NATIONAL COOPERATIVE RAIL RESEARCH PROGRAM

NCRRP

Web-Only Document 1:

Technical Document for the Multi-Modal Passenger Simulation Model for Comparing Passenger Rail Energy Consumption with Competing Modes

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Summary

The objective of NCRRP Project 02-01, "Comparison of Passenger Rail Energy Consumption with Competing Modes," is to provide like-for-like comparisons of energy consumption and greenhouse gas (GHG) emissions of commuter and intercity passenger rail operations with competing modes of travel. In the context of this research, "passenger rail" includes higher speed, high speed, intercity, and commuter rail operations - those rail systems that are operated under the jurisdiction of the Federal Railroad Administration (FRA). "Competing modes of travel" include passenger automobiles, light-duty trucks used for personal transportation, suburban commuter bus services, intercity bus services, and air transportation.

This research project involved a literature review to collect data on relevant passenger transportation system characteristics and performance, formulation of an analytical framework for each passenger transportation mode considered, development of a quantitative decision-support tool based on these analytical frameworks, and finally applying the decision-support tool to numerous case studies which explore a range of commuter and intercity passenger rail operations and compares their fuel/energy consumptions and GHG emissions with those of competing modes of transportation for comparable door-to-door trips. The quantitative decision-support tool developed specifically for this research is called the Multi-Modal Passenger Simulator (MMPASSIM). It is an open-source Microsoft Excel macro enabled worksheet which may be used to predict and compare fuel and energy consumption and GHG emissions for a wide range of commuter and intercity passenger transportation scenarios.

The results of this research project are documented in two parts: *NCRRP Report 3: Comparison of Passenger Rail Energy Consumption with Competing Modes* and *NCRRP Web-Only Document 1: Technical Document and User Guide for the Multi-Modal Passenger Simulation Model for Comparing Passenger Rail Energy Consumption with Competing Modes*. The purpose of this NCRRP WOD 1 is to describe the technical details of the analytical framework underlying the MMPASSIM quantitative decision-support tool and also provide documentation and guidance on how to set up and use the MMPASSIM model to evaluate passenger transportation alternatives. NCRRP Report 3 documents the findings of the literature review and details a series of rail technology evaluation and modal comparison case studies performed in this research project. The MMPASSIM spreadsheet files, together with the Technical Document and User Guide, are provided on CRP-CD 176, which accompanies NCRRP Report 3. The MMPASSIM files also may be downloaded from the NCRRP Report 3 web page at www.trb.org.

The analytic framework developed uses common energy and emissions metrics across transportation modes and fuel types in order to facilitate like-for-like comparisons. Each modal trip involves a principal leg and, optionally, up to five access and egress legs. However, the focus is on the principal modal leg of a full door-to-door trip which requires relatively detailed simulations.

The calculated energy and emissions performance over a principal leg will differ from simpler average performance measures of a transportation mode. The energy and emissions performance for access and egress legs are assessed using default average performance metrics provided for each of the access and egress modes selected.

Each transportation mode is modeled, within the limits of publicly available data, such that seasonal, regional and equipment-specific characteristics are reflected in the modal energy and emissions performance. Examples of the limitations of publicly available data in the rail mode are auxiliary power requirements for rail, resistance coefficients for specific types of rail equipment, and engine performance for recent vintage locomotives.

Intercity scheduled bus operations also do not have load factors by region or service. This document and the case study analysis in the companion document indicate where estimates were used to characterize modal characteristics.

A common element of the mode-specific simulation modules used in the spreadsheet-based model is the ability to specify the equipment and route characteristics involved in making the specific trip of interest. Default choices are available for the user to select in a quick simulation comparison; however, the user also has the ability to modify the default characteristics or define new characteristics for each transportation mode if desired.

Railway Mode Model

The passenger train simulation implemented in the MMPASSIM model, unlike a traditional Train Performance Calculator (TPC), simplifies energy and emission calculations by treating passenger trains as a lumped mass. This approach is feasible since passenger train consists are short and light with high power to weight ratios such that their performance is not limited by track grades. However, despite this simplification, the influence of gradient and train length on the calculated energy and GHG emission intensities are included in the model.

A rail trip is specified by defining the characteristics of a passenger train and the route characteristics of the track over which it is to operate. The train characterization includes: the length and masses of the vehicles, the passenger capacity and load factor, parameters defining the inherent train resistance, and the auxiliary load and traction power capabilities. Inherent train resistance is modeled using a quadratic relationship which provides for a constant term to represent rolling friction and ground hysteresis losses, a speed-sensitive term representing dynamic rolling losses, and a term associated with aerodynamic losses which varies with the square of train speed.

The variation of a locomotive or power car's maximum tractive effort with train speed is modeled using a multi-segmented relationship where each segment of the tractive effort versus speed curve is described using an equation with a constant term, a linear speed-sensitive term and a term which varies inversely with train speed. These equation coefficients used in combination with up to a maximum of 5 speed segments facilitates accurate modeling of diesel-electric locomotives and electric power cars. The tractive effort for most diesel-electric locomotives may be accurately characterized using a 2-segment curve where the first segment represents a linear low-speed torque limited region and the second segment represents a power limited region where the tractive effort decreases inversely proportional to speed. Modeling electric power car tractive effort often requires additional straight line segments between the low speed tractive effort limit and a high-speed power limited region, and the highest speed region may also exhibit a fall-off in tractive effort beyond that of a constant power relationship. The additional limitation on passenger locomotive acceleration performance due to diesel engine loading rate is also modeled.

The default rail vehicle data set included with the MMPASSIM model includes characterizations for a number of commuter and intercity passenger rail consist. These may be used directly, modified by a user or used as templates to develop new passenger rail consist.

The rail model's route characterization is based on data that will usually be available to a rail-agency and rail system operators but may not be accessible to the general public. One of the key influences of passenger train performance is the number of speed changes involved on a route. Permanent speed limits shown in railway timetables are more generally available than are track gradient profiles and we recommend that actual speed limit tables be used in simulating a passenger rail service wherever possible. These are input into the model by specifying the start location of all speed limit changes on the route. The location of all stops to be made along a route must also be specified.

Gradients have less impact on passenger train performance and for this reason the model is able to use a more generalized gradient distribution representation instead of the detailed grade profiles specified in a railway track chart. The gradient distribution used in the rail model summarizes the actual track grades in a segment of track into six gradient bins which categorize the actual average of all grades collected in a gradient bin and the percent of total track segment distance associated with all grades in each bin. A route may be characterized using up to eight separate segments having different grade distributions when there are significant differences in track profile over the route's overall length. The model is provided with several default region and service-specific rail route grade characteristics which were developed and used for case studies. These grade characteristics were developed using a range of actual track gradient profiles and may be used with reasonable accuracy when grade profiles for a specific route cannot be supplied.

The rail mode simulation uses the passenger equipment's inherent resistance and tractive effort characteristics to calculate detailed profiles of acceleration, coasting and braking performance which can be achieved on level and tangent track. These calculations are stored in one mile per hour increments in lookup tables which the model then uses as the basis for determining the duration of acceleration and braking operations required at all speed limit changes and for stops. This provides for a more computationally efficient method of evaluating passenger train performance than a second-by-second simulation of movement along the entire track.

The MMPASSIM model performs a rail mode simulation by stepping through a route and evaluating the duration of acceleration, cruising (at a constant speed limit), and braking phases for each section of track bounded by a speed limit change. The work done at the rails to overcome inherent resistance during cruise and acceleration phases is broken out into rolling, dynamic and aerodynamic components and the additional work done by brakes to maintain speed limits while traveling on downgrades or for speed reductions and stops is calculated. The rail module accumulates the energy associated with each of the sub- categories of energy dissipation such that the effectiveness of alternative technologies can be gauged from the model output for a single train run.

Highway Mode (LDV and Bus) Models

The highway modes' energy and emissions performance in MMPASSIM are derived by simulating the second-by-second movement of a specified vehicle over a set of pre-defined speed profiles (drive schedules) in urban areas and uses the vehicle's cruise performance for calculations over rural intercity segments. Vehicle resistance to motion is based on rolling and aerodynamic resistance coefficients, vehicle power and energy performance is governed by specified engine and drivetrain characteristics and auxiliary loads are associated with regional climates as specified for three seasons of the year (summer, winter, and other).

Eight drive schedules are implemented in the model to characterize the influence of traffic congestion on the movement of a simulated LDV or bus in urban areas. These were selected from a range of speed profiles developed by the U.S. Environmental Protection Agency (EPA). The specific congestion performance for a simulation is characterized by specifying the proportion of a trip which is to follow the speed profile of each of these eight drive schedules. These proportions may be individually specified for 5 different time-of-day congestion intervals to allow for traffic variability and default sets of values are provided to represent driving through typical large and small cities in these 5 time periods. The time-of-day periods include:

- a.m. peak
- p.m. peak
- mid-day
- shoulder periods (next to peak periods)

- overnight

Users of the MMPASSIM model are also able to develop customized sets of time-of-day based drive schedule proportions specifically tailored to urban areas of interest. Note that the light duty vehicle (LDV) drive schedules contain a high-acceleration performance drive schedule that is not included in the bus drive schedules; however, the simulation process is the same for both modules.

Default bus performance characteristics are provided for a limited set of four representative bus types as follows:

- 45 foot bus with 56 passenger seats
- 41 foot bus with 48 passenger seats
- double deck bus with 81 passenger seats
- hybrid commuter bus with 57 seats

These typical bus types are characterized using publicly available data for resistance coefficients, drivetrain efficiency, auxiliary loads and diesel engine efficiency and do not represent any particular manufacturer's vehicle. Commuter bus operating characteristics and energy intensity performance are calibrated using data reported for commuter buses by municipal operators in the Federal Transit Administration's (FTA) National Transit Database (NTD). The intercity buses are calibrated using data reported in the NTD for short-distance intercity commuter bus travel combined with data reported in a 2013 survey of major North American bus operators undertaken for the American Bus Association. The average fuel economy for the two sources is 42.3 L/100-km or 5.59 mpg (average of 6.09 and 5.08 mpg from the ABA and NTD sources respectively).

The default light duty vehicle performance characteristics provided in this model were derived from sales-weighted class-average values published annually by the U.S. Environmental Protection Agency (EPA). Specifically, the characteristics of 2011 model-year LDVs were grouped on the basis of similar coast-down resistance coefficients to develop a set of six representative vehicle classes as follows:

- Small cars (Sm-Car)
- Midsize cars and all station wagons (Mid-car/SW)
- Minivans and non-truck SUVs (Mini-V/sm-tSUV)
- Large cars, medium-truck SUVs and small pickup trucks (Lg-car/cSUV/smPU)
- Large pickup trucks (PU)
- Large truck SUVs (Lg-tSUV)

The six individual class-average vehicles are provided as user-selectable default vehicles in the MMPASSIM model. In addition, three composite vehicles are provided which typify the performance of the mix of vehicles used for specific types of trips which include:

- a composite based on the estimated mix of personal LDVs used in local trips
- a composite based on the estimated mix of personal LDVs used for intercity trips
- a composite based on the estimated LDV mix for taxis

Additional "sales-weighted" and "driven-fleet" composite vehicles were developed from EPA fuel economy data for the 2011 model year. These class-average performance characteristics were developed by applying class-specific modifiers to a generic engine fuel-map and a generic six-speed transmission such that the EPA's sales-weighted average performance is obtained when simulating operation over the EPA's underlying certification drive schedules. A similar process is used to characterize the 2011 "driven fleet" to reflect the relative performance of older vehicles with an appropriate vehicle age distribution. An algorithm is provided to create "sales-weighted" and "driven-fleet" composite LDV characterizations for years beyond the 2011 base data year. Default composite values for "sales-weighted" and "driven-fleets" for 2012 and 2013 are provided in MMPASSIM and the model architecture supports addition of future year composite fleet values as EPA estimates of fuel economy for those years become available.

The EPA estimates that actual driving conditions lead to fuel economies which fall below the reported values by between 12% and 15% due to various factors not considered in the 5 cycle test process. These include:

- Road and tire condition
- Effect of wind on aerodynamic drag
- Effect of temperature on aerodynamic drag
- Seasonal cold-start fuel consumption
- Seasonal auxiliary power loads
- Road grade effects

The MMPASSIM model considers the impact which these factors have on the running performance of LDVs. However, driver-behaviour, auxiliary power usage and vehicle maintenance can all affect the fuel economy of a specific vehicle and there will always be a range of fuel economy performance around any derived average. Our objective is to inherently model most parameters and provide an average in-service fuel economy that is representative of the real-world experience.

Air Mode Model

Air mode trips are analyzed differently than rail and highway mode trips. The flight of a specific aircraft is not simulated on a second-by-second basis while accumulating distance traveled and fuel consumed in moving from the origin to the destination. Rather, the fuel consumption and emissions intensities for an air trip are derived by applying fuel intensity coefficients to the distance traveled. This approach is feasible since very detailed aircraft in- service performance data is published by the U.S. Bureau of Transportation Statistics (BTS).

The route to be followed is defined by specifying a sequence of up to four IATA (International Air Transport Association) airport codes. A direct flight would involve only two IATA airport codes, one for the departure airport and the other for the destination airport, while multi-leg flights may be configured with up to three legs by specifying up to two intermediate airport codes. The air-mode model automatically computes the great-circle distance (shortest distance along the earth's sphere) traveled between two airports based on their latitude and longitude. A user may easily expand the list of available airports by adding IATA codes, latitude and longitude.

The default aircraft characterization data provided with the model are based on 2011-2012 operations of domestic U.S. scheduled air carriers and can be updated by the user as desired in future years as air technology and operations practices change. The default data is organized into the following five categories of aircraft:

1. Turboprops (TP)
2. Small Regional Jets (SRJ) (defined here as jet aircraft with less than 50 seats)
3. Regional Jets (RJ) (defined here as short-range jet aircraft with 50 to 89 seats)
4. Narrow Body Jets (NBJ) (defined here as jet aircraft with greater than 89 seats in a single aisle configuration)
5. Wide Body Jets (WBJ) (defined here as jet aircraft with greater than 89 seats configured with more than one aisle)

Air mode trips are assumed to be serviced by a distribution of these five aircraft types rather than by a specific aircraft. A default mix of aircraft types was derived from the BTS data and is provided for seven ranges of trip length. The air model automatically assigns the proportions of aircraft types used in each leg of an air trip according to the distributions associated with the applicable trip length range. However, a user may adjust the proportions of aircraft types assigned to each leg of an air trip.

Fuel intensity coefficients for each representative aircraft category have been derived separately for the LTO (landing and takeoff) and cruise phases of a flight. The cruise phase fuel intensity values have been adjusted to account for the average incremental distance traveled in excess of the shortest path between origin and destination under both peak and off-peak period conditions. The fuel consumed in the cruise phase of an air trip leg is computed by multiplying the great-circle distance traveled by the fuel intensity coefficient for the representative aircraft type. Where a distribution of aircraft types is specified, the calculation applies the fuel intensities in those proportions.

Access and Egress Modes

Only the primary transportation modes being compared are simulated in detail in the model whereas the performance attributes of access and egress modes are simple averages provided in default lookup tables. The model architecture supports specification of different performance attributes for an access/egress mode to be associated with city size, time-of-day, day-of-week and season. The attributes of public transportation modes have been derived from the 2011 National Transit Database's *Service and Energy* Tables. The electricity supply used for public transportation modes is region-dependant but all other performance metrics are based on one average applied to all regions.

Attributes for personal automobiles and taxis were derived with the detailed LDV simulation model in a one-time simulation of the 2011 driven-fleet composite vehicle. The following assumptions were made for the highway access/egress modes:

- taxis were assumed to travel 1.5 km for every km of passenger carrying travel
- drop-off and pick-up was assumed to have 60% return-to-origin travel and 40% being part of a 2-person trip that incurs 10% extra travel distance
- carpools are assumed to involve 3 persons and the trip length is 15% longer than any one-person trip

The fuel intensity of highway modes is adapted to congestion conditions via peak and off-peak multipliers, which are specified for three city sizes (large, small and rural municipality).

Regional Influences

The MMPASSIM model provides a default regional characterization for Northeast, South, Midwest and West regions of the continental U.S. and can be optionally updated by a user to include additional user defined regions. The primary regional influences are seasonal and include travel variations, temperature variations, and average use of climate controls and auxiliary power for ground transportation modes. Congestion factors for travel in urban and rural areas during peak and off-peak periods are also specified for a region. Finally, the fuel and emissions intensities of access and egress modes are defined for each region.

Electricity generation is further disaggregated into nine sub-regions with the distribution of fuels used in generating that electricity derived from U.S. Energy Information Administration data for 2011 and upstream fuels consumed were derived from the GREET model.

MMPASSIM Model Structure

The MMPASSIM model performs multi-modal door-to-door passenger trip comparisons of energy and GHG intensity. Additional details on energy dissipation sources are provided in conjunction with rail-only simulations to facilitate comparisons between different rail technologies. The model is implemented as a macro enabled Microsoft Excel worksheet which supports the following three types of analyses:

1. *Single Train Simulation* - a single train service is assessed for its performance and energy/GHG emissions breakout.
2. *Rail Technology Evaluation* - a comparison of up to four passenger rail technologies to compare and assess the energy/GHG emissions savings realized.
3. *Mode Comparison* - a comparison of up to four passenger modes (rail, bus, air, light duty vehicle) to compare and assess the energy/GHG performance in a door-to-door trip.

The primary user interface for all simulations is provided in the 'Master-I-O' worksheet (blue tab) from where a user configures all required simulations for an analysis. However each transportation mode is configured and operated as a semi-independent sub-model which may be configured and controlled independently by a user if desired. The sub-model user interfaces are provided in the 'Rail-I-O', 'Air-I-O', 'Bus-I-O' and 'LDV-I-O' worksheets (all with blue tabs). A system of pop-up user forms (menus) and Visual Basic for Applications (VBA) macros coordinates the configuration of all desired simulations as well as the transfer of data to and from the sub-model worksheets. The results are displayed to the user in formatted output tables on the 'Master-I-O' worksheet which are automatically brought into view while the simulation proceeds.

Simulations can be specified from the Master-I-O sheet using the wide range of case study defaults for routes and equipment in each mode. In addition new routes and equipment can be specified and default values can be modified within the model's other worksheets as discussed below. The model uses green to indicate model inputs, yellow to indicate default values, orange to indicate calculation formulae and blue to indicate output sheets/areas.

The 'Regional-Properties' worksheet (yellow tab) contains regional data for: average daytime temperature and air conditioning usage by season. In addition it contains default characteristics for fuel, energy and GHG emissions intensities used for the access and egress modes. The access and egress modes support differentiation by size of city and time- of-day congestion for the highway modes.

The 'Energy-Emissions' worksheet (yellow tab) provides the GHG emissions rates by fuel/energy-source and the indirect (upstream well-to-pump) energy consumption/GHG- emissions associated with each fuel/energy-source. For electricity these factors are also provided for different geographical regions.

Mode-specific equipment worksheets (green tabs named 'Rail-Consist', 'Bus-Type', 'LDV-Type' and orange tab named 'LDV-Resist') store the characteristics describing the physical attributes and capabilities of ground transportation mode vehicles. New equipment/vehicles can be introduced into the model by adding data to these worksheets.

Mode-specific 'Route' worksheets (green tabs named 'Rail-Route', 'Bus-Route' and 'LDV-Route') store the characteristics describing the routes which may be followed by a ground transportation mode. New routes can be introduced into the model by adding to these worksheets.

The highway mode drive schedule worksheets (yellow tabs named 'Bus-Drive-Schedules' and 'LDV-Drive-Schedules') define the second-by-second speed profiles used to represent movement of buses and LDVs in urban areas. The mixes of drive schedules used to represent time-of-day congestion in different urban centers are also declared in those worksheets. Default drive schedule mixes for large and small urban centers have been provided. Users may adjust these defaults and also add new city-specific drive schedule mixes to these worksheets.

The 'Engine' worksheets (yellow tabs named 'Bus-Engine' and 'LDV-Engine') provide the needed modal engine efficiency characteristics for the highway modes. Representative fuel maps are used for propulsion systems using non-continuously variable transmissions (applicable to most conventional LDV and buses) while coefficients for a single optimal performance equation are provided for representing vehicles using a continuously variable transmission (CVT).

The ‘Simulation’ worksheets (orange tabs named ‘Rail-Simulation’, ‘Bus-Simulation’, ‘LDV-Simulation’ and ‘Air-Simulation’) implement the algorithms used to simulate the movement of a modal vehicle (or a fleet-average characteristic vehicle) representative of the specific service/region being simulated.

MMPASSIM Model Outputs

The primary MMPASSIM model outputs are provided in simulation mode-specific tables located on the ‘Master-I-O’ worksheet. The output tables are different for each of the three analysis scenarios.

The output from a *Single Train Simulation* is provided in two tables with sufficient detail to permit assessment of the underlying sources of energy consumption and GHG emissions. This information is a first step in validating the input data used for the simulation and in assessing the relative impact that technological changes to specific source components of energy consumption would have. The first table provides the absolute and proportional values of energy consumption and GHG emissions for: seven categories of traction energy (three sub-elements of inherent train resistance, three sub-elements of brake dissipation, and curving resistance); for the traction system’s transmission losses; and for provision of hotel power. The second table provides performance metrics where energy and emissions intensities are output for three divisors (per-trip, per-seat-distance, and per-passenger-distance) and for two service-performance metrics (travel-time and average speed).

The output from a *Rail Technology Comparison* is provided in three tables. The first table provides the same components of energy consumption and GHG emissions as output for a single train simulation but adds additional rows which indicate the percent-reduction in energy and emissions realized by using the alternative technologies. The second table provides performance metrics and indicates the percent reduction compared with the baseline technology case. The third table outputs the total energy and emissions intensities when the indirect consumption and emissions associated with well-to-pump fuel provision are included.

The output from a *Mode Comparison* analysis focuses on performance metrics comparable across transportation modes and expands the comparison to include access and egress legs of a trip. Four tables are output with the same energy/emissions intensity values as were used in the rail technology comparison tables but with an indexed comparison to the baseline rail mode replacing the %-reduction from the baseline rail technology that was used in the technology comparison table. The first table compares direct energy/emission for the modal leg of the trip, the second table compares direct energy/emission for only the access/egress legs of the respective modal trips, the third table compares direct energy/emission for the complete door-to-door trips, and the fourth table compares the full energy/emissions (including indirect well-to-pump) for the complete door-to-door trips.

Using the MMPASSIM Model

See the front end of the User Guide in Appendix A for an overview and quick reference guide.

1 Introduction

The National Cooperative Railroad Research Program (NCRRP) is a research program administered by the Transportation Research Board (TRB) which "conducts applied research on problems of interest to freight, intercity passenger, and commuter rail practitioners." This web-only document is one of two reports which together detail the research and results of NCRRP Project 02-01 entitled "Comparison of Passenger Rail Energy Consumption with Competing Modes."

The objective of NCRRP Project 02-01, as suggested by its title, is to provide like-for-like comparisons of energy consumption and greenhouse gas (GHG) emissions of commuter and intercity passenger rail operations with competing modes of travel. In the context of this research, "passenger rail" includes higher speed, high speed, intercity, and commuter rail operations—those rail systems that are operated under the jurisdiction of the Federal Railroad Administration (FRA). "Competing modes of travel" include passenger automobiles, light-duty trucks which are often used for personal transportation, suburban commuter bus services, intercity bus services, and air transportation.

To accomplish the objectives of this research project, a targeted literature review was performed and the findings then used to inform the development of an analytical framework for equivalent comparison of mode-to-mode fuel and energy consumption and GHG emissions. The literature review covered passenger rail efficiency research, passenger rolling stock characteristics, characteristics of the modes used by passengers to access and egress from rail and bus stations and airports, and finally an examination of technologies which can improve the energy efficiency of rail equipment, infrastructure and the overall operations of a rail system. A quantitative decision-support tool, the Multi-Modal Passenger Simulator (MMPASSIM), was developed specifically for this project and used to predict and compare fuel and energy consumption and GHG emissions in a series of case studies. The MMPASSIM model is a fundamental product of this research effort and is available for use.

A range of case studies were used to calibrate the analytical model, to examine the details and sensitivities of specific passenger rail systems and to evaluate the prospective impact of improving operational strategies, rolling stock, motive power and the supply of fuel or electricity for traction power. The barriers and opportunities to improve the fuel and energy efficiency and reduce the GHG emissions from intercity and commuter passenger rail systems were also examined. Numerous case studies were developed to explore a range of commuter and intercity passenger rail operations and compared their fuel and energy consumptions and GHG emissions with those of competing modes of transportation for comparable door-to-door trips.

NCRRP Report 3: Comparison of Passenger Rail Energy Consumption with Competing Modes documents the findings of the literature review and the details of the series of rail technology evaluation and modal comparison case studies performed in this work. It also presents findings on the barriers and opportunities to improve the fuel and energy efficiency and reduce the GHG emissions from intercity and commuter passenger rail systems.

This document, *NCRRP Web-Only Document 1: Technical Document and User Guide for the Multi-Modal Passenger Simulation Model for Comparing Passenger Rail Energy Consumption with Competing Modes*, has a two-fold purpose:

a) to provide technical documentation describing the analytical framework underlying the development of the MMPASSIM model – a Microsoft Excel macro enabled spreadsheet model of fuel, energy and greenhouse gas emissions of passenger rail, highway (bus and light duty vehicles) and air travel.

b) to provide a User Guide (in this volume's Appendix A) to guide users in applying the MMPASSIM model to predict and compare the fuel and energy consumed and the greenhouse gases emitted by prospective door-to-door trips made by passenger rail services and other competing modes of travel.

The User Guide provided here in Appendix A contains its own table of contents and functions in the most part as a stand-alone document. Although some occasional references are made in the User Guide to technical details provided in the main body of this web-only document, it should not be necessary for a user to read and understand the entire technical document in order to make effective and productive use of the MMPASSIM model in answering questions of fuel and energy consumption and greenhouse gas emissions related to passenger travel modes. More advanced uses of the model involving detailed customization of equipment and route characterizations will necessarily require a more thorough understanding of the material set forth in the main body of this web-only document in addition to the User Guide in Appendix A.

2 Performance Evaluation Framework

2.1 Methodology Overview

The background section of the terms of reference for this project noted the limitations of using averages for the energy performance of rail and other competing modes. In particular it noted that:

- *Passenger rail fuel consumption data may not fully represent impacts, since they are based on broad averages that include many different variations in distance traveled, amenities provided, speeds, operating environment, type of train operated, and form of propulsion. Similarly, energy consumption estimates for competing modes usually represent broad averages that do not necessarily reflect the energy profiles of comparable trips on modes that compete with passenger rail service accurately.*

- *Using disaggregated data, linked more directly to where and how the fuel and energy attributable to specific trips is consumed, can provide a greater understanding of what is actually occurring. In addition, significant variations in fuel and energy consumption can occur by regions of the country and by individual states and metropolitan areas, and these variations should also be taken into account when analyzing comparable modes of travel, along with specific characteristics of available technologies and operating environments.*

The key objective of this project, as stated in the terms of reference, is:

> *to provide like-for-like comparisons of energy consumption and greenhouse gas emissions for commuter and intercity passenger rail operations and for competing travel modes.*

In order to accomplish the objective the terms of reference required development of:

- *A quantitative decision-support tool for evaluating and comparing fuel and energy consumption and GHG emissions by commuter and intercity passenger rail operations and by competing modes of transportation for comparable trips; and*

- *An evaluation of opportunities to improve fuel and energy efficiency and reduce GHG emissions for intercity and commuter passenger rail.*

To meet the project objective, common energy intensity metrics are used across modes and fuel types. The focus is on the principal modal leg of a full door-to-door trip and each mode is simulated in detail for this principal leg. Overcoming the shortcomings of working with readily available averages for modal performance requires development of relatively detailed simulation models that reflect the variations in performance across regions, seasons and equipment types. Each mode is modeled, within the limitations of publicly available data, such that seasonal, regional and equipment-specific characteristics are reflected in the modal energy and emissions performance. Examples of the limitations of publicly available data in the rail mode are auxiliary power requirements for rail, resistance coefficients for specific types of rail equipment, and engine performance for recent vintage locomotives. Intercity scheduled bus operations also do not have load factors by region or service. This document and the case study analysis indicate where estimates were used to characterize modal characteristics.

A common element of the mode-specific simulation modules used in the spreadsheet-based model is the ability to specify the equipment and route characteristics involved in making the specific trip of interest. Default choices are available for the user to select in a quick simulation comparison; however, the user also has the ability to modify the default characteristics or define new characteristics for each mode if desired.

The requirement for an "*evaluation of opportunities to improve fuel and energy efficiency and reduce GHG emissions for intercity and commuter passenger rail"* means that the rail simulation module requires additional details on the technological attributes of equipment such that the energy/emissions performance of alternative technologies can be assessed. Therefore, in addition to a comparison with other modes, the rail mode can be simulated in isolation and in comparison with other rail mode technologies for the same trip.

The energy/emissions intensities of modes used in access and egress legs are included and separately identified; however, simple averages are used rather than detailed simulations. Indirect 'well-to-pump' energy and emissions intensities are included as a separately identified metric for each leg of a door-to-door trip.

The principal leg of each modal trip is simulated in detail such that variations from the average performance are discernable. For example, when an automobile is used as the main leg of a trip, it is simulated in detail for the specified equipment, route and traffic congestion characteristics specified; however, when used as an access/egress leg to other modes, pre-processed averages for a composite vehicle can be used. The default average performances for access/egress by highway modes have been pre-processed for varying levels of traffic congestion. If the user wishes to simulate a new access/egress scenario in detail, it can be done as a separate one-time simulation of the relevant route and equipment used for the access/egress trip.

2.2 Mode Specific Data Constraints and Methodology Influences

The types and level of details available to characterize modal energy and GHG intensities vary across the modes. The approach taken within each mode reflects the types of data available. In general terms:

- The light-duty-vehicle (LDV) mode has very detailed performance data at the individual vehicle level but has poor in-service performance data. Traffic congestion influences are significant and the LDV module supports local commute and intercity traffic characteristics for five time-of-day periods. Seven generic LDV classes are characterized in conventional and hybrid configurations.
- The bus mode has less detail than LDVs for individual vehicle performance but has much less variability in types of vehicles available and better aggregate energy performance data. Intercity and local commuter bus services are characterized by road type and traffic congestion in the same way as the LDV module.
- Simulation of individual air mode trips on a second-by-second aircraft movement basis is a significant undertaking and beyond the scope of this project. The air mode has good in-service performance data which allows differentiation of equipment types by trip length as well as assessment of congestion effects. The equipment mix and equipment-specific energy performance are characterized by trip length for five representative types of aircraft.
- The data available for the rail mode vary across services — detailed characterization data exist for some types of equipment but not all and the level of aggregation in total-fleet performance reports does not provide enough detail to accurately calibrate/validate individual services or equipment types. Intercity and commuter services are characterized for several generic conventional equipment types and a high speed equipment type.

The mode-specific data constraints and associated methodological details for rail, bus, LDV and air are each discussed in the following subsections.

2.3 Highway Modes (LDV and Bus) Methodology

The highway modes' energy and emissions performances are derived via simulation modules which simulate second-by-second movement of a specified vehicle over a set of pre-defined speed profiles (drive schedules) in urban areas and use cruise performance for rural intercity segments. The LDV drive schedules contain a high-acceleration performance drive schedule that is not included in the bus drive schedules; however, the simulation process is the same for both modules. Vehicle resistance to motion is based on rolling and aerodynamic resistance coefficients, vehicle power and energy performance is governed by specified engine and drivetrain characteristics and auxiliary loads are associated with regional climates by three seasons of the year (summer/winter/other).

The engine efficiency of the highway modules are based on representative fuel maps from the literature – the bus module uses 2010 vintage fuel maps for 350 hp and 455 hp engines in the EPA's Greenhouse Gas Emissions Model (GEM) [EPA, 2010] while the LDV vehicles are based on 2004 vintage fuel maps noted on Appendix C to Volume 1 of this report. The fuel maps are normalized to the engine's minimum brake specific fuel consumption (bsfc) to allow different engine powers and fuel efficiency data to be used.

2.3.1 Bus Characterization

The default characterization data are generic composites rather than any one specific bus. A typical bus is characterized using publicly available data for resistance coefficients, drivetrain efficiency, auxiliary loads and diesel engine efficiency. Bus rolling resistance is based on Australian test work {Biggs, 1987] and calibrated with published test track data for trucks as reported in Appendix B of the freight mode comparison study undertaken by English and Hackston [English, G., and D.C. Hackston, 2013]. The bus aerodynamic drag coefficient is set at 0.5 based on the observations of work of Patten et al. who indicate: "it is not unrealistic to expect their [North American intercity buses] drag coefficient to be in excess of 0.50" [Patten et al. 2012, p52]. Patten also cites an advanced European bus that is in service and has achieved a Cd of 0.35.

The bus module is calibrated to a typical U.S. operating environment using two main data sources. Commuter bus operating characteristics and energy intensity performance are calibrated with data reported for commuter buses by municipal operators in the Federal Transit Administration's (FTA) National Transit Database (NTD) [Federal Transit Administration, 2011]. Intercity buses are calibrated to data reported in the NTD-Service Table for short-distance intercity commuter bus travel (total-miles/revenue-miles X revenue car-miles/gallon for commuter bus (CB) operations of the Maryland Transit Administration, 2011) combined with data reported in a 2013 survey of major N.A. bus operators undertaken for the American Bus Association (ABA) [John Dunham & Associates, for the American Bus Association Foundation, 2013, Table 2-5, pg. 13]. The average fuel economy for the two sources is 42.3 L/100-km or 5.59 mpg (average of 6.09 and 5.08 from the ABA and NTD sources respectively). In calibrating bus performance to be in this fuel efficiency range, we used a Cd of 0.5 for a standard 45 ft bus and increased the fuel consumption of the EPA's 2010 engine by 5% to reflect the mix of older less-efficient buses in service. Someone with more detailed data on specific bus performance might find a different combination of Cd and minimum bsfc that produces the same average results.

Occupancy and non-revenue travel data are reported for commuter buses in the National Transit Database; while only occupancy is reported in the ABA's 2013 survey of operators. We believe that the intercity commuter bus operations would understate the occupancy attained by longer distance intercity scheduled carriers and the average occupancy reported for all operators surveyed in the ABA would be higher than that of scheduled carriers (since charter carriers realize very high load factors and account for over 50% of the operators surveyed). In the absence of route-specific data, the default occupancy used in the present modal comparisons is the average of that realized by the intercity commuter bus travel (passenger-miles / vehicle-revenue-miles for commuter bus (CB) operations of the Maryland Transit Administration, 2011) and that reported for all bus services in the ABA survey (i.e. an average of 32.6 riders). With an estimated distribution of buses having the following seating capacity: 90% with 56 seats, 5% with 81 seats and 5% with 48 seats, the average load factor is 57%.

The model also supports simulation of hybrid buses in commuter service. Hybrid performance is characterized with lithium ion batteries having charge/discharge efficiencies based on data from Hofman et al, [2008,Table 6].

2.3.2 LDV Characterization from Test Data

The Light duty vehicle module is similar to the bus module but since there is a vast amount of certification data for LDVs, it is possible to calibrate a number of classes of vehicles. Our calibration/validation of LDVs was undertaken by modifying the minimum bsfc of our generic fuel map and the average weight of vehicles in each of the classes. The approach is similar to that taken by Ates in modeling light and medium duty vesicles and we used Ates's data for LDV transmission and differential efficiency coefficients [Ates, M, 2009, p.72]. This calibration process is described in the section. In the subsequent section we describe the steps we then took to present real-driving conditions/environment to be used in the simulations.

The EPA requires LDV manufacturers to provide coast-down data coefficients for each LDV-model sold in the U.S. In addition, EPA requires that each LDV's energy performance be measured or calculated in the generation of the EPA's city/highway fuel economy label. These publicly available characterization data are more detailed than all the other passenger modes. However, details of the in-service performance of LDVs are survey-based and have much more uncertainty than is typically available for the other passenger modes. Details of engine and transmission characteristics are not as publicly available for LDV as for the other modes. Also, the range of technologies deployed and the range of equipment types are much wider than for the other modes.

Each year the EPA publishes the sales-weighted class-average performance of LDV for several classes of new vehicle. The class-averages reflect the actual mix of vehicles sold within each class in the U.S. during that year. We grouped LDVs for MY-2011 on the basis of exhibiting similar coast-down resistance coefficients. Default parameters are developed for the following six representative vehicle classes from 2011:

- Small cars (Sm-Car)
- Midsize cars and all station wagons (Mid-car/SW)
- Minivans and non-truck SUVs (Mini-V/sm-tSUV)
- Large cars, medium truck-SUVs and small pickup trucks (Lg-car/cSUV/smPU)
- Large pickup trucks (PU)
- Large truck SUVs (Lg-tSUV)

The six individual class-average vehicles are provided as user-selectable default vehicles. In addition, four composite vehicles are provided to typify the performance of the following specific mixes of vehicles:

- the EPA's sales-weighted composite vehicle,
- a composite based on the estimated mix of personal LDVs used in local trips,
- a composite based on the estimated mix of personal LDVs used for intercity trips, and
- a composite based on the estimated LDV mix for taxis.

In relation to the EPA sales-weighted vehicle-mix, the vehicle composite for local commuting assumes a shift from large to smaller vehicles, the intercity travel mix assumes a shift from smaller to larger vehicles and the taxi mix assumes a larger proportion of midsize vehicles, no pickup trucks and a higher proportion of hybrid vehicles (Note: these alternates are illustrative estimates at this point – to be refined as data is located). In each case one must recognize that the default vehicles are representative of the composite-class of LDVs being simulated and that individual vehicle types within the class could provide significantly better or worse performance. As noted above with respect to the higher-efficiency side of the range, the model does separately simulate hybrid vehicles within each class. As discussed later, driver-behavior and other factors can also lead to variations and decreases in operational fuel economy (FE) of any one specific vehicle.

The relative 2011 MY sales distribution and the estimated distribution of derived composite vehicles are summarized in Table 1.

Table 1. LDV Class Distributions used for Composite Vehicles

Class	2011 MY Proportion of Sales[a)]	Local Travel[b)]	Intercity Travel[b)]	Taxi[b)]
Sm-car	17.70%	22.70%	14.70%	0.00%
Mid-car/SW	25.40%	28.40%	23.40%	40.00%
Mini-V/sm-tSUV	5.30%	5.30%	5.30%	50.00%
Lg-car/cSUV/smPU	28.00%	25.00%	30.00%	10.00%
PU	14.10%	11.10%	14.10%	0.00%
Lg-tSUV	9.50%	7.50%	12.50%	0.00%

Sources: a) derived from EPA data, b) TranSys Research Ltd illustrative assignments (to be refined as data is located).

The actual market shares of individual vehicles are not published and the variation of class-specific performance across manufacturers can be significant. Our analyses are based on the 2011 model year (MY) fuel economy trends report [EPA, March, 2012]. In 2011 two standard deviations of manufacturers' averages per class ranged from a low of +/-22% for midsize cars to a high of +/-27% for large cars. In all classes, the sales-weighted average demonstrated better fuel economy than the simple average of all manufacturers. Our LDV module provides class average performance characteristics which are developed by applying class-specific modifiers to a generic engine fuel-map and a generic six-speed transmission such that the EPA's sales-weighted average performance is exhibited when simulated on the EPA's underlying certification drive schedules. The variation can be due to differences in vehicle resistance parameters and/or engine/drivetrain losses. A somewhat arbitrary assignment was made to adjust the resistance coefficients and vehicle mass by 50% of the initial error and the engine/drivetrain losses by 50% of the initial error. As the model's initial average parameters were based on the simple average of published LDVs rather than the sales-weighted average, most modifiers reduce resistance parameters and loss-factors to attain the sales-weighted average performance.

A similar process is used to characterize the 2011 “driven fleet” to reflect the relative performance of older vehicles with an appropriate vehicle age distribution. The algorithm processor assumes that 50% of the difference in fleet-average fuel economy of the new model year relative to the 2011 sales-weighted fleet is due to drive-train efficiency (engine and/or transmission efficiency is scaled by 50% of the fuel economy difference) and 50% is due to vehicle body design or fleet composition (the 2011 fleet average weight and resistance coefficients are scaled by 50% of the fuel economy difference).

The LDV characterization data for the model year 2011 are summarized in Table 2.

Table 2. MY 2011 LDV Sales-Weighted Characterization Data

Model Development Phase	Class	Derived Averages for EPA Classes of MY 2011 LDVs						Derived Composites				
		small	mid/SW	MV/ Sm-tSUV	Lg/cSUV / smPU	PU-truck	Lg-tSUV	Local [d]	Inter-city[d]	Taxi [d]	2011-Sales-weighted	2011 Driven Fleet
Initial Base Parameters[a]	a (N)	141.77	171.21	164.86	211.70	225.63	238.72	185.42	194.81	172.1	191.09	N.A.
	b (Nsm^{-1})	2.407	2.416	3.256	4.462	5.963	6.360	3.659	4.066	3.04	3.907	N.A.
	c (Ns^2m^{-2})	0.418	0.455	0.567	0.628	0.670	0.672	0.536	0.565	0.53	0.554	N.A.
	Mass (kg)	1,496	1,590	1,828	2,040	2,397	2,554	1,856	1,958	1,75	1,917	N.A.
	Power (kW) [b]	121	133	163	189	233	253	166	179	153	174	N.A.
	Hybrids [c]	8.00%	1.88%	0.40%	1.88%	0.40%	0.40%	3.86%	3.86%	10%	2.2%	1.3%
	non-Hyb-CVTs	4.00%	9.99%	6.90%	9.99%	6.90%	6.90%	6.74%	6.74%	8.00%	7.8%	2.9%
Initial FE Difference		-2.8%	8.2%	-2.4%	9.8%	-9.6%	2.7%	N.A.	N.A.	N.A.	4.5%	-7.9%
Adjusted Model Parameters to get Sales-weighted FE	loss reduction	-1.4%	4.1%	-1.2%	4.9%	-4.8%	1.4%	N.A.	N.A.	1.9%	2.3%	-4.0% [e]
	a (N)	143.78	164.19	166.87	201.31	236.46	235.47	182.35	191.57	169.2	187.16	194.51
	b (Nsm^{-1})	2.44	2.32	3.30	4.24	6.25	6.27	3.61	4.01	3.00	3.83	3.98
	c (Ns^2m^{-2})	0.42	0.44	0.57	0.60	0.70	0.66	0.53	0.56	0.52	0.54	0.56
	Mass (kg)	1,517	1,524	1,851	1,940	2,512	2,520	1,828	1,929	1,729	1,878	1,952
Final FE Difference		-0.7%	0.1%	-0.6%	0.3%	1.0%	0.0%	N.A.	N.A.	N.A.	0.3%	N.A.

Source: TranSys Research Ltd. analysis of EPA fuel economy data.

Notes:

a) Resistance Parameter Units are: N – Newton; Nsm^{-1} – Newton / (meter/second); Ns^2m^{-2} – Newton / $(\text{meter/second})^2$

b) Average power for each group is based on a derived power/weight equation for the MY 2011 data: P= -86.933 + 0758W; with P (hp) and W (lb).

c) Conventional vehicles and hybrid vehicles are separately characterized and simulated in the model and default proportions of hybrid vehicles are included within each class's characterization data. If one wishes to only simulate a hybrid (or only a conventional) LDV the default proportion-of-hybrids can be set to one or zero accordingly.

d) These composites are illustrative estimates pending better data for user updates.

e) The value used in LDV-Resist sheet of the model is a different number and includes an offset by the loss-reduction already included in the Sales-weighted composite (i.e. -0.017 = -0.079/2 + 0.023) which is the reference vehicle used for 2011 and future year composite vehicles.

Source: TranSys Research Ltd., derived from data in: EPA, Fuel Economy Guide for DOE-2013; and Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 through 2012, EPA-datasheets, 2013.

2.3.3 Adjustment of LDV Characteristics to Reflect Driving Conditions

The characteristics developed above are for the running performance of LDVs. All LDVs experience worse fuel economy on start-up and this initial fuel penalty increases with colder temperatures. The increase has a significant impact on short commuter trips but is less consequential for intercity travel. We estimated the cold-start fuel increment on the basis of dynamometer tests of hot and cold starts for a 2009 Jetta diesel published by DOE [Argonne National Laboratory, D^3 website. http://webapps.anl.gov/D3/index.html]. The 13.5% incremental fuel consumed over the 7.46 mi long UDDS test cycle when cold versus hot was adopted as representative of all LDVs. The value is pre-processed by simulating each default vehicle over the same UDDS drive schedule and applying the 13.5% factor to get the fuel/start value. The resulting 'cold start' fuel increment for the Sales-weighted 2011 MY at 22ºC is 0.1136 kg.

The influence of temperature on the cold-start fuel increment follows the EPA's derived equations assuming a 12-hr or greater soak time for the forward trip and 9 hr. for the reverse trip (100% and 87.5% of the cold-start fuel increment respectively). The ratio 'R' of cold-start fuel at ambient temperature (Ta) relative to the cold-start fuel at 75 ºF is [EPA, Final Technical Support Document Fuel Economy Labeling of Motor Vehicle Revisions to Improve Calculation of Fuel Economy Estimates, EPA-420-R-06-017, December, 2006]:

$$\boldsymbol{R = 1 + a(T_a - 75) + b(T_a - 75)^2} \qquad \textbf{Equation 1}$$

where:

Ta = ambient temperature of interest in ºF

R is the ratio of cold-start fuel increment at ambient temperature Ta divided by the cold-start fuel increment at an ambient temperature of 75ºF.

a and b are estimated coefficients; which for gasoline engines are:

a = -0.01971

b =0.000219

and for diesel engines are:

a = - 0.00867

b = 0.000096

The running performance of LDVs is derived by the EPA and manufacturers via dynamometer and coast down tests. The test conditions are ideal in relation to actual driving conditions and the drive schedules are not necessarily representative of any one particular journey made on a specific time-of-day and season. The EPA discusses a wide range of factors which influence the translation of lab test results into real-world experience [EPA-420-R-06-017, December, 2006]. The assessment (Table III.A-28. of EPA-420-R-06-017) indicates about a 12%-to-15% decrement to predicted 5-cycle fuel economy due to various non-test factors; most of which EPA believes relate to wind ~ 6%, road surface ~ 1.4% – 3.2%, road gradient ~ 1.9% and fuel quality ~ 1.1 – 1.5%.

We specifically model many of these factors and others via specified trip input data. Table 3 summarizes how these FE-influencing factors are treated in the model. Still, we note that driver-behavior, auxiliary power usage and vehicle maintenance can all affect the FE of a specific vehicle. There will always be a range of FE performance around any derived average. Our objective is to inherently model most parameters and provide an average in-service FE that is representative of real-world experience.

Table 3. Adjustments Made to Test-based Characteristics to Reflect Actual Driving Conditions and the Driven Fleet

Factor	Assumption / Treatment in the Model	Source Reference
Road/tire condition resistance factors	An estimated 10/30/50/10 mix of concrete/smooth-/medium-/rough-asphalt pavement is adopted relative to an estimated 30/70 mix of concrete/smooth-asphalt for test conditions. The corresponding increase in rolling resistance coefficients (a and b) is 12%.	TranSys Research Ltd estimates of road type usage. Biggs, 1987 for relative road type influence.
Aerodynamic drag (wind effect)	Wind increases aerodynamic drag for most yaw angles except those approaching 180º (a pure tailwind) where it reduces drag. We adopt an average 3.5% increase in aerodynamic drag for LDV (and use the same factor in the bus and rail modules).	TranSys Research estimate.
Seasonal aerodynamic drag (temperature effect)	Aerodynamic drag varies directly with air density and the density of air is negatively correlated to its absolute temperature (º Kelvin or º Rankine). This temperature dependence is applied to LDV (and also bus and rail mode) simulation modules.	Marks' Handbook for Mechanical Engineers, 8th Edition, McGraw-Hill.
Seasonal cold-start fuel consumption (temperature effect on tires, and engine/ drivetrain friction losses).	EPA has developed an equation to estimate the incremental impact of colder temperatures on the 'cold start' fuel consumption. The basis of the dynamometer data used does not include the aerodynamic impact noted above so the effects are additive. We apply the EPA equations for incremental cold start fuel consumption on the basis that all our rail-competitive trips occur after 12 hr. of sitting (soak time) for the forward trip and 9 hr. for the return trip.	EPA-420-R-06-017.
Seasonal auxiliary power loads	Average base auxiliary power is set at 0.75 kW. The air conditioning compressor, when on, is estimated to add 2.67 kW when running and 1.1 kW at idle. Actual AC power varies with technology and can be higher or lower than the average default values. Usage is based on regional temperature and humidity profiles. The blower is estimated to add another 0.5 kW 100% of the time in winter and summer.	[Rugh, John P. (NREL) et al.]. for AC compressor power and usage.
Gradient	Specific road gradients are not included in the time-step drive schedules. The gradient influence on the FE of LDVs is assessed as the probability that potential energy recovery on downgrades is lost because the vehicle is braking for speed reduction purposes. The same procedure is used for the rail and bus modules.	Distributions of gradient severity are estimated by region.

The default vehicles are based on —and are thus representative of— 2011 technology and class proportions. If one wishes to consider an age distribution, the model assumes the fleet average performance enhancement that was reported by the EPA for the intervals 1990-2004, 2004-2011 [EPA-420-R-1 3-001, 2013 - Table 1 (cars and trucks) 2012 Fuel Economy Trends Report]. For the interval 1990-2004 the average trend was a 0.55% annual decrease in fuel economy (from 21.2 to 19.3 mpg), while for 2004 – 2011 the average trend was a 2.15% annual increase in fuel economy (from 19.3 to 22.4 mpg).

The EPA estimates the relative usage of various calendar years (CY) in generating its annual GHG emissions inventory. The effects of using the CY usage distribution (or the 'driven-fleet') on fuel economy and GHG emissions are summarized in Table 4. The EPA's

CY usage distribution in 2011 as adopted in its GHG inventory [EPA, 430-R-12-001, April, 2012] reduces the fleet efficiency to 91.32% of the sales-weighted 2011 MY's efficiency (or 1/.9132 = 1.095 times more fuel is consumed by the 2011 driven-fleet).

The CO_2e emissions intensity of LDVs also varies with age. While the CO_2 ratio is constant with fuel type, the N2O and CH4 emissions ratios vary with the regulatory period. The EPA's emissions factors for cars were constant from 2009 to 2011 at 3.6 mg/mi and 17.6 mg/mi for N2O and CH4 respectively [EPA, Emission Factors for Greenhouse Gas Inventories, 2011]. Even with the higher CO2-equivalency factors for these gases, the impacts are minimal — CO_2 emissions are 3.172 kg/kg-fuel and with the fuel intensity in 2011 at 0.126 kg/mi (22.4 mpg) is 0.3997 kg/mi. The CO_2-equivalent emissions were:

$$CO_2e\ (kg/mi) = 0.3997 + 298 * 3.6/10^6 + 25 * 17.6/10^6 = 0.40121 \quad \textbf{Equation 2}$$

Thus, the impact of CH_4 and N_2O emissions post 2009 are a 0.37% increase over CO_2 emissions. The N_2O and CH_4 emissions rates are based on the ftp certification cycle and include a g/start factor allocated over the 7.4 mi ftp route distance. The running emission rates are an even smaller proportion than the 0.37% shown above.

Scaling the impacts for the fleet average MY composition by usage leads to a greater impact but it is still relatively small. The above cited EPA fuel economy trends report was used to estimate the 2011 fleet average emissions rate by applying MY fuel economy and MY emissions factors in the same way as the fleet-average fuel economy was derived. The resulting fleet average scale factors relative to the modelled 2011 sales mix were: 4.13 and 1.11 for N2O and CH4 respectively. We estimate the 2011 LDV driven-fleet to have a GHG emission intensity of:

$$CO_2e = 0.375\ kg/start + 3.19\ kg/kg\text{-}fuel\text{-}running. \quad \textbf{Equation 3}$$

Table 4. Performance of the 2011 Sales-weighted and 2011Driven Fleets

Fleet composition	Fuel Economy		Cold Start*	GHG emissions Intensity				
				Running				Starting
				CO_2	N_2O	CH_4	CO_2e	CO_2e
	mpg	kg/km	kg/start	kg/kg	mg/kg	mg/kg	kg/kg	kg/start
2011 sales weighted	22.37	0.126	0.114	3.172	14.19	59.85	3.178	0.363
2011 driven fleet	20.67	0.137	0.123	3.172	54.470	71.71	3.19	0.373
scale factors applied	0.913	1.095	1.095	N.A.	3.84	1.20	N.A.	N.A.

* Cold start is the incremental fuel consumed over the initial few miles of travel (before the engine, drivetrain and tires warm up) following 12 hr of sitting stopped, versus the fuel consumed over the same trip with a fully warmed vehicle. The base value shown is for an ambient temperature of 22ºC.
Source: TranSys Research; derived from EPA emissions sales-weighted and MY usage data (see text).

The EPA has developed a range of speed profiles to characterize the influence of traffic congestion on individual vehicle speed variations on freeway, urban and arterial streets. However, no single drive schedule provides a realistic characterization of a specific commuter or intercity trip. In the LDV and Bus simulation modules, the user specifies the proportion of each of eight individual drive schedules encountered in making the trip being simulated. Different congestion performance can be specified for 5 specific time-of-day congestion intervals. The user is guided with feedback of the total delay encountered when making the specified trip during each time of day. Default values for the matrix are provided for a typical large urban city and a smaller urban city as developed for the case studies undertaken within the project. Table 5 illustrates the matrix involved and the illustrative data for origin and destination (O and D) cities involved in an intercity trip.

Table 5. Illustrative Proportional Allocation of Congestion Encountered by Time-of-Day (% of route)

Location	Time Period	Creep	LOS-F	City Streets	Urban Arterial	Urban FW LOS-E	FW-cruise	FW LOS-F	FW-access US06	Delay (min / 10-km)
		~0.9 km/h	~14 km/h	~25 km/h	~40 km/h	~75 km/h	~119 km/h	~33 km/h	~100 km/h	
Arterial (O and D)	a.m. pk	3%	7%	25%	65%					30.2
	p.m. pk	3%	12%	10%	75%					25.1
	midday			15%	85%					9.0
	shoulders			5%	95%					2.9
	overnight				100%					0.0
Urban FW (O)	a.m. pk	3%	12%		30%	20%	5%	15%	15%	56.3
	p.m. pk	3%	5%		25%	27%	5%	10%	25%	38.8
	midday				20%	25%	25%	5%	25%	19.1
	shoulders					30%	50%		20%	5.8
	overnight					5%	75%		20%	0.0
Urban FW (D)	a.m. pk	3%			30%	25%	5%	20%	17%	47.0
	p.m. pk	3%			20%	35%	12%	10%	20%	31.4
	midday					20%	60%		20%	4.3
	shoulders					10%	70%		20%	2.0
	overnight					5%	85%		10%	0.0

Source: TranSys Research Ltd., for illustration only.

2.4 Air Mode Methodology

2.4.1 Air Made Analytic Framework

Simulation of individual air mode trips on a second-by-second time-step simulation is complex and requires knowledge of many parameters that are not readily available. There are a few complex simulation models that take this approach (e.g. the SAGE program sponsored by the US FAA [Federal Aviation Administration, 2005] and the BADA model in Europe [European Organisation for the Safety Of Air Navigation, 2009]. Such detail is not required for this project as the US Bureau of Transportation Statistics publishes good in-service performance data for air mode operations in the U.S. and it is the final in-service performance that is relevant for a modal comparison. The published data [Research and Innovation Technology Administration, Bureau of Transportation Statistics (BTS), 2013] are used to define congestion effects on energy performance by equipment type and trip length for typical U.S. domestic scheduled service operations.

The air mode has some complexities that require flight segmentation in order to assess GHG intensity. The warming effects of emissions from aircraft at cruise altitudes are higher than emissions on the ground and low altitudes. The effects of aviation on the atmosphere and climate were considered comprehensively in the 1999 IPCC Report [Intergovernmental Panel on Climate Change, 1999]. The effects are complex, and poorly understood in some respects, due to the complexities of the chemical processes in the atmosphere. The prime contribution to global warming is expected to be through emissions of carbon dioxide, which bear a fixed relationship to aviation fuel use, and which are assumed to be "well-mixed" with emissions from other sources, and to have the same radiation-forcing[1] potential as other emissions. In addition, emissions of nitrogen oxides from aircraft in the troposphere and lower stratosphere are expected to contribute to the formation of ozone more effectively than at ground level, further contributing to global warming. The effect is limited somewhat by the fact that in this process, nitrogen oxides reduce the atmospheric concentration of methane, which has the effect of reducing global warming. Aircraft also produce water vapor, which is eliminated rapidly in the troposphere, but in the upper atmosphere forms contrails (condensation trails) which can persist and even form cirrus clouds, and is expected to contribute further to global warming. The relative extents of these effects are uncertain, particularly the latter. The IPCC report estimated that in the mid-1990s aviation contributed about 2% of man-made CO_2, and about 3.5% of man-made radiation-forcing, excluding the possible effects of water vapor in cirrus cloud.

The report also cautioned about the uncertainty as follows:

> "The total radiative forcing due to aviation (without forcing from additional cirrus) is likely to lie within the range from 0.01 to 0.1 Wm^{-2} in 1992, with the largest uncertainties coming from contrails and methane. Hence the total radiative forcing may be about two times larger or five times smaller than the best estimate."

Later in the summary the IPCC concluded:

> "Over the period from 1992 to 2050, the overall radiative forcing by aircraft (excluding that from changes in cirrus clouds) for all scenarios in this report is a factor of 2 to 4 [times] larger than the forcing by aircraft carbon dioxide alone. The overall radiative forcing for the sum of all human activities is estimated to be at most a factor of 1.5 [times] larger than that of carbon dioxide alone."

That statement has proven somewhat ambiguous, with the implication of the latter sentence being overlooked, leading to interpretations that aviation emissions contribute 2 to 4 times as much to global warming as other emissions. The full statement that the ratio of radiation forcing to CO_2 from aviation was 2-4 and for other sources "at most …1.5" meant in fact that the relative radiation forcing from aviation emissions versus the worst case in other emissions could be between (2/1.5) and (4/1.5), or approximately 1.33 to 2.67.

The IPCC's estimate that aviation contributed 2% of CO_2 and 3.5% of radiation-forcing shows that the best (circa 1999) estimate was that its radiation-forcing proportion was 1.75 times that of the proportion of CO_2 alone. In 2007 the Air Transport Bureau of the

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[1] Radiation forcing is the measure of heat flux associated with greenhouse gases (and other geophysical energy fluxes). Heat flux is defined as the amount of thermal energy transferred across a unit area over a time interval. Radiative heat flux is measured as Watts per square meter (W/m^2 or Wm^{-2}).

International Civil Aviation Organisation (ICAO) asked the Intergovernmental Panel on Climate Change (IPCC) to update its opinion to reflect that the impact is not as great as originally believed — its estimate of total radiative forcing was reduced from 3.5% to 3%, while its estimate of CO_2 contribution remained at its prior estimate of 2%.[2] Using this update, air mode GHG intensities for the cruise phase would be adjusted with a multiplier of 1.5 times CO_2 emissions. The recent IPCC Fifth Assessment appears also to have endorsed the lower estimate of radiative forcing from persistent contrails but publication is scheduled for early 2014. The draft WGI report had included a combined RF for contrails and high cirrus in 2011 to be +0.05 (+0.02 to +0.15) W m-2, but the overall estimate for aviation CO_2 in that year remained unpublished.[3] One can expect the CO_2e/CO_2 ratio to change for aviation with further scientific investigation; and the default factor of 1.5 adopted in the model should be modified as appropriate. The updated IPCC report was not available during this project and users should monitor and update the model if the IPCC's final report modifies these values.

Recognizing this higher-altitude GHG multiplier for aircraft emissions requires segmentation of the energy consumed at higher altitudes from that consumed in landing-and-takeoff (LTO), climb-out and descent phases of an air trip. Fortunately, data exist to support the segmentation of flights by equipment type. The U.S. DOT data noted above [Research and Innovation Technology Administration, Bureau of Transportation Statistics, 2013] provides information on the overall trip energy intensity by equipment type. Jet engine emissions certification data published by ICAO (ICAO Aircraft Engine Emissions Databank) includes data on fuel consumption for a typical landing and takeoff cycle and is required for all jet engines greater than 2,200 lb (9.8 kN) thrust. The ICAO engine database is maintained by and available from the European Aviation Safety Agency (http://easa.europa.eu).

The two data sets (BTS and ICAO) are used to develop a model of air mode performance by equipment type. The data are assessed to provide the energy performance by flight segment for five representative equipment types: The default characterization data provided with the model are based on 2011-2012 operations of domestic US scheduled air carriers and can be updated by the user as desired in future years as air technology and operations practices change. The following five representative types of aircraft are assessed:

6. Turboprops (TP)
7. Small Regional Jets (SRJ) (defined here as jet aircraft with less than 50 seats)
8. Regional Jets (RJ) (defined here as short-range jet aircraft with 50 to 89 seats)
9. Narrow Body Jets (NBJ) (defined here as jet aircraft with greater than 89 seats in a single aisle configuration)
10. Wide Body Jets (WBJ) (defined here as jet aircraft with greater than 89 seats configured with more than one aisle)

The Bureau of Transportation Statistics' data (Table 254, Air Carrier Traffic and Capacity Statistics by Aircraft Type) for 2011 and 2012 is filtered to remove air cargo and air charter operators, operators with fewer than 65 flights per quarter and flights greater than 3,000

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[2] ICAO website March, 2010: http://www.icao.int/icao/en/env/aee.htm.

[3] IPCC Working Group I Contribution to the IPCC Fifth Assessment Report Climate Change 2013: The Physical Science Basis, Final Draft Underlying Scientific-Technical Assessment, version September 26, 2013 (Unpublished but available at http://www.climatechange2013.org/images/uploads/WGIAR5_WGI-12Doc2b_FinalDraft_All.pdf.

great-circle miles (GC-mi) in length. The combined 2011-12 filtered dataset of US scheduled carriers is then analyzed to provide an indication of the mix of aircraft used in meeting the demand for different trip lengths. Each aircraft type is also analyzed to provide an indication of its average load factor and its per-seat fuel intensity (kg/seat-GC-mi).

The ICAO engine emissions database is used to derive the LTO fuel consumption for a sample of engines used in each of the jet aircraft types and simulation-based data in the European Environmental Agency's CORINAIR database (an inventory of air emissions) are used to derive LTO fuel consumption for a representative turboprop aircraft. The LTO data are used to identify fuel use during the landing and takeoff cycle (kg/seat-LTO) for each aircraft type thereby permitting the segmentation of fuel consumption into the LTO/climb-out/descent phase and the cruise phase of a trip. Climb-out and descent are estimated to occur at 3000 ft/minute for all aircraft and the average of the climb-out and descent fuel consumption rate is considered to be the same as the average rate during the cruise phase. All aircraft but turboprops are considered to cruise at altitudes above the 25,000 ft floor associated with exacerbated 'high altitude' impacts from emissions. Thus, emissions from all types but turboprops are assessed to have a higher effective impact at cruise altitude.

2.4.2 Air Mode Default Characterization Tables

Five aircraft types were characterized using operating reports from US domestic scheduled airlines for the years 2011 and 2012 [http://www.transtats.bts.gov]. The reports include quarterly totals of key operating metrics by aircraft. We processed the data to group individual aircraft into the five classes (TP, SRJ, RJ, NBJ, WBJ). Not all of the reports included fuel consumption data. The full dataset was assessed in determining proportional usage of aircraft type by trip length and load factor, whereas the energy intensities were derived on the basis of those reports that included fuel consumption information. Fuel consumption was reported for 35% of the turboprop seat-miles, 44% of the small regional jet seat-miles and about 49% of the three other aircraft types. The mix of operators and specific aircraft involved in fuel-reported versus not-reported did not suggest any bias in the data for jet aircraft. However, the turboprops with fuel reported tended to be larger aircraft and thus, the fuel intensity of turboprops might not be representative of the overall turboprop fleet. Nonetheless, we believe the larger turboprops are likely to provide a better representation of the turboprop fleet used in larger centers where rail services are present.

The resulting mix of aircraft usage (seat-GC-km) by seven trip length segments (GC-km) is summarized in Table 6. The upper boundary of each segment is shown in the second row (GC-mi) and the third row (GC-km). The seventh data-column indicates the upper limit of the data analyzed (i.e. 3,000 mi). For trips less than 250 GC-mi (402 GC-km) turboprops account for 81.5% of the seat-mi, small regional jets account for 16.5% and regional jets account for 1.9% of the seat-mi. For distances in segment 4 (750 to 1000 GC-mi) narrow body jets account for 94.9% and regional jets account for 4.5% of the seat-mi. This is the default distribution of aircraft used in performing a 'representative' air leg simulation. If desired, a user can override this distribution by indicating one specific aircraft type (or any alternate distribution) for the air leg of a simulated trip.

Table 6. Proportional Aircraft Usage (%-seat-miles) by Trip Segment Length

Segment No.	1	2	3	4	5	6	7
Min (GC-mi)	0	250	500	750	1000	1,500	2,000
Max (GC-mi)	250	500	750	1,000	1,500	2,000	3,000
Max (GC-km)	402	805	1,207	1,609	2,414	3,219	4,828
TP	81.5%	6.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SRJ	16.5%	6.1%	0.0%	0.0%	0.0%	0.0%	0.0%
RJ	1.9%	80.0%	22.0%	4.5%	0.0%	0.0%	0.0%
NBJ	0.1%	8.0%	78.0%	94.9%	92.1%	77.7%	0.0%
WBJ	0.0%	0.0%	0.0%	0.6%	7.9%	22.3%	100.0%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Source: TranSys Research Ltd. via analysis of Table 254 Air Traffic Data for years 2011-2012 [U.S. BTS, 2013 (http://www.transtats.bts.gov)].

The average load factor (as measured by total revenue-passenger-miles / total revenue-seat-miles) for each aircraft type for the 2011-12 interval is summarized in Table 7. Load factor is seen to increase with the size (and associated longer range) of the aircraft.

Table 7. Average Load Factor by Aircraft Type

Aircraft Type	TP	SRJ	RJ	NBJ	WBJ
Load Factor	69.93%	74.29%	78.16%	83.27%	86.76%

Source: TranSys Research Ltd. via analysis of Table 254 Air Traffic Data for years 2011-2012 [US BTS, 2013 (http://www.transtats.bts.gov)]

The energy intensity of each aircraft type was derived via regression analysis of those records in the filtered dataset that contained fuel consumption. As there is a wide range of individual aircraft sizes within each type/class, the fuel consumption data were normalized by number of seats. Regressions were performed (with a forced zero coefficient) for each aircraft type with fuel consumed (kg/seat) as the dependent variable and the number of LTO cycles and the total GC-km traveled for the aircraft/quarter as the independent variables.

Two regressions were reassessed on different metrics. The SRJ regression did not provide a good fit when done on a kg/seat basis. Upon review it was determined that all SRJs had the same engine regardless of seating capacity. Thus, a regression based on fuel consumption per aircraft gave a better fit to the data than one based on kg/seat. The regression results in kg/aircraft were then adjusted to kg/seat on the basis of the average seating capacity of 40.5 seats per SRJ in the dataset. The initial regression of WBJ was not significant in the LTO term so that term was dropped from the final regression. Also, the WBJ data displayed a meaningful proportion of cargo being carried (11.9% by weight). To facilitate allocation of fuel between cargo and passengers, the WBJ regression was undertaken on the basis of kg-fuel/payload capacity. The results were then allocated to seats on the basis of 178.6 kg-payload/seat (with 11.6% of fuel going to cargo and 88.4% going to passenger seats).

The final regression results are presented in Table 8. All regressions display a high explanation of data variation (adjusted R-square values all exceed 0.93). All final coefficients were significant (t-statistics > 2.0) though the significance was somewhat less for the SRJ and RJ categories than for the other categories.

Table 8. Direct Results from the Raw Regression Results

AC Type	Number of data points	Adjusted R Square	Coefficient	Coefficient Values	t Stat	P-value
TP	48	0.9674	kg/seat-LTO	10.62	11.30	7.16E-15
			kg/GC-skm	0.011222	4.59	3.43E-05
SRJ*	18	0.9363	kg/seat-LTO*	11.457	6.38	0.000
			kg/GC-skm*	0.045	2.53	0.022
RJ	228	0.9314	kg/seat-LTO	8.888	2.69	0.00766
			kg/GC-skm	0.039004	9.25	1.72E-17
NBJ	374	0.9850	kg/seat-LTO	6.814	8.26	2.57E-15
			kg/GC-skm	0.0224	35.06	6E-120
WBJ**	121	0.9887	kg/PL-km**	0.157325	201.02	1.4E-153

Source: TranSys Research Ltd, analysis of Table 254 Air Traffic Data for years 2011-2012 [US BTS, 2013 (http://www.transtats.bts.gov)].
Notes:
* The SRJ regressions did not provide a good fit when done on a kg/seat basis (since most SRJs have the same engine regardless of seating capacity). The regression was done on the basis of kg/aircraft and adjusted to kg/seat on the basis of the average seating capacity of 40.5 seats.
** Because WBJs had a significant proportion of cargo, the WBJ regression was done on the basis of payload capacity (kg/PL-km) so that the cargo and passenger fuel could be allocated. The WBJ regression did not provide a statistically significant result for the LTO coefficient so that term was dropped from the final regression.

While the regression results provide meaningful data, the confines of the data prevent a literal interpretation of the results (i.e. the kg-fuel / seat-LTO is not a direct measure of fuel consumed in a LTO cycle). In general the resulting coefficients had higher values for LTOs and lower values for distance traveled than would be expected from the engineering relationships. This is because the distance traveled in the data is simply the GC distance between each origin-destination (OD) pair rather than the actual distance flown. The actual distance flown will always be higher than the GC distance and involves incremental distance related to:

- takeoff and landing headings that are constrained by runway layout and wind direction and are not the direct GC alignment headings for the OD,
- following actual navigation points between the OD pair, and
- landing delays (circling an airport) while awaiting a landing slot.

These additional en route travel distances are somewhat independent of flight distance and show up as an increment in the LTO regression coefficient. While the interpretation of the regression result does not matter in generating the total fuel consumed, it does matter to the GHG emissions from aircraft since the effects of emissions at cruise altitudes are different than those emitted during the LTO cycle.

Thus, the initial regression results were adjusted to reflect the actual fuel consumed in the LTO cycle, and the en route incremental distance quantity was transferred to the cruise segment of the flight. The difference between the regression-based LTO fuel and the

ICAO-based LTO fuel was then allocated to the cruise portion of the flight. The resulting coefficient (kg/GC-km) can be interpreted as the product of two parameters:

1) the kg/km that one would get from a simulation model or direct measurement of fuel consumed and distance traveled applied to the GC-distance, and
2) the adjustment factor that scales the GC-distance to the actual miles flown.

The above interpretation is not required to make use of the data, but does allow one to assess the reasonableness of the coefficients by assessing the reasonableness of the underlying parameters. We went through this exercise for each of the aircraft types, using published SAGE simulation model predictions [FAA-EE, (Appendix C), 2005] for a sample of aircraft in each aircraft-type group.

In addition to the transfer of fuel from LTO to cruise segments, the forced zero nature of the regressions led to varying levels of bias in the total results. This bias was factored out of the final coefficients such that the application of the coefficients produced no bias in the predicted total fuel consumption. The resulting coefficients and the scale-factor inherent to the underlying kg/GC-km values are presented in Table 9. As can be seen, the largest proportional impacts are on the short-range aircraft – turboprops and small regional jets experience scale factors of 1.335 and 1.444 respectively. The long-range aircraft have decreasing multipliers — values of 1.114 for NBJ with an average GC-trip distance of 1,436 km and 1.061 for WBJ with an average GC-trip distance of 2,591 km. The results are a reflection of the impact of a relatively fixed extra distance having a greater impact on shorter trips than on longer trips. It could also reflect a lower priority being allocated to smaller aircraft when vying with larger aircraft for landing slots during times of congestion and/or the short range aircraft being used more for peak-period commuter travel and thus more frequently exposed to congestion. The higher multiple for SRJs than TPs could reflect the fact that the SRJs are mainly used in the east serving major airports, whereas the turboprops have higher usage in the Midwest and Pacific regions and service smaller airports.

The average scale factors (Implied GC Multiplier in Table 9) are composites of all flights reported for each aircraft type. One can expect the multiplier to vary between peak and off-peak travel times. Reynolds found in-flight delays lead to average extra distances flown of 14% for intra-European flights and 12% for intra-U.S. flights [Reynolds, 2008]. He also found the delays to increase with traffic density. We provide a peak versus off-peak delay calculation in the model and make estimates of the relative impact as initial default values; however, research is required to refine these estimates. In generating the parameters, we distribute the delay component such that peak-period flights receive a 25% increment to the average excess-distance and additionally estimate that 45% of all domestic seat-arrivals occur during peak periods. Based on these estimates, weekend and off-peak periods receive a 5.1% decrement from the average excess-distance while week-day peak periods receive a 6.3% increment. The resulting average, peak and off-peak fuel intensities of each aircraft type are shown in Table 10.

Table 9. Derived Fuel Intensity Coefficients by Aircraft Type

AC Type	Regression Bias due to Forced-Zero Origin	Coefficient Units	Original Coefficient Values	Derived Values[1]	Average Trip Distance (km)	Implied GC Multiplier	Implied Extra Travel (km/trip)
TP	-5.9%	kg/seat-LTO	10.62	4.70	375	1.335	126
		kg/GC-skm	0.011222	0.0294			
SRJ[2]	16.4%	kg/seat-LTO	11.457	8.34	631	1.444	281
		kg/GC-skm	0.045	0.0514			
RJ	-1.8%	kg/seat-LTO	8.888	7.50	789	1.102	80
		kg/GC-skm	0.039004	0.0325			
NBJ	-1.2%	kg/seat-LTO	6.814	6.88	1,436	1.114	164
		kg/GC-skm	0.0224	0.0228			
WBJ[3]	-2%	kg/seat-LTO	Not Significant	8.26	2,591	1.061	158
		kg/PL-km	0.157325				
		kg/GC-skm	Not Applicable	0.0219			

Source: TranSys Research Ltd, analysis of Table 254 Air Traffic Data for years 2011-2012 [US BTS, 2013 (http://www.transtats.bts.gov).

Notes:

1. Derived values adjust for regression bias and force the LTO fuel consumption to ICAO certification data (see text).
2. SRJ regressions are per-aircraft and average seats/aircraft used since per-seat values provided poor regression results (see text).
3. WBJ regressions are based on payload capacity (kg/PL-km) rather than seats since WBJ aircraft had a significant proportion of cargo. Fuel is split between cargo and seat-payload-capacity to get per-seat km fuel intensity (see text).

Table 10. Cruise-phase Fuel Intensities by Aircraft Type and Traffic Congestion.

AC Type	Trip GC-Distance Multiplier			Fuel Rate (kg/GC-skm)		
	Implied GC Multiplier	Estimated WD-peak Multiplier	Estimated non-peak Multiplier	Average	Peak Period	Off-Peak Period
TP	1.335	1.419	1.267	0.0294	0.031219	0.027866
SRJ	1.444	1.556	1.354	0.0514	0.055317	0.048133
RJ	1.102	1.127	1.081	0.0325	0.033252	0.031887
NBJ	1.114	1.143	1.091	0.0228	0.023429	0.022364
WBJ	1.061	1.076	1.048	0.0219	0.022167	0.021597

Source: TranSys Research Ltd: Average values based on analysis of BTS data. Peak and off-peak values are preliminary best-estimates requiring further research.

GHG intensities during the LTO phase are calculated on the basis of factors used in EPA's inventory model, which adopts zero emissions of CH_4 from aircraft and 0.1 g/kg of N_2O [EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2010]. The CO_2-equivalent emission during the high-altitude cruise phase of flight is based on the 1.5 multiplier factor discussed above. Thus, the equations for air-mode GHG emissions are:

GHG ($kg\text{-}CO_2e$) = GHG(LTO) * Fuel(LTO) + GHG(cruise) * Fuel(cruise) **Equation 4**

where:

GHG(LTO) = 3.158 + 25 * 0 + 298 * 0.0001 = 3.188 $kg\text{-}CO_2e$/kg-fuel

GHG(Cruise) = 3.158 * 1.5 = 4.737 $kg\text{-}CO_2e$/kg-fuel

LTO includes fuel allocated to climb out and descent to/from 25,000 ft.

An alternate measure of Air-mode GHG emissions is provided with the high altitude impacts ignored to facilitate comparison of the impact of the high-altitude multiplier on air-mode GHG intensities.

2.5 Rail Mode Methodology

2.5.1 Analytic Overview

Since the focus of the model is on energy intensity rather than overall train performance, some simplifications can be made in the simulation model over what would be required by a detailed train performance calculator. Also, passenger services have characteristics that allow additional simplifying assumptions. Specifically, passenger consists are short relative to freight trains, which make a lumped mass approach more realistic and the power-to-weight ratio of passenger trains is much higher than freight trains, which makes the influence of gradients much less important for passenger than for freight trains. Gradient and train length influences on energy intensity are included in the model; however, due to the simplifying assumptions (which are reasonable for passenger services), the model will not provide accurate results for freight trains. It is a rail passenger service simulation model, not a general purpose railway simulation model.

The model is based on characterization data that will usually be available to a rail-agency and rail system operators; however, the data will not necessarily be publicly available. Detailed track gradient and curvature profiles that are required by most railway train performance calculators are not used as inputs; however, condensed route characteristics are included. The model has been developed with some default region-and service-specific characteristics (as developed for the case studies) built in. Nonetheless, simulation of a specific service will benefit from development of data specific to that service. One of the key influences of passenger train performance is the number of speed changes involved on a route. Permanent speed limits shown in railway timetables are more generally available than are track gradient profiles and we recommend that actual speed limit tables be used in simulating a service wherever possible. Gradients have less impact on passenger train performance and the regional gradient characteristics developed as default regional tables may be more generally applied without significant impact on the accuracy of the results. The gradient characteristics developed for the default tables were developed from a range of actual track gradient profiles and do not represent any one track subdivision or any one railway. We caution again that the regional characteristics and the model itself are not applicable to freight trains.

As with the other ground modes, energy intensity and associated emissions of GHG involve similar calculations. However, since the model supports comparisons of rail mode technologies, additional breakout details of energy dissipation components are provided for the rail mode. The rail simulation module is configured to separate the individual components of energy dissipated in overcoming inherent resistance. In addition to inherent resistance, power is required to:

1) accelerate the mass of the vehicle, its rotating elements and the load it is carrying to a desired speed, and

2) climb uphill grades encountered.

These two additional power requirements do not directly translate into energy as they are essentially stored energy. The potential energy gained in climbing grades can be partially or fully recovered to overcome inherent resistance on downgrades. Similarly, the kinetic energy/inertia gained in acceleration can be partially recovered in deceleration. It is only through braking (and to a lesser extent, drivetrain-drag during coasting) that these stored energy components are lost/consumed.

The rail module accumulates the energy associated with each of the sub-categories of energy dissipation such that the effectiveness of alternative technologies can be gauged from the model output for a single train run.

2.5.2 Rail Equipment Characterization

Table A-1 of Volume I of this report summarizes the publicly available passenger locomotive characterization data, and Table A-2 of Volume I of this report summarizes the publicly available passenger rail coach and trainset characterization data that have been located for use in the model case study simulations.

2.6 Access Egress Modes Characterization

Only the primary modes being compared are simulated in detail in the model; the performance attributes of access and egress modes are simple averages provided in default lookup tables located in the Regional-Properties worksheet. The attributes of public transport modes have been derived from the 2011 National Transit Database's *Service* and *Energy* Tables. The electricity supply is region-dependent but all other performance metrics are based on one average applied to all regions. The properties included in the calculation of the various modal averages are shown in Table 11.

Table 11. Transit Properties Included in Modal Averages

Property	MB	CB	CR (D2)	CR (el)	HR (el)	LR (el)
Central Puget Sound Regional Transit Authority		X	X			X
Maryland Transit Administration		X	X		X	X
Georgia Regional Transportation Authority		X				
City of Los Angeles Department of Transportation		X				
Massachusetts Bay Transportation Authority	X		X		X	X
Southeastern Pennsylvania Transportation Authority	X			X	X	
Washington Metropolitan Area Transit Authority	X				X	
Utah Transit Authority	X		X			X
South Florida Regional Transportation Authority			X			
Metro Transit (Minneapolis/St. Paul)			X			
Denton County Transportation Authority			X			
Peninsula Corridor Joint Powers Board dba: Caltrain			X			
Southern California Regional Rail Authority dba: Metrolink			X			

Legend: MB = Municipal Bus, CB = Commuter Bus, Cr = Commuter Rail, HR = Heavy Rail (defined as dedicated commuter tracks), LR = Light Rail, D2 = diesel, el = electricity

Attributes for personal automobiles and taxis were derived with the simulation model in a one-time simulation of the 2011 driven fleet composite vehicle. The following assumptions were made for the highway access/egress modes:

- Taxis were assumed to travel 1.5 km for every km of passenger carrying travel;
- drop-off/pick-up was assumed to have 60% return-to-origin travel and 40% being part of a 2-person trip that incurs 10% extra travel distance.
- Carpools are assumed to involve 3 persons and the trip length is 15% longer than any one-person trip.

The resulting characteristics (for the Continental U.S. electricity generating fuel mix for upstream energy and emissions) are presented in Table 12.

Table 12. Access/Egress Modes' Default Performance Data

Mode	Average Speed (mph)	Fuel Source	Direct Travel			Upstream	
			Fuel Intensity	Energy Intensity	CO2-e Emission Intensity	Energy Intensity	CO2-e Emission Intensity
			(kg/p-mi) (kWh/p-mi)	(kJ/p-mi)	(g/p-mi)	(kJ/p-mi)	(g/p-mi)
Walk	3.1	N.A.	0	0	0	0	0
Bicycle	10	N.A.	0	0	0	0	0
Walk/Bicycle	10	N.A.	0	0	0	0	0
Auto: Drive alone & park	25	Conv. gasoline	0.125	5,431	399	1,091	99.5
Auto: Drop off / Pick up	25	Conv. gasoline	0.236	10,251	753	2,060	187.7
Carpool, Van, Shuttle	25	Conv. gasoline	0.048	2,082	153	418	38.1
Taxi	25	Conv. gasoline	0.188	8,147	598	1,637	149.2
City Bus	12.4	U.S. conv. diesel	0.089	3,801	310	761	69.6
Commuter Bus	24.4	U.S. conv. Diesel	0.055	2,357	192	472	43.2
Subway	21.2	Electricity Continental U.S. Mix	0.396	3,322	228	337	23.0
Streetcar/Light Rail	13.8	Electricity Continental U.S. Mix	0.338	2,840	195	288	19.7
Commuter Rail (elec)	26.9	Electricity Continental U.S. Mix	0.373	3,129	215	317	21.7
Commuter Rail (diesel)	33.4	U.S. conv. Diesel	0.064	2,743	205	549	50.2

Source: TranSys Research analysis: public modes derived from the National Transit Database and LDV derived via commuter-trip simulation.

The fuel intensity of highway modes is adapted to congestion conditions via peak and off-peak multipliers, which can be specified for three city sizes (large, small and rural municipality).

2.7 Regional Characterization

2.7.1 Region and Season Definitions

The model provides default regional characterization data for four regions of the continental U.S. and electricity generation characteristics are further disaggregated into 9 sub-regions. Table 13 defines the state composition of each region and sub-region.

Three seasons are defined – summer, winter and 'other' being spring and fall. Summer and winter each have 3 months and 'other' has 6 months. Summer is comprised of June, July and August; winter is comprised of December, January and February; and 'other' is the remaining months.

Table 13. State Composition of Regions and Sub-regions

Region	Sub-region	States
Northeast	Middle Atlantic (MA)	NY, CT, PA, NJ
	New England (NE)	NH, VT, ME, MA, RI
South	West South Central (WSC)	OK, AR, LA, TX
	East South Central (ESC)	KY, TN, MS, AL
	South Atlantic (SA)	WV, VA, DE, MD, DC, NC, SC, GA, FL
Midwest	West North Central (WNC)	ND, SD, MN, NE, IA, KS, MO
	East North Central (ENC)	WI, MI, IL, IN, OH
West	Pacific	WA, OR, CA
	Mountain (MTN)	MT, ID, WY, NV, UT, CO, AZ, NM

Source: U.S. Energy Information Administration (Weather Data Regional Composition)

2.7.2 Emissions Intensity of Electricity Generation by Region

The distribution of fuels used in generating electricity by region was derived from the Energy Information Administration's data for fuels used in electricity generation by state in 2011 [Energy Information Administration, 2012]. The upstream fuels consumed in providing the fuels for electricity generation was derived from the GREET model [Argonne National Laboratory, GREET1_2012].

Table 14 indicates region breakdown in 2011of the energy content of carbon fuels usage in electricity generation (Direct) and the incremental upstream carbon fuels consumed in getting fuels to the electricity generation stations.

Table 14. Direct and Upstream Carbon Fuels Usage in Electricity Generation by Region in 2011

Region	Electricity Generation		Upstream Fuel Increment	
	Carbon fuels (BTU/kWh)	CO2e (kg/kWh)	Carbon fuels (BTU/BTU)	CO2e (kg/kWh)
Northeast	6,976	0.397	16.7%	0.066
South	8,297	0.614	12.2%	0.075
Midwest	8,623	0.730	7.0%	0.051
West	6,865	0.421	13.1%	0.055
Continental U.S.	7,938	0.577	11.2%	0.065

Source: TranSys Research Ltd, derived from Energy Information Administration's state data for fuels used in generating electricity and GREET1_2012 data for fuel properties and upstream fuel intensities.

2.7.3 Climate-Influences by Region

Seasonal climate properties influence auxiliary power usage and aerodynamic drag for all modes. Seasonal daytime temperatures for each region were derived from the National Climate Data Center's (NCDC) hourly readings data for 1981-2010 [National Climate Data Center, 2013]. Air conditioning usage by LDVs was derived from previous work undertaken by Rugh et al. [Rugh, 2004], who derived estimates of annual air conditioning usage by state for automobiles and light duty trucks (LDTs). Their analysis derived average air conditioning usage weighted by the total light duty vehicle registrations in each state. The analysis concluded that 7 billion gallons of fuel (about 5.5% of total LDV consumption) was consumed annually by LDVs for air conditioning usage. We applied the same vehicle registration weighting by state to get weighted average values of daytime temperatures for each of our four defined regions and for the continental U.S. We derived seasonal variations of air conditioning usage on the basis of these temperatures and Rugh's data on average temperature while air conditioning was on for each state. The resulting seasonal values are shown by region in Table 15.

Table 15. Regional Climate Related Characteristics

Region	Measure	Season		
		Winter	Summer	Other
Northeast	Temperature C	-0.1	23.3	11.9
	Temperature F	31.8	74.0	53.3
	LDV Air conditioning time on	0.0%	82.0%	2.3%
South	Temperature C	9.5	27.9	19.4
	Temperature F	49.2	82.2	67.0
	LDV Air conditioning time on	0.0%	90.9%	39.6%
Midwest	Temperature C	-2.4	23.9	11.6
	Temperature F	27.6	75.0	52.9
	LDV Air conditioning time on	0.0%	92.7%	2.2%
West	Temperature C	7.5	24.5	16.0
	Temperature F	45.6	76.1	60.8
	LDV Air conditioning time on	0.0%	77.8%	19.5%

Continental U.S.	Temperature C	4.4	25.4	15.4
	Temperature F	39.8	77.6	59.7
	LDV Air conditioning on	0.0%	87.0%	19.2%

Source: TranSys Research Ltd., derived from NCDC climate data and Rugh's AC-usage data (see text).

2.7.4 Infrastructure Gradient by Region

Highway and Railway gradient data are in the model for a sample of specific routes assessed in the case studies that were undertaken. Appendix D of Volume of this report discusses he development of highway gradient data. Railway gradient data were derived from railway profiles and from the literature as discussed in Section 2.7.4 of Volume I of this report. A preprocessor is provided with the model to process distance based gradient profiles into the gradient severity matrix structure used in the model.

3 Simulation Model Structure

3.1 Run-type Scenarios and Associated Outputs

The model supports multi-modal door-to-door passenger trip comparisons of energy and GHG intensity. Added details of energy dissipation sources are provided in support of rail-only simulations. The user can choose from the following three formats in running the simulation model:

4. A single train service to assess its performance and energy/GHG breakout;
5. A comparison of up to four passenger rail technologies to compare and assess the energy/GHG savings realized.
6. A comparison of up to four passenger modes (rail, bus, air, light duty vehicle) to compare and assess the energy/GHG performance in a door-to-door trip.

The outputs are different for each of the three scenarios as indicated in the illustrative output tables presented over the following five pages.

The output format from a single-train service simulation, as indicated in Table 16, allows one to assess the underlying sources of energy consumption and GHG emissions. This information is a first step in validating the input data used for the simulation and in assessing the relative impact that technological changes to specific source components of energy consumption would have. Absolute and proportional values of energy consumption and GHG emissions are output for seven categories of traction energy (three sub-elements of inherent train resistance, the three sub-elements of brake dissipation and curving resistance), for the traction system's transmission losses and for hotel power provision.

A second Table provides the performance metrics for the single-train simulation. As indicated in Table 17, energy and emissions intensities are output for three divisors (per-trip, per-seat-distance and per-passenger-distance) and for two service-performance metrics (travel-time and average speed).

The same information is provided for a technology comparison simulation; however, an additional row with the percent-reduction realized by the alternative technology is added for each alternative simulated (see Table 18 and Table 19). An additional table of performance metrics is output for technology comparisons (Table 20) to indicate the total energy and emissions when the indirect consumption/emissions associated with well-to-pump fuel provision are included.

The outputs from a modal comparison simulation focus on the performance metrics and expand the comparison to include access and egress legs of a trip. Four tables are output with the same energy/emissions intensity values as were used in the technology comparison tables but with an indexed comparison to the rail mode replacing the %-reduction from the baseline rail technology that was used in the technology comparison table. Table 21 compares direct energy/emission for the modal leg of the trip, Table 22 compares direct energy/emission for only the access/egress legs of the respective modal trips, Table 23 compares direct energy/emission for the complete door-to-door trips, and Table 24 compares the full energy/emissions (including indirect well-to-pump) for the complete door-to-door trips. Table 22, Table 23 and Table 24 include columns for per-seat-distance intensity; however, seat-distance (seat-km or seat-mi) data are not available for all access/egress modes and thus these columns are not filled in in the present model. The columns exist in the tables in the event future research provides source data.

Table 16. Single Train Simulation Output Table Showing Energy Dissipation Components

Com-ponent	Units	Inherent Resistance			Brake Dissipation			Track Curve Resis-tance	Total Traction (after combust ion)	Traction Power Trans-mission Losses	Total Hotel (after combus tion)	Total per round trip
		Rolling	Dynamic	Aero-dynamic	Scheduled Stops/ Permanent Slow-Orders	Other Stops/ Temporary Slow-Orders	Down Grades					
Energy	(kJ)											
	(%-traction)											
	(%-total)											
	(%-sub-total)											
GHG emiss-ions	(kg-CO2-eq)											
	(%-traction)											
	(%-total)											
	(%-sub-total)											

Note: Metric units shown, U.S. units provide (Btu) and (lb-CO2-eq)

Table 17. Single Train Simulation Output Table Showing Performance Metrics

Category	Intensity Measures*						Service Metrics	
Divisor	per trip		per seat-km		per passenger-km		travel time	average speed
Units of Measure	(kJ)	(kg - GHG)	(kJ)	(g - GHG)	(kJ)	(g - GHG)	(hrs)	(km/h)
Parameter Values								

* GHG is measured in kg of CO_2-equivalent

Note: Metric units shown, U.S. units provide intensities per seat-mi and per passenger-mi, (Btu), (lb-GHG) and (mph).

Table 18. Technology Comparison Simulation Output of Absolute Values and Proportional Savings for a Round Trip

Com-ponent	Alter-native	Units	Inherent Resistance			Brake Dissipation			Track Curve Resis-tance	Total Traction (after combusti on)	Traction Power Trans-mission Losses	Total Hotel (after combu stion)	Total per round trip
			Rolling	Dynamic	Aero-dynamic	Scheduled Stops/ Per-manent Slow-Orders	Other Stops/ Tem-porary Slow-Orders	Down Grades					
Energy	Baseline	(kJ)											
	Alt-1	(kJ)											
		(%-reduction)											
	Alt-2	(kJ)											
		(%-reduction)											
	Alt-3	(kJ)											
		(%-reduction)											
GHG emiss-ions	Baseline	(kg-CO2-eq)											
	Alt-1	(kg-CO2-eq)											
		(%-reduction)											
	Alt-2	(kg-CO2-eq)											
		(%-reduction)											
	Alt-3	(kg-CO2-eq)											
		(%-reduction)											

Note: Metric units shown, U.S. units provide (Btu) and (lb-CO2-eq)

Table 19. Technology Comparison Table of Performance Metrics I (Direct Transportation Activity)

Category		Intensity Measures*						Service Metrics	
Divisor		per trip		per seat-km		per passenger-km		travel time	average speed
Units of Measure		(kJ)	(kg - GHG)	(kJ)	(g - GHG)	(kJ)	(g - GHG)	(hrs)	(km/h)
Baseline	value								
Alt.1	value								
	%-reduction								
Alt.2	value								
	%-reduction								
Alt.3	value								
	%-reduction								

* GHG is measured in kg of CO_2-equivalent

Note: Metric units shown, U.S. units provide intensities per seat-mi and per passenger-mi, (Btu), (lb-GHG) and (mph)

Table 20. Technology Comparison Table of Performance Metrics II (Including Well-to-Pump Energy and Emissions)

Category		Intensity Measures*						Service Metrics	
Divisor		per trip		per seat-km		per passenger-km		travel time	average speed
Units of Measure		(kJ)	(kg - GHG)	(kJ)	(g - GHG)	(kJ)	(g - GHG)	(hrs)	(km/h)
Baseline	value								
Alt.1	value								
	%-reduction								
Alt.2	value								
	%-reduction								
Alt.3	value								
	%-reduction								

* GHG is measured in kg of CO_2-equivalent

Note: Metric units shown, U.S. units provide intensities per seat-mi and per passenger-mi, (Btu), (lb-GHG) and (mph)

Table 21. Modal Comparison Performance Metrics I (Modal Leg Only / Direct Transportation Energy/Emissions)

Category		Intensity Measures*						Service Metrics	
Divisor		per trip		per seat-km		per passenger-km		travel time	average speed
Units of Measure		(kJ)	(kg - GHG)	(kJ)	(g - GHG)	(kJ)	(g - GHG)	(hrs)	(km/h)
Rail	value								
Mode1	value								
	Indexed-to-Rail								
Mode 2	Value								
	Indexed-to-Rail								
Mode 3	Value								
	Indexed-to-Rail								

* GHG is measured in kg of CO_2-equivalent

Note: Metric units shown, U.S. units provide intensities per seat-mi and per passenger-mi, (Btu), (lb-GHG) and (mph)

Table 22. Modal Comparison Performance Metrics II (Access/Egress Legs Only / Direct Transportation Energy/Emissions)

Category		Intensity Measures*						Service Metrics	
Divisor		per trip		per seat-km		per passenger-km		travel time	average speed
Units of Measure		(kJ)	(kg - GHG)	(kJ)	(g - GHG)	(kJ)	(g - GHG)	(hrs)	(km/h)
Baseline	value								
Mode 1	value								
	Indexed-to-Rail								
Mode 2	value								
	Indexed-to-Rail								
Mode 3	value								
	Indexed-to-Rail								

* GHG is measured in kg of CO_2-equivalent

Note: Metric units shown, U.S. units provide intensities per seat-mi and per passenger-mi, (Btu), (lb-GHG) and (mph)

Table 23. Modal Comparison Performance Metrics III (Door-to-Door / Direct Transportation Energy/Emissions)

Category		Intensity Measures*						Service Metrics	
Divisor		per trip		per seat-km		per passenger-km		travel time	average speed
Units of Measure		(kJ)	(kg - GHG)	(kJ)	(g - GHG)	(kJ)	(g - GHG)	(hrs)	(km/h)
Baseline	value								
Mode 1	value								
	Indexed-to-Rail								
Mode 2	value								
	Indexed-to-Rail								
Mode 3	value								
	Indexed-to-Rail								

* GHG is measured in kg of CO_2-equivalent

Note: Metric units shown, U.S. units provide intensities per seat-mi and per passenger-mi, (Btu), (lb-GHG) and (mph)

Table 24. Modal Comparison Performance Metrics IV (Door-to-Door, Including Indirect Well-to-Pump Energy/Emissions)

Category		Intensity Measures*						Service Metrics	
Divisor		per trip		per seat-km		per passenger-km		travel time	average speed
Units of Measure		(kJ)	(kg - GHG)	(kJ)	(g - GHG)	(kJ)	(g - GHG)	(hrs)	(km/h)
Baseline	value								
Mode 1	value								
	Indexed-to-Rail								
Mode 2	value								
	Indexed-to-Rail								
Mode 3	value								
	Indexed-to-Rail								

* GHG is measured in kg of CO_2-equivalent

Note: Metric units shown, U.S. units provide intensities per seat-mi and per passenger-mi, (Btu), (lb-GHG) and (mph)

3.2 Worksheet Roles and Interfaces

The structure of the MS-EXCEL© spreadsheet based model is illustrated in Figure 1. The worksheets in Figure 1 are color coded to reflect their primary purpose: green sheets require user input to define a simulation scenario, yellow sheets provide technical default data that can be optionally expanded and/or modified by the user, orange sheets are calculation procedures at the core of the simulation and blue sheets are output sheets. More details of the user interfaces and data inputs are presented in the MMPASSIM User Guide (included as Appendix A of this document). This Chapter provides an overview and general description of the simulation process.

3.2.1 User Interface Sheets

The main user interface is the '*Master-I-O'* worksheet (green box at lower left of Figure 1). For a user who wishes to draw from the existing list of pre-defined default datasets or who has created the various input data for a desired simulation, this will be the main interface sheet. As noted in the previous section, the first step required by the 'Master-I-O*'* worksheet is the selection of the type of simulation to be performed (single-train, rail technology comparison or modal comparison). In all cases the second step is to identify the rail service to be simulated. The menu form provided allows the user to select from pre-defined trips, consists and routes. The simulation automatically generates a mirror image of the selected trip for the return trip. If a different return trip is desired it must be separately selected.

In a rail technology comparison scenario, up to three additional consists and/or routes can be selected for comparison with the base case rail consist/route. Similarly, in a modal comparison scenario the user can select up to three other modes to be compared with the base-case rail consist/route. In all cases a trip is defined by selecting a route and the equipment which operates over that route, and may be either selected from a list of previously defined trips or a new trip may be created by the user using the system of pop-up menus.

In addition to the 'Master-I-O' worksheet, there are individual 'Modal- I-O' worksheets ('Air-I-O', 'Rail-I-O', 'LDV-I-O' and 'Bus-I-O' which are collectively represented by the green box at the upper left of Figure 1) from which a user can define and run simulations of the selected individual mode.

For a modal comparison, some of the information provided for the base-case rail trip characteristics are applied to other modes being compared. Specifically, time-of-day, day-of-week, and region lead to a pre-defined set of default characteristics for the alternate modes and the access/egress modes applicable to each primary mode. The modal comparison is the only simulation scenario that incorporates access and egress legs of a trip into the simulation results, the other rail-only simulation scenarios only simulate the rail leg of the trip. The inputs for access and egress legs of each modal trip are selected on a "Trip Access and Egress Leg Selection" menu *and stored on the mode specific '*Modal I-O' worksheet. As with the rail-only trip, modal trips are defined as round-trips and the default characteristics of the return trip (including access/egress legs) are mirror images of the forward trip. If the user wishes to modify the characteristics of the return trip a separate simulation data set must be created for that trip.

With the simulation scenario selected and the applicable datasets selected, the simulation is initiated by selecting the "Calculate Selections" button at the top of the 'Master-I-O' worksheet. The user will then be taken to the appropriate output results tables region of the 'Master-I-O' worksheet associated with the selected simulation scenario.

3.2.2 Macro Supervisory Control

The ‘*Macro’* (orange box in the top middle of Figure 1) transfers the appropriate parameters for each mode/trip-leg/drive-schedule/trip-direction combination into the required locations within the model, initiates recalculation of the mode-specific ‘*Simulation’* worksheet (orange box in middle of Figure 1) and transfers the mode-specific ‘*Simulation’* worksheet outputs to an accumulation area in the mode –specific ‘Modal-I-O*’* worksheet specific to the type of simulation scenario being run.

3.2.3 Default Data Sheets

Default input data sheets are highlighted in yellow in Figure 1. The ‘*Regional-Properties’* worksheet (yellow box at central left of Figure 1) and the ‘*Energy-Emissions’* worksheet (yellow box at right side of Figure 1) are common to all modes.

The ‘Regional-Properties’ worksheet contains regional data for: average daytime temperature and air conditioning usage by season. In addition it contains default characteristics for fuel, energy and GHG emissions intensities used for the access and egress modes. The access and egress modes support differentiation by size of city and time of day congestion for the highway modes.

The ‘Energy-Emissions*’* worksheet provides the GHG emissions rates by fuel/energy-source and the indirect (upstream well-to-pump) energy consumption/GHG-emissions associated with each fuel/energy-source and for electricity these factors are also provided for different geographical regions. The ‘Macro’ identifies in step sequence the appropriate fuel characteristics for the mode being simulated in the overall simulation process and calculates the direct and upstream GHG emissions associated with that mode/leg of trip being simulated.The physical characteristics and capabilities of each ground mode are specified in mode-specific ‘Equipment’ worksheets (collectively represented by the yellow box in the upper right of Figure 1). The rail mode equipment data is maintained in the ‘Rail-Consist’ worksheet. The bus mode equipment data is maintained in two worksheets: ‘Bus-Type’ which characterizes parameters for several representative classes of buses and ‘Bus-Resist’ which define rolling resistance coefficients applicable to all bus types. The light duty vehicle mode equipment data is also maintained in two worksheets: the ‘LDV-Resist’ worksheet which contains a master table of all vehicle characteristics and the ‘LDV-Type’ worksheet which facilitates customization of the regionally specified auxiliary (climate control) load for individual vehicles. The air mode is handled differently and has one properties sheet, ‘Air-Default-Data’, which combines both equipment and route information. The ‘Macro*’* identifies in step sequence the appropriate pointer to the resistance and propulsion characteristics of the mode being simulated in the overall simulation process.

The ‘*Modal Route Information*’ (yellow box in middle of right hand side of Figure 1) represents the collection of mode-specific ‘Route’ worksheets which provide default route characteristics for the ground modes by region (named ‘Rail-Route’, ‘Bus-Route’ and ‘LDV-Route’ in the MMPASSIM model). The ‘Macro’ identifies in step sequence the appropriate pointer to the route characteristics (for example grade classification, scheduled stop locations, posted speed table and unscheduled delay frequency/severity) for the mode being simulated in the overall simulation process.

‘Highway and Bus Drive Schedules’ (represented by the green block near the upper left of Figure 1) worksheets are used by the highway modes and contain a number of second-by-second speed profiles (drives schedules) depicting either LDV or bus speed variation on various types of roads and at various levels of traffic congestion. The LDV drive schedules are defined in the ‘LDV-Drive-Schedules’ worksheet while the bus drive schedules are defined in the ‘Bus-Drive-Schedules’ worksheet. The drive schedules are selected from the

EPA database of drive schedules. The 'Macro' brings in the appropriate drive schedules from the mode-specific drive schedule worksheet in a proportional distribution that best matches the average speed expected at the time-of-day and road type being simulated. The drive schedules are discussed in more detail in the Highway Modes Simulation Chapter (Subsection 5.3).

The '*Engine'* worksheets (yellow box near lower right hand corner in Figure 1) provide the needed modal engine efficiency characteristics for the highway modes (they are named 'Bus-Engine' and 'LDV-Engine'). Representative fuel maps are used for propulsion systems using non-continuously variable transmissions (most conventional LDV and buses) while coefficients for a single optimal performance equation are provided for vehicles using a continuously variable transmission (CVT). This is the case for most non-electrified railway propulsion systems as well as hybrid and non-hybrid CVT highway vehicles). The engine information for the rail and air modes is part of the equipment data worksheets. The 'Macro' identifies in step sequence the appropriate pointer to the engine characteristics for the mode being simulated in the overall simulation process.

3.2.4 Simulation Sheets Overview

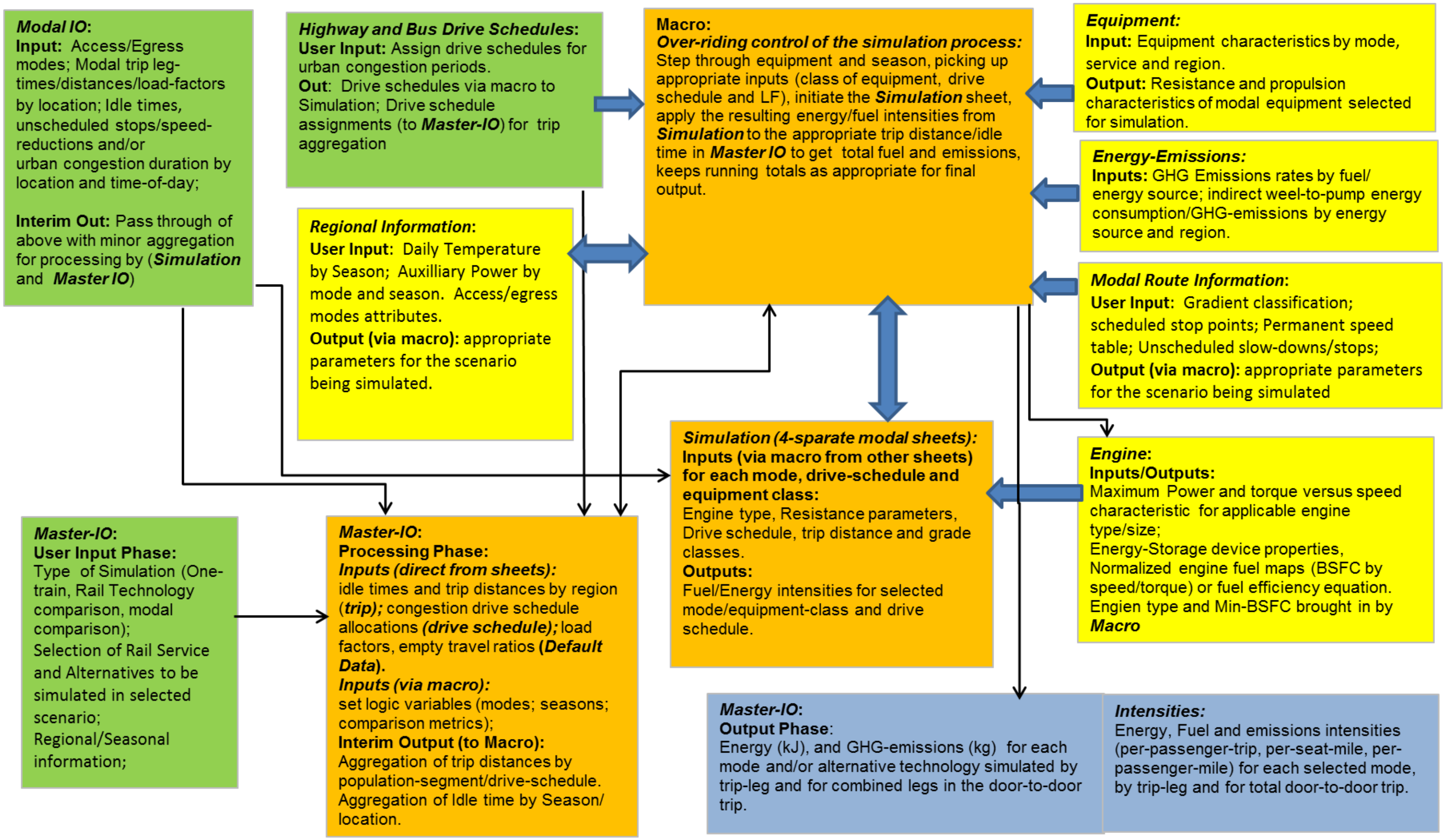
At the core of the MMPASSIM model are the '*Simulation'* worksheets (the orange block near the center of Figure 1), which simulate the movement of a modal vehicle (or a fleet-average characteristic vehicle) representative of the specific service/region being simulated. The details of each mode's simulation sheet are provided in separate modal chapters to follow. This chapter describes the overall structure and purpose of the various worksheets and only a brief overview of the modal simulation sheets is provided in the remainder of this section.

The highway modes include personal light duty vehicles (LDV) and buses. The urban portion of LDV and bus trips is simulated via a second-by-second time-based simulation over a user-selectable distribution of drive schedules (with default proportions by time-of-day). The drive schedules are drawn from the U.S. Environmental Protection Agency's (EPA) database of drive schedules to typify various levels of urban congestion and queue delays. The drive schedules selected have decreasing average speeds with increasing congestion and proportional allocation of different drive schedules can be made to attain a close relationship to average speed observations on the urban highway segments of interest. The duration of, and drive schedule distribution for, each of the following five time-of-day periods are specified for each urban area to depict urban highway congestion:

- a.m. peak;
- p.m. peak;
- midday;
- shoulder periods;
- overnight;

The urban trip simulation is the only component of the highway simulation sheet that is used for comparisons with commuter rail and for access egress legs of intercity trips. The intercity portion of highway mode trips is simulated in a similar way to the long haul portion of all modal trips. The energy and emissions associated with long segments at cruise speed are determined with a single calculation for each speed. The energy and emissions associated with scheduled stops are also determined via a single calculation for the applicable cruise speed. Unscheduled stops and slow speed-segments are treated as a combination of designated delay incident frequency, with drive schedules attached to the highway delays. Gradient influences are simulated via a pre-processed frequency/severity distribution of gradient applicable to the specific modal route(s) or general regional characteristics associated with the selected simulation.

Figure 1. Overall Model Structure (Worksheet Data Flows and Interaction)



color legend (primary purpose of Sheet):

- User input,
- Optional User overrides of technical defaults;
- Calculation processing Sheets/Macro;
- Output

4 Rail Mode Simulation Module

4.1 Rail Module Layout and Equations

4.1.1 User Inputs

The overall model structure was illustrated in Figure 1. Those worksheets specific to simulating the rail passenger mode are discussed in more detail here. The rail mode will normally be simulated in all simulation scenarios (although non-rail modes could be simulated in isolation if desired). As discussed in Chapter 3, two of the simulation scenarios only involve the rail mode.

Input data required to make a rail-only simulation run are the train consist characteristics, and the route characteristics. The list of data required for a train consist and rail route are provided in the MMPASSIM Spreadsheet Model User Guide provided in Appendix A of this document.

4.1.2 Rail Simulation Worksheet Layout

The structure of the 'Rail-Simulation' worksheet and its direct interface to default datasets is illustrated in Figure 2. The areas of the worksheet are color coded to reflect their primary purpose: green indicates it is a user input (not applicable for the 'Rail-Simulation' worksheet), yellow indicates technical default data that can be optionally modified by the user, orange indicates calculation procedures at the core of the simulation, and blue indicates interim output data for transfer and/or aggregation by the 'Macro'.

The 'Rail-Simulation' worksheet simulates the movement of a train (or a fleet-average characteristic train) which is representative of the specific service/region being simulated. Since speed changes are a key factor in passenger train performance, the simulation processes each speed segment on one row of the simulation area of the worksheet. The worksheet functions in a bottom-up sequence. The Pre-processed lookup tables for acceleration, coasting and braking are created at the bottom of the worksheet. The core simulation area (in the middle of the worksheet) uses these lookup tables in simulating the time-and-distance and energy-dissipated in each speed segment of the route. Finally at the top of the sheet the aggregations are made for the complete route and formatted for use by the 'Macro'.

Movement over each permanent slow order segment of track (taken from the route's Speed Table which in turn would be derived from the applicable Railway Operating Timetable) is simulated for the three phases of movement as applicable to that section (i.e. acceleration, cruise and braking). Scheduled stops occurring within a speed segment are also simulated on that row of the worksheet. Average expected temporary slow orders and interference delays (speed reductions and/or stops) are treated in a separate location ('Rail-Simulation'!A29:AK42) and are based on departures from the average cruise speed.

Figure 2. Rail Simulation Sheet Layout

color legend (primary purpose of Sheet):

User input,

Optional User overrides of technical defaults;

Calculation processing Sheets/Macro;

Output

4.1.3 Rail Simulation Process and Equations

4.1.3.1 Pre-processed lookup tables

Acceleration, coasting and braking lookup tables (at 'Rail-Simulation'!E583:V804, 'Rail-Simulation'!Y583:AP804 and 'Rail-Simulation'!AR583:BJ804 respectively) are calculated for zero-gradient and zero-curvature conditions and used as look-up tables by the core-simulation module. The three lookup tables are generated with rows of one-mph increments (0.447 m/s) up to the balance speed for the consist, or a maximum speed of 220 mph (354 km/h). The columns of each table provide cumulative distance, time and traction energy by resistance component for each speed-step row of the tables. The equations used in generating the tables are based on the inherent resistance components and traction performance of the train consist, as follows:

$$IR = C_{ra} + \mathrm{C}_{\mathrm{rb}}\,\mathrm{V} + \mathrm{C}_{\mathrm{rc}} V^2 \qquad \textbf{Equation 5}$$

where:

IR = Inherent Resistance Force (N);

V = speed (m/s);

C_{ra}, C_{rb} and C_{rc} are coefficients.

C_{ra} is normally associated with rolling friction and ground hysteresis losses. C_{rb} is a dynamic factor associated with speed-sensitive rolling losses and is often set to zero. C_{rc} is associated with aerodynamic drag and can be further expanded as follows:

$$C_{rc} = \tfrac{1}{2} \cdot \rho \cdot C_d \cdot A \cdot V^2 \qquad \textbf{Equation 6}$$

where:

ρ = density of air (kg/m^3);

C_d = drag coefficient;

A = Frontal Area (m^2);

V = speed (m/s).

The density of air is temperature dependent, such that it can be scaled for departures from 20º Celsius (C) with the following formula:

$$SF = {(273+20)} \big/ {(273+\mathrm{T})} \qquad \textbf{Equation 7}$$

where:

SF = scale factor for aerodynamic drag;

T = the ambient temperature (in degrees C) to be used in the simulation.

Tractive effort (TE) can be characterized for most diesel locomotives by two regions: one torque limited and the other power-limited. Electric high speed rail locomotives, push the boundaries farther and the tractive effort envelope is often more complex. The model supports characterization of up to five speed segments with a nonlinear equation of the form:

$$TE_i = C_{rai} + C_{rbi} V + C_{rci} / V^{C_{rdi}}$$ **Equation 8**

where:

TE_i = Tractive Effort (N) from all power axles in the consist in speed segment i;

V = train speed (m/s);

C_{rai}, C_{rbi}, C_{rci} and C_{rdi} are coefficients applicable to each speed range i.

For a conventional diesel locomotive consist characterized with two regions the data would be:

1) a fixed torque-limited region where C_{ra1} has the locomotives low speed traction limit in Newtons and all other coefficients are set to 0, and;
2) a power limited region where C_{rc2} is set to the locomotives power rating at the wheels in Watts, the speed exponent coefficient C_{rd2} is set to 1.0 and all other coefficients are set to zero.

For electric locomotive consists additional straight line segments are often introduced between the low speed TE limit and the power limited region and the highest speed region has a fall-off in TE beyond that of constant power and thus the coefficient C_{rd2} is set to a value greater than 1.0. All other coefficients are set to zero. The speed segments must be set in sequence of increasing speed and the lower speed limit associated with a range must be set to yield a continuous profile. If only two segments are used, the upper segments should have a high speed value setting (for example 999) such that the coefficients are never called in by the simulation sheet. Table 25 illustrates the input format for the tractive effort curve with illustrative values for a conventional diesel locomotive consist with 4 power axles and a Very High Speed Rail (VHSR) consist with 12 power axles; while Figure 3 illustrates the corresponding TE curves.

Table 25. Input Data for Two Illustrative Consists

Equipment	Item	Speed Region				
		1	2	3	4	5
VHSR	lower speed limit (m/s)	0	21.7	38.3	63.9	77.8
	Cra	273,000	409,500	203,255		
	Crb		-6,300	-900		
	Crc				9,266,000	18,596,413
	Crd	1	1	1	1	1.16
Diesel	lower speed limit (m/s)	0	15.1	999	999	999
	Cra	178,291		0	0	0
	Crb			0	0	0
	Crc		2,688,942	0	0	0
	Crd	1	1	1	1	1.16

Source: TranSys Research Ltd. - derived illustrative estimates for an Alstom AGV-11 with 6 traction units (Alstom Transport Brochure) and a 4,000 hp diesel locomotive with separate hotel power gen-set.

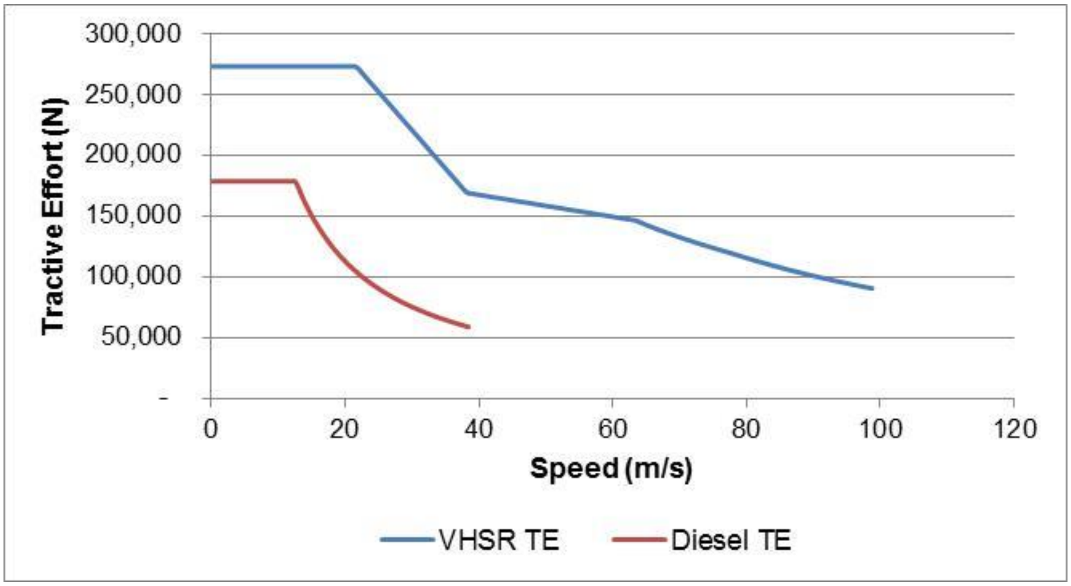


Figure 3. Illustrative Tractive Effort Curves for Conventional Diesel and VHSR Consists

For diesel passenger locomotives, the loading rate of the engine is a relevant factor in its performance as the rate at which the engine can be loaded can constrain its ability to attain the rated torque during acceleration. Thus, the characteristic engine loading time-constant is added as a constraint to initial acceleration. The tractive effort envelope as calculated above is modified at initial loading from a stop by the following equation:

$$TE = MIN[1, 0.25 + a \times MAX(1, t - 10)^{b}] \times TE_i \qquad \textbf{Equation 9}$$

where:

TE =Tractive Effort (N) from all power axles at time (t);

MIN[] = an operator to select the minimum of the two calculated values in the brackets;

MAX() = an operator to select the maximum of the two calculated values in the brackets;

TE_i = Tractive effort envelope without loading time constraint;

t = time since power was applied (s);

a and b are coefficients with default values specified in the model.

The acceleration between steps is calculated as:

$$\boldsymbol{A} = {(\boldsymbol{TE} - \boldsymbol{IR})}\Big/{(\boldsymbol{M} + \boldsymbol{N_a K_r})} \qquad \textbf{Equation 10}$$

where:

A = acceleration (m/s^2)

TE = tractive Effort (N)

IR = inherent train resistance (N)

M = Mass of the consist (kg)

N_a = number of axles

K_r = mass-equivalent rotational inertia of each axle (kg)

Time is cumulated in seconds with each step's duration calculated as the speed step-increment divided by the acceleration. The distance traveled is cumulated with an incremental travel distance of $V\ dt + 1/2\ A\ dt^2$.

Acceleration traction energy is cumulated in kilojoules (kJ) (also equal to kW-seconds), for four components (rolling resistance, dynamic resistance, aerodynamic resistance and stored kinetic energy) as well as for the combined energy of all components.

The coast table ('Rail-Simulation'!Y586:AP812) is generated with a TE value of zero. For braking, the contribution of the powered axles is driven by the negative value of the tractive effort characteristic data input (Figure 3), with the power P set to the appropriate brake power capacity of the powered axles in the consist. In addition, airbrakes can be blended with the powered brakes to attain a specified target brake rate, with an adhesion/power limiting characteristic that falls off with increasing speed.

The Coast table includes a calculation of brake energy recoverable and the slack time required in the schedule to coast from cruise speed to the present row's simulation speed before applying brakes at a stop. These two parameters (brake energy recoverable and the associated slack time required) are then sorted into ascending sequence of slack-required to facilitate a table lookup by the core simulation.

In the brake table, brake energy is cumulated on the basis of all braking sources. In addition, the proportion of brake energy available from the powered axles is calculated to provide an indication of the proportion of brake energy recoverable via regenerative braking at the same consist braking rate. A second scenario of utilizing only regenerative braking can also be simulated as an option (by setting the locomotive-only brake flag in the consist input data), but will result in lower braking rates and an associated longer trip time.

Figure 4 illustrates the cruise and brake speed profile of a 1 locomotive/4 bilevel coach consist braking from (80 mph) and overlays the coast characteristic that could be utilized if the stop had 20 seconds of schedule slack available. As illustrated about 2 miles of cruise-speed traction power (and a portion of brake pad wear) could be eliminated if the coast strategy was implemented at the stop.

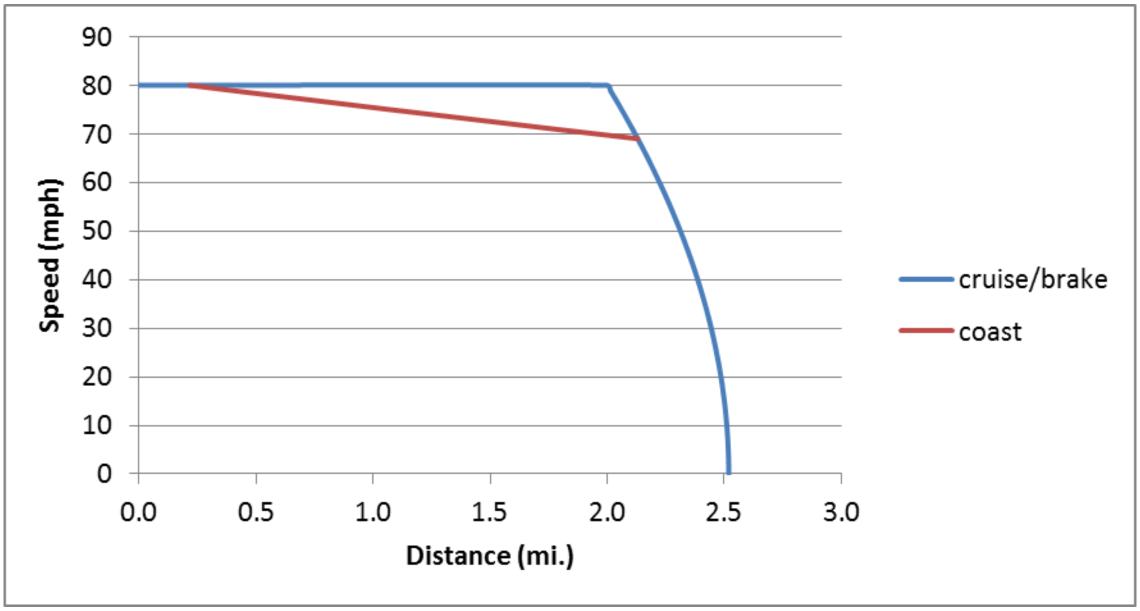


Figure 4. Speed/Distance Profile of 1L/4BLC Consist With And Without Coasting Source: derived from MMPASSIM brake and coast curves for a 1L/4BLC consist.

4.1.3.2 Core Simulation of Timetable Speed Segments

4.1.3.2.1 Time and Distance

With these pre-processed look-up tables calculated, the segment simulation can begin. The model accommodates up to 480 speed changes in one simulated route. The permanent slow order speed table (in miles from origin and associated speed in mph for the upcoming segment) is loaded into cells 'Rail-Simulation'!B79:C500. 'Macro' specified pointers are also used to load the relevant consist and route characteristic data. With these data loaded, distance, time and energy consumption are calculated for each of the three driving phases (i.e. accelerate, cruise, brake) as appropriate for the speed-segment.

While the train is simulated as a lumped mass with respect to gradient profile, train length is included in the treatment of the effective length of slow order segments. An approach buffer is also included at the entrance boundary of a slow order. Thus, the length of slow order segment is increased by the entrance buffer at the entrance and by the train length at the exit into a higher speed segment (and the adjacent two segments are shortened by the corresponding lengths). The indication of whether a speed segment involves a speed increase or a speed reduction from the previous segment is determined in column 'Rail-Simulation'!D81:D500 and an appropriate flag is set (+1 for increase, -1 for decrease).

Columns 'Rail-Simulation'!J82:K500 calculate the distance and times associated with acceleration, columns 'Rail-Simulation'!L82:M500 the distance and times for cruising and columns 'Rail-Simulation'!N82:O500 calculate the distance and times during braking which apply to each speed segment. The distance and times for acceleration and brake phases are found by table lookup of the pre-processed tables. Also, if one or more scheduled stops are indicated for the segment, the stop time and distance and the re-acceleration times and distances are found by table lookup of the brake and acceleration tables. These calculations are performed in columns 'Rail-Simulation'!T82:W500. With all of the transition distances known, the length of the segment transited at cruise speed is calculated (in column 'Rail-Simulation'!L82:L500) as the remaining distance in the segment, with an adjustment for train length at a boundary with a prior lower-speed segment and an approach buffer at a boundary with an upcoming lower speed segment.

It is possible that some short segments might produce a negative value for the cruise phase distance. In this case, an adjustment is made (in column 'Rail-Simulation'!P82:P600) to the acceleration distance such that a zero cruise distance is set, the acceleration distance is shortened and the associated lower speed noted. If the segment is so short that the revised acceleration distance is also negative, the prior segment cruise speed is shortened (in column 'Rail-Simulation'!R82:R500) and braking begins in the prior segment. Similarly, the re-acceleration distance from a scheduled stop is compared with the distance to the next speed segment boundary and if the distance is constrained, a new exit speed is calculated for the boundary and the distance/time for the re-acceleration from the stop is shortened (in columns 'Rail-Simulation'!Z82:AB500).

A single iteration is undertaken for short segments. The model applies some filtering of input speed tables in the 'Rail-Route' worksheet to avoid unrealistically short speed segments. The 'Rail-Route' worksheet logic checks user inputs for increased speed segments between two lower speed segments where the high speed segment is less than 0.25 miles. When such a situation exists, the higher of the two adjacent speed limits is extended into the highest speed segment. Nonetheless, some problematic situations may still arise. If a constraint remains after the simulation sheet takes the iterative steps, the associated negative distance is ignored and the 'Macro*'* flags the simulation run, advising the user to review the input speed table and manually merge any remaining short segments with an adjacent lower speed segment and then rerun the simulation with the revised speed table.

Short inter-stop distances within one speed segment are accommodated in an area beside the scheduled stop table – the average of the acceleration speed attainable between stops in a multi-stop speed segment is calculated (at 'Rail-Simulation'!F46:M70) and used in the stop re-acceleration calculation (at column 'Rail-Simulation'!V82:V500).

4.1.3.2.2 Energy Consumption

With the times and distances know for each of the movement phases in the segment, the energy consumed in the segment is calculated. The inherent resistance is relevant to the acceleration and cruise phases and is separately calculated (columns 'Rail-Simulation'!AD82:AI500) for each resistance component (i.e. rolling, dynamic and aerodynamic). The energy that is inherently stored in the train as kinetic energy (1/2 MV^2) during the acceleration phase is used to overcome inherent resistance during braking and the rest is either dissipated in the brakes (as heat energy in either friction brakes or dynamic brake resistance grids) or regenerated to onboard storage devices, wayside storage devices or for use in wayside consumption. The total energy consumed in the train's braking systems is calculated (column 'Rail-Simulation'!AJ82:AJ500) and the total recoverable energy available from the powered axles via regeneration is separately identified for the locomotive power limits (column ‘Rail-Simulation’!AK82:AK500) and for onboard storage power limits (column ‘Rail-Simulation’!AL82:AL500).

The last of the energy components are those associated with track profile — the energy dissipated in brakes to maintain speed limits on down grades and the energy required to overcome curving resistance on curves. The gradient component is calculated on the basis of the segment speed and the track gradient characteristics. Representative default route characteristics are provided for several regions. Downgrades are cumulated for each direction of travel into severity classes of -0.2% grade decrements. The average grade for all grades within each severity class is provided. Depending on the concentration of grades along a route and the availability of detailed data, the gradient profiles can be specified by route segment. Up to eight segments can be accommodated by the model; however, many routes can be adequately characterized by one uniformly applied gradient distribution profile.

The process of calculating energy dissipated in braking on downgrades involves the following steps:

1) Calculate the break-even downgrade for the segment speed (column ‘Rail-Simulation’AM82:AM500):

$$G_{be} = (C_{ra} + \mathrm{C}_{\mathrm{rb}}\,\mathrm{V} + \mathrm{C}_{\mathrm{rc}} V^2) \Big/ Mg \qquad \textbf{Equation 11}$$

where:

G_{be} = Break-even downgrade beyond which braking is required

C_{ra}, C_{rb}, C_{rc} are resistance coefficients

V = train speed (m/s)

M = Mass of the consist (kg)

g = acceleration due to gravity

2) Cumulate all downgrades of breakeven severity or greater on the basis of the gradient severity distribution for that segment.

    This is done via lookup of the grade severity table (‘Rail-Simulation’!CC5:DD14) which is loaded from the ‘Rail-Route’ worksheet. Indices for the lookup are calculated in columns ‘Rail-Simulation’!AN27:AO27.

3) Calculate the brake energy to maintain speed for non-train-acceleration segments as the downgrade energy can be recovered in those segments and add the probability of all down grade energy recovery for the proportion of the route that involves speed reductions as the downgrade energy cannot be recovered in these segments.

4) Calculate the brake force associated with the cumulative downgrades and convert to energy by multiplying the force by the distance traveled under braking:

    (steps 2, 3 and 4 are combined in one formula in Column ‘Rail-Simulation’:AP82:AP500).

Curves on the route are pre-aggregated into total change of central angle for the route. Curving resistance is characterized by 0.04% gradient-equivalent per degree of central angle (which is equivalent to 0.8 lb/ton/degree of curvature). Curving resistance is calculated once for the whole route rather than individual speed segments. Similar to gradient, curve resistance is adjusted to eliminate those segments where traction energy is not required (i.e. during braking, when the curve resistance contributes to the brake effort and traction energy is not being used). Curving energy is calculated (at 'Rail-Simulation'!AP19), excluding the proportional distance involving braking (at cell 'Rail-Simulation'!AP25).

4.1.3.2.3 Braking Energy Recovery

Brake energy recovery systems are considered in columns 'Rail-Simulation'!AS82:AY500. Column 'Rail-Simulation'!AS82:AS500 brings in the data provided in the '*Rail-Route*' worksheet on wayside storage use at scheduled stops (a positive value indicates the receptivity of the wayside storage device at a scheduled stop, while a zero indicates no wayside storage is used). Since smaller capacity onboard storage devices could be considered for hotel power provision in diesel locomotives, the next column ('Rail-Simulation'!AT82:AT500) calculates the hotel power required in each segment. Column 'Rail-Simulation'!AU82:AU500 calculates the regenerative energy available with an electric locomotive for the powered axle component of braking at speed reductions and stops (from column 'Rail-Simulation'!AK82:AK500) and 100% of the braking required for speed maintenance on downgrades (from column 'Rail-Simulation'!AP82:AP500). The energy saving potential is calculated as the sum of these two components multiplied by the receptivity factor and the cycle efficiency factor (both of which are input as part of the consist data).

Column 'Rail-Simulation'!AV82:AV500 calculates energy recovery potential of the selected wayside energy storage sites. This is done via a brake table lookup for the segment cruise speed multiplied by the receptivity value at the stop (column 'Rail-Simulation'!AS82:AS500 via data input on the 'Rail-Route' worksheet) and the cycle efficiency (input as part of the consist data).

Column 'Rail-Simulation'!AW82:AW500 calculates energy recovery potential of an onboard energy storage device (from column 'Rail-Simulation'!AL82:AI500 for device-power-limited energy at speed reductions and from column 'Rail-Simulation'!AP82:AP500 for 100% of the braking energy used in speed maintenance on downgrades). The minimum value (column 'Rail-Simulation'!AX82:AX500) and maximum value (column 'Rail-Simulation'!AY82:AY500) of the storage device's charge state are calculated on the basis of brake energy recovered and hotel energy provided in each segment. The net loss or gain in stored energy over the full trip is later calculated at 'Rail-Simulation'!AW26 and the difference is accommodated by an increase (or reduction) in the energy provided by the traction engine for hotel power.

4.1.3.2.4 Fuel Consumption

The above steps have provided the traction energy consumed at the wheels and the hotel energy at the engine shaft or pantograph. The next steps taken in the simulation are determination of the energy required at the power-source and the fuel consumed by the power source. Energy for both traction and hotel power are considered in the fuel calculations.

The efficiency of the traction system's transmission is characterized by two modes: acceleration, which involves a high load factor of the components and cruise which involves a lower load factor. These values are read from the 'Rail-Consist' worksheet on rows 38 and 39, respectively, and may be adjusted to suit the performance characteristics of the traction system being simulated. Application of the transmission efficiencies leads to the energy required at the engine for a diesel locomotive and at the pantograph for an electric locomotive.

A diesel-electric locomotive has a continuously variable transmission. This allows the engine's efficiency characteristic to be simplified into a single load-factor-dependent equation rather than a complex fuel mapping. The efficiency characteristic is specified by two factors, the minimum brake specific fuel consumption (bsfc) and the efficiency penalty incurred as the engine load factor departs from the load-factor associated minimum brake specific fuel consumption. The engine efficiency of the diesel locomotives identified in the literature search can be characterized (at column 'Rail-Simulation'!BB82:BB500) with a simplified straight line equation for efficiency loss below a threshold load factor. If future engines demonstrate a different characteristic these parameters can be modified.

Hotel power requirements are specified on a per-car basis for three seasons (summer, winter and other). Most dg-set manufacturers provide a fuel consumption characteristic of the type:

$$\boldsymbol{F_h = a + bP} \qquad \textbf{Equation 12}$$

where:

F_h = Hotel diesel generator fuel consumption rate (lb/hr)

P = Hotel Power output (kW)

a and b are equipment-specific coefficients.

This is the equation that is applied at column 'Rail-Simulation'!BC82:BC500 if the hotel power is provided by a separate dg-set. If it is provided by the traction engine then the traction engine's average fuel rate is used. The traction engine's fuel rate is influenced by the nature of hotel provision as specified in the consist data ('Rail-Consist' worksheet). If hotel power is provided via an inverter, the traction engine operates at variable speed, and if it is provided by a coupled generator directly, which requires a constant engine speed, a higher fuel penalty characteristic is incurred for decreasing engine load factors. This fuel penalty is incurred by the traction engine in providing both traction and hotel power.

Columns 'Rail-Simulation'!BD82:BD500 and 'Rail-Simulation'!BE82:BE500 provide calculations of traction and hotel energy required at the pantograph by electric locomotives or EMUs.

The last columns of the core simulation area identify dual fuel boundaries ('Rail-Simulation'!BF82:BF500) and allocate segment energy requirements between on-board fuel and wayside electricity ('Rail-Simulation'!BG82:BJ500).

4.1.3.3 Grade Climbing and Unscheduled Delays

The delay involved in grade climbing is calculated at 'Rail-Simulation'!AM27:AS27. Delays are based on the assumption that all grades are climbed at the average cruise speed for the route. The break-even grade for climbing is the maximum grade where cruise speed can be maintained at full traction power. The breakeven upgrade is calculated at 'Rail-Simulation'!AM27 as:

$$G_{mx} = {(P/V - (C_{ra} + \mathrm{C}_{\mathrm{rb}}\,\mathrm{V} + \mathrm{C}_{\mathrm{rc}}V^2))}\big/{Mg} \qquad \textbf{Equation 13}$$

where:

G_{mx} = the maximum grade that can be climbed at cruise speed

P = traction power (kW)

V = train speed (m/s)

C_{ra}, $C_{rb,}$ C_{rc} are resistance coefficients

M = Mass of the consist (kg)

g = acceleration due to gravity

The indices for the grade-severity lookup table are set at 'Rail-Simulation'!AN27:AO27 and the total height attained on grades exceeding the breakeven grade is calculated at 'Rail-Simulation'!AP27 (based on the grade severity and corresponding length provided in the grade severity table at 'Rail-Simulation'!CC5:DD14). The average grade force on grades exceeding the breakeven grade severity threshold is calculated at 'Rail-Simulation'!AP27 and the average steady state speed attained is found by lookup at AQ27. The total distance involving grades exceeding the breakeven grade is calculated at AQ29 and the time lost due to speed reductions on upgrades greater than G_{mx} is calculated at AS27 by assuming there is one upgrade segment for route segments less than 100 miles and 3 separate upgrade segments for longer route segments. The delay is the difference between the time required to transit the upgrades at cruise speed versus the transit time at the average of the deceleration distance/speed and the balance speed for the remaining distance to the top of the grades. The energy costs of grade climbing are captured via the brake dissipation calculation made elsewhere and the energy savings for inherent resistance to motion at lower speed is considered to be small and is ignored.

The delay and energy cost due to unscheduled stops are calculated at row 31 of the 'Rail-Simulation' worksheet using data provided on the 'Rail-Route' worksheet. An unscheduled stop is characterized by the expected number of occurrences in a one-way trip across the route being simulated, as well as the average length of siding and speed limit in the siding (if used when making a stop) and the average dwell time-per-stop spent idling at unscheduled stop locations. The relevant data are brought into 'Rail-Simulation!B29:G29, while the calculations (performed in cells 'Rail-Simulation'!J29:O29 and 'Rail-Simulation'!AC29:AK29) follow similar table lookup procedures as discussed above in the core simulation of speed segments.

The delay and energy cost due to temporary slow orders (TSO) are calculated at rows 35 to 40 of the 'Rail-Simulation' worksheet. TSOs are characterized by the average number of occurrences per one-way trip and the average distance imposed for each of up to 6 TSO speed limits. The delay and energy cost calculations are performed in a similar fashion to the unscheduled stops in columns 'Rail-Simulation'!J35:O40 and 'Rail-Simulation'!AC35:AK40.

4.1.3.4 Output Area

The output area provides interim results for the 'Macro' to use in aggregating/transferring results to the final 'Master-I-O' worksheet. Some additional details are provided on the worksheet to assist in scenario creation and data checking. The basic trip time performance of the run is provided at 'Rail-Simulation'!I4:K10. The minimum run time (without unscheduled stops and excluding station dwell times at scheduled stops) is output as well as the simulation run time with these components included. The run times are compared to the scheduled trip time and the 'schedule slack' associated with each runtime is calculated. The total calculated trip time is also shown and compared with the input data. An 'error flag' is shown at 'Rail-Simulation'!L4 if the calculated distance differs from the input data. Such an occurrence could happen if unrealistically short speed-segments exist in the route data. If an error is flagged, the 'Macro' provides an indication in the header of the output results table on the 'Master-I-O' worksheet (red message at 'Master-I-O'!AB606, 'Master-I-O'!AB706 or 'Master-I-O'!AB806) associated with the type of analysis being performed. The error is also flagged in the detailed rail results tables for the affected rail trip on the 'Rail-I-O' worksheet ('Rail-I-O'!EX100, 'Rail-I-O'!EX150, 'Rail-I-O'!EX200, 'Rail-I-O'!EX250, 'Rail-I-O'!EX300, 'Rail-I-O'!EX350, 'Rail-I-O'!EX400 and 'Rail-I-O'!EX450).

The other interim results from the time and distance calculations are calculated for each of the core simulation columns, with time and distance summaries at 'Rail-Simulation'!J15:W19 and Energy totals at 'Rail-Simulation'!AC15:BD30. The 'Macro' takes the final energy/fuel results for the simulated route/consist scenario from cells 'Rail-Simulation'!BA27:BD28. However, each simulation also provides calculations of what the potential performance would be if the same train was run under a different energy-recovery or energy-source scenario. The table at 'Rail-Simulation'!AZ20:BD26 provides results for the energy dissipated under seven different technology scenarios (provided the relevant data were input on the consist worksheet). The table is always output but some rows will not be applicable to all simulations – for example high speed trains and wayside storage devices would normally be associated with electric trains, while onboard storage would be an option for diesel-electric trains. Table 26 illustrates the output format for the comparisons. The first data column is applicable to either an electric or a diesel consist (of the same power and weight characteristics) and provides the traction energy at the engine shaft or electric pantograph for each of the identified energy-recovery scenarios. The last three data columns provide the fuel consumption for an assumed diesel powered consist. The output is intended to provide some insight into the relative performance of different energy recovery technologies for the simulated service. Simulation of an actual alternative technology would require a dedicated simulation run with other changes to the consist data (e.g. weight increase for onboard storage devices and/or interface equipment) that use of the technology would necessitate.

Table 26. Illustrative Summary Output Within the Rail-Simulation Worksheet

Energy Recovery System	Traction Energy at shaft/ pantograph	Fuel Consumed		
		Traction	Hotel	Combined*
	(kWh)	(kg)	(kg)	(kg)
None	5,716	1,525	146	1,671
Regen to electricity grid	5,426	N.A.	N.A.	N.A.
Regen to wayside storage (all stops)	5,644	1,506	146	1,652
Wayside at one-max-site	5,681	1,516	146	1,662
Selected stops (Route input data)	5,687	1,517	146	1,664
Onboard storage	5,471	1,525	20	1,546
Optimal Coast at Scheduled Stops	5,453	1,455	146	1,601

* In addition to the traction fuel and hotel fuel consumed during the simulated trip, the ‘Combined’ fuel includes locomotive auxiliary power and extra idle fuel consumed before and after a trip and any incremental fuel consumed in non-revenue movements.

5 Highway Modes Simulation Modules

5.1 Common Elements to All Highway Vehicles

The ‘Bus-Simulation’ and ‘LDV-Simulation’ worksheets are structured in a similar way to one another. The main difference is due to the fact that intercity and commuter coaches do not vary significantly by manufacturer while light duty vehicles vary significantly by class and by manufacturer within specific classes. For bus simulations, only four representative coaches are characterized in the default dataset and one coach is selected for a simulation. The ‘LDV-Simulation’ worksheet is organized to simulate representative composite vehicles, including proportions of hybrid vehicles and non-hybrid CVT vehicles within the composite class being simulated. Functionally, the ‘Bus-Simulation’ worksheet has one core simulation area while the ‘LDV-Simulation’ worksheet repeats the simulation area such that three separate variations of drivelines can be simulated for each vehicle (i.e. conventional, hybrid and non-hybrid CVT). In addition, the ‘LDV-Simulation’ worksheet uses higher performance drive schedules than does the ‘Bus-Simulation’ worksheet.

Figure 5 illustrates the layout of the highway simulation modules (‘Bus-Simulation’ and ‘*LDV-Simulation*’). The top left corner of the spreadsheet contains vehicle characteristics as loaded by the ‘Macro’, including the following:

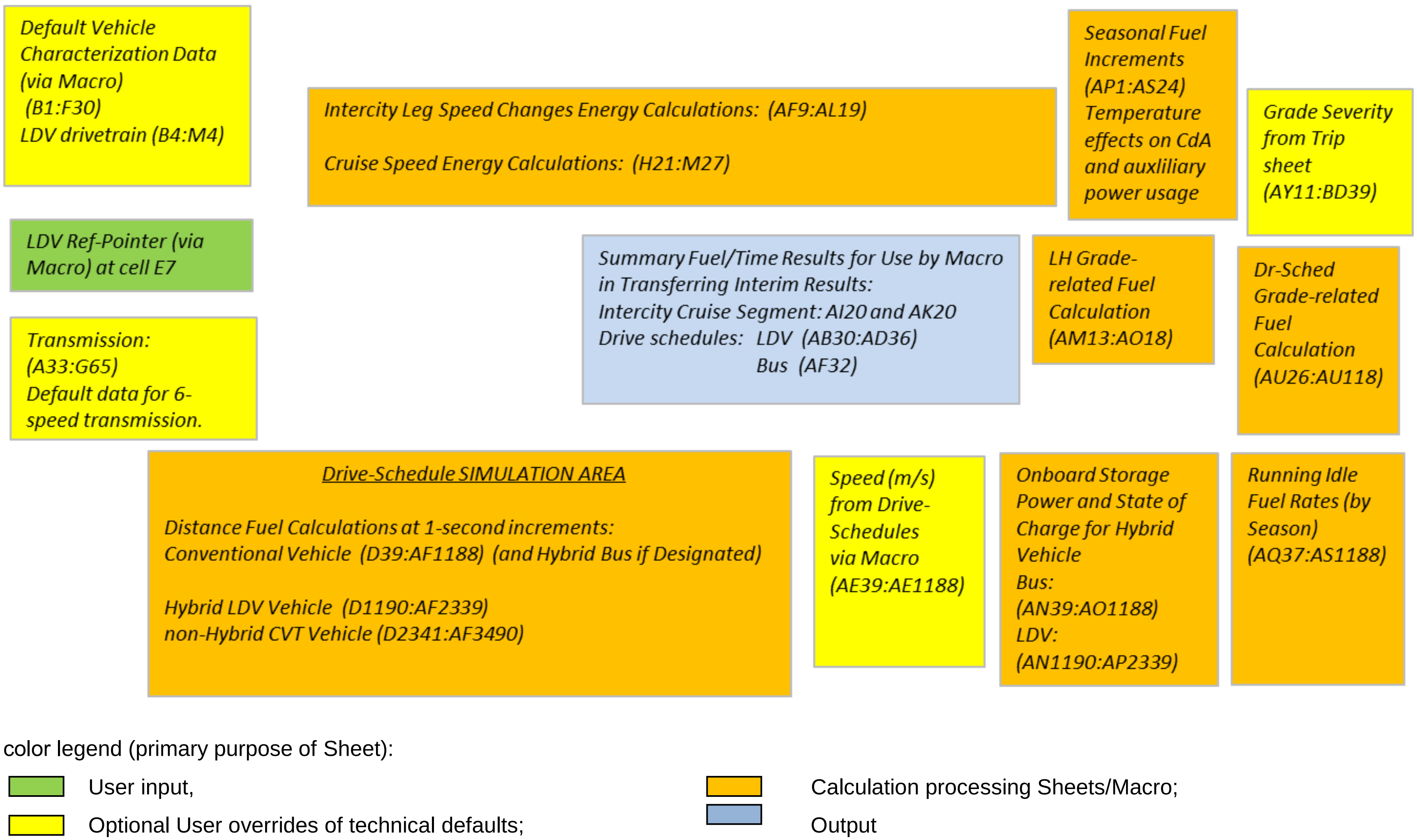
engine power,
transmission loss coefficients,
vehicle mass and coast-down resistance coefficients,
auxiliary power, and
onboard storage characteristics (for a hybrid vehicle).

Below the basic vehicle characteristics, a default 6-speed transmission is defined (with fixed gear ratios and shift points for all coaches in the ‘Bus-Simulation’ worksheet but with ratios and shift points varying with engine power for the ‘LDV-Simulation’ worksheet).

After the ‘Macro*’* loads the appropriate drive schedule and vehicle type, the core simulation proceeds in the following sequence:

- Define the operating-mode (accelerate, cruise, decelerate, stop) in column H;
- Select a gear (given the mode, speed and acceleration rate) in column J;
- Determine the restive and inertial force/power on the vehicle (columns L – O);
- Determine the engine speed (column P) and its fractional value in relation to the fuel map lookup table (column Q);
- Determine the power required at the wheels (column R);
- Determine the power provided by the engine (given any energy recovery from onboard storage and engine performance limits) (column S);
- Determine the engine torque at the shaft (given the power provided at the wheels and the engine speed) (column W);
- Normalize the engine torque and do a double interpolation of the engine’s normalized fuel map (in the ‘LDV-Engine’ or ‘Bus-Engine’ worksheet);
- Apply the fuel increment above the engine’s minimum bsfc and adjust the fuel for the generic engine fuel map with factors developed for the vehicle being simulated (column AF).

Figure 5. Highway Vehicle Simulation Sheets Layout



The top part of the simulation area simulates vehicle performance at fixed cruise speeds (as input in the 'Bus-Route' or 'LDV-Route' worksheet) in 'cruise' mode with fuel output in kg/km-of-travel. The lower part of the simulation area performs a second-by-second movement of the vehicle over a drive-schedule (speed profile) brought in by the 'Macro'. The equations used in the step-by-step movement of the vehicle over the drive schedule are the same as those described for the rail vehicle pre-processed acceleration profile (see Section 4.1.3.1) with the exception of the locomotive tractive effort envelope and fuel efficiency equation which do not apply. The locomotive's properties are replaced by the highway vehicle engine's torque/speed envelope and its fuel map of relative fuel efficiency for all torque-speed combinations within that envelope.

The 'Bus-Simulation' worksheet calculates the power flow and energy storage state of a hybrid vehicle (if one is being simulated) at columns 'Bus-Simulation'!AN39:AO1187 while the 'LDV-Simulation' worksheet performs a separate simulation of the drive schedule for a hybrid version of the vehicle (on rows 1190 through 2339). The 'LDV-Simulation' worksheet also performs a separate simulation of a non-hybrid vehicle with a CVT (on rows 2341 to 3490). Either individual or composite LDVs can be simulated. The default is a composite vehicle (e.g. the 2011 CY driven fleet) with appropriate proportions of hybrid and non-hybrid CVT vehicles as specified on rows 44 and 45 of the 'LDV-Resist' worksheet. The resulting fuel intensity is the performance of the composite mix. If one wishes to simulate a sole-hybrid (or conventional or CVT) vehicle, either the proportion needs to be set to 100% in the input data column for that vehicle in the 'LDV-Resist' worksheet data table or the default mix can be temporarily overridden using the "Engine Option" selection available on the 'Auto/LDV Type Selection' pop-up menu. Selecting "default mix" will use the mix as defined in the 'LDV-Resist' data table while selecting the "Hybrid" option sets 100% hybrid and 0% non-hybrid CVT or selecting the "Non-hybrid" option sets 0% hybrid and 100% non-hybrid CVT.

The output from the simulation sheet is the fuel intensity (kg/vkm) for the particular drive schedule being simulated. The 'Macro' iteratively brings in each drive schedule and builds up the total trip fuel intensity in proportion to the allocated drive schedules as defined in the 'LDV-Route' or 'Bus-Route' worksheets and the 'LDV-Drive-Schedules' or 'Bus-Drive-Schedules' worksheets.

Gradient influences are calculated at cells AM13:AO18 for the intercity leg of a trip and at cells AU26:AU118 for the drive-schedule part of a trip on both the 'LDV-Simulation' and 'Bus-Simulation' worksheets..

Seasonal variations (temperature influence on aerodynamic drag and auxiliary power usage) are calculated on the upper right side of both the bus and LDV simulation worksheets (cells *AP1:AS24)*. The 'Macro' selects the appropriate values for the season and region being simulated.

5.2 LDV Characteristics Sheet and Future-Year Preprocessor

The 'LDV-Resist' worksheet contains the default characterization data for LDVs. Default data exist for different classes of 2011 vehicles as well as composite vehicles for the sales-weighted and driven fleets for the years 2011, 2012 and 2013.

The ‘LDV-Resist’ worksheet also includes a processor to generate data for fleet average composite vehicles in future years. The algorithm of the preprocessor assumes that 50% of the difference in fleet-average fuel economy of the new model year relative to the 2011 sales-weighted fleet is due to drive-train efficiency (engine and/or transmission efficiency is scaled by 50% of the fuel economy difference) and 50% is due to vehicle body design or fleet composition (the 2011 fleet average weight and resistance coefficients are scaled by 50% of the fuel economy difference). The lower part of the worksheet contains the necessary data and formulae. Use of the preprocessor is described in more detail in the User Guide (Sections A.6.8 and A.7.16).

5.3 Highway Drive Schedules

A series of fixed drive schedules (speed – time) are used to represent urban travel. Speed is specified at 1-second intervals for each representative drive schedule. All are derived from EPA drive schedules, either as direct copies or with slight modifications. MMPASSIM simulates the movement of a vehicle over each drive schedule and scales the kg/Vkm fuel intensity output to the total distance for that road condition as specified by the user for a given trip. The model is responsive and thus, acceleration and braking rates are held within the capability of the vehicle rather than purely following the speed-time profiles. The drive schedules are derived from EPA drive schedules for Heavy Duty, Medium Duty and LDVs.

Traffic congestion is typically characterized by the level of service (LOS) which is based on the level of reduction below free-running speed of the traffic. For a freeway with an average 110 km/h (68 mph) free flow speed, increasing congestion leads to decreasing average speed. LOS A through LOS D involve modest decreases, while LOS E depicts traffic at capacity conditions and LOS F depicts traffic beyond capacity covering a range of conditions from frequent slow-downs to full stop-and-go progress. Non-freeway travel involves intersection stops and idle periods.

The bus and LDV modules use some common drive schedules and some performance-specific drive schedules for urban travel. There are seven drive schedules in each vehicle’s worksheet as illustrated below.

A Creep drive schedule is used for queuing delays or fully congested travel and the output is presented in fuel consumption per unit time. Queue delays can be encountered at manual toll booths, some maintenance activities, congested arterial and city-street intersections and severely congested freeways. The Creep Schedule is composed of intermittent short advances and long idle periods as illustrated in Figure 6. The drive schedule is derived from the front end of EPA’s LOS-F drive schedule and is used by both the bus and LDV modules.

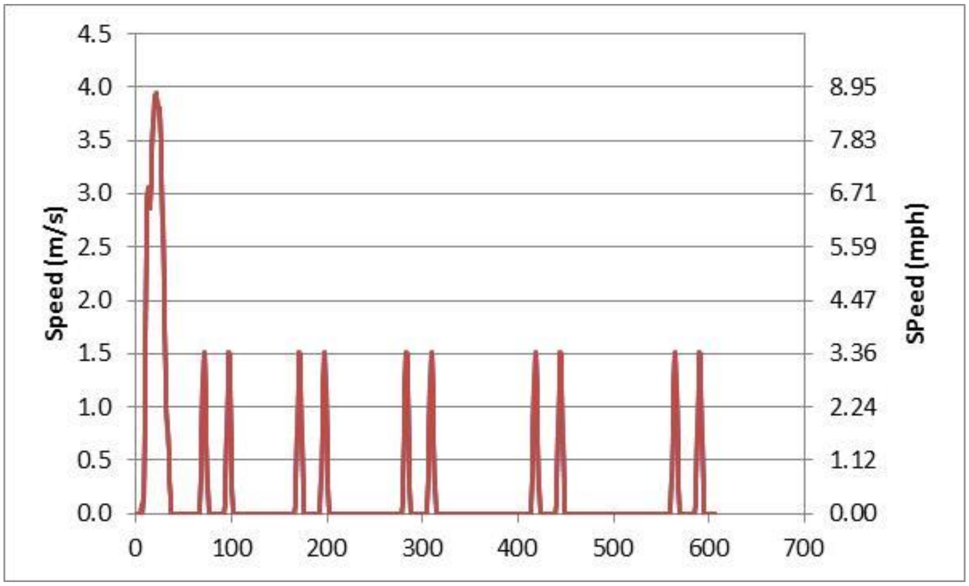


Figure 6*.* Creep Drive Schedule (0.9 km/h)

Source: Derived from EPA Drive Schedules used in MOVES.

There are two non-freeway drive schedules, with stops and speed variation from a shared-traffic in an urban environment. An arterial road (see Figure 7) is depicted by an average speed of about 40 km/h (25 mph) with stops at about 2 km intervals. The drive schedule is EPA's non-Freeway HDD25 drive schedule. The user input specifies the total distance traveled on intermediate urban access roads (more for bus intermediate stops than for LDVs) for the intercity segment and as a proportional incurrence by time-of-day for the urban origin and destination. The same drive schedule is present in both 'Bus-Drive-Schedules' and 'LDV-Drive-Schedules'.

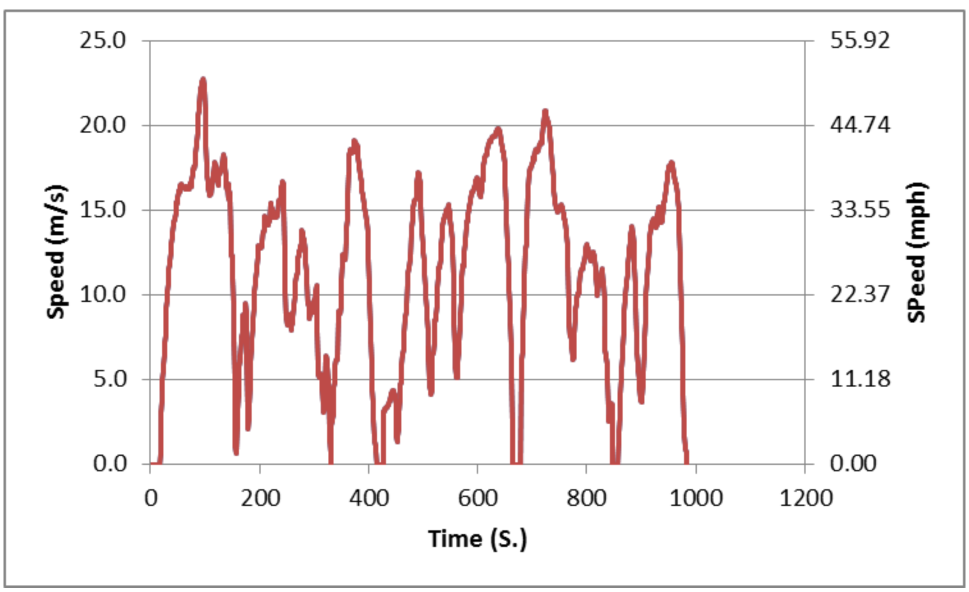


Figure 7. Urban Arterial/City Drive Schedule (40 km/h)

Source: Derived from EPA Drive Schedules used in MOVES.

Figure 8 illustrates a congested traffic condition which could be encountered on either freeway or non-freeway roads. The LOS-F (14 km/h) is present in both the ‘Bus-Drive-Schedules’ and ‘LDV-Drive-Schedules’ worksheets.

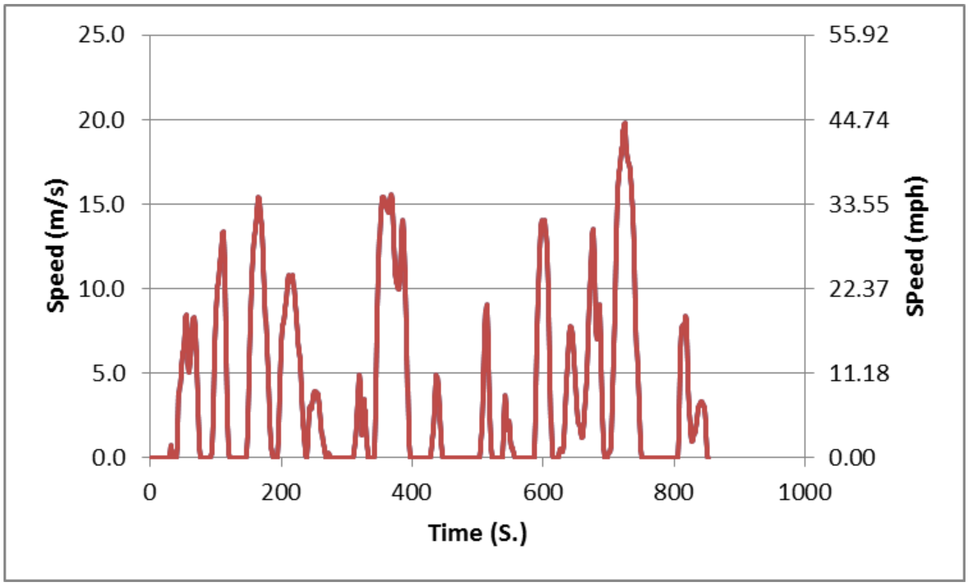


Figure 8. LOS-F Stop and Go Drive Schedule (14 km/h)

Source: Derived from EPA Drive Schedules used in MOVES.

The ‘LDV-Drive-Schedules’ worksheet also has a city street as depicted in Figure 9.

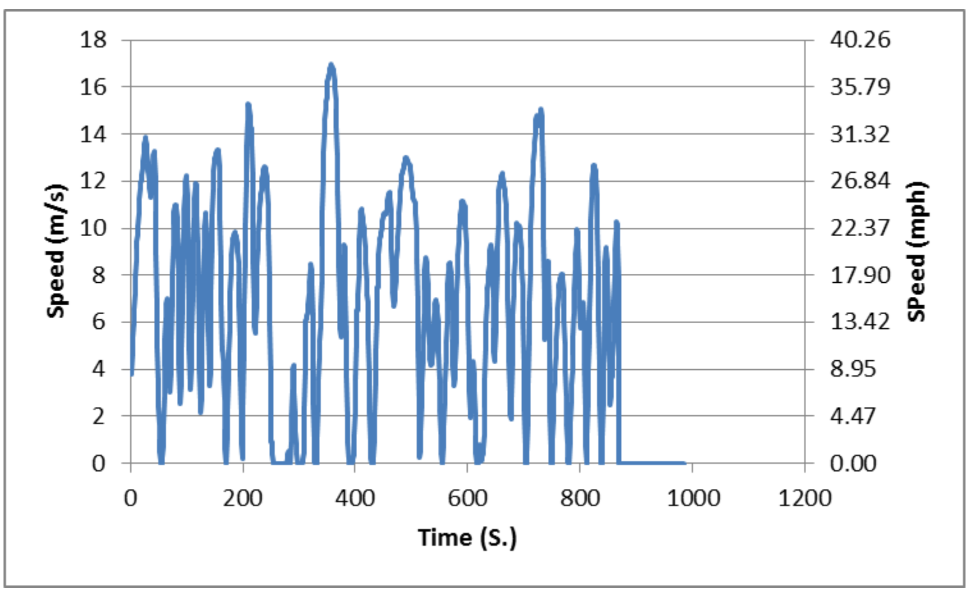


Figure 9. City Street Drive Schedule for LDVs (25 km/

h) Source: Derived from EPA Drive Schedules used in MOVES.

Urban freeways have several drive schedules to simulate the degree of congestion. Each has an average speed associated with congestion conditions. The approximate average speeds involved for each drive schedule used in the 'Bus-Drive-Schedules' and 'LDV-Drive-Schedules' worksheets are:

Bus Freeflow	117 km/h (73 mph), (see Figure 10)
LDV Freeflow	119 km/h (74 mph), (see Figure 11)
LOS-B/C	105 km/h (65 mph), (see Figure 12)
LOS-E	75 km/h (47 mph), (see Figure 13)
LOS-E (Bus)	50 km/h (30 mph), (see Figure 14)
Access/exit urban freeway	100 km/h (62 mph), (see Figure 15)

New drive schedules can be used in place of the seven drive schedules in the middle of the Table. The creep drive schedule (col C) and cruise drive schedule (col K) cannot be replaced. The length limitation is a maximum of 1149 seconds duration and the active length of the intended drive schedule must be entered in row 29 at the top of the replacement drive schedule. The user can also manually introduce a speed governor for buses in the 'Bus-Drive-Schedules' by capping the maximum speed of the existing speed profiles with the appropriate speed limit. Thus for example, a 65 mph (25.058 m/s) governor setting would cap the maximum speed at 65 mph rather than the 79 mph (35.32 m/s) attained in the non-governed "Bus Freeflow" drive schedule of Figure 10 and the 67 mph (29.95 m/s) attained in the 'LOS-E 75 km/h' drive schedule of Figure 13.

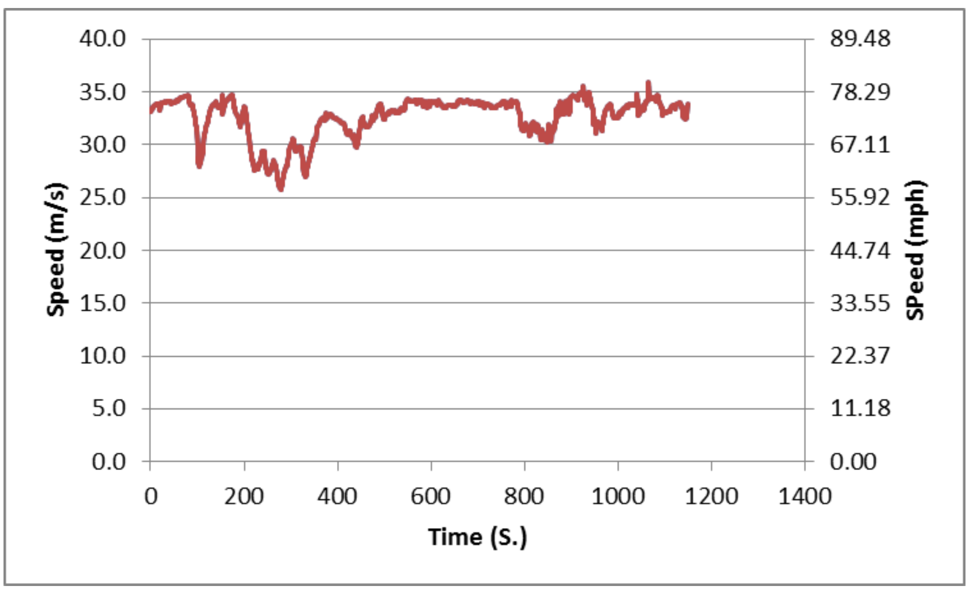


Figure 10. Urban Freeway Bus Free-flow - 117 km/h Drive Schedule Source: Derived from EPA Drive Schedules used in MOVES.

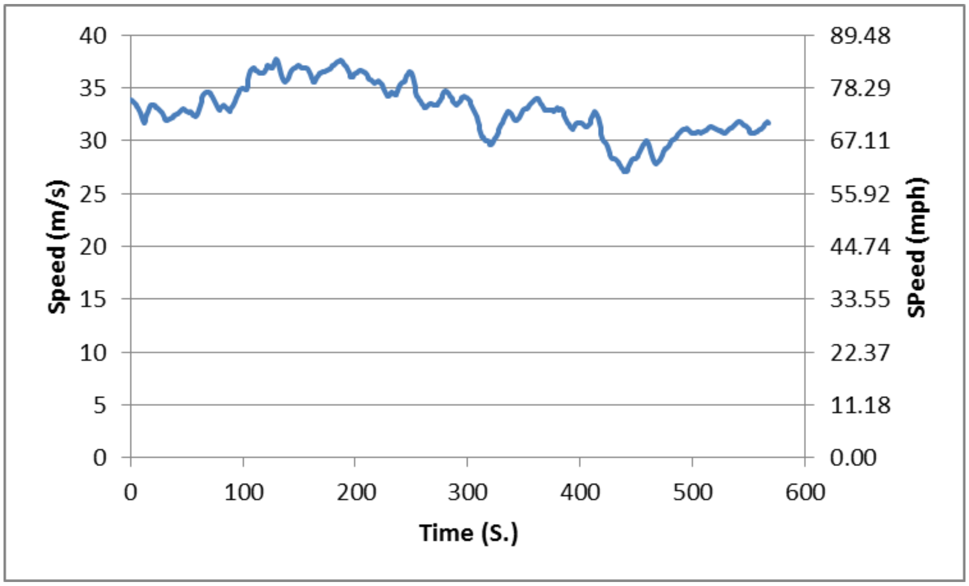


Figure 11. Urban Freeway LDV Free-flow - 119 km/h Drive Schedule Source: Derived from EPA Drive Schedules used in MOVES.

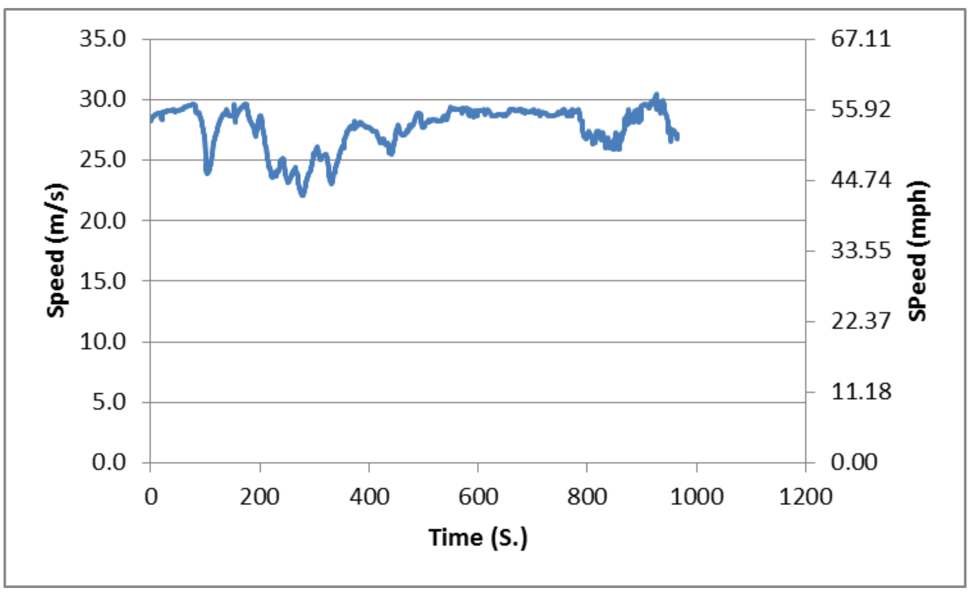


Figure 12. Urban Freeway LOS-B/C - 105 km/h Drive Schedule Source: Derived from EPA Drive Schedules used in MOVES.

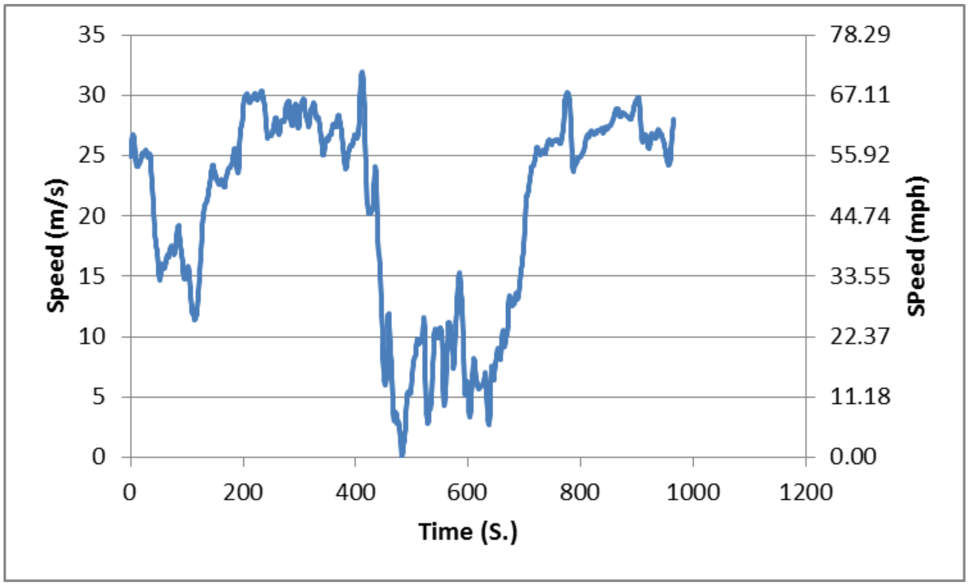


Figure 13. Urban Freeway LOS-E - 75 km/h Drive Schedule

Note: This is the LDV drive schedule, the Bus drive schedule is the same except the speed peaks are capped at 65 mph (29 m/s).
Source: Derived from EPA Drive Schedules used in MOVES.

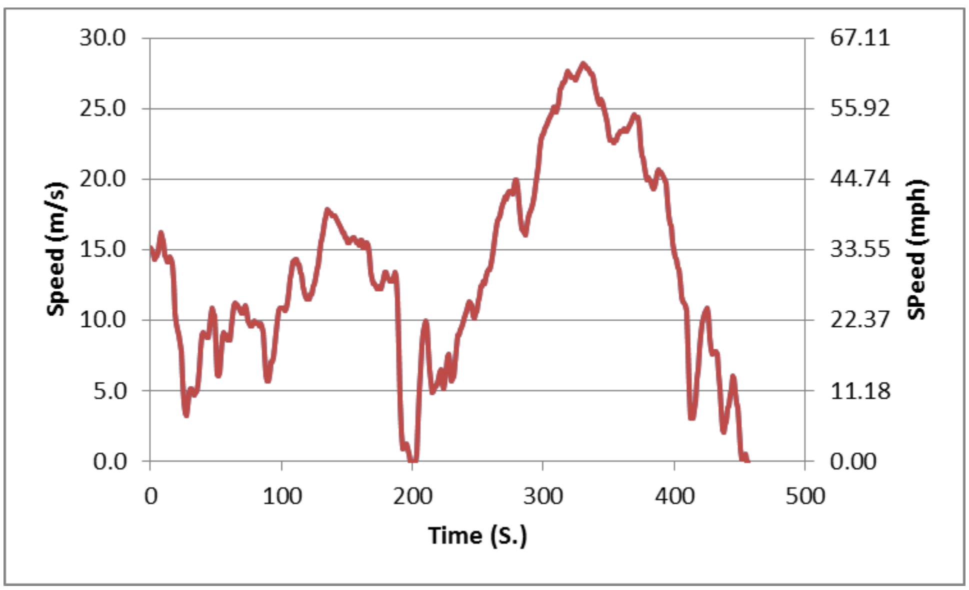


Figure 14. Urban Freeway – LOS-E 50 km/h Drive Schedule Note: This drive schedule is used in the Bus simulation.

Source: Derived from EPA Drive Schedules used in MOVES.

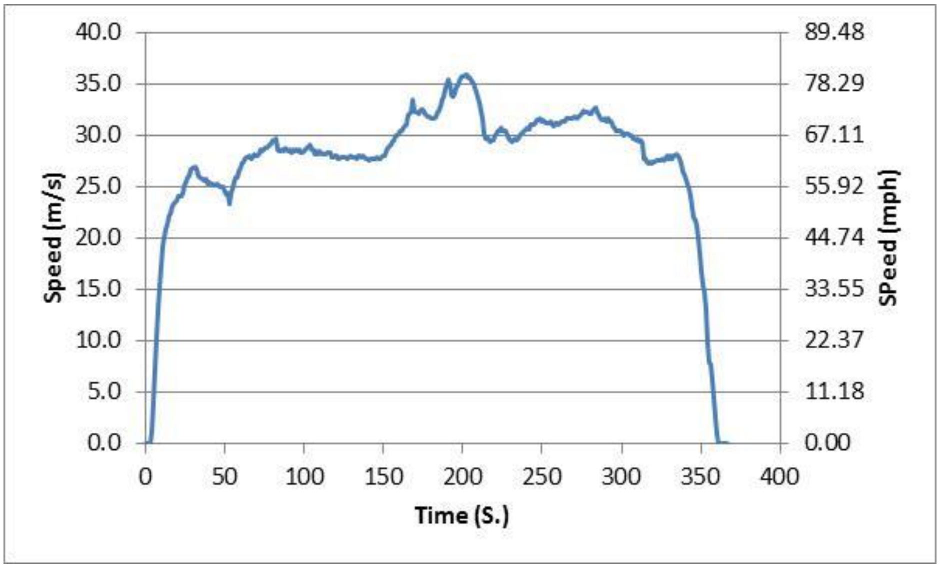


Figure 15. Short Urban Freeway Access LDV Drive Schedule (EPA-US06)

Source: EPA's Fuel Economy Certification Drive Schedule US06.

5.4 Inter-City Road Maintenance/Weather Delays

The congestion drive schedules described in the previous section are also used to depict maintenance delays for the intercity segment of the intercity long haul trip. The user specifies the distribution of trips by time-of-day congestion conditions and the model determines the average fuel intensity in relation to the input distribution. Long haul maintenance activity is also characterized by the same fixed duty cycles. The user specifies the distance and probability of occurrence for maintenance and/or weather delays. The LOS-E 75 km/h drive schedule is assumed to characterize these delays.

6 Air Mode Simulation Module

6.1 Overview

The air simulation module simulates the air leg of a full door-to-door passenger trip generating the energy and emissions intensities of the air leg of the passenger trip. The air module is unlike the other modal simulation modules as it does not 'simulate' the movement of an aircraft but uses energy intensity characterization data that are published each year by the US Bureau of Transportation Statistics [Research and Innovation Technology Administration, Bureau of Transportation Statistics, 2013]. The default characterization data provided with the model are based on 2011-2012 operations of domestic US scheduled air carriers and can be updated by the user as desired in future years as air technology and operations practices change. The following five types of aircraft were assessed:

1. Turboprops (TP)
2. Small Regional Jets (SRJ) (defined here as jet aircraft with less than 50 seats)
3. Regional Jets (RJ) (defined here as jet aircraft with 50 to 89 seats)
4. Narrow Body Jets (NBJ) (defined here as jet aircraft with greater than 89 seats in a single aisle configuration)
5. Wide Body Jets (WRJ) (defined here as jet aircraft with greater than 89 seats configured with more than one aisle)

The data were analyzed to provide an indication of the mix of aircraft used in meeting the demand for different trip lengths. Each aircraft type was analyzed to provide an indication of its average load factor, its per-seat fuel intensity during the landing and takeoff cycle (kg/seat-LTO) and for the cruise segment (kg/seat-GC-mi).

The default coefficients used in the Air Simulation sheet are presented in the Air Mode Methodology (Section 2.4).

6.2 Air Module Layout

6.2.1 User Inputs

The overall model structure was illustrated in Figure 1 of Chapter 3. Those worksheets specific to simulating the air passenger mode are discussed in more detail here.

The minimum input data required to make an air simulation run are the coordinates for the origin, destination and any intermediate airports involved in the trip. A database of airport coordinates is not published; however, the data can be obtained for individual airports from publicly available websites. The co-ordinates for a sample of airports (i.e. those involved in our case study locations) are included with the model and the user can build an internal dataset as new trips are defined and simulated.

With the airport coordinates specified, the model calculates the GC-distance for each leg of the trip, applies the average proportions of each aircraft type used for the trip distance involved and then calculates the aircraft specific energy and emissions intensities for the air legs of the trip.

The 'Air-Simulation' worksheet simulates the energy intensity of an air mode trip using a default distribution of aircraft types typical of the trip leg distances. A user can specify a single aircraft type or alternative mix of aircraft types. Similarly, representative proportions of direct and indirect (hub and spoke or multi-stop) trips can be specified or a 100% allocation to one or the other trip scenario can be made. Also, the default mirror-image return trip can be overridden with a user-specified trip if desired.

The default data are presented in Subsection 2.4.2.

6.2.2 Air Simulation Worksheet Layout

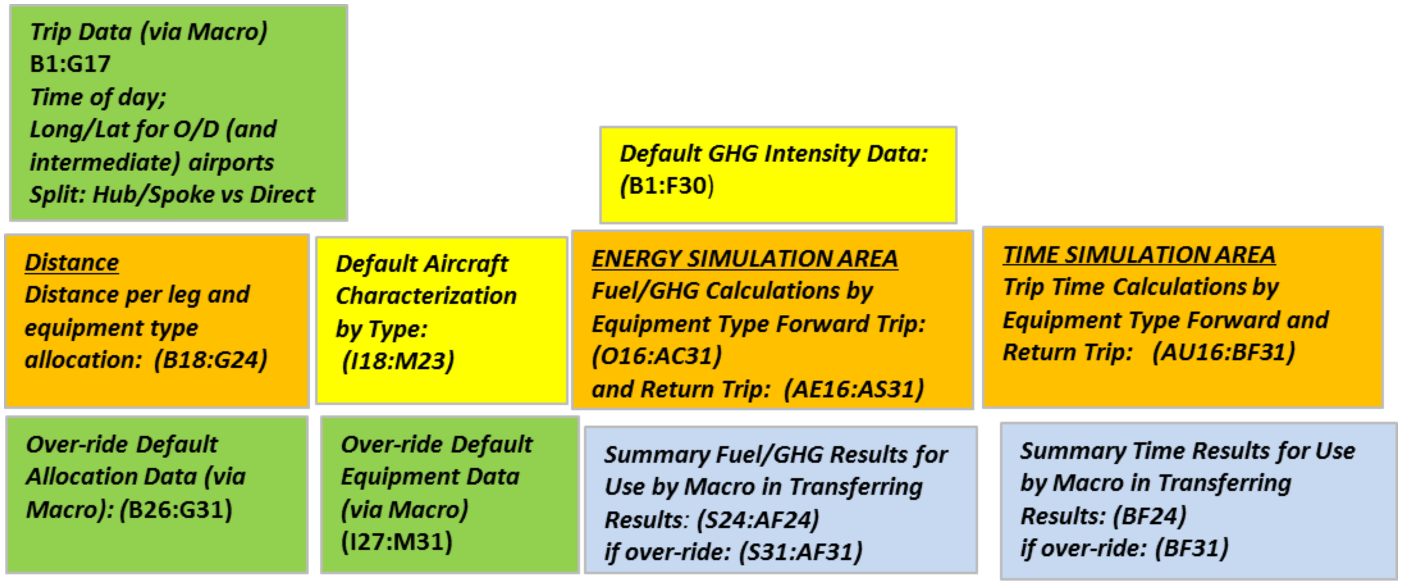
The structure of the 'Air-Simulation' worksheet and its direct interface to default datasets is illustrated in Figure 16. The areas of the worksheet are color coded to reflect their primary purpose: green indicates it is a user input, yellow indicates technical default data that can be optionally modified by the user, orange indicates calculation procedures at the core of the simulation, and blue indicates interim output data for transfer and/or aggregation by the 'Macro'.

The LTO and cruise legs of the air trip are calculated separately such that the differentiated impact of cruise-altitude emissions can be applied. The following fuel, energy and GHG intensities are calculated for the defined origin-destination trip:

- kg-fuel consumed per seat-Great Circle-km traveled (kg/sGCkm),
- kg-fuel consumed per passenger-Great Circle-km traveled (kg/pGCkm),
- kg-fuel consumed per passenger-trip (kg/trip),
- kJ of energy consumed per seat-Great Circle-km traveled (kJ/sGCkm),
- kJ of energy consumed per passenger-Great Circle-km traveled (kJ/pGCkm),
- kJ of energy consumed per passenger-trip (kJ/trip).
- Grams CO_2e emitted per seat-Great Circle-km traveled (g/sGCkm),
- Grams CO_2e emitted per passenger-Great Circle-km traveled (g/pGCkm), and
- kilograms CO_2e emitted per passenger-trip (kg/trip).

In addition, the travel time of the air leg(s) of the trip is calculated, including dwell time at intermediate stops and airport arrival / departure processing/waiting times.

Figure 16. Air-Simulation Worksheet Layout



color legend (primary purpose of Sheet):

- Green: User input,
- Yellow: Optional User overrides of technical defaults;
- Orange: Calculation processing Sheets/Macro;
- Blue: Output

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Appendix A

MMPASSIM Spreadsheet Model User Guide is available as a separate PDF file on the CRP-CD-176.

Appendix B

Terms, Abbreviations and Equation Variables

B.1 Terms

Balance speed	Speed at which a train's tractive effort equals the sum of its up-grade and resistive force.
Breakeven grade	Speed at which a train's downgrade force equals the resistive force.
Cruise segment	Portion of a trip taken at constant 'cruise' speed.
Cruise speed	Speed maintained on a long haul segment of a trip.
Consist	The locomotives and cars comprising a train.
Delay	Unscheduled events that add to a trips minimum travel time.
Dg-set	Diesel generator set used to generate hotel power.
Dynamic braking	Slowing a train by using traction motors to convert kinetic energy into electricity which is then dissipated as heat in resistance grids.
Hotel power	Electrical power provided for use by passenger compartments.
Regeneration	Conversion of kinetic energy into electrical energy during braking (usually back into the electricity grid or onboard storage rather than simply dissipated as heat as in dynamic braking).
Schedule slack	Time allowance built into a schedule in excess of the minimum run time to accommodate unscheduled delays.
Steps	Segments of track processed in one calculation row of the rail simulation sheet (segments are normally based on lengths of constant posted speed).
Tractive effort	The propulsive force generated at a powered axle's wheel (mostly by electric traction motors).
Wayside	At the side of the tracks.

B.2 Abbreviations

ABA – American Bus Association
AC – Aircraft
AREMA – American Railway Engineering and Maintenance-of-Way Association
A T R I – American Transportation Research Institute
Bsfc – Brake specific fuel consumption
BTS – Bureau of Transportation Statistics
C N – Canadian National
CVT – Continuously variable transmission
CY – Calendar year
D – Destination
DEM – Digital elevation models
DMU – Diesel multiple unit
DOT – Department of Transportation
EMU – Electric multiple unit
FE – Fuel economy
FW – Freeway
GC – Great circle
GHG – Greenhouse gas
GHGeq – Greenhouse gas equivalent
HEP – Head-end power
HSR – High speed rail
ICAO – International Civil Aviation Organisation
IPCC – Intergovernmental Panel on Climate Change
IR – Inherent resistance
LDT – Light duty truck
LDV – Light duty vehicle
LOS – Level of service (a highway capacity metric)
LTO – Landing and takeoff
MBTA – Massachusetts Bay Transportation Authority
MY – Model year
NBJ – Narrow body jet
NCDC – National Climate Data Center
NTD – National Transit Database

O	– Origin
OD	– Origin-destination
pGCkm	– passenger great circle kilometer
PL	– Payload
RDC	– Rail diesel car
RF	– Radiative forcing
RJ	– Regional jet
sGCkm	– seat great circle kilometer
skm	– seat kilometer
SRJ	– Small regional jet
TE	– Tractive effort
TP	– Turboprop
TSO	– Temporary slow order
UDDS	– Urban Dynamometer Driving Schedule
VHSR	– Very high speed rail
Vkm	– vehicle kilometer
WBJ	– Wide body jet
WGI	– Working Group I

B.3 Equation Variables

a	Coefficient
A	Acceleration
A	Frontal area
b	Coefficient
Cd	Aerodynamic drag coefficient
Cra	Coefficient of rolling resistance & hysteresis
Crai	Tractive effort envelope coefficient
Crb	Coefficient of dynamic resistance
Crbi	Tractive effort envelope coefficient
Crc	Coefficient of aerodynamic resistance
Crci	Tractive effort envelope coefficient
Crdi	Tractive effort envelope coefficient
dt	Time step
Fh	Hotel power diesel generator set fuel consumption rate
g	Gravitational acceleration
Gbe	Breakeven down grade
Gmx	Maximum grade that can be climbed at cruise speed
IR	Inherent Resistance
Kr	Mass-equivalent rotational inertia of an axle
M	Mass
Na	Number of axles
P	Power
R	Ratio of cold-start/hot start fuel increment
SF	Scale factor for aerodynamic drag
t	Time
T	Temperature
TE	Tractive effort
TEi	Tractive effort
Ta	Ambient temperature
V	Speed
ρ	Density of air