PPPGDP     | For per-capita FPA-PPPGDP up to 15,925 (2005 \$US)<br>$t.p. = 1,000 * e^{-3.83617 * e^{(-2.2 \times 10^{-5}) * \text{GDP}}}$<br>For per-capita FPA-PPPGDP > 15,925 (2005 \$US)<br>$t.p. = 1,000 * e^{-2.59032 * e^{(2.22 \times 10^{-6}) * \text{GDP}}}$ | First equation:<br>$r^2 = 0.18$<br>$t_{IP} = -56$ ; $t_{GRP} = -11$<br>$n = 551$<br>Second equation:<br>$r^2 = 0.00$<br>$t_{IP} = -21$ ; $t_{GRP} = 1.1$<br>$n = 324$   |

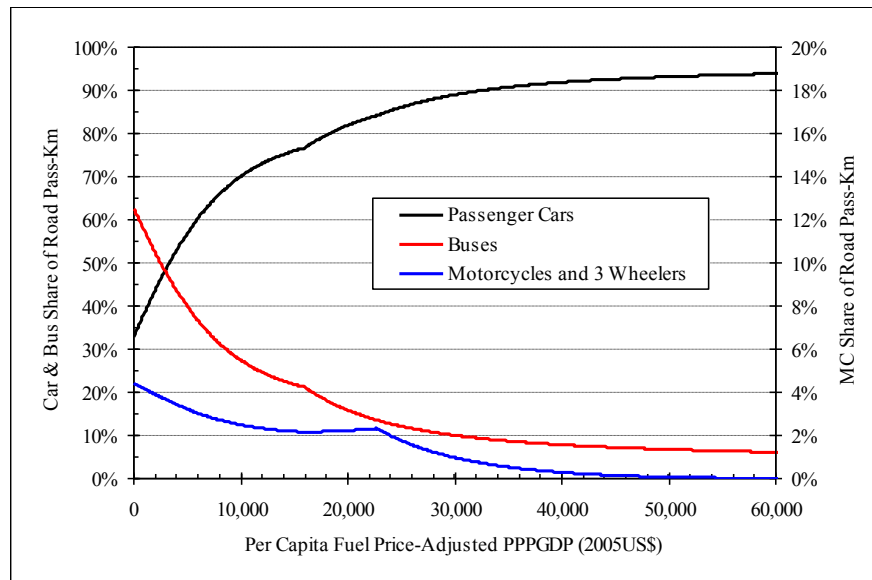
Load factors that convert VKT to passenger kilometers of travel are assumed to be 1.5 for passenger cars and motorcycles and 20 for buses. These assumptions are based on limited analysis of available data. While considered reasonable as global averages, these load factors can be expected to vary locally. Moreover, while these factors influence passenger kilometer mode shares, the shares themselves are not utilized directly—only the relative relationships between mode-specific shares are used to determine changes in mode share over time. In effect, the absolute predictions are of little consequence so long as they are consistent across time.

Finally, mode-specific shares of overall transportation passenger activity are calculated by dividing predicted mode-specific activity by the sum of the predicted activity for passenger cars, motorcycles, and buses. The resulting mode split functions are depicted in FIGURE 7. To

<sup>4</sup> As one might expect, per-capita bus activity varies tremendously throughout the world in accordance with many factors beyond the analysis scope of this first-cut effort. This variation is especially true in the higher GDP ranges. As a result of this variation, the ability of any nominal relation to fit the behavior observed in any given country is limited at best -- as exhibited by the essentially non-existent correlation and insignificant rate of change parameter as per capita GDP rises above about 16,000 (2005 US\$). Nevertheless, since the resulting regression equation holds per capita bus demand essentially flat across the higher GDP range, it was deemed reasonable for this first-cut effort -- especially given that the relation is not used in an absolute sense (i.e., only the ratio of predictions are utilized to forecast changes in, as opposed to absolute levels of, activity). It should also be noted that although 874 observations are implied in the presented bus regression statistics, there are actually a total of 726 observations. To ensure a smooth transition between the lower and upper range GDP functions, 148 “boundary area” observations were included in the regression analysis for both GDP ranges.

reiterate, the forecasted mode shares are used *only* to predict expected changes in country-specific mode shares. Country-specific activity estimates by mode (developed independent of the regression analysis) are always used for at least the 2000 and 2005 calendar years (and other years where available). Activity forecasts for all years for which local activity data are not available are estimated by adjusting the local activity data for the last available data year by the change in predicted transportation activity over those same years, ensuring that local deviations from nominal socioeconomic-transportation relations are maintained throughout the forecast period.

**FIGURE 7. PASSENGER ACTIVITY MODE SHARES FUNCTION**



### **Freight Activity**

Freight activity forecasts are based on the same data sources and general methodologies as passenger activity forecasts – specifically, a global-scale regression analysis is performed to develop a nominal relationship between socioeconomic and transportation activity, and that relationship is used to forecast changes in (as opposed to absolute values of) transportation activity over time. Activity forecasts are developed separately for road freight, rail freight, and inland waterway freight. Because there is no ability to resolve the road data into specific vehicle types, the statistical relationship for road activity as a whole is used without change to forecast *changes* in light-heavy, medium-heavy, and heavy-heavy duty truck activity (i.e., the rate of change, as opposed to the level of activity, is the same across all vehicle types).

An outlier analysis identical to that described above for passenger vehicle mode share data was performed for the road, rail, and inland waterway freight data. A total of 6 outliers were removed from 627 road freight observations, 84 outliers were removed from 1,239 rail freight observations, and 39 outliers were removed from 719 inland waterway freight observations.

The following table shows the regression results for predicting changes in freight activity based on measures of GDP. The parameter estimates are reported according to the following function, as described earlier in this section:

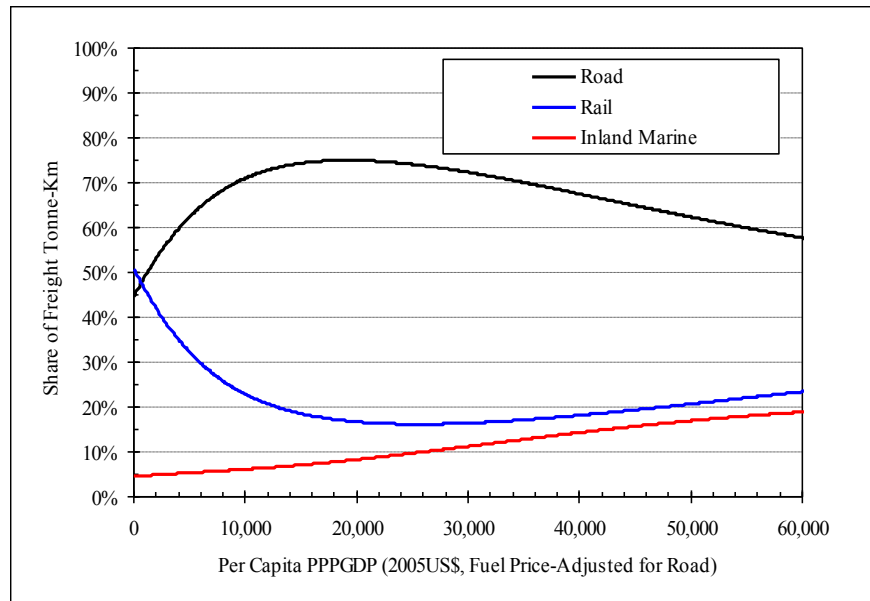
$$\text{transportation parameter} = \text{UBL} \times e^{\left[ \text{IP} \times e^{(\text{GRP} \times \text{socioeconomic parameter})} \right]}$$

**TABLE 11. FREIGHT ACTIVITY REGRESSION RESULTS**

| Transportation parameter                                  | Measure of GDP | Parameter estimates   | Model fit and number of observations                             |
|---|----------------|---|--|
| On-road freight activity (ton-km/year) per capita         | FPA-PPPGDP     | $t.p. = 8,000 * e^{-4.36364 * e^{(6.9 * 10^{-5}) * \text{GDP}}}$  | $r^2 = 0.18$<br>$t_{IP} = -16$<br>$t_{GRP} = -12$<br>$n = 621$   |
| Rail freight activity (ton-km/year) per capita            | PPPGDP         | $t.p. = 8,000 * e^{-4.23512 * e^{(-2.5 * 10^{-5}) * \text{GDP}}}$ | $r^2 = 0.14$<br>$t_{IP} = -44$<br>$t_{GRP} = -14$<br>$n = 1,155$ |
| Inland waterway freight activity (ton-km/year) per capita | PPPGDP         | $t.p. = 4,000 * e^{-5.96753 * e^{(-4.2 * 10^{-5}) * \text{GDP}}}$ | $r^2 = 0.33$<br>$t_{IP} = -39$<br>$t_{GRP} = -18$<br>$n = 680$   |

Mode-specific shares of overall transportation freight activity are calculated by dividing predicted mode-specific activity by the sum of the predicted activity for road, rail, and inland waterway freight. The resulting mode share functions are depicted in FIGURE 8. As stated above, the forecasted mode shares are used only to predict expected changes in country-specific mode shares. Country-specific activity estimates by mode (developed independent of the regression analysis) are always used for at least the 2000 and 2005 calendar years (and other years where available). Activity forecasts for all years for which local activity data are not available are estimated by adjusting the local activity data for the last available data year by the change in predicted transportation activity over those same years, ensuring that local deviations from nominal socioeconomic-transportation relations are maintained throughout the forecast period.

**FIGURE 8. FREIGHT ACTIVITY MODE SHARE FUNCTIONS**



### **Socioeconomic Baseline and Forecast Data**

As described above, transportation activity estimates are based on historic activity estimates that have been adjusted to account for changes expected to result from changing socioeconomic conditions. Therefore, calculating activity changes naturally requires forecasts of socioeconomic data, specifically data for population, PPPGDP, and relative fuel prices.

The WEO database used to develop the historic socioeconomic/transportation activity relations also contains data on population and PPPGDP for 2000 through 2014 (with forecasts generally beginning either in 2007 or 2008, varying by country). Generally, data were available for 180 country-level jurisdictions throughout this period, with minor exceptions. The exceptions were both population and PPPGDP data for 2000 and 2001 for Afghanistan and population and PPPGDP data for 2000-2003 for Iraq. In all cases, these missing data were estimated through simple extrapolation of the 2001-2002 data for Afghanistan and 2004-2005 data for Iraq. Data for 2015 were estimated for all 180 jurisdictions by applying the calculated annual 2010-2014 growth rate to forecasted 2014 data. This resulted in baseline population and PPPGDP estimates for 2000, 2005, and 2010, as well as corresponding forecast data for 2015, required as input for the Transportation Roadmap model.

Population forecast data through 2050 were obtained from the U.S. Census Bureau's International Data Base (IDB). The 228 country-level jurisdictions included in the IDB were consistent with the 180 country-level jurisdictions included in the WEO database once appropriate aggregations were undertaken (the IDB database reports data for many island protectorates separately, while the WEO aggregates populations under protecting country for its data). Since the IDB data may be inconsistent with the base data and forecasts developed by the WEO, the IDB data were converted to annual population growth rates for the five year periods 2015-2020, 2020-2025, 2025-2030, 2030-2035, 2035-2040, 2040-2045, and 2045-2050. The resulting growth rates were then applied to the estimated WEO 2015 data to develop WEO-consistent data for 2020, 2025, 2030, 2035, 2040, 2045, and 2050 as required for the Transportation Roadmap model.

GDP forecast data for 22 countries were obtained from a report produced by Goldman Sachs Economic Research (GSER) in 2007. Nine of these countries matched, on a one-to-one basis, one of the 16 regions included in the Transportation Roadmap model. Four of the EU27 countries were included in the 2007 report, as were five Asian, three Middle Eastern, and one African country, all of which are modeled in the Transportation Roadmap as components of aggregate regions. Thus, in total, the GSER report included data for 13 of the 16 regions included in the Transportation Roadmap model (data for the "rest of Europe," "rest of Latin America," and Australia were not included). The GDP forecasts included in the GSER report were based on population forecasts that differed somewhat from those used to derive the Transportation Roadmap population forecasts (as described above). To equilibrate the data, the GSER forecasts were converted to per-capita GDP using GSER population data and overall GDP estimates were then revised to reflect the population estimates used for the Transportation Roadmap. Since the resulting data may still be inconsistent with the base data and forecasts developed by the WEO, the adjusted GSER data were converted to annual GDP growth rates for the five-year periods 2015-2020, 2020-2025, 2025-2030, 2030-2035, 2035-2040, 2040-2045, and 2045-2050. The resulting growth rates were then applied to the estimated WEO 2015 data to develop WEO-consistent data for 2020, 2025, 2030, 2035, 2040, 2045, and 2050 as required by the



Transportation Roadmap model. This approach was used without exception for each of the 13 Transportation Roadmap regions covered by the GSER data.

For those regions not covered directly by the GSER data, an alternative approach was employed. Under this approach, the GSER growth rate data were used to create a two-element database with each record consisting of a country-specific growth rate for one five year period and the corresponding country-specific growth rate for the next five-year period. This resulted in a database containing 154 matched pairs of growth rates (22 countries multiplied by 7 growth rate pairs per country -- including the 2010-2015 period that was not used for the countries covered directly since forecast data for 2015 was available in the primary WEO dataset). These data were then regressed to determine if the GDP growth rate for one period could reasonably be estimated from the GDP growth rate for a preceding period. The resulting regression equation indicates that such an assumption is reasonable, with the growth rate for period “x” being equal to the growth rate for period “x-1” times 0.975784292 plus 0.000848845 (with a correlation coefficient of 0.97 and t statistics for the coefficient and intercept of 69 and 1 respectively). Although the regression could have been reformulated with the intercept dropped, it was implemented as described given the essentially minor variation from a one-to-one relationship. With this relationship, the GDP growth rates for the regions not covered directly by the GSER data were developed for the five-year periods 2015-2020, 2020-2025, 2025-2030, 2030-2035, 2035-2040, 2040-2045, and 2045-2050 from the calculated WEO growth rates for 2010-2015. The resulting growth rates were then applied to the estimated WEO 2015 data to develop WEO-consistent data for 2020, 2025, 2030, 2035, 2040, 2045, and 2050 as required by the Transportation Roadmap model

Relative fuel prices were developed on the basis of gasoline price ratios calculated from the IRF database. Price ratios were calculated at the WEO country level for the latest year in which data were available and then weighted by population to determine an aggregate ratio for each of the regions included in the Transportation Roadmap model. Fuel price data for 2008 were used for 161 of the 180 country-level jurisdictions, while data for the other jurisdictions were based on 2006 data (4 jurisdictions), 2004 data (2 jurisdictions), 2002 data (1 jurisdiction), and 1994 data (1 jurisdiction). Fuel price data were not available for 11 minor jurisdictions, and thus these jurisdictions were not included in the population-weighted averages for the affected regions. The resulting ratios were applied without change across the Transportation Roadmap forecast period.

All transportation activity forecasts were then derived using the resulting socioeconomic forecast dataset. Both the socioeconomic forecasts and the dependent transportation activity forecasts are available for review as part of the “Socio” module of the Transportation Roadmap model.

### **Baseline Transportation Activity Data**

As described above, nominal transportation activity estimates are based on forecasted socioeconomic activity. However, the resulting transportation activity estimates are used solely to derive expected *changes* in transportation activity, as opposed to absolute activity levels. Thus, it is necessary to develop baseline transportation activity estimates for each of the regions included in the Transportation Roadmap model -- to which the forecasted changes in transportation activity can be applied.

Generally, the baseline data estimates were developed by analyzing data from the IRF transportation activity database. However, as described above, there are considerable “missing”



data in this database and it is necessary to account for this to ensure that derived estimates are accurate. For this reason, absolute transportation activity estimates (e.g., passenger kilometers, freight tonne-kilometers) are initially calculated on a per-capita basis. They are then expanded using the U.S. Census Bureau's population estimates from the IDB (International Data Base) described in the previous section to derive equivalent activity estimates for the complete regions covered by the Transportation Roadmap.

Additionally, there can be considerable variability in the IRF data across time. Therefore, while baseline data for calendar years 2000 and 2005 were developed, the data for these years was generally not used directly as inputs. To ensure consistency in the developed data, average per capita activity estimates were developed for the 1997 through 2007 data period and the resulting average estimates were applied to 2000 and 2005 population estimates to derive absolute activity estimates for 2000 and 2005, respectively. To further ensure consistency, data was only included in the 1997 through 2007 averaging process if the fraction of total regional population reflected in the data was not dramatically different from that of other years in the 1997 through 2007 period. For example, if 40 percent of the population was reflected in the 2003 data, while 90 percent of the population was reflected in the data for other years, the 2003 data were omitted from the averaging procedure.

Finally, there were some instances where no data were available for the 1997 through 2007 time period. In such cases, data from earlier years was used as available -- again, on a per capita basis so that the data are "time corrected" when applied to 2000 and 2005 population estimates. In cases where data from earlier years were not available, per capita activity estimates from nearby and similar geographic areas were substituted.

Using this methodology, freight activity data were developed for road, rail, and inland waterway tonne-kilometers individually. However, the IRF road data is not differentiated by the light-heavy (LH), medium-heavy (MH), and heavy-heavy (HH) vehicle categories used in the Transportation Roadmap model. As a result, a supplemental analysis was employed to disaggregate these data. Available data for the U.S. was employed to estimate the LH, MH, and HH fractions as follows. Truck population and average annual kilometer per truck data, by class (1-8), were obtained from Table 5-4 of the 2009 Transportation Energy Data Book published by Oak Ridge National Laboratory for the U.S. Department of Energy. These data were disaggregated into gasoline/diesel and commercial/non-commercial shares using vehicle class-specific data from the U.S. Environmental Protection Agency's MOBILE6.2 and MOVES2010 emission factor models. Using an assumption that each class of trucks carries, on average, one-half of its allowable gross vehicle weight, total class-specific tonne-kilometer estimates were calculated. Finally, assigning truck class 2a (<3856 kg GVW) to the LH truck category, truck classes 2b-6 (3856-11794 kg GVW) to the MH truck category, and truck classes 7 and 8 (>11794 kg GVW) to the HH truck category, yielded tonne-kilometer fractions of 6.3, 13.2, and 80.5 percent for LH, MH, and HH trucks respectively. In the absence of alternative data, these same fractions were applied across geographic regions for both the 2000 and 2005 calendar years to disaggregate total road freight data into corresponding LH, MH, and HH components.

Baseline total passenger kilometer activity (road plus rail) was determined from the IRF data using the average 1997-2007 per capita approach described above. The road share of total passenger activity was similarly determined from the IRF data using the same average 1997-2007 approach, but not on a per capita basis. *Vehicle* kilometer (as opposed to passenger

kilometer) activity was also estimated separately for passenger cars, motorcycles, and buses using the average 1997-2007 per capita approach. These data were converted to passenger kilometer equivalents using global average passenger-per-vehicle estimates of 1.5 for passenger cars, 1.0 for motorcycles, and 10.0 for buses. These load factors were selected such that *total* global activity using the converted vehicle kilometer data was within one percent of total road passenger activity using the aggregate passenger kilometer data. Greater variation is observed within specific regions, however. Passenger kilometer mode shares were developed by dividing the mode-specific passenger kilometer estimates by the sum of the individual mode estimates.

Since the Roadmap model treats motorcycles and three-wheelers separately, it is necessary to further disaggregate the motorcycle mode share into its two and three wheeler components. The IRF database provides no data at this level of resolution, so data from the WBCSD-IEA/SMP Transport Model were used to disaggregate the motorcycle mode share data. Since three-wheeled vehicles are generally limited to India, China, and the “Other Asia” regions of the Transportation Roadmap model, the three-wheeler share of activity for all other regions was set to zero. Based on WBCSD-IEA/SMP data, the Asian region three-wheeler shares were set to 20.6, 23.1, and 17.5 percent of motorcycle passenger activity for the India, China, and “Other Asia” regions.

All of the developed baseline data are available for review as part of the “Socio” tab in the Roadmap model. Ultimately, all such data are subject to continuing review and ideally should be replaced by locally-provided data to ensure that the most robust dataset available is utilized.

#### 4.1. SURVIVAL

##### Survival Inputs

The “Survival” tab contains vehicle fleet turnover information, sales growth and VKT by age distributions. The purpose of the survival tab is to calculate the share of VKT by vehicles in each age category, since emissions and fuel efficiency vary by model year and vehicle age. The vehicle fleet turnover model is characterized by a Weibull distribution reliability function with three parameters ( $b$ ,  $g$  and  $T$ ) as follows:

$$x(k) = \exp \left\{ - \left[ \left( \frac{k - g}{T} \right)^b \right] \right\}$$

where  $x(k)$  is the probability that lifetime is greater than or equal to  $k$ ;  $k$  is the vehicle age in years;  $g$  is the age at which vehicles are removed from the fleet ( $g \geq 0$ );  $b$  is the failure steepness; and  $T$  is the characteristic service life.

FIGURE 9 shows the effects of changing  $b$ ,  $g$ , and  $T$  for a sample survival curve, where the horizontal axis denotes vehicle age and the vertical axis denotes the percent of vehicles that survive until the next year. As shown, increasing the parameter  $b$  increases the steepness of the slope, increasing  $g$  shifts the curve to the right, and increasing  $T$  stretches the curve along the horizontal axis.

**FIGURE 9. SAMPLE SURVIVAL CURVE**

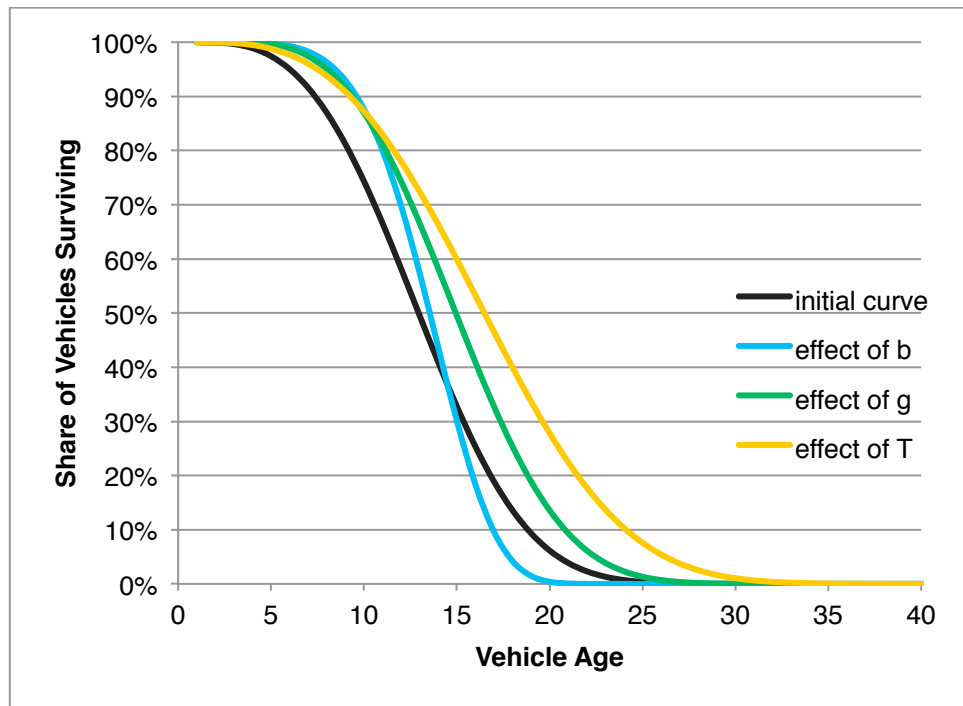


TABLE 12 shows sample survival curve coefficients for different modes.

**TABLE 12. SAMPLE SURVIVAL CURVE PARAMETERS**

| Mode     | b   | T    | g   |
|----------|-----|------|-----|
| LDV      | 1.9 | 16.0 | 4.0 |
| HDT      | 1.8 | 20.0 | 2.0 |
| Rail     | 2.5 | 29.0 | 0.0 |
| Aviation | 4.1 | 26.0 | 7.0 |
| MCs      | 6.0 | 8.5  | 0.0 |

The Weibull Distribution coefficients in the model are fitted against actual survival curve data points (see model for references). Due to data considerations, unique survival curves have not been estimated for each region and mode covered by the model; rather, a set of representative curves have been estimated and applied to groups of similar regions. The model allows for three user-defined curves to be entered and applied to specific modes or countries.



Users interested in using custom survival curves estimated from country-specific data should keep in mind that the probability of survival for each vehicle of age  $k \leq g$  should be equal to one. The share of vehicles surviving past age  $k = g$  should be calculated using the Weibull distribution function.

### **Survival Methods**

As in other tabs, the trajectory and base case are displayed side by side in the “Survival” tab.



The following table describes the “Survival” tab calculation process which is identical for both the base and trajectory cases.

**TABLE 13. SURVIVAL TAB STRUCTURE**

| Table  | Description   |
|--|---|
| Survival rate - Weibull distribution coefficients                                | Contains survival curve coefficients for representative regions and each mode category. Estimated coefficients were fitted against actual survival curve data points. Includes three user-defined curves.   |
| Survival rates at age x  | Computes share of vehicles surviving at each age (0 thru 40 years). Based on Weibull Distribution Coefficients in the previous table according to the following equation:<br>$x(k) = \exp \left\{ - \left[ \left( \frac{k - g}{T} \right)^b \right] \right\}$ |
| Share of vehicles retiring at age x  | Computes the share of vehicles retiring each year for each general distribution function. For each vehicle at age x:<br>$\text{Share of vehicles retiring}_x = \% \text{ surviving}_{x-1} - \% \text{ surviving}_x$   |
| Annual distance accumulation   | <b>Input.</b> Normalized or absolute annual distance traveled by vehicle age.   |
| Absolute VKT* for vehicles x years old given an annual % increase in sales (VKT) | Annual distance traveled by vehicles of age x, corrected for annual sales growth:<br>$\text{Absolute VKT}_x = \text{Survival rate}_x * \left( \frac{\text{distance}}{\text{vehicle}_x} \right) * (1 + \% \text{ annual sales growth})^{40-x}$                 |
| VKT share by age (%)   | Share of VKT by vehicles of age x:<br>$\text{Share of VKT}_x = \text{Absolute VKT}_x / \sum_{x=0}^{40} \text{Absolute VKT}_x$   |
| Share of VKT by vehicles older than x years (%)                                  | Share of VKT traveled by vehicles age x or older:<br>$\text{Share of VKT}_{age \geq x} = \text{Share of VKT}_x + \text{Share of VKT}_{age \geq (x+1)}$  |
| Share of VKT by vehicles older than x years (%) – LDV, MC, HDT**, Rail, Aviation | Share of VKT by vehicles age x or older given by previous table. Users can specify which general distribution function is applied to each region and mode.  |

\*Aviation calculations use RPKT instead of VKT.

\*\*Buses use the same survival curve distributions as Heavy Duty Trucks.

The survival tab’s primary outputs are the share of VKT for vehicles at each age. These are used to determine the **share of vehicle activity**, **fleet average fuel economy**, and the **share of VKT by emission standards** in the mode-specific “Calc” tabs. For on-road modes and rail, the share of VKT by age calculated in the “Survival” tab is used to compute **VKT fractions by emission level bins** for gasoline and diesel vehicles. In these tables, vehicles are sorted into emissions standard categories based on vehicle age and region.

## 5. REFERENCES

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Data references are included in the “Reference” tab of the model. This section documents some of the key data sources used and discusses needs for additional data.

### **Data Sources & Needs**

International Road Federation (IRF), World Road Statistics Compilation, 1963-1999. This IRF database provides historic fleet characterization and activity data for road vehicles. These data were used to develop statistical relationships between economic and transportation activity, allowing standardized economic forecasts to serve as the primary driver of Transportation Roadmap activity. Both availability and quality of the IRF data vary widely across countries and over time. As a result, it is difficult, in most cases, to develop precise relationships on a country-specific basis. Nevertheless, analysis of data in the aggregate allow for general globally-based *relative* trends to be developed.

International Monetary Fund, World Economic Outlook (WEO) Database, October 2009 edition. This WEO database provides historic economic data by country (e.g., purchasing power parity gross domestic product). Linking these data to the transportation data extracted from the IRF database forms the basis for a statistical analysis dataset, allowing for the derivation of historic relationships between economic and transportation activity.

Central Intelligence Agency, The World Factbook 2009. The World Factbook contains a wide range of information collected by various U.S. government agencies, including data on the geography and transportation systems of all global countries. Data such as roadway, inland waterway, and rail system lengths, as well as geographic land area, were used to develop various national-level unit metrics (e.g., activity per roadway kilometer) for evaluation as potential economically-dependent parameters.

U.S. Census Bureau, International Data Base (IDB), accessed as of June 15, 2010 at: <http://www.census.gov/ipc/www/idb/index.php>. The IDB contains a wealth of demographic data for countries and country-level areas of the world, including population forecasts through 2050. Population forecasts from the database were used to develop population growth rates for each of the regions included in the Transportation Roadmap.

Goldman Sachs Economic Research, “The N-11: More Than an Acronym,” Global Economics Paper No: 153, March 28, 2007. This Goldman Sachs paper includes GDP forecasts through 2050 for 22 countries. These forecasts were used in conjunction with WEO GDP forecast data through 2015 to develop GDP growth rates through 2050 for each of the regions included in the Transportation Roadmap.

U.S. Department of Energy, Oak Ridge National Laboratory, “Transportation Energy Data Book,” ORNL-6984, Edition 28, 2009. The Transportation Energy Data Book contains a wealth of information on fleet characteristics and transportation activity. Since these data are predominantly applicable to the U.S., the Data Book is not considered to be a primary data source, but the data are valuable (and were used for limited purposes as described in the sections below) in the absence of alternative globally-scoped data sources.

U.S. Environmental Protection Agency, MOBILE6 Vehicle Emission Modeling Software, accessed as of June 15, 2010 at: <http://www.epa.gov/otaq/m6.htm>. The MOBILE6.2 emission factor model includes substantial data related to fleet characteristics and transportation activity. Since these data are predominantly applicable to the U.S., MOBILE6.2 is not considered to be a primary data source, but the included data are valuable (and were used for limited purposes as described in the sections below) in the absence of alternative globally-scoped data sources

U.S. Environmental Protection Agency, MOVES (Motor Vehicle Emission Simulator), accessed as of June 15, 2010 at: <http://www.epa.gov/otaq/models/moves/index.htm>. The MOVES2010 emission factor model includes substantial data related to fleet characteristics and transportation activity. Since these data are predominantly applicable to the U.S., MOVES2010 is not considered to be a primary data source, but the included data are valuable (and were used for limited purposes as described in the sections below) in the absence of alternative globally-scoped data sources

World Business Council for Sustainable Development, IEA/SMP Transport Model, accessed as of June 15, 2010 at: <http://www.wbcsd.org/plugins/DocSearch/details.asp?type=DocDet&ObjectId=MTE0Njc>. The IEA/SMP Transport Model is conceptually similar to the Transportation Roadmap model. As a result, it can serve as a secondary source of transportation activity indicators in instances where primary data are lacking. While reliance on the IEA/SMP Transport Model is intentionally limited due to uncertainty over data sources, etc., it is nevertheless an important reference when alternatives are non-existent.

Additional data needs. Given the first-cut nature of the socioeconomic analyses and baseline data development work performed to date, ongoing development work will proceed as the Roadmap project continues. To support this work and the extensive time series requirements needed to relate transportation and socioeconomic activity, more refined data sources are desirable. While it is recognized that such sources are unlikely to surface on a globally-consistent scale, every effort will be undertaken to ensure the highest quality data possible given existing resources.

## APPENDIX A. LIST OF ACRONYMS

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| Acronym           | Term                                 |
|-------------------|--------------------------------------|
| BC                | Black carbon                         |
| CH <sub>4</sub>   | Methane                              |
| CNG               | Compressed natural gas               |
| CO                | Carbon monoxide                      |
| CO <sub>2</sub>   | Carbon dioxide                       |
| CO <sub>2</sub> e | Carbon dioxide-equivalent            |
| FPA               | Fuel price-adjusted                  |
| GDP               | Gross domestic product               |
| GHG               | Greenhouse gas                       |
| GVWR              | Gross vehicle weight rating          |
| HHDT              | Heavy heavy-duty trucks              |
| LDV               | Light-duty vehicles                  |
| LHDT              | Light heavy-duty trucks              |
| LPG               | Liquified petroleum gas              |
| MHDT              | Medium heavy-duty trucks             |
| N <sub>2</sub> O  | Nitrous oxide                        |
| NO <sub>x</sub>   | Oxides of nitrogen                   |
| PM                | Particulate matter                   |
| ppm               | Parts per million                    |
| PPP               | Purchasing power parity              |
| RPKT              | Revenue passenger kilometer traveled |
| SECA              | Sulfur emission control area         |
| SO <sub>2</sub>   | Sulfur dioxide                       |
| TTW               | Tank-to-wheels                       |
| VKT               | Vehicle kilometer traveled           |
| WTT               | Well-to-tank                         |
| WTW               | Well-to-wheels                       |

## APPENDIX B. ON-ROAD EMISSION FACTOR STUDY

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To better understand vehicle emissions modeling, the ICCT undertook a project to review some of the software tools that are employed by various government agencies and research organizations to estimate the emission impacts of on-road transportation. The primary objectives of the study were to: 1) understand the different methodologies for generating vehicle emission estimates employed by each model, and 2) use data from each of the models to develop a set of *average lifetime* emission factors that could be used in the Roadmap model. The models selected have been highly vetted in the vehicle emission modeling community and have been used to serve a variety of regulatory and research purposes. Though these particular models were designed to estimate vehicle emissions in each of their respective regions (California, the United States and the European Union), they have also been employed by policy-makers and analysts in developing countries. The models analyzed were:

1. EMISSION FACTOR (EMFAC) model, version 2007 – the California Air Resources Board
2. MOTOR Vehicle Emissions Simulator (MOVES), version 2010a – the U.S. Environmental Protection Agency
3. The Handbook on Emission Factors for Road Transport (HBEFA), version 3.1 – Developed by a consortium of research organizations in Europe and lead by Graz University of Technology
4. COPERT, version 4 – the European Environment Agency and the Joint Research Centre
5. The Speciated Pollutant Emissions Wizard (SPEW) – Prof. Tami Bond of the University of Illinois

The average lifetime emission factors considered for the Roadmap model are given in grams of pollutant per kilometer and designed to take into account the deterioration that typically occurs in an emission control system over the life of the vehicle. To account for deterioration, the emissions were totaled for the entire vehicle lifetime and then divided by that vehicle's total lifetime kilometers traveled.

The five models analyzed during this project all use different methodologies for estimating vehicle emissions, which typically involves accounting for various parameters such as driving patterns, meteorology, vehicle age, etc. In order to compare the results across the five models and develop a set of emission factors for the specific vehicle groups in the Roadmap, it was necessary to make a number of assumptions. The main assumptions were related to: 1) choosing representative vehicle types in each of the five models that correspond to the Roadmap vehicle groups, and 2) selecting vehicle model years for EMFAC and MOVES that correspond to the European progression in emission standards (i.e. Euro 1/I, 2/II, 3/III,..., 6/VI).

After developing the average lifetime emission factors for each of the five models and selecting the representative vehicle types, the final task involved analyzing the data and determining the emission factors that might be used in the Roadmap. In reviewing the data, there was generally a large degree of variance in the emission factors of the five models. Simply averaging the five data points for each pollutant and vehicle type did not seem like an ideal solution given this high degree of variance. To avoid the straight average approach, a simplified methodology was developed to identify *outliers*. Certainly, it is difficult to designate an outlier with any statistical significance with the limited number of data points (there was a maximum of five data points per pollutant and emission level). Nevertheless, the steps of the method were as follows:

1. Determine the mean and the standard deviation for each pollutant and emission level.



2. An *outlier* is defined as any data point greater than the mean plus one standard deviation or less than the mean minus one standard deviation.
3. Average the non-outlier data points to derive potential Roadmap emission factors.

**While the results of this analysis were considered for use as TTW on-road emission factors in the mode-specific input tabs of the Roadmap tool, we determined due to the large degree of variance in emission factors across models that it was better at this stage to use a single data source for consistent lifetime average emission factors across modes and regions. As a result, the Roadmap model version 1-0 uses average lifetime emission factors extracted from the U.S. EPA's MOBILE6, available at <http://www.epa.gov/oms/m6.htm>.**

In recognition that there is potential for improving the accuracy and global applicability of the emission factors used in the Roadmap, the ICCT is in the process of developing a new set of emission factors; upon completion, this set will be released in an updated version of the Roadmap.

## APPENDIX C. POWER SECTOR EMISSION FACTORS

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The purpose of the Power Sector Roadmap is to calculate current and forecast future electricity grid emission factors (gCO<sub>2</sub>e/KW-hr, gSO<sub>x</sub>/MW-hr, gNO<sub>x</sub>/MW-hr, gPM<sub>10</sub>/MW-hr) for all Roadmap regions. The model provides a total of 340 emission rate outputs.

### MODEL DESCRIPTION

- In the first step, IEA data from 2010-2030 is collected to determine the electric generation fuel type (coal, natural gas, oil, nuclear, renewables) for each of the 17 Roadmap Regions. In a few cases, geographic adjustments are necessary due to difference in geographic boundaries between the Roadmap Regions and IEA data.
- The second step allocates fossil fuel power plants into sub-categories.
  - Gas power production is broken down into legacy boilers, simple cycle gas turbines, and more efficient combined cycle plants.
  - Each power plant basic design is further categorized by efficiency and emission rates characteristic of new builds in a particular year (all pre-2000 legacy coal plants are assigned “1980”, the oldest category in the model)
    - Fossil plants are also assigned a nominal vintage, which may or may not represent the actual date of construction
      - For instance, “gascombined2000” represents natural gas power plants with uncontrolled emissions of 700 g/kw-hr CO<sub>2</sub> and 175 g/NO<sub>x</sub> regardless of the date of construction or operational year. (Sox and fine particulate emissions are small)
  - Power plant stock representing 2010 is added to the model. Assignment of 2010 power plants by sub-category is based on nominal vintage taking into account several factors.
    - First is the age of electric utility infrastructure. For instance, the US legacy fleet of coal power plants is quite old.
    - Secondly, the physical age is adjusted based on emissions characteristics.
      - For instance, the existing stock of Chinese coal plants has characteristics more in line with older coal plants despite the newer physical age (though policy is reducing these emission rates).
      - California emission control laws push more advanced combined cycle power plant technologies into the market.
  - Population of future year power plants sub-categories are based on several factors:
    - IEA data through 2030 determines basic fuel type
    - Total rates of new builds populated in each time period after 2010 is based on 1) IEA electricity consumption growth rates and 2) a probability-based turn-over algorithm for power plants that within the range of potential retirement ages. For instance, US coal plants are assigned an assumed lifespan of 50 years with half retired within +/- 5 years of the assumed lifespan.
    - Future power plant vintages are assigned based on year of construction adjusted by 1) past track record on emission rates for the Region , 2) and engineering judgment.

- The third step is determining emission rates for all fossil power plants, by Region for each time period.
  - Determining CO<sub>2</sub> emission rates is fairly straightforward using uncontrolled emission factors based on mass balance and plant efficiency.
  - The model has the potential to incorporate integrated combined cycle power plants with carbon capture and sequestration, but this technology is assigned zero penetration rates in current analysis due to uncertainties about potential utilization.
- Determining final post-control SO<sub>x</sub>, NO<sub>x</sub>, and fine PM emissions requires several additional layers of analysis.
  - Uncontrolled emission rates are defined for each fossil power plant sub-category, and for coal plants are adjusted up or down by a coal quality factor.
  - Second, emission control factors are applied based on a phase-in schedule.
    - A “Tier 1” emission control phase-in is based on emission control technology leaders. All Regions are assigned Tier 1, 2, or 3 with Tiers 2 and 3 lagging Tier 1 phase-in rates.
- The forth step is determining the average electric generation power emission rates for each pollutant in each region. Emission rates for each plant type are weighted by plant type distribution and summed
  - a transmission and distribution loss factor is applied to provide final emission values for CO<sub>2</sub>, SO<sub>x</sub>, NO<sub>x</sub>, and PM in g/MW (CO<sub>2</sub>) and g/KW (others) and g/MJ (all).
  - Steps three and four are integrated into a single table for each region and pollutant.

## DATA SOURCES

- Basic resource type (coal, natural gas, oil, renewables) and overall rate of consumption increase through 2030 is primarily from the World Energy Outlook 2009.
- Efficiency levels for future new builds are based on current best-in-class permits, manufacturer literature, and engineering judgment. Projections past 2030 are preliminary. Power plant uncontrolled pollutant emission rates are determined primarily from mass-balance (CO<sub>2</sub>, SO<sub>x</sub> and fine particulate) and assigned control rates (NO<sub>x</sub>).
- Coal quality SO<sub>x</sub>, NO<sub>x</sub>, and fine particulate emissions adjustments are based on USGS coal quality data.
- Transmission & distribution losses are set based on country-specific data where available, or at a US default level of 8%.
- The projected schedule for emission factors in "Tier 1" countries is based on ICCT's judgment. The rate of emissions control improvement is lagged in non-"Tier 1" countries, and the tiering of countries can be customized by the user.

## SOURCES OF UNCERTAINTY

- The model contains several types of uncertainty.
- All predictions of future resource utilization and technology advancement are inherently uncertain
- Estimates of fine PM, SO<sub>x</sub> and NO<sub>x</sub> emission controls are contingent on policy decisions and implementation.
  - Fine PM emissions are extremely sensitive to emission control effectiveness. For instance, a 1% variation in emission removal rates from a 95% effective emissions control can affect emissions by about +/- 20%.
- Coal quality adjustment factors are based on available USGS samples, and were not analyzed for representative distribution.

- CCS was assigned a zero deployment rate due to lack of certainty about future policy actions and availability of storage sites. Given strong policy drivers and adequate storage, significant CCS deployment rates are technically viable.
- Results past 2030 are based on projections of trends through 2030. Results for 2040 and 2050 are subject to significant uncertainty, as generally can be expected for long-term projections.