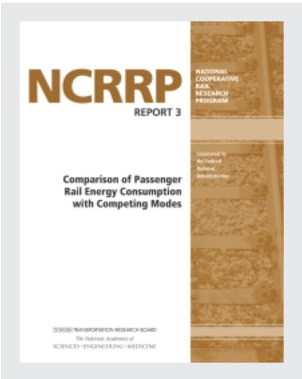

Comparison of Passenger Rail Energy Consumption with Competing Modes

DETAILS

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NATIONAL COOPERATIVE RAIL RESEARCH PROGRAM

NCRRP REPORT 3

Comparison of Passenger Rail Energy Consumption with Competing Modes

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NATIONAL COOPERATIVE RAIL RESEARCH PROGRAM

The National Cooperative Rail Research Program (NCRRP) conducts applied research on problems important to freight, intercity, and commuter rail operators. Research is necessary to solve common operating problems, adapt appropriate new technologies from other industries, and introduce innovations into the rail industry. NCRRP carries out applied research on problems that are shared by freight, intercity, and commuter rail operating agencies and are not being adequately addressed by existing federal research programs. NCRRP undertakes research and other technical activities in various rail subject areas, including design, construction, maintenance, operations, safety, security, finance and economics, policy, planning, human resources, and administration.

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C O O P E R A T I V E   R E S E A R C H   P R O G R A M S

FOREWORD

By Lawrence D. Goldstein
Staff Officer
Transportation Research Board

NCRRP Report 3: Comparison of Passenger Rail Energy Consumption with Competing Modes provides a comprehensive model that allows the user to compare the energy consumption and greenhouse gas (GHG) emissions of intercity and commuter passenger rail with those of competing travel modes along a designated travel corridor. This report summarizes the research used to develop the model and presents a set of case study applications. A Technical Document and User Guide for the Multi-Modal Passenger Simulation Model (MMPASSIM) and the spreadsheet tool for using and customizing the model are provided as a CD attached to this report. The Technical Document and User Guide also are available online as NCRRP Web Only Document 1.

Under NCRRP Project 02-01, the TranSys Research Ltd. team identified effective strategies for addressing the complex issues involved in comparing energy use and GHG emissions by mode. Lower fuel and energy consumption, as well as lower GHG emissions per passenger trip, are often cited as benefits of passenger rail in comparison with other travel modes. In the past, however, these benefits have not been well documented, nor have effective procedures for measuring them been delineated. Given these limitations, this study was designed to (1) provide a method for comparative measurement of energy consumption and GHG emissions for a given travel corridor and (2) create a model that could be customized by users based on door-to-door travel characteristics.

Building on their analysis, the research team developed MMPASSIM, a comprehensive and flexible model to simulate intercity travel modes (air, automobile, motor coach and rail) or commuter travel modes (automobile, commuter bus, and commuter rail) in detail. Access/egress legs of either intercity or commuter trips are incorporated into the model using typical average performance values, or user-provided alternative values, for energy and GHG emissions intensities of typical access/egress modes (i.e., subway, transit bus, taxi, personal-automobile, commuter rail and non-motorized cycling/walking).

The flexible nature of the model allows users to customize individual trips for detailed comparisons based on specific trip characteristics. For example, MMPASSIM users can specify combinations of access/egress modes and trip lengths. If the model will be used to assess average travel behavior rather than an individual trip, default values are provided based on proportional distribution by mode as a function of distances used for access. MMPASSIM also supports user assessments of the energy and GHG emissions intensities of various technological and operations alternatives for the rail mode. The analytical model can be applied by rail industry practitioners as well as government and other operating authorities to evaluate alternative regional transportation system development strategies to best meet future demands for passenger rail transportation.

CONTENTS

Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color versions.

SUMMARY

Comparison of Passenger Rail Energy Consumption with Competing Modes

The primary objective of NCRRP Project 02-01 was to provide like-for-like comparisons of energy consumption and greenhouse gas (GHG) emissions of commuter and intercity passenger rail operations and competing travel modes. To accomplish this main objective, additional objectives were to:

- develop an analytical framework for equivalent comparison of mode-to-mode energy consumption and GHG emissions of passenger trips;
- apply the framework to selected case studies to evaluate and compare energy and GHG emissions intensities of passenger rail operations and competing modes of transportation for comparable door-to-door trips; and
- explore opportunities to improve energy efficiency and reduce GHG emissions of intercity and commuter passenger rail while identifying barriers to adoption of these technologies within the passenger rail industry.

In the context of this research, passenger rail includes higher-speed, high-speed, intercity, and commuter rail—those systems that are operated under the jurisdiction of FRA. Competing modes of transport include passenger automobiles, light-duty trucks often used for personal transportation, suburban commuter bus services, intercity bus services and air transportation.

This research addresses energy consumed and GHG emissions related to the direct activity of the modal leg (propulsion, on-board auxiliary power and on-board amenities) and direct activity of the access and egress legs; energy consumed and GHG emissions produced in the generation of electricity for the modal, access or egress legs (where appropriate); and upstream energy and GHG emissions required for exploration, recovery, transportation and refinement of the fuels consumed by internal combustion and electricity generation.

Passenger Rail Efficiency Benchmarks and Previous Research

The most widely available measures of passenger rail energy efficiency are those based on the reported annual gross average purchased energy intensity of passenger transportation modes in the United States (Table S-1). This approach uses annual statistics, such as fuel or electric power consumed and transported passenger-miles, to estimate the energy efficiency and emissions of passenger rail systems per passenger-mile. However, passenger rail efficiency metrics may vary with the type of service (long-distance, regional intercity and commuter) and be influenced by other factors that will vary between different passenger rail operations. Thus, research is required to determine measures of passenger rail efficiency that are more appropriate for specific comparisons to competing travel modes.

Table S-1. Energy intensity of passenger travel modes in 2011 (U.S. DOT BTS, 2013).

Mode	Energy Intensity (Btu/passenger-mi)
Air	3,058
Light-duty Vehicle	4,689
Motorcycle	2,669
Transit Bus	3,343
Amtrak	1,628

Additional factors complicating the analysis of passenger rail energy efficiency and limiting the utility of gross average statistics include:

- use of electrified and diesel-electric operations, sometimes on the same train trip;
- seasonal and daily variations in ridership load factors;
- consideration of energy consumed by on-board passenger services and amenities or meal and lounge cars;
- increasing operating speed on emerging higher-speed rail corridors; and
- the inherent multi-modal nature of door-to-door passenger rail trips.

The most recent examination of passenger rail energy efficiency that parallels this research dates to the work of Mittal (1977), who determined the energy intensity of passenger rail using statistical and analytical methods and compared it to averages of competing modes. The comparison suggested that passenger rail had the potential to operate with an energy intensity per seat-mile lower than that for automobiles and aircraft. Based on the passenger rail load factors observed during the era, however, passenger rail could not attract enough riders to take advantage of its potential efficiency.

Mittal did not consider the energy and emissions of modes used to access passenger rail in door-to-door trips. Although this has been done by other researchers for specific routes, there has not been a broad modal comparison study of the energy efficiency of specific case study routes while considering trip purpose, temporal variation in factors and the access modes used in making a specific door-to-door trip.

Multi-Modal Passenger Simulation Tool

To move away from simple averages, the project team developed Multi-Modal Passenger Simulation (MMPASSIM), a Microsoft® Excel-based simulation tool that quantifies energy consumption and GHG emissions of passenger rail and competing passenger modes for door-to-door passenger trips. MMPASSIM has four primary applications:

- **single-train simulation,** used to determine the energy intensity and GHG emissions intensity of a passenger rail trip on the rail modal leg from departure to arrival station;
- **technology evaluation,** used to determine the sensitivity of rail modal leg energy intensity and GHG emissions intensity to changes in rail equipment, operating and infrastructure parameters;
- **single-train simulation with access modes,** used to determine the energy intensity and GHG emissions intensity of a complete door-to-door passenger rail trip from origin to destination, including access to the departure station and egress from the arrival station; and

- **modal comparison,** used to benchmark the energy intensity and GHG emissions intensity of a complete door-to-door passenger rail trip against light-duty vehicle (LDV), bus and air travel modes.

MMPASSIM requires information on passenger rail route infrastructure, rolling stock and operations. To perform modal comparisons, the simulation tool requires information on highway infrastructure, traffic congestion and selected highway vehicles and aircraft. MMPASSIM outputs the combined energy and GHG emissions of the main modal travel segments and access and egress modes (where applicable) per round trip, seat-mile and passenger-mile. Metrics can report direct activity and also can include upstream energy and GHG emissions. The model was validated by simulating two passenger rail routes with publicly available fuel consumption data.

Single-Train Simulation of Passenger Rail Energy Efficiency

To investigate the energy and GHG emissions intensities of the rail modal leg in isolation, five commuter rail systems, nine regional intercity systems, two long-distance intercity systems, and one high-speed rail (HSR) system were analyzed via MMPASSIM single-train simulation case studies. Although the potential energy intensity of the passenger rail services clustered around 500 Btu/seat-mile, the energy intensity per passenger-mile ranged from just under 1,000 Btu to just under 2,500 Btu, depending on the assumed load factor (Figure S-1).

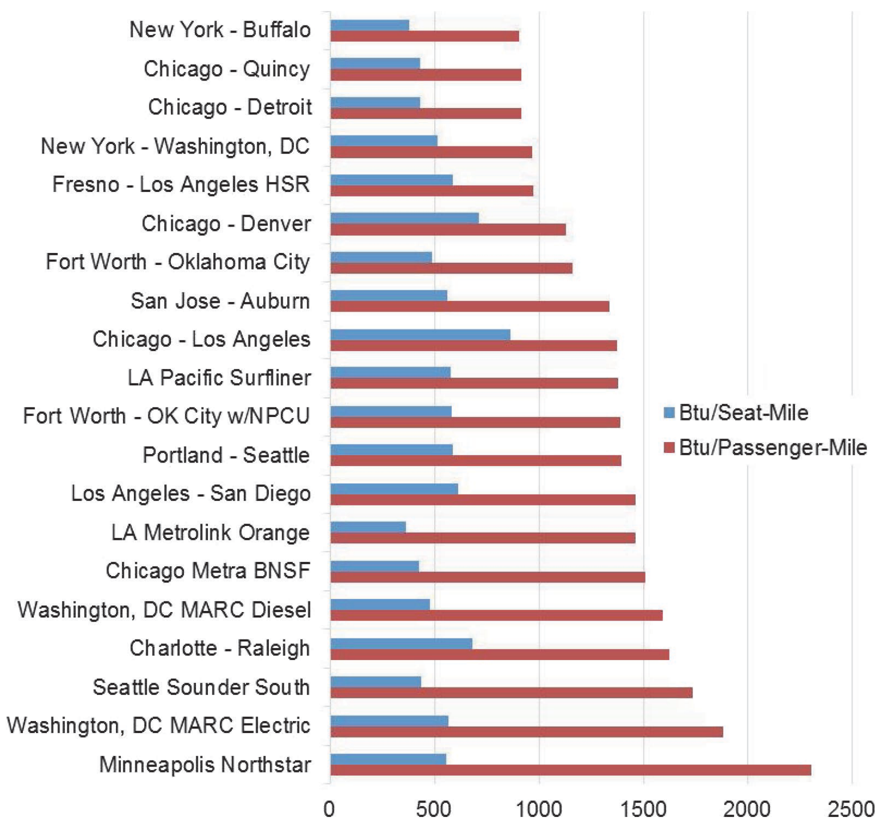

Figure S-1. Energy intensity of simulated passenger rail services—modal leg.

The commuter rail services, with the lowest average load factor, exhibited the highest energy intensity. A combination of high load factor, stop spacing and train length made several of the regional intercity passenger services the most efficient passenger rail operations.

The California HSR case study route ranks near the top for both energy and GHG emissions per passenger-mile. The simulated conditions (i.e., lightweight equipment, low aerodynamic drag, optimized alignment design, high load factor and relatively clean sources of electricity) combine to offset the increased energy demands of high-speed operation (near 200 mph).

Technologies to Improve Passenger Rail Energy Efficiency

MMPASSIM provides industry practitioners with the ability to assess the effectiveness of specific strategies or technologies in saving energy and reducing GHG emissions of specific passenger rail operations. These approaches can be broadly grouped into four categories:

- operational strategies,
- railcar design and utilization,
- motive power and fuels, and
- alternative energy sources.

MMPASSIM was used to run simulations based on additional case studies for selected combinations of energy-saving technologies and the passenger rail routes developed for the single-train analysis. Certain technologies are better suited to commuter rail operations that experience more frequent acceleration and braking events. A different set of technologies are required for intercity service, where trains travel at maximum track speed for extended periods.

NCRRP Project 02-01 was not intended to be a comprehensive investigation of the potential benefits of specific technologies and strategies across all passenger rail systems. However, in demonstrating MMPASSIM capabilities through simulation of energy-saving approaches on the case study routes, certain trends became evident:

- The operating strategy of optimal coasting potentially offers substantial efficiency improvement for diesel-powered commuter rail systems.
- Across all simulated passenger rail operations, improvements to the equipment (e.g., tare weight reduction, seating density increase and consist rearrangement) offer the greatest potential reductions in energy consumption and GHG emissions.
- When single-level railcars are replaced by a smaller number of bi-level railcars to maintain the number of seats per train, commuter rail energy efficiency can increase by more than 40%.
- Provided that ridership can maintain a constant load factor, increasing train length increases efficiency but degrades running-time performance. The need for additional locomotives to maintain running-time performance sets a lower bound on energy intensity as train length is increased.
- Electrification can reduce energy intensity and GHG emissions intensity, but it is dependent on the regional electricity generation profile and requires significant capital investment. Electrification with higher horsepower locomotives also can facilitate higher operating speeds and more rapid acceleration, which increase direct energy consumption and potentially offset GHG emissions gains.
- For an equivalent number of seats, an electric multiple unit (EMU) is more energy efficient than an electric locomotive-hauled train consist.

- Under ideal conditions, regenerative braking and on-board storage can reduce energy consumption by 8% to 14%, as shown for the simulated case study services.
- The simulated systems are largely insensitive to head-end "hotel" electric power configuration, aerodynamic improvements, and changes in unplanned stops and speed reductions. Therefore, any uncertainty in assumed MMPASSIM inputs for these parameters may not substantially alter provided performance metrics.

The conclusions presented are specific to the case study routes considered in this research project. Depending on their exact characteristics, simulations conducted for certain routes and operations may reveal more or less benefit from a particular approach to reducing the energy and GHG emissions intensities of passenger rail.

Barriers to Passenger Rail Energy Efficiency Innovation

To date, decisions about train types and operating patterns in the passenger rail industry have not been strongly influenced by energy use and efficiency concerns. Instead, many technology and operations decisions have been motivated primarily by safety concerns, the ability to use proven equipment designs, initial implementation costs and the need to work within existing operating and infrastructure constraints.

In NCRRP Project 02-01, industry practitioner outreach was conducted to address the following questions:

- What barriers to energy efficiency improvements exist in the passenger rail industry?
- How can the identified barriers be addressed?

The barriers to improving passenger rail energy efficiency that were identified through practitioner outreach fall into the following categories:

- cost of energy efficiency upgrades, constrained funding and uncertainty in future funding when many systems struggle to maintain a state of good repair;
- internal accounting structures that do not provide employees with incentives to improve efficiency;
- conservatism and the trade-off between customer service and efficiency;
- difficulty in avoiding backhaul or improving off-peak load factors;
- regulations specific to North America that limit access to the global market for passenger rolling stock; and
- outstanding technical issues that limit the feasibility of alternative fuels.

An overarching takeaway is that energy efficiency improvements compete with other, higher, priorities of passenger rail operations. Although improving energy efficiency is a priority, achieving a state of good repair and improving customer service is of higher concern. Even though improving customer service hopefully increases ridership (and thus load factors and energy efficiency per passenger), these efforts also can retard efficiency gains by adding equipment weight or increasing energy draw.

Actions that passenger rail operators can take to address barriers to energy efficiency include the following:

1. Implement improved asset management strategies and lifecycle maintenance techniques to reduce maintenance backlogs and ensure equipment runs at its highest possible efficiency.
2. Seek opportunities to leverage existing data, such as on-board locomotive reports, or to implement technologies to collect new data on an ongoing basis, such as trip fuel efficiency monitors.

3. Create a department and executive position responsible for coordinating investments in energy efficiency improvements to ensure that all of the possible company/agency-wide benefits and costs are considered during financial and economic evaluations.
4. Seek opportunities for energy efficiency improvements that not only reduce operational costs but also reduce impacts on the surrounding community.
5. Understand and respond to potential demographic trends, such as the growth of reverse commuting, by making service and pricing changes.
6. Identify alternative funding and financing mechanisms for energy efficiency improvements, such as those described in *NCRRP Report 1: Alternative Funding and Financing Mechanisms for Passenger and Freight Rail Projects*.

Modal Comparisons of Energy Consumption and GHG Emissions

MMPASSIM was used to model the energy consumption and GHG emissions of specific door-to-door trips using passenger rail and the competing travel modes available in each respective region. Four commuter rail systems, five regional intercity systems, one long-distance intercity service, and one HSR system were used in the case studies, and represented very specific round trips, each from a defined origin to a particular destination and return. Besides indexing the performance of other passenger modes to passenger rail, the case studies provided insight into how the following factors influenced the modal energy and GHG emissions comparison:

- congestion and peak/off-peak load factor;
- commuter versus regional intercity trainsets;
- electric versus diesel-electric operations;
- push-pull operation with a cab car compared to turning the trainset;
- snack cars and other passenger amenities;
- access and egress distance; and
- choice of access and egress mode.

Despite the differences in individual case study conditions, an overarching takeaway reinforces the strong influence of modal load factor on the relative energy and GHG emissions intensities of any of the modes under study. Driving alone is inefficient, and none of the other travel modes operates efficiently if the load factor is low. At the same time, the differences in the inherent efficiency of each mode are sufficiently large to prevent the mode with highest load factor from always being the most efficient. Although a full aircraft or automobile is more competitive with rail, many rail operating and ridership scenarios exist for which a below-capacity train will be more energy efficient than air or auto (Figure S-2).

The following general conclusions were reached for the majority of case studies relative to automobile trips:

- Auto mode with one occupant is three to four times more energy and GHG emissions intense than rail mode under average load factors (Figure S-3).
- An automobile with four passengers approaches the performance of regional intercity trains, but cannot match the energy and GHG emissions performance of commuter trains under average load factors.
- During peak periods—when the majority of commuting trips take place—roadways are congested and rail operates at higher load factors. At these times, the auto mode with one occupant is more than 10 times as energy and GHG emissions intense as commuter rail.

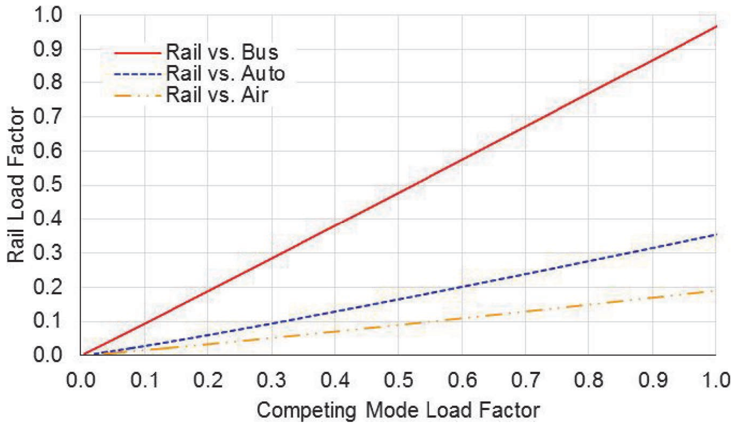

Figure S-2. Lines of equal energy intensity for competing modes between New York City and Buffalo, NY, showing sensitivity to modal load factors.

The commuter rail stations used in the case studies were spaced at close enough intervals that the length of auto access and egress trip legs had little effect on the comparison between rail mode and auto mode. This was true even when the commuter drove the "wrong" direction to access and egress commuter rail, effectively lengthening the rail trip and shortening the competing auto trip. On regional intercity rail routes with larger intervals between stations, access distance could have a greater influence on the modal comparison.

Choice of access and egress mode affected the overall energy efficiency of commuter rail trips more significantly than it did other rail trips. For one case study route, under an average load factor, switching from auto to bicycle access decreased round-trip energy consumption by 20%. Given the amount of energy consumed by the rail mode used during the main segment of the trip, choice of access and egress mode had less influence on the energy

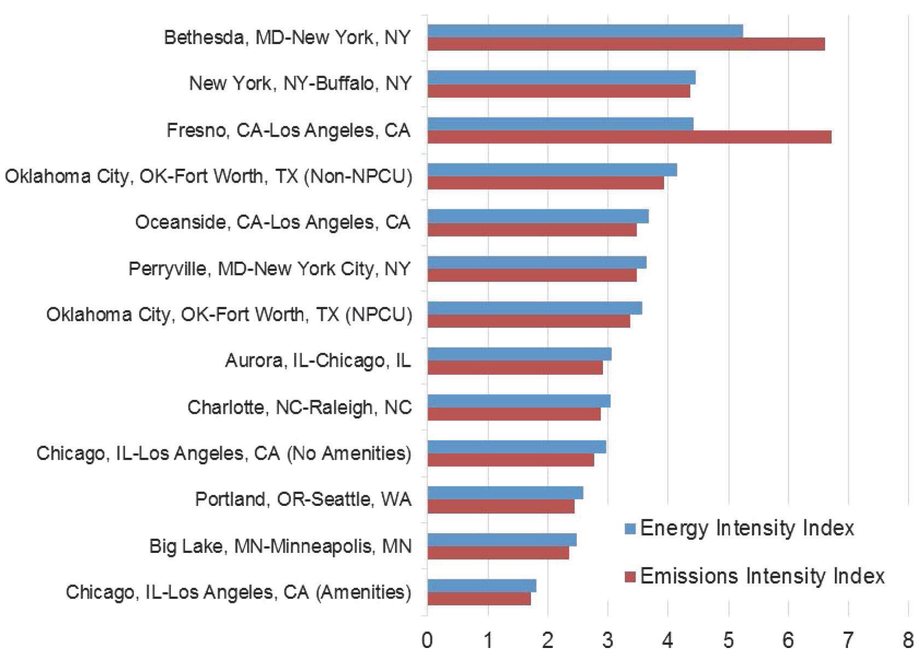

Figure S-3. Auto mode energy and GHG emissions intensities indexed to rail values.

efficiency of regional intercity rail. In either case, however, the difference in energy and GHG emissions is unlikely to change the relative modal comparison to auto and air.

For the regional and long-distance intercity case study routes relative to air trips:

- A compromise between trip time and energy consumption is apparent. Air alternatives reduce travel time by 25% to 90% relative to the equivalent rail trip, but increase energy intensity per passenger by as much as four times in some cases (Figure S-4).
- Air mode can be up to six to seven times more GHG emissions intense than electrified passenger rail services that use relatively clean electricity. This effect is particularly evident for the California HSR case study.

Electrification does not generally improve passenger rail energy efficiency when direct and upstream energy consumption is considered, unless the regional generation profile contains a substantial amount of renewable power generation. When combined with track upgrades, implementation of higher horsepower electric locomotives may facilitate more rapid acceleration and higher operating speeds that actually increase energy consumption.

The GHG emissions benefits of electrification are highly dependent on regional electricity generation profiles. On certain case study routes, auto emissions are up to seven times higher than emissions for passenger rail under average load factors. When driving alone, a traveler can produce an order of magnitude more GHG emissions than a passenger on a train operating at peak load factor.

The GHG emissions benefits of rail are particularly apparent in the case studies of urban areas where auto and bus modes experience extensive highway congestion, and idling in slow traffic increases their GHG emissions intensity. This factor is of particular importance because these same congested urban areas tend to have air quality concerns and are where

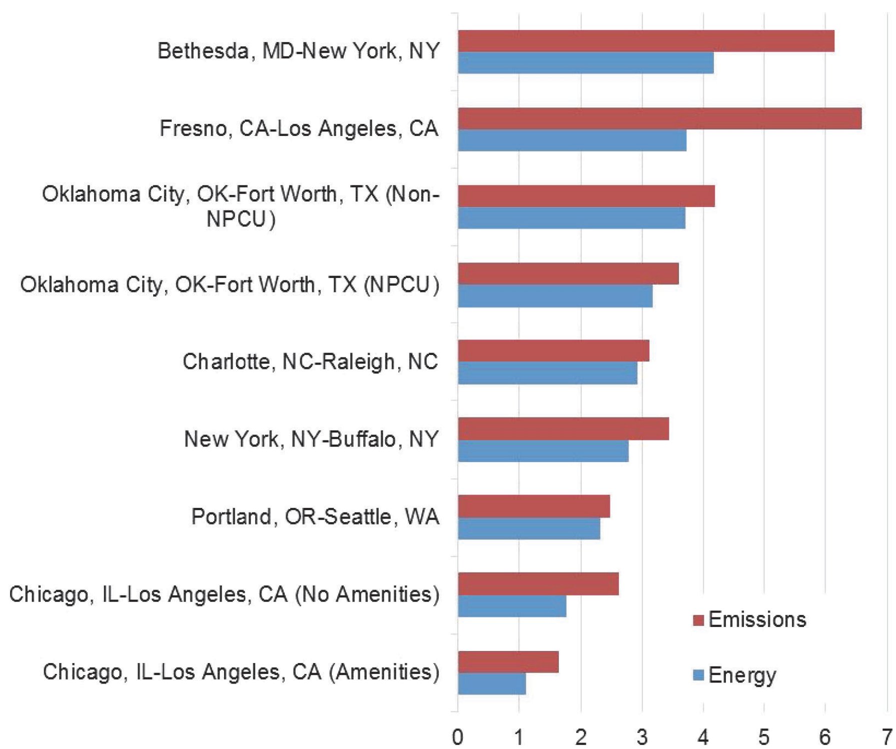

Figure S-4. Air mode energy and GHG emissions intensities indexed to rail values.

the environmental benefits of rail are used as one justification for investment in commuter and regional intercity passenger rail service (along with urban rail transit). Having said this, the researchers note that NCRRP Project 02-01 addressed energy and GHG emissions performance; criteria air contaminant (CAC) emissions that contribute to local air quality were not compared. The structure of MMPASSIM allows for an extension of the model to track local CAC emissions, but it is not presently coded in the model.

The modal comparison case studies in this project reinforced the influence of seating density and train consist weight on energy and GHG emissions intensities relative to auto and air:

- The performance of the Heartland Flyer regional intercity train increases relative to competing modes when the non-powered control unit (NPCU) is removed and additional miles of travel are added to turn the train.
- Despite its higher load factor, the Pacific Surfliner regional intercity train is only slightly more energy efficient than the Metrolink commuter train that travels between the same two stations. The greater seating density of the Metrolink commuter railcars makes the service more competitive with the other modes.
- The Southwest Chief long-distance intercity train demonstrates how on-board passenger services and amenities degrade energy and GHG emissions performance relative to competing modes to the point at which an air trip is competitive with rail with regard to energy intensity. Although rail performance can be improved by removing service cars (and replacing them with coach seats if ridership warrants), the on-board amenities (and the extra comfort offered by the lower seating density on longer distance trains, compared to commuter trains like the Metrolink) are required to sustain ridership and load factor.

The MMPASSIM case study simulations conducted in NCRRP Project 02-01 suggest that intercity bus tends to be the least energy and GHG emissions intense passenger travel mode, followed by rail. On some routes, bus and passenger rail offer nearly equal energy and GHG emissions performance when operating at the same load factor; on other routes, bus has clear advantages. The disparity in performance between the bus and rail modes occurs partly because of differences in ridership and load factor between the modes, but also because of differences in routing and train consists. The bus mode gains some of its advantage by having a higher seating density and by not providing on-board passenger amenities that are required for trips over longer distances; however, it incurs delays at more frequent and/or longer stops at wayside facilities for meals and “stretch” breaks. Buses also are subject to congestion in urban areas, which negatively affects the mode’s GHG emissions performance on case study routes in urban areas.

Although bus mode is more efficient than rail mode, rail’s greater comfort—and in some applications higher speeds—makes it more successful at attracting people away from using cars and planes. From a pragmatic perspective, bus and rail modes should be viewed as complementary components of an integrated network that can provide passenger transportation three to four times more efficiently, in terms of energy, than can auto or air. Industry practitioners are correct when they promote rail as a “green” alternative to driving or flying.

The research in NCRRP Project 02-01 illustrates the capabilities of MMPASSIM to simulate the energy consumption and GHG emissions of specific rail routes, as well as the equivalent auto, bus and air trips. This tool can be applied by rail industry, government and operating authority practitioners to analyze specific existing and planned passenger rail services. The resulting analyses will support decisions about regional transportation development, rail service expansion investment, system operating plans and energy consumption/GHG emissions reduction strategies that best meet future demands for passenger rail transportation and public mobility.

CHAPTER 1

Introduction

1.1 Objectives

The primary research objective of NCRRP Project 02-01 was to provide like-for-like comparisons of energy consumption and greenhouse gas (GHG) emissions of commuter and intercity passenger rail operations and competing travel modes.

To accomplish this main objective, additional objectives were to:

- develop an analytical framework for equivalent comparison of mode-to-mode energy consumption and GHG emissions of passenger trips;
- apply the framework to selected case studies to evaluate and compare the energy and GHG emissions intensities of passenger rail operations and competing modes of transportation for comparable door-to-door trips; and
- explore opportunities to improve energy efficiency and reduce GHG emissions of intercity and commuter passenger rail while identifying barriers to adoption of these technologies within the passenger rail industry.

1.2 Background

The most widely available measures of passenger rail energy efficiency are those calculated on an annual gross average basis. Annual statistics, such as fuel or electric power consumed and transported passengers, are used to estimate the energy efficiency and GHG emissions of passenger rail systems per passenger-mile. However, passenger train efficiency metrics may vary with the type of service (long-distance, regional intercity or commuter) and be influenced by other factors that vary among different passenger rail operations. Research is required to determine measures of passenger rail efficiency that are more appropriate for specific comparisons to competing travel modes.

More-robust metrics of freight transportation energy efficiency have been developed through research (Sierra Research 2004, ICF 2009, Tolliver et al. 2014), but developing a representative passenger metric is somewhat more complicated than developing the freight metric, for several reasons:

- **Passenger rail operations make extensive use of electrified operations.** Unlike rail freight transportation, for which diesel prime movers in diesel-electric locomotives provide the propulsive energy for virtually all freight ton-miles, many passenger rail trips rely solely on electric propulsion, and some passenger rail trips use both diesel propulsion and electric propulsion on different segments of the same trip. These electrified operations confound simple aggregate measures of passenger-miles per gallon of fuel consumed.

- **Seasonal and daily variations in the ridership load factor can greatly affect the efficiency of a passenger rail operation.** As for-profit enterprises, freight operations have a strong incentive to conduct their operations in the most efficient manner, with railcars that are optimized to minimize tare weight for a given gross railcar load. While still being fiscally responsible, passenger operations—particularly in the realm of commuter rail—serve the greater purpose of increasing public mobility. Thus, passenger rail operations must balance operating plans that maximize passenger loads with plans that offer more comprehensive service at the expense of more train-miles at a given level of passenger traffic.
- **Energy consumed to provide light, heat, ventilation and air conditioning to trailing passenger cars increases fuel consumption and GHG emissions beyond the levels required simply for train movement.** As an extension of this issue, long-distance and regional intercity train consists include meal-service cars and lounge cars that are needed to provide passengers with appropriate amenities but increase train weight, resistance, energy consumption and GHG emissions without adding seats for additional passenger-miles.
- **Future operating conditions may also affect passenger rail efficiency.** As incremental higher-speed rail projects are completed and train speeds increase to 90 and 110 miles per hour (mph), the efficiency of passenger trains in these corridors will be affected as additional energy is required to overcome aerodynamic drag. Research has shown that on shared corridors, as the speed differential between passenger and freight traffic increases, both passenger train delay and run time variability also increase on both single-track and double-track lines (Sogin et al. 2011, Sogin et al. 2013). Increased delay and variability in run time can result in extended schedules to maintain reliability, which comes at the expense of increased idle time and less-efficient operations.
- **Passenger rail trips are inherently multi-modal.** Although many freight shippers have direct access to rail, virtually all passengers must use some other form of transportation to access a departure station or egress from the arrival station at the end of the rail trip (Figure 1-1). With the exception of auto, this is also true for competing travel modes. Consideration of multiple transportation modes with different load factors (and hence individual modal leg efficiencies) complicates calculations of door-to-door energy and GHG emissions of passenger rail trips.

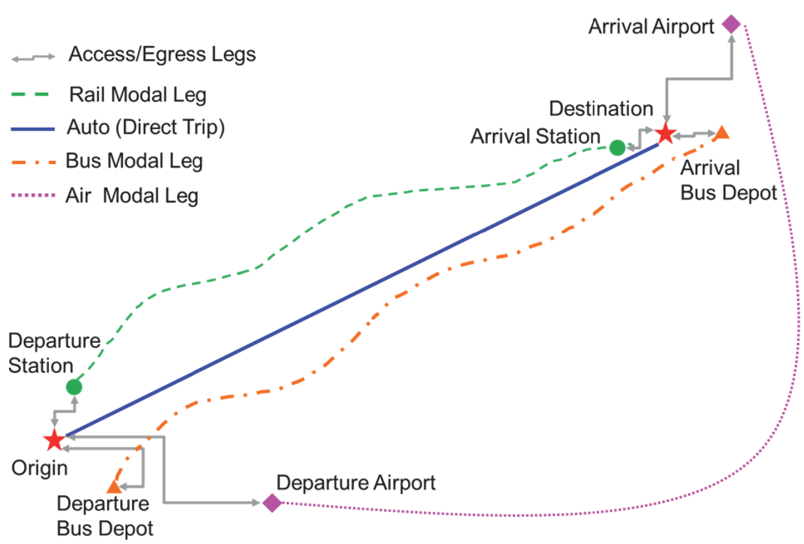

Figure 1-1. Modal and access/egress legs for door-to-door trips.

1.3 Scope

This research focuses on the energy and emission intensity of passenger rail service and equipment types found in North America. The efficiency and emissions of passenger rail in Europe and Asia are introduced only to provide global benchmarks for North American systems.

In the context of this research, the term *passenger rail* includes commuter rail, regional intercity passenger rail and long-distance intercity passenger rail operating at conventional speed, higher-speed and high-speed—in other words, those systems that are operated under the jurisdiction of FRA. Light rail, heavy rail, subway and other forms of rail transit and rapid transit, including monorail and people-movers, are not considered as primary modes of passenger travel within this research. Transit systems are considered only in relation to their use to access or egress from passenger rail stations, bus depots or airports as part of door-to-door trips.

Competing modes of passenger transport include passenger automobiles, light-duty trucks often used for personal transportation, suburban commuter bus services, intercity bus services, and air transportation.

Energy and GHG emissions include the energy use and GHG emissions associated with direct activity of the modal leg (propulsion, on-board auxiliary power and on-board amenities); those associated with direct activity of the access and egress legs; energy consumed and GHG emissions produced in the generation of electricity for the modal, access or egress legs if appropriate; and upstream energy and GHG emissions required for exploration, recovery, transportation and refinement of the fuels consumed by internal combustion and electricity generation. In the context of this research, these values do not include energy and GHG emissions associated with station/airport services, infrastructure construction or vehicle manufacturing and disposal. Moreover, GHG emissions consider GHGs expressed in carbon dioxide equivalent (CO_2e). Where the study team has used the term *GHG emissions* in *NCRRP Report 3*, CO_2e emissions are implied, and vice versa. Criteria air contaminant (CAC) emissions are not included in this research because their impacts are local and tied to specific routes and populations.

The comparative performance measures generated through this research focus on the rail-competitive leg of the trip; however, access legs/modes are included for bus, rail and air to get a true door-to-door, full-trip comparison. The performance of unique access modes is included, but it is not modeled at the same level of detail as those modes used for the principal modal leg of the trip.

The Multi-Modal Passenger Simulation (MMPASSIM) spreadsheet tool developed as part of this research assignment allows users to specify parameters that are associated with any infrastructure and/or equipment for which they have appropriate characterization data. The case study applications of the simulation model described in *NCRRP Report 3* are based on publicly available characterization data and/or engineering judgment in deriving estimates. Although the model was validated within the various limitations of available data for each mode, no proprietary or confidential data were provided to the research team. The case studies should therefore be treated as illustrative examples of the types of analyses that can be made with a validated model rather than as individually validated case studies.

MMPASSIM's equations are in metric units; however, the user can specify that the output tables display either U.S. or metric units. U.S. units appear in this report because all the case studies are U.S. based, and readers most interested in those case studies will likely be more familiar with U.S. units. Readers interested in the metric outputs can load the case studies and run the simulations with metric outputs displayed.

1.4 Structure

NCRRP Project 02-01 generated three separate deliverables:

- *NCRRP Report 3* (this report), which provides a general literature review, illustrative case study applications of the MMPASSIM tool in rail technology and modal comparison assessments, and a discussion of barriers to energy efficiency innovation in the U.S. passenger rail industry;
- *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* (*NCRRP WOD 1*); and
- the open-source MMPASSIM spreadsheet tool, coded in Microsoft® Excel.

The Technical Document included in *NCRRP WOD 1* describes the layout and equations used in the MMPASSIM tool to simulate the energy and GHG emissions intensities of passenger rail and competing modes. An appendix in *NCRRP WOD 1* presents the complete User Guide for the MMPASSIM. The files for the MMPASSIM spreadsheet tool, together with copies of the Technical Document and User Guide, are provided on *CRP-CD 176: The Multi-Modal Passenger Simulation Model—A Spreadsheet Tool for Comparing Passenger Rail Energy Consumption with Competing Modes*, which is bound into *NCRRP Report 3.* The spreadsheet tool also can be downloaded from the report's web page at www.trb.org (search for "NCRRP Report 3").

The balance of *NCRRP Report 3* is organized into seven chapters plus appendices, as follows:

- Chapter 2 defines efficiency metrics and summarizes both previous research and published benchmarks of passenger rail energy efficiency;
- Chapter 3 describes MMPASSIM as it was developed in the course of this research to simulate the energy and GHG emissions intensities of passenger rail and competing modes;
- Chapter 4 applies MMPASSIM to case studies of specific train services on actual routes to determine the direct energy and GHG emissions intensities of the passenger rail modal leg;
- Chapter 5 introduces technologies and approaches to reduce passenger rail energy consumption and GHG emissions, and quantifies their effects through MMPASSIM analysis of specific case studies;
- Chapter 6 presents the results of industry practitioner outreach to identify barriers to energy efficiency innovation in the passenger rail industry;
- Chapter 7 applies MMPASSIM to case studies of specific train services on actual routes and compares the rail energy use and GHG emissions to those of competing modes for equivalent door-to-door trips;
- Chapter 8 summarizes the conclusions of this research; and
- Appendices A through G provide supporting data and additional details on case study development via MMPASSIM.

CHAPTER 2

Passenger Rail Energy Efficiency Research and Benchmarks

In the early 1970s, the peak of U.S. petroleum production and the ensuing "oil crisis" led to increased study of the energy efficiency of all transportation modes, including passenger rail. Even during this tumultuous period for the railroad industry, with several carriers in bankruptcy and the formation of Conrail and Amtrak, the rail mode was viewed as crucial to meeting future demand for energy-efficient transportation. Along this theme, in 1974 the U.S. DOT organized a conference on "The Role of the U.S. Railroads in Meeting the Nation's Energy Requirements" (U. Wisc. 1974). The conference highlighted the opportunity presented by the energy efficiency of the rail mode. Research from this era concerned itself mainly with fuel economy and overall energy demand. Several new lightweight passenger trainsets were developed and tested during this period, and the Association of American Railroads began extensive research into the energy efficiency of trains. The resulting Train Energy Model, although developed primarily for freight applications, also allowed for the most detailed simulations of passenger trains to date.

As scientists have reached consensus on the relationship between human activities and global warming, more recent research has focused on the potential for reducing greenhouse gas (GHG) emissions from the transportation sector through passenger rail. This research has examined technologies and alternative energy sources with the potential to directly reduce GHG emissions and improve energy efficiency. Recent research also has examined the role of passenger rail in reducing highway congestion, leading to improved efficiencies among all passenger-related surface transportation modes.

This chapter summarizes past research into passenger rail energy efficiency. The chapter starts with a discussion of different efficiency metrics and commonly cited averages for various modes. This discussion is followed by summaries of more detailed studies of the efficiency of passenger rail, either alone or relative to competing modes. Finally, the chapter provides a summary of international benchmarks of conventional and high-speed passenger rail efficiency.

2.1 Passenger Transportation Energy Efficiency

2.1.1 Units of Measurement

Several metrics are used to describe the efficiency of passenger transportation. Transportation productivity can be defined in terms of *passenger-miles, seat-miles, train-miles* or *vehicle-miles.* Accordingly, where diesel-electric propulsion is used, the efficiency of passenger rail systems can be described using *passenger-miles per gallon, seat-miles per gallon, train-miles per gallon*, and *vehicle-miles per gallon.*

Passenger-miles per gallon—a metric used to describe the energy efficiency of individual passenger trips—is calculated in relation to *system ridership* and *load factor* (the percentage of seats occupied with passengers). Because the value of passenger-miles dominates calculations for this metric, differences in ridership can disguise variations in the inherent base efficiency of different transportation systems.

Seat-miles per gallon measures the potential per-trip efficiency of a passenger transportation system. This metric is independent of ridership but is heavily influenced by the number of seats per vehicle (or railcar), however, and changes in seating configuration can overshadow the base efficiency of the system.

Train-miles per gallon measures the overall energy efficiency of the entire train. This metric is independent of both ridership and the number of seats per railcar. It is directly correlated with the weight (and hence the length) of the train, however, with the result that longer, heavier trains appear to be less efficient as measured by this metric.

Vehicle-miles per gallon describes the efficiency of each railcar (vehicle) in a train consist and is independent of both ridership and the number of seats. Although this metric is partially influenced by train length, with longer trains gaining efficiencies of scale and improved aerodynamics, vehicle-miles per gallon measures the inherent efficiency of the combination of rolling stock, infrastructure and operations present on a particular system. Which of these four metrics will be most appropriate for measuring and comparing energy efficiency across modes depends on the exact comparisons being made. For example, when comparing door-to-door trips on competing modes over specific routes, passenger-miles per gallon may provide the best comparison for a given ridership. When examining the potential of new technologies to improve efficiency, vehicle-miles per gallon may best describe the direct improvements to the inherent efficiency of the system.

Per gallon metrics are familiar to the public given their association with automobiles and other light-duty passenger vehicles, but not all passenger travel modes obtain propulsion energy from internal combustion of gasoline and diesel fuel. For electric propulsion, similar metrics can be developed on a per kilowatt-hour (per kWh) basis. Equivalent metrics also can be developed per unit of natural gas or hydrogen fuel. When measured per kWh or per unit-mass or volume of fuel, however, the efficiency of systems that use different sources of energy can be difficult to compare. To facilitate these comparisons, efficiency can be expressed in terms of the unit of energy, such as per British thermal unit (Btu) or per kilojoule (kJ).

The reciprocal of energy efficiency is *energy intensity*. Energy intensity quantifies the amount of energy required to provide one unit of transportation productivity. For passenger rail, energy intensity is usually described in Btu per passenger-mile (Btu/passenger-mi) or kJ per passenger-kilometer (kJ/passenger-km)—or their per seat equivalents—to provide reasonable working values without excessive use of decimals.

A Note about Abbreviations

NCRRP Report 3, NCRRP WOD 1 and the MMPASSIM spreadsheet tool use terms that, for convenience, may be variously abbreviated in text, tables, or figures, as follows:

Term	Abbreviations
passenger-mile	passenger-mi; pass-mi; pmi
passenger-kilometer	passenger-km; pass-km; pkm
seat-mile	seat-mi; smi
seat-kilometer	seat-km; skm
train-mile	train-mi; tmi
train-kilometer	train-km; tkm

2.1.2 Average Passenger Transportation Energy Intensity

The most widely available measures of passenger rail energy efficiency are those calculated on an annual gross average basis. This approach uses annual statistics, such as fuel or electric power consumed and transported passenger-miles, to estimate the energy efficiency and GHG emissions of passenger rail systems per passenger-mile. This method yields an effective high-level measure of passenger rail energy efficiency; however, annual gross average efficiencies should not be used to describe individual train runs and passenger trips. Each system, route, train run and passenger trip has unique characteristics that can cause the efficiency of that journey to significantly deviate from the annual average. To describe the performance of specific individual trips, the energy consumption and GHG emissions of each passenger mode on a specific route must be measured in the field or modeled via simulation. The latter approach has been taken for this project.

The U.S. DOT Bureau of Transportation Statistics (BTS) reports the annual gross average purchased energy intensity of passenger transportation modes in the United States via the National Transportation Statistics database (see Table 2-1). Based on the information in the table, in 2011, on an annual gross average basis, passenger rail service operated by Amtrak was the least intense (most efficient) mode of passenger transportation. On average, light-duty vehicles (LDVs), such as automobiles and small trucks consumed nearly three times the energy of Amtrak trains per passenger-mile. (The most appropriate comparison to Amtrak service would be intercity buses; however, a measure of intercity bus energy use per passenger-mile isn't available in the United States, as the BTS does not consider national passenger-mile statistics reliable.)

A complicating factor is that the energy intensity figure for Amtrak includes both diesel-electric and electric motive power, whereas the competing modes are all powered by liquid fossil fuels. The presence of these two different sources of purchased energy—and the differing efficiency of their conversion to motion—clouds direct comparisons of purchased energy such as that made in Table 2-1.

When viewed in isolation, electric locomotives can appear to be more efficient than diesel-electric locomotives. The energy consumed by an electric locomotive is readily measurable at the substation power meter or pantograph of the locomotive. Information about the fuel consumed in generating the electricity used by the locomotive is not readily available, however, and generation fuel types vary by region. Thus, two commuter systems with identical ridership, equipment and operating characteristics also can have widely varying efficiency/emissions based solely on the source fuels used in electricity generation (e.g., coal in one region as opposed to renewable energy sources in a different region).

Just considering the electric locomotive's transmission efficiency, the work performed at the wheels is approximately 76–85% of that provided at the engine's output shaft or pantograph (Lukaszewicz 2001).

Table 2-1. Energy intensity of passenger travel modes in 2011 (U.S. DOT BTS 2013).

Mode	Energy Intensity (Btu/pass-mi)
Air	3,058
Light-duty Vehicle	4,689
Motorcycle	2,669
Transit Bus	3,343
Amtrak	1,628

Diesel-electric locomotive efficiency also can be readily measured in terms of the fuel consumed by the locomotive. For a diesel-electric locomotive, this measure includes both the drivetrain efficiency, which is common with the electric locomotive, and the combustion efficiency of the engine, which is not usually reported for the electric locomotive. The combined efficiency for a diesel locomotive is approximately 28–30% (Hoffrichter 2012).

MMPASSIM overcomes the intrinsic difference in the efficiency of electric and diesel-electric locomotives by incorporating the energy input for fuels used to generate electricity for the region being simulated. Thus, while the Btu or kJ of energy reported by MMPASSIM for simulated diesel-electric or straight electric propulsion systems considers the fuel consumed in each case, the Btu or kJ reported for electrified systems will be higher than that reported by most reference literature or by any agency that measures the energy at the substation meter or on board the electric locomotive.

As illustrated by the flow of energy through diesel-electric and electric locomotives (Figure 2-1), a tank or "meter-to-wheels" comparison ignores potentially significant losses associated with the generation and transmission of electricity from a remote generating site to the electric locomotive. The conversion of diesel fuel to energy for traction takes place on board the diesel-electric locomotive, so any losses that occur in conjunction with the conversion are incorporated into efficiency measurements. By contrast, losses associated with the generation and transmission of purchased electricity from a remote station to an electric locomotive occur before the electricity arrives at the train, so they generally are not reflected in measures of efficiency for the train. Measures of efficiency that are based on comparisons of the energy content of the purchased fuel to purchased kWh of electricity are thus skewed in favor of the electric train.

In addition to differing energy conversion efficiencies, the energy and GHG emissions associated with transporting different fuels to the energy conversion site will vary by fuel type and by mode. These "upstream" energy/emissions differences are included in MMPASSIM via the

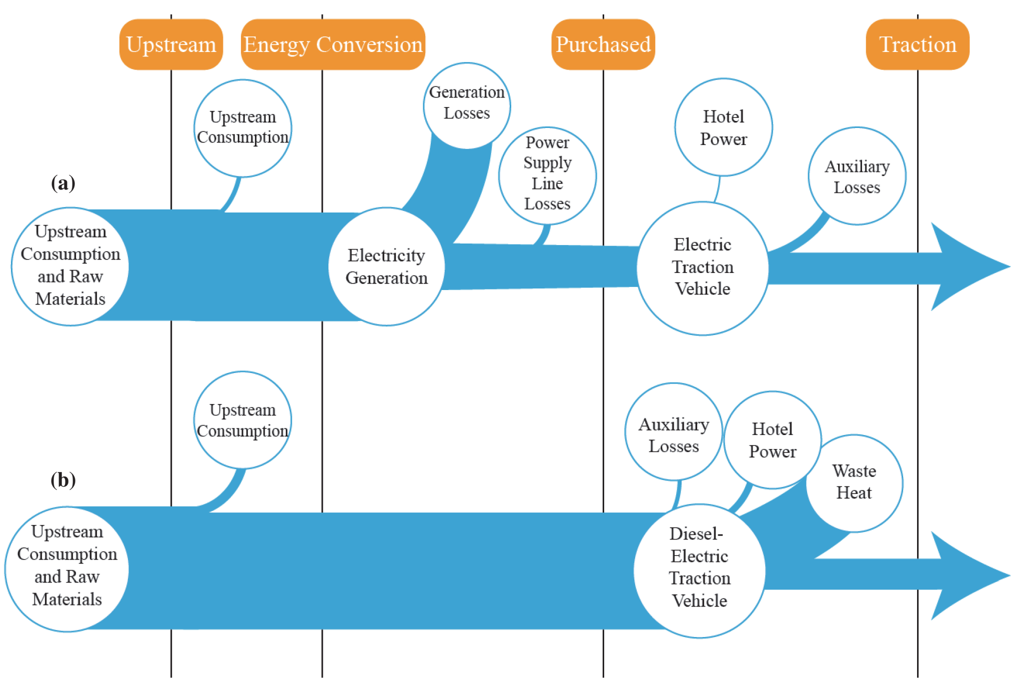

Figure 2-1. Energy flow of (a) electric and (b) diesel-electric locomotives.

relationships shown in Argonne National Laboratory's GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model (Argonne National Laboratory 2012) with continental U.S. regional electricity generation fuel supply updated to the 2011 data from the U.S. Energy Information Administration.

A complete well-to-wheels analysis on a per Btu basis does account for electric power generation losses and differences in energy associated with fuel supply to provide a more accurate comparison between electric traction and internal combustion engines running on fossil fuels. Although electricity is provided by an interconnected grid of generation plants located in different states, the specific mix of generation sites supplying electric power to a commuter rail operator might differ from the regional groupings provided in the model. Thus, differences in supply may occur that are different from those represented by the regions included in the model.

For specific cases in which a user agrees to pay more for electricity from a new renewable energy site as a basis for getting GHG credits, the model includes a "wind-only" generation source that can be selected in place of the actual grid supply for the region from which the train would receive electricity. Solar and any other isolated electricity supply sources are not modeled, but as an open-source model, the user can add input data coefficients as desired.

Although a well-to-wheels analysis accounts for geographic variation in electricity generation, it does not account for temporal variation within a region as different generating plants come on and offline during the course of a day. Because MMPASSIM is an open-source model, users can provide alternative regional supply characteristics and/or update the existing 2011-based supply grid.

As outlined in the scope of work for NCRRP Project 02-01, this research does not consider lifecycle energy consumption and emissions from vehicle manufacture and disposal or infrastructure raw materials and construction (as may apply to different technologies or modes).

2.2 Previous Studies of Passenger Rail Energy Efficiency

Many previous studies have quantified the energy intensity of passenger rail transportation based on analytical models, simulation and field data collection. To varying degrees, several of these studies have made direct comparisons between travel modes for specific routes. These studies also have taken differing approaches to considering ridership, access modes, time of day, trip purpose and upstream energy and emissions. The balance of this section provides summaries of several noteworthy studies, presented in chronological order.

2.2.1 FRA Study of Rail Fuel Consumption (Hopkins 1975)

In May 1975, J. B. Hopkins of U.S. DOT completed a FRA study titled Railroads and the Environment—Estimation of Fuel Consumption in Rail Transportation. The first volume of the Hopkins study presented analytical models of fuel consumption for branchline freight service, line-haul freight service and passenger service. The freight analysis presented comparisons to highway mode, but passenger rail service was not compared in this manner.

Hopkins developed a simple model of passenger rail fuel efficiency based on typical train resistance coefficients and locomotive fuel consumption for conventional passenger equipment of the era. Derived from first principles of power, tractive effort and train resistance, the model assumed a locomotive fuel consumption rate of 20.9 horsepower-hours per gallon to calculate efficiency in terms of seat-miles per gallon. The fuel efficiency calculation can be expressed as:

$$S_{mpg} = 8.16 \times \frac{10^7}{(vW_s)},$$

where

S_{mpg} = passenger train fuel efficiency in seat-miles per gallon,
v = train speed in mph, and
W_s = train weight per seat in pounds.

The simplified assumption of train resistance in pounds per ton embedded in this equation is assumed valid for speeds of 40 to 80 mph.

The form of the equation indicates that fuel efficiency decreases as train weight per seat increases and also decreases as speed increases. The derived relationship reinforces the need for lightweight equipment to maintain efficiency as speed increases. Hopkins illustrated that, at 60 mph, conventional equipment operates at approximately 180 seat-miles per gallon while the more modern, lightweight equipment then being developed for high-speed rail (HSR) would operate at approximately 550 seat-miles per gallon.

Hopkins did not consider ridership or load factor to calculate the actual energy intensity of a passenger trip; however, Hopkins indicated that, because the weight of the passenger load is only 5% to 10% of train weight, the seat-miles per gallon metric is essentially independent of passenger load and can provide a better standard of measurement of the efficiency of the passenger train than passenger-miles per gallon.

Hopkins acknowledged that, besides the two factors included in the equation, passenger train efficiency will vary with grade, train length, stop spacing and idle time. The report presented specific examples of the influence of each factor for trains with a given speed and weight per seat. Although the effect is small, increasing train length improves efficiency as the fixed drag and resistance of the locomotives is distributed over more railcars and seats in the longer train. Station stops and idling can greatly influence efficiency in practice; as much as 15% of passenger train fuel consumption occurs during idling time at stops.

To reflect the HSR systems in service or being planned at the time of the study, Hopkins extended his model to trains designed to operate at speeds between 90 and 160 mph. This was accomplished by assuming that, at the design cruising speed for each train, the aerodynamic and rolling resistance of the train on a 0.5% grade exactly balances the tractive effort generated by the full rated horsepower of the trainset. The required horsepower-hours for the train to travel 1 mile are converted to gallons of fuel and then used to estimate seat-miles per gallon. Because the model is based on rated horsepower, the same approach is applied to diesel-electric, turbine and electric trainsets (Table 2-2). In the case of electric trains, this represents the equivalent amount of diesel fuel required to produce the required horsepower in a locomotive diesel prime mover.

The values in Table 2-2 are for service on level grades and do not include stops or idling. Some designs were still in development in 1975, so the values presented in the table may differ from the final in-service condition. For example, the TGV prototype listed was powered by gas turbines at the time of the study, before later redevelopment as an electric train. An interesting comparison is between the U.S. TurboTrain and the longer Turbo version operated in Canada by Canadian National (CN). The CN train, with its greater seating capacity (326 seats versus 144 seats) and lower operating speed (95 mph versus 120 mph) is over twice as efficient in terms of seat-miles per gallon.

Table 2-2. Estimated fuel efficiency of high-speed trains (Hopkins 1975).

Train (nation)	Motive Power	Cruise Speed (mph)	Rated Power (hp)	Seats	Weight (tons)	HP/Seat	Estimated Seat-mi/ Gal.
Metroliner (U.S.)	Electric	110	5,900	246	360	23.9	65–95
TurboTrain (U.S.)	Turbine	120	2,000	144	128	13.9	70–100
Turbo (Canada)	Turbine	95	1,600	326	199	4.9	160–230
LRC (Canada)	Diesel	118	5,800	288	452	20.1	115–170
Tokaido Shinkansen (Japan)	Electric	130	11,900	987	820	11.4	180–270
HST (UK)	Diesel	125	4,500	372	600	12.1	220–330
TGV001 (France)	Turbine*	185	5,000	146	223	34.5	45–65
ER200 (U.S.S.R.)	Electric	125	13,800	872	1,010	15.8	120–180

* The first TGV prototype used gas turbines before rising petroleum costs led to development of an all-electric design in 1974.

2.2.2 U.S. DOT Study of Passenger Rail Energy Intensity (Mittal 1977)

Completed in December 1977, a study with a scope similar to that of the 1975 FRA study by Hopkins was conducted by R. K. Mittal for the U.S. DOT and FRA. This study, titled Energy Intensity of Intercity Passenger Rail, examines the contemporary and future energy intensity of intercity passenger rail systems; the impact of new technologies and operating characteristics on the energy intensity; and the energy intensity of competing intercity travel modes.

Mittal determined the energy intensity of passenger rail using statistical and analytical methods. The statistical approach used gross figures for annual fuel consumption and annual passenger-miles to calculate average Btu per passenger-mile for different train services. The analytical approach used known physical and engineering relationships of train performance to derive the energy intensity of particular trips via simulation. Fuel consumption rates of particular locomotives were used to calculate the energy consumption of the train service. The number of passengers on the train (expressed as the number of seats multiplied by the load factor) was used to determine the energy intensity per passenger-mile.

To compare electric and diesel-electric trains, Mittal calculated energy in Btu based on the consumed diesel fuel and the electricity input to the traction motors. The electricity input to the traction motors was based on an electric locomotive efficiency of 85%. Mittal provided some examples for which the energy intensity of the electric locomotives was derived from the energy consumed by the electrical generating station, based on an assumed generation efficiency of 35% and a transmission efficiency of 95%. Although this raised the energy intensity of the electric locomotives by a factor of three, the lower traction input values were used more extensively in the report.

Mittal used analytical methods to calculate the energy intensity of different train consists at constant speed on level track. The values of various parameters were then changed to determine the sensitivity of energy intensity to factors such as train speed, passenger load factor, and train consist. Mittal then simulated the operations of trains over actual routes to determine the energy intensity of diesel-electric passenger trains between Albany, NY, and New York City, and of electric passenger trains between New York City and Washington, DC.

Common diesel-electric locomotives of the time were included in the analysis: the General Motors Electro-Motive Division (EMD) E-8, SDP40F and F40PH, the General Electric (GE) P30CH and the Bombardier LRC. Mittal also considered the Ateliers de Construction du Nord de la France's (ANF) Turboliner, powered by a gas turbine; the Metroliner, with its electrified multiple-unit trainset; and three different electric locomotives: the GE E60CP, the Alstom CC14500 from France and the Swedish RC4a (later adapted to the AEM7 used by Amtrak). Although several of these locomotive types have been retired from service, several are still operated in commuter and intercity passenger service today.

The railcars considered in the study included refurbished 1950s-era passenger cars, newer single-level Amfleet coaches, and the lightweight coaches of the LRC and Turboliner trainsets. With the exception of the Turboliner, all of the railcars can still be found in service. Mittal also considered the presence of lounge, snack and meal-service cars in train consists in calculating energy intensity per seat and passenger-mile.

The Mittal study offers many interesting conclusions. For a given load factor, passenger trains are found to reach their peak efficiency (lowest energy intensity) at cruising speeds in the range of 20 to 30 mph. These cruising speeds are lower than those at which light-duty passenger vehicles reach peak efficiency(50 to 60 mph). To provide intercity service times competitive with automobiles, passenger trains must operate outside their most efficient speed range.

Mittal confirms the finding of Hopkins that the efficiency of passenger trains can be improved by increasing the number of passenger coaches in the train consist. This is found to be particularly important for trains of conventional passenger cars hauled by heavier diesel-electric locomotives and less important for lightweight equipment such as the LRC. Lounge and snack cars are found to negatively impact passenger train efficiency, but Mittal suggests such passenger amenities are required to satisfy passenger demand and maintain an adequate load factor. At low load factors, passenger rail becomes very inefficient.

Mittal verifies the assumption made by Hopkins that the weight of the passengers has little impact on passenger train fuel consumption. Energy intensity per train-mile or vehicle-mile is nearly the same under full-load and partial-load factors.

Mittal makes an interesting comparison between the analytical passenger train energy intensity at a constant cruising speed of 65 mph and the energy intensity derived from simulating actual train operations on route grade profiles with speed restrictions and station stops. The real operating environment greatly increases the energy intensity of the passenger trains per seat-mile compared to steady cruising at 65 mph (Table 2-3). For the diesel-electric train consists,

Table 2-3. Energy intensity of constant-speed cruising and actual service operating cycle (Mittal 1977).

Propulsion	Motive Power	Cruising Energy Intensity (Btu/seat-mi)	Cruising Speed (mph)	Operating[b] Energy Intensity (Btu/seat-mi)	Average Operating Speed (mph)
Diesel-Electric	E-8	443	65	820	49.3
	P30CH	378	65	582	50.5
	SDP-40F	412	65	555	50.5
	LRC	289	65	528	50.4
Gas Turbine	Turboliner	881	65	1,956	50.3
Electric[a]	CC14500	365	65	963	68.3
	Metroliner	310	65	1,019	78.4

[a]Electric energy intensity is based on input to traction motors and not on energy consumed at the power plant.

[b]New York City–Albany, NY, for diesel-electric and gas turbine trains; New York City–Washington, DC, for electric trains.

the energy intensity increases by a factor of 50% to 100% under real operating conditions. The electric trains, with their higher operating speeds and more rapid acceleration, are approximately 200% more energy intense under real operating conditions. This finding highlights the need for calculation of passenger train energy efficiency based on actual routes and specific train operations.

Mittal's data in Table 2-3 can be compared with the Hopkins data shown in Table 2-2. Hopkins estimates the efficiency of the LRC as 115 to 170 seat-miles per gallon and the efficiency of the Metroliner as 65 to 95 seat-miles per gallon. These numbers are equivalent to 670 to 991 Btu per seat-mile for the LRC and 1,200 to 1,750 Btu per seat-mile for the Metroliner. The values fall slightly above the in-service values presented by Mittal. However, given the assumptions for operating speed and grade made by Hopkins, they appear to offer reasonable agreement. The high energy intensity of the Turboliner compared to the diesel-electric and higher-speed electric trains parallels the low efficiency of the gas turbine TGV prototype in the Hopkins study.

Mittal also surveyed the literature to determine the energy intensity of intercity passenger travel by aircraft, automobile and bus (Table 2-4). Historical trends of fuel consumption and load factor were considered for each mode. Comparison across modes suggested that passenger rail has the potential to operate with an energy intensity per seat-mile lower than that for automobiles and aircraft. Based on the passenger rail load factors observed during the era, however, the energy intensity of passenger rail per passenger-mile was found to be greater than that of some competing modes. Bus was found to be the most efficient passenger transportation mode, followed closely by compact automobiles. At the time, passenger rail could not attract enough riders to take advantage of its potential efficiency.

Mittal suggests the best way to improve the efficiency of passenger rail is to increase the load factor by attracting more ridership. Increased ridership can be accomplished by such things as (a) decreasing travel time (through improving track condition to allow higher operating speeds); (b) increasing the frequency of train departures; (c) improving the quality of service (e.g., seating density, amenities); and (d) lowering the cost of travel (i.e., ticket price). Mittal recognized the complex interactions between these factors and conducted additional analysis to determine the effects of making track improvements to decrease travel time. Although increased ridership and load factor resulting from reduced travel time worked to improve efficiency, an increase in operating speed had an overall mixed effect on energy intensity. Elimination of speed restrictions and their associated acceleration events to create a more uniform speed profile tended to improve train energy efficiency, but increasing maximum operating speed increased aerodynamic drag and decreased efficiency. For the given routes and their

Table 2-4. Energy intensity of intercity passenger transportation modes (Mittal 1977).

Mode	Possible Energy Intensity (Btu/seat-mi)	Energy Intensity with Load Factor (Btu/pass-mi)
Auto—Compact	1,100	1,900
Auto—Average	1,600	2,650
Bus	500	1,100
Air—Wide-body	3,000	5,500
Air—Current Fleet	3,600	6,500
Rail—Intercity	1,000	3,500
Rail—Metroliner	1,000	2,000

distribution of speed restrictions, these two effects counteracted each other to maintain energy intensity for a given load factor. Thus, when the increased ridership from reduced running time was factored in, the track improvements and increased speeds decreased energy intensity per passenger-mile. Mittal acknowledged that this might not be the case for all corridors. If an increase in operating speed did not result in a large enough ridership increase, the efficiency of the passenger rail operation would ultimately decrease.

It is important to note some differences between Mittal's work and the scope of NCRRP Project 02-01. Although some of the same locomotives may still be in use, significant increases in energy efficiency have been obtained across all modes of passenger transportation over the last four decades. These changes make many of the results of the earlier study outdated. Also, Mittal does not consider the access and egress portions of the trip to make a true door-to-door comparison. The provided per-mile comparisons may also neglect the influence of circuity where one mode takes a shorter, more direct route between two points than competing modes.

Mittal's values of Btu per passenger-mile (see Table 2-4) can be compared to the current national averages reported by the BTS (see Table 2-1). As would be expected through improved efficiency of modern equipment and increased load factor, both the air and rail modes currently exhibit much lower energy intensity per passenger-mile. LDVs, however, appear to be much less efficient than in Mittal's estimates. This observation is surprising given the large advances that have been made in LDV fuel efficiency since 1977. It could reflect a combination of the BTS data considering congested city trips that are inherently less efficient than highway travel, and Mittal's assumed occupancy rate of 2.4 persons per automobile. This occupancy rate is far greater than current FHWA statistics, which suggest that the current vehicle occupancy rate is closer to 1.15 persons per automobile.

2.2.3 Amtrak Northeast Corridor Testing, 1992–1993 (Lombardi 1994)

As detailed by E. J. Lombardi (1994), during testing of new high-speed trainsets on the Amtrak Northeast Corridor in 1992 and 1993, energy consumption of different trains was measured and compared for trips between Washington, DC, and New York City (Table 2-5). A conventional train with one AEM7 and six Amfleet passenger coaches consumed 7,500 kWh for a single trip. The Swedish X2000 consumed 4,300 kWh of electricity, whereas the German ICE consumed 7,000 kWh. The two high-speed trainsets used regenerative braking to return approximately 17% of their consumed energy back to the grid. Lombardi attributed the higher energy consumption of the ICE train (compared to the X2000) to its higher horsepower, heavier weight and a faster operating speed, which exceeded the X2000 and AEM7 by 10 mph. The lower energy consumption of the two high-speed trainsets compared to the conventional train was attributed to aerodynamics.

Table 2-5. Energy intensity of different trains on Amtrak's Northeast Corridor.

Train	Energy Consumption[a] (kWh)	Seats	Possible Energy Intensity (Btu/seat-mi)	Possible Energy Intensity (kWh/seat-km)
AEM7 and Six Amfleet Coaches	7,500	504	226	0.041
Swedish X2000 (1L-5C trainset)[b]	4,300	355	183	0.033
German ICE (L-6C-L trainset)[b]	7,000	441	241	0.044

[a]Source: Lombardi 1994.
[b]These are integrated trainsets (L = power car, C = coach).

The energy consumption data provided by Lombardi can be combined with trainset data to estimate the possible fully loaded (seat-mile) energy intensity of the different trainsets over the 225-mile route (Table 2-5). Although the trains all had very low energy intensity, the values are based on the metered electric power consumption and do not consider the energy consumed in generating the electricity. When adjusted for load factor and source generation energy, these electric trainsets are more efficient than conventional trains hauled by diesel-electric locomotives.

2.2.4 Study of Metrolink Commuter Rail in Los Angeles (Barth et al. 1996)

Barth et al. (1996) presented a paper titled Emissions Analysis of Southern California Metrolink Commuter Rail that estimated the emissions of a morning peak Metrolink commuter rail trip and compared them to the emissions of an equivalent automobile commute from Riverside to downtown Los Angeles, CA. Emissions for the line-haul portion of the commuter rail trip were determined by recording locomotive throttle settings for an actual train run and then multiplying by specific throttle-notch emissions factors developed during full-scale laboratory testing of the same locomotive model.

The Metrolink study also included emissions from the station access segment of the commuter rail trip. Surveys conducted on the train during a morning peak-period commuting trip asked passengers to detail their trip origin/destination, trip purpose, access mode, access duration, access length, model of vehicle, egress mode, egress duration and egress length. The collected data were used to build a distribution of vehicle-trip profiles, and the emissions related to rail passenger access to and from Metrolink were calculated using the California Air Resources Board (CARB) EMFAC7F emissions model. A similar approach was used to determine the automobile emissions of the highway trips required to transport the same number of commuters if they drove alone in their own vehicles instead of riding Metrolink.

Total per passenger emissions for the Metrolink commute, including the train trip and access modes, were found to be less than those for the equivalent automobile commute when 300 highway commuters were compared to 300 train passengers that drove to the Metrolink station alone. Barth's analysis was focused on local air quality/CAC emissions (i.e., carbon monoxide [CO], hydrocarbons [HC], nitrogen oxides [NO_x], and particulate matter [PM] and did not assess GHG emissions). Compared to the automobile trip's CAC emissions, the Metrolink commuter rail trip had lower CO and HC emissions, but higher NO_x and PM emissions. The authors estimated that for the four morning trains under study, fewer than 100 rail passengers had to be diverted from the highway to result in a net reduction in CO and HC; 2,000 passengers for a net reduction in PM; and 1,500 to 2,000 passengers for a net reduction in NO_x. Stated differently, each morning train produced CO and HC emissions equivalent to fewer than 25 automobiles, PM emissions equivalent to 500 automobiles and NO_x emissions equivalent to 375 to 500 automobiles.

Locomotive duty cycle data, as provided by Barth et al. in the paper, can be used to deduce the fuel consumption and energy intensity of the Metrolink commuter rail trip. (Locomotive duty cycle data also are given in Appendix A of *NCRRP Report 3*.) Using throttle-notch fuel consumption data for the EMD F59PH, each train run would consume 101 gallons of diesel fuel in direct propulsion and, given a minimum demand, another 25 gallons for head-end hotel power. Four morning trains carrying a total of 1,100 passengers would operate at 94 passenger-miles per gallon—equivalent to an energy intensity of 1,378 Btu per passenger-mile.

2.2.5 Transport Canada Study of Passenger Transportation Emissions (Lake et al. 1999)

Lake et al. (1999) conducted a study for Transport Canada titled Measures to Favour Passenger Modal Shift for GHG Reduction. This study characterized the GHG intensity of passenger travel modes for different origin-destination pairs in Canada. The analysis considered actual travel patterns, load factor and market share for different passenger travel modes. The per passenger estimates of emissions for most city pairs reflected the general expectation that the most favorable mode was bus, followed by rail, while auto and air were the least favorable modes.

In the long-distance markets, however, emissions from rail were the highest or the second highest among all modes because of the need for sleeping and food-service cars on long-distance trains, which reduces the overall number of seats per railcar (and increases the train weight per seat). On certain routes where bus service had a relatively low load factor, automobile mode could produce the least emissions. Rail mode could also produce fewer emissions than bus mode on routes where strong rail ridership resulted in a high load factor.

In addition to emissions data, the 1999 Transport Canada study included metrics for average energy efficiency of the different passenger transportation modes on the basis of passenger-miles and seat-miles (Table 2-6). On average, intercity bus was the most efficient mode. Comparison of rail intensity per seat-mile to bus intensity per passenger-mile indicates that, even if the passenger trains were operated at full capacity, they would only be more efficient than intercity bus at a typical load factor on a limited number of routes.

2.2.6 German Passenger Transportation Case Studies (Wacker and Schmid 2002)

In their 2002 paper titled Environmental Effects of Various Modes of Passenger Transportation: A Comprehensive Case-by-Case Study, Wacker and Schmid developed a complete energy consumption and emissions model for passenger transportation. Their methodology included the energy used in the main travel segment propulsion, access and egress mode propulsion, fuel production and supply, and in producing, maintaining and disposing of various transportation vehicles and infrastructure.

Table 2-6. Energy intensity of Canadian passenger travel modes in 1996 (Lake et al. 1999).

Mode	Energy Intensity (Btu/passenger-mi)	Possible Energy Intensity (Btu/seat-mi)
Intercity Bus	1,156	551
Rail—Average	2,114	--
Rail—VIA* Corridor East of Toronto	--	1,046
Rail—VIA Corridor West of Toronto	--	1,156
Rail—VIA Eastern Long-Distance Trains	--	1,542
Rail—VIA Western Long-Distance Trains	--	1,431
Air	3,665	--
Automobile	4,847	1,212

*VIA Rail Canada

Besides considering access modes, the study by Wacker and Schmid is noteworthy for its consideration of trip purpose and time of day. The following trip scenarios were considered by appropriately adjusting the load factor of each transportation mode:

- Commuter traffic: depart 8:00 a.m., return 4:30 p.m.
- Shopping traffic: depart 10:00 a.m., return 12:00 p.m.
- Leisure traffic: depart 7:30 p.m., return 10:30 p.m.
- Sunday leisure traffic: depart 11:00 a.m., return 5:00 p.m.

Case studies of a typical 20-mile interurban (IU) trip for leisure and commuter traffic were examined using different access/IU trip/egress mode combinations to reflect door-to-door travel. The modes included for one or more legs of the trips were automobile, transit bus, light rail transit, commuter rail, regional express trains, bicycle and walking.

Direct energy use and emissions for automobile and bus transportation were calculated using the Handbook of Emission Factors for Road Transport (HBEFA). The Handbook database (a Microsoft® Access application) accounts for parameters such as traffic situation, road grade, motor system, and cubic engine capacity. For rail vehicles, the study used computer simulations to calculate energy consumption and emissions.

Indirect energy consumption and emissions were calculated separately in three categories: (1) production of fuel and electricity; (2) vehicle production, maintenance and disposal; and (3) infrastructure construction, maintenance and disposal. The energy and emissions of vehicle production, maintenance and disposal were distributed evenly over the lifetime of the vehicle.

For the case studies analyzed, light rail transit was the most environmentally friendly of the passenger travel modes. However, the results depended heavily on the time of day considered. For commuter traffic, trips involving rail were very competitive with those made by an automobile carrying four passengers. For mid-day leisure trips outside peak travel hours—when rail and public transit modes have a low load factor—the automobile with four passengers, or even with one passenger, was more efficient than rail and public transit.

Additional long-distance intercity passenger rail case studies conducted as part of this research indicated that the German ICE high-speed train was more efficient and resulted in fewer emissions than the automobile with a single occupant. Only when the ICE train had a low load factor could an automobile with four occupants approach its level of efficiency. Wacker and Schmid also noted that for rail travel over longer distances, depending on the exact route and implemented technology, passenger rail could yield poorer results than an automobile with a single occupant.

2.2.7 Swedish Passenger Train Energy and Modal Comparison Study (Andersson and Lukaszewicz 2006)

Andersson and Lukaszewicz (2006) led a Bombardier Transportation study to determine the average energy consumption and emissions of the modern passenger trainsets in Sweden. The study report, titled Energy Consumption and Related Air Pollution for Scandinavian Electric Passenger Trains, compared the measured energy consumption and related emissions for modern trainsets to older locomotive-hauled trains and averages for other modes of passenger transportation.

For passenger trains, the energy calculations only accounted for energy used in propulsion, passenger comfort (i.e., head-end power, or HEP) and idling outside of scheduled service. The study did not include energy used in other activities, such as maintenance, operations of fixed installations or heating of facilities. Losses in the electric traction power supply system were accounted for by applying a scaling factor to the energy consumed by the electric trainsets at the pantograph. Regenerated energy from the train braking was subtracted from this total.

Table 2-7. Energy intensity of passenger modes—Stockholm to Gothenburg, Sweden (Andersson and Lukaszewicz 2006).

Mode	Possible Energy Intensity (Btu/seat-mi)	Energy Intensity with Load Factor (Btu/pass-mi)	CO_2 Emissions		NO_X Emissions	
			(g/pkm)	(g/pmi)	(g/pkm)	(g/pmi)
Rail (6-car X2000)	231	423	7	11	16	26
Air (Boeing 737-800)	1,757	2,800	130	210	600	968
Bus (Euro 3 Emissions)	373	1,098	53	85	360	581
Automobile (Mid-size car)	714	1,921	87	140	40	65

g/pkm = grams per passenger-kilometer; g/pmi = grams per passenger-mile

However, losses at the power-generating station were not considered. This study considered the average emissions, marginal CO_2 emissions, and average amount of electricity produced from renewable sources in estimating the emissions of the electric trains.

Average energy consumption and emissions of other modes were not measured. Instead, averages were obtained from the Network for Transport and Environment, a Swedish non-profit organization aimed at establishing common base values for the environmental performance of transportation.

Modal comparisons were made for trips from Stockholm to Gothenburg, Sweden, a distance of 283 miles (455 km) using the X2000 trainset (Table 2-7), and from Stockholm to West Aros, Sweden, a distance of 66 miles (107 km) using the Regina trainset (Table 2-8). For both routes, passenger rail exhibited the lowest energy intensity per seat-mile and per passenger-mile when load factor was considered.

2.2.8 Transport Canada Studies of Intercity Passenger Rail (2007 and 2010)

In 2007, English, Moynihan and Lawson prepared a study for Transport Canada titled *Assessment of Environmental Performance and Congestion Relief Benefits of Intercity Passenger Rail Services in Canada.* The study, which was updated in 2010, used detailed spreadsheet models to simulate the emissions of rail, air, intercity bus and automobile trips. Confidential activity and load factor data were provided by all common carriers. Similar to the 1999 Transport Canada study, the work by English, Moynihan and Lawson determined that bus was the most efficient mode for all trips when load factor was used to calculate energy and emissions per passenger-mile (Table 2-9).

Table 2-8. Energy intensity of passenger modes—Stockholm to West Aros, Sweden (Andersson and Lukaszewicz 2006).

Mode	Possible Energy Intensity (Btu/seat-mi)	Energy Intensity with Load Factor (Btu/pass-mi)	CO_2 Emissions		NO_X Emissions	
			(g/pkm)	(g/pmi)	(g/pkm)	(g/pmi)
Rail (3-car Regina)	165	478	8	13	18	29
Bus (Euro 3 Emissions)	412	1,208	59	95	409	660
Automobile (Mid-size car)	714	2,031	93	150	43	69

g/pkm = grams per passenger-kilometer; g/pmi = grams per passenger-mile

Table 2-9. Energy intensity of passenger modes—selected Canadian routes (English et al. 2007).

Origin-Destination	Distance (mi)	Energy Intensity with Load Factor (Btu/passenger-mi)			
		Rail	Air	Bus	Auto
Victoria–Courtenay*	140	1,596	28,737*	1,290	3,530
Ottawa–Montreal	116	2,518	10,727	860	3,530
Toronto–Montreal	335	1,699	4,308	880	3,530
Toronto–Vancouver	2,776	2,047	2,369	921	2,477

*The Victoria–Courtenay air service involved two short flight segments via Vancouver, as a direct service was not available.

The only route on which rail mode efficiency approached bus mode efficiency was for the service on Vancouver Island, where VIA Rail service was provided by a self-propelled diesel multiple-unit (DMU) railcar. For the longest transcontinental trip, Toronto to Vancouver, the improved load factor and distribution of the energy-intensive aircraft landing and take-off cycle over sufficient cruising distance brought the efficiency of the air trip within the range of the rail mode (with sleeping accommodations) and the auto mode.

2.2.9 Spanish Passenger Train Energy and Modal Comparison Study (Alvarez 2010)

A. G. Alvarez conducted a study in 2010 titled Energy Consumption and Emissions of High-Speed Trains that compared the efficiency of conventional rail and HSR to competing modes of transportation on 10 different routes in Spain. The comparison was made via simulation software calibrated for rail operations in Spain. The analysis considered the actual distance traveled by each mode between a particular origin-destination pair because the shortest and longest modal paths could differ in length by as much as 30%. The comparison also used known load factors for each transportation mode and route in Spain to determine energy consumption and emissions per passenger-kilometer. Alvarez acknowledged the difficulty of comparing the electrified modes of transportation to other modes, and to each other, given that the emissions factors of power generation systems could vary between regions and also temporally within the same region.

On seven of the 10 routes analyzed, the high-speed train produced fewer emissions than any other mode (Table 2-10; not all routes are shown). On the other three routes, the conventional

Table 2-10. Emissions and energy intensity of passenger modes—selected routes in Spain (Adapted from Alvarez 2010).

Route and Shortest Distance	Auto	Bus	Air	Conventional Rail	High-Speed Rail
	CO_2 Emissions (g/passenger-mi)				
Madrid–Barcelona (302 mi)	209	48	235	57	46
Madrid–Alicante (223 mi)	197	54	263	46	53
Madrid–Valladolid (101 mi)	141	58	N/A	64	41
Average of 10 Routes	182	52	272	61	43
	Energy Intensity with Load Factor (Btu/passenger-mi)				
Average of 10 Routes	2,635	659	2,965	1,427	1,043

Numbers are derived from original metric units.

train produced the lowest emissions because of the circuity in HSR routing between these points, which were more directly connected by the conventional rail network. On average, the conventional train produced over 40% more emissions than the high-speed train, and emissions for air and auto were four to five times that of the high-speed train. In terms of energy efficiency, however, the bus was the most efficient mode, followed by HSR as the second-most efficient mode, ahead of the conventional train.

In concluding that the high-speed train was more energy efficient than the conventional train, Alvarez's findings defy the "power law" convention by which higher speeds require greater energy consumption than lower speeds. Alvarez suggests that this arose from other factors that varied when the high-speed and conventional trains were compared between the same origin and destination. Besides attracting a higher load factor, the high-speed trains operated on routes that were typically shorter, with a more homogenous speed profile and with fewer stops and curves. The high-speed trainsets were also designed to have less weight per seat and better aerodynamic performance than the conventional trains. In Spain, the high-speed trains operated on a 25kV DC electrification system, while the conventional trains operated on a less-efficient 3kV DC system. Finally, the faster running time of the high-speed trains reduced the total cumulative power consumption of hotel and auxiliary power services between origin and destination, increasing energy efficiency.

2.2.10 Study of U.S. Corridor Transportation Energy (Sonnenberg 2010)

In 2010, A. Sonnenberg at the Georgia Institute of Technology completed a study of Transportation Energy and Carbon Footprints for U.S. Corridors. Sonnenberg compared transportation-related carbon emissions by applying an emissions inventory framework to intercity travel modes including automobile, bus, air and passenger rail. Similar to Mittal, Sonnenberg utilized a corridor-based approach, rather than a door-to-door assessment, to apply the framework to three future HSR corridors in the United States: (1) San Francisco–Los Angeles–San Diego, CA; (2) Seattle–Portland–Eugene in the Pacific Northwest; and (3) Philadelphia–Harrisburg–Pittsburgh, PA.

To compare the emissions of all modes, Sonnenberg employed a full lifecycle assessment, including the upstream and downstream emissions of transportation activity. For electric trains, the regional electric power generation profile was considered in the emissions analysis. Because the objective of the work was to determine the most effective strategies for reducing the overall transportation greenhouse gas (GHG) emissions in each corridor, Sonnenberg examined the relative effectiveness of changes to the fuel economy of different modes, introduction of alternative fuels, development of new forms of transportation such as higher-speed and HSR, and changes to policy such as carbon taxes.

With the goal of examining changes in overall corridor emissions, Sonnenberg did not directly compare energy intensity or emissions of competing modes for equivalent trips. However, Sonnenberg indicated that the introduction of 125-mph rail service did little to reduce corridor emissions and may actually have a negative impact. The trains may not be fast enough to obtain significant diversions from the air mode. If sufficient train frequency was implemented to obtain significant diversion from the highway mode, the extra train runs decreased the overall rail load factor, offsetting any efficiency and emissions gains per passenger. Also, for the corridor in Pennsylvania where the predominant electricity source is coal-fired power plants, the addition of electric trains had a much more negative impact than on other corridors where a greater proportion of clean and/or renewable source fuels is used to generate electricity.

A 200-mph rail service was found to have a positive effect on corridor emissions, but only on the order of 0.5% to 1.5% reduction. Although HSR travel times were more competitive, the

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rail service frequency required to divert trips from competing modes results in a low rail load factor. Also, because the express HSR service did not serve some smaller intermediate stations, conventional rail service was retained at lower load factors due to the loss of passengers to the HSR system. With a decreased load factor, the emissions from passengers at intermediate points bypassed by the HSR system actually increased, offsetting gains for passengers diverted to the new system.

Sonnenberg came to the interesting conclusion that the best way to improve overall corridor efficiency and emissions was through automobile-based strategies. Autos had a large share of the main trip segment miles traveled, and they also represented a large share of the access and egress trips to the air, bus and rail modes. Thus, improvements to auto efficiency and emissions would actually improve the door-to-door performance of all modes.

2.2.11 North Carolina Regional Rail Study and Modal Comparison (Frey and Graver 2012)

Frey and Graver investigated in-service fuel consumption and emissions rates for the North Carolina Department of Transportation (NC DOT) Rail Division on Amtrak regional intercity rail service between Raleigh and Charlotte, NC. The study, summarized in a 2012 report titled Measurement and Evaluation of Fuels and Technologies for Passenger Rail Service in North Carolina, used actual field measurements to determine the potential fuel and emissions savings for rail transportation compared to automobiles between cities along the rail corridor. The study also examined the implications of substituting B20 biodiesel as an alternative fuel in place of regular ultra-low sulfur diesel.

A portable emissions measurement system (PEMS) was used to measure locomotive emissions during "over-the-rail" testing in service from Raleigh to Charlotte. Throttle position data collected during the tests were used to calculate fuel consumption and average energy intensity over the route (Table 2-11). The values for passenger rail included fuel and emissions associated with both the locomotive prime mover and the diesel-generator set used for hotel power functions. On average, the HEP unit was responsible for roughly 8% of emissions and energy consumption. The rail results included a route average and a separate peak average for the most efficient segment of the route.

Table 2-11. Energy intensity of passenger modes—Raleigh–Charlotte, NC (Frey and Graver 2012).

Mode	Energy Intensity with Load Factor (Btu/pass-mi)	CO_2 Emissions (g/pass-mi)
Rail (Corridor Average)	3,125	246
Rail (Greensboro–Charlotte, NC)*	2,806	221
Automobile (1 occupant/vehicle)	4,993	384
Automobile (1.69 occupants/vehicle)	2,954	227

*The Greensboro–Charlotte segment was reported to have the lowest rail energy/emissions intensity for all combinations of the five locomotives and five origin-destination pairs monitored. However, the NCRRP Project 02-01 research team notes that—from the data in Table 5-6 on page 82 of the Frey and Graver report—the number presented in the text (221 g/passenger-mile) is for Locomotive No. 1755, which is 20% higher than the locomotive cited by Frey and Graver (Locomotive No. 1865, at 184 g/passenger-mile) and 10% higher than the fleet average number for that segment (201 g/passenger-mile). The automobile intensity numbers Frey and Graver report are based on the average of the five origin-destination pairs monitored/reported.

Source: Frey and Graver (2012), pp. 84 (Rail) and 87 (Auto).

Comparable highway trips were simulated with the EPA Motor Vehicle Emission Simulator (MOVES) software. The authors also presented two values for automobiles: one for vehicles with a single occupant and one with 1.69 persons per vehicle to match Department of Energy assumptions.

Passenger rail was more efficient than the automobile if each traveler on the highway was in a separate vehicle. With greater highway-vehicle occupancy, the efficiency of passenger rail and highway vehicles became nearly equal, with the automobile more efficient on average but rail more efficient on certain segments (e.g., Greensboro–Charlotte) that had high ridership.

With one occupant per highway vehicle, the CO_2 emissions produced by 10 automobiles were equivalent to those produced by 15 passengers on the train, indicating that rail mode effectively reduced emissions. As in the earlier Metrolink study, a significant increase in rail ridership would be required to reduce other emissions factors, such as NO_x. The study by Frey and Graver also found that, although B20 biodiesel reduced CO emissions by 12% compared to the ultra-low sulfur diesel fuel, NO_x increased by 15%, HC by 6% and PM by 32%.

This study also concluded that travel time is a significant factor in determining the emission factors on in-service trips. A delay of approximately 5% of the scheduled travel time increased the rail emissions rates for NO_x, HC, CO_2 and PM by roughly 16% per passenger-mile. The authors did not consider highway congestion and delay but acknowledged that examining these factors could improve the comparison in favor of passenger rail.

2.2.12 FRA Improved Passenger Equipment Evaluation Program (Bachman et al. 1978)

This simulation-based assessment of HSR corridors in the United States was undertaken through the FRA's Improved Passenger Equipment Evaluation Program (IPEEP) in the late 1970s (Bachman et al. 1978). Although the equipment characterized in the IPEEP studies is less relevant now, the corridors remain relevant. As discussed in the case study section (Chapter 4) of this report, the researchers for NCRRP Project 02-01 drew from the IPEEP reports for gradient and speed data for many of the railway corridor simulations in the MMPASSIM.

2.2.13 Summary of Previous Studies

The studies examined for NCRRP Project 02-01 are all consistent in that none of them showed the automobile to be the most energy-efficient mode of transportation (Table 2-12). Of the six studies that included bus transportation (including the three North American studies), four identified bus as the most efficient mode of transportation. When compared to bus, rail was only the most efficient in Germany and Sweden, where the combination of lightweight trainsets requiring less energy and fast, frequent rail service that is well integrated with other modes to increase load factor results in very efficient passenger rail operations. The extremely low energy intensity of rail service in Sweden is attributable to a combination of efficient equipment, a high load factor and a regional generation mix in Scandinavia that favors hydroelectric power.

The North American values of passenger rail energy intensity vary greatly, from a low of 1,378 Btu/passenger-mile for Metrolink in Southern California to a high of 2,806 Btu/passenger-mile for Amtrak regional intercity service in North Carolina. The main source of variation between these values is likely the load factor, with the morning Metrolink commuter train representing a nearly ideal case of peak ridership while the NC DOT service represents average passenger loads. During the peak holiday season, ridership on the NC DOT passenger rail service may reach higher load factors that produce lower energy intensities per passenger-mile. This variability reinforces the need for modal comparisons of energy efficiency to not only consider specific case study routes but to also consider trip purpose, temporal variation in factors and the access modes used in making a specific trip.

Table 2-12. Summary of previous passenger rail energy efficiency research.

Study	Country	Most Energy-Efficient Mode				Passenger Rail Energy Intensity with Load Factor (Btu/pass-mi)	Considerations			
		Auto	Bus	Rail	Air		Load Factor	Source Generation	Access Modes	Time/Trip Purpose
Mittal (1977) U.S. DOT/FRA	United States					2,000				
Barth et al. (1996) Metrolink	United States		N/I			1,378		N/A		
Lake et al. (1999) Transport Canada	Canada					2,114		N/A		
Wacker and Schmid (2002)	Germany				N/I	N/I				
Andersson and Lukaszewicz (2006)	Sweden					423				
English et al. (2007) Transport Canada	Canada					1,596		N/A		
Alvarez (2010)	Spain					1,043				
Sonnenberg (2010)	United States		N/I			N/I				
Frey and Graver (2012) NC DOT	United States		N/I		N/I	2,806		N/A		

N/I = Not included in this study.
N/A = Not applicable to this study.

2.3 Domestic and International Efficiency Benchmarks

Previous sections in this chapter summarized research and formal experiments designed to investigate passenger rail energy and efficiency, either in isolation or in comparison to competing travel modes. In addition to providing context for the research conducted in NCRRP Project 02-01, the results of these past studies can assist in validating energy and GHG emissions outputs from the MMPASSIM tool. Because several of the studies do not reflect current operating conditions, additional benchmarks of the efficiency and emissions of existing passenger rail systems are needed to compare the outputs of the model to real-world results. Additional published efficiency and emissions data from commuter, conventional intercity and HSR systems around the world are summarized in the balance of this section.

2.3.1 Commuter Rail

Data on the energy consumption of individual commuter rail operations within the United States can be obtained from the National Transit Database (NTD). The NTD is the primary national database for FTA statistics on public transit. Transit systems that receive FTA grants are required to report various annual revenue, expense, ridership, operating and safety statistics for inclusion in the NTD. Although the majority of information in the NTD relates to bus, light rail and heavy rail transit systems, the NTD includes data on 26 different commuter rail systems that fall within the scope of this study.

Specific NTD values of interest for this study are annual energy consumption in gallons of diesel, gallons of biodiesel or kWh of electricity; and transportation productivity in terms of passenger-miles, train-miles and vehicle-miles. The reported values of train-miles and vehicle-miles include deadhead and non-revenue movements. The consumed fuel and electricity were converted into common units of energy and used to determine the energy intensity of each system in Btu per passenger-mile, per train-mile and per vehicle-mile. The specific types of equipment being operated on each system were researched to estimate the Btu per seat-mile for each commuter rail operation. Because electric power consumption is reported as purchased electricity, it does not include generation losses from the mix of sources in the region. Thus, the data presented in this section reflect a tank or meter-to-wheels analysis.

Although the goals of this study are to avoid gross average measurements of efficiency and to develop metrics for specific trips, the energy intensity values derived from the NTD provide a baseline for more detailed analysis. Also, because a unique energy intensity can be calculated for each of the 26 commuter rail operations, the calculated values indicate the wide variation in efficiency resulting from differing system route, equipment, operating and ridership characteristics.

The systems were categorized into four groups based on the type of propulsion in use: diesel-electric locomotive-hauled trains, self-propelled DMUs, electric and mixed or dual-mode systems. The latter category includes systems that utilize dual-mode locomotives that switch between electric and diesel-electric propulsion during a trip, and systems that operate different lines that each use different forms of propulsion. Given that statistics are reported at the system level and by line, ridership and operating statistics for the electric and diesel-electric operations of each system are combined in the NTD. Thus, it is not possible to calculate separate electric and diesel-electric performance metrics for the systems operating separate lines of each type.

The weighted-average intensity of the 14 systems exclusively using commuter trains hauled by diesel-electric locomotives is 2,242 Btu per passenger-mile and 574 Btu per seat-mile (Table 2-13). Significant variation occurs, with two systems operating below 1,600 Btu per

Table 2-13. Energy intensity of diesel-electric locomotive-hauled commuter rail systems in 2011.

State	System	Energy Intensity (Btu/pass-mi)	Possible Energy Intensity (Btu/seat-mi)
CA	Altamont Commuter Express	1,575	451
CA	North County Transit District—Coaster	2,662	516
CA	Peninsula Corridor Joint Powers Board—Caltrain	1,905	585
CA	Southern Calif. Regional Rail Authority—Metrolink	1,914	495
CT	Connecticut DOT—Shore Line East	13,946	1,491
FL	South Florida RTA—Tri-Rail	2,787	741
MA	Massachusetts Bay Transportation Authority	2,153	509
MN	Minneapolis Metro Transit—Northstar	2,722	618
NM	Rio Metro Regional Transit District—Rail Runner	2,656	700
TN	Nashville RTA—Music City Star	6,881	909
TX	Trinity Railway Express	3,322	770
UT	Utah Transit Authority—Front Runner	4,247	627
VA	Virginia Railway Express	1,525	726
WA	Central Puget Sound RTA—Sounder	2,306	658
	Passenger-mile-weighted Average	2,242	574

passenger-mile while several systems operate in excess of 3,000 Btu per passenger-mile. Less variation is seen in the energy intensity per seat-mile, as this metric is independent of load factor and provides a better measure of the actual efficiency of the equipment, infrastructure and operations. An interesting comparison can be made between the Altamont Commuter Express, with the lowest energy intensity (451 Btu per seat-mile), and the Virginia Railway Express, with an above-average energy intensity (726 Btu per seat-mile). This comparison suggests that the equipment, infrastructure and operations of the former system are inherently 40% more efficient than those of the latter system. Based on the NTD, however, the Virginia Railway Express operates with almost twice the load factor of the Altamont Commuter Express, resulting in a nearly equal passenger trip efficiency of approximately 1,550 Btu per passenger-mile.

Many of the systems with the highest energy intensity tend to be newer commuter rail operations that began service during the past decade. Presumably this is because the newer systems are not yet fully integrated into regional transportation and development patterns and thus operate at a lower load factor. However, examination of the possible energy intensity per seat-mile suggests that load factor alone cannot explain this result. The newer systems tend to have higher energy intensity per seat-mile compared to the older, established, systems despite often having newer equipment with greater seating capacity. Further analysis of the NTD suggests that the newer services are operating primarily two- and three-railcar trains, whereas the older services with larger ridership are operating more efficient trains from four to seven railcars in length.

The high energy intensity value per seat-mile for the Nashville system shows the compounding effects of short trains and less-efficient second-hand equipment. It is not known why the Connecticut DOT Shore Line East trains exhibit such poor performance per seat-mile (the poor passenger-mile performance can be attributed to an estimated load factor of 10%).

A final observation can be made by examining the energy intensity per seat-mile of Minnesota's Northstar, New Mexico's Rail Runner and Utah's Front Runner. These three systems all use the same types of locomotives and similar-size trains of the same bi-level passenger railcars. Operating with essentially identical trains, the systems have an energy intensity per seat-mile of 618 Btu, 700 Btu and 627 Btu per seat-mile, respectively—all within 13% of each other. With ridership and equipment normalized, the remaining variation between the systems can be attributed to differences in infrastructure and operating patterns.

The weighted-average energy intensity of the five systems that use DMU railcars is 2,319 Btu per passenger-mile and 659 Btu per seat-mile (Table 2-14).

Table 2-14. Energy intensity of DMU commuter rail systems in 2011.

State	System	Energy Intensity (Btu/pass-mi)	Possible Energy Intensity (Btu/seat-mi)
CA	North County Transit District—Sprinter	2,011	563
NJ	New Jersey Transit—River LINE	2,104	648
OR	TriMet*—Westside Express	4,512	1,254
TX	Capital Metro—Austin MetroRail	2,318	606
TX	Denton County Transportation Authority—A-Train	6,612	857
	Passenger-mile-weighted Average	2,319	659
	Average of Systems Using European DMUs	2,097	617

*Tri-county Metropolitan Transportation District.

The three systems that use modern European-designed DMUs (Sprinter, River LINE and Austin MetroRail) exhibit fairly consistent energy intensity values of 563 Btu, 648 Btu and 606 Btu per seat-mile. These values differ by less than 8%, which suggests that any differences in infrastructure and operations between the systems have little influence on the base efficiency of the DMU. At the time of data collection, the Denton County A-Train was still using refurbished vintage rail-diesel cars (RDCs) at higher energy intensity per seat-mile while awaiting arrival and approval of their modern DMUs. The Westside Express uses a domestic DMU and trailer that is fully FRA compliant and weighs more than the European DMUs.

Overall, the values for the DMU systems indicate that they are not substantially more efficient than the average system operating with diesel-electric locomotive-hauled trains. However, the DMU is not intended for markets that can support operations of very efficient trains of four to six passenger railcars. When the three systems operating European DMUs are compared to the three newer commuter systems operating shorter trains (Minnesota's Northstar, New Mexico's Rail Runner and Utah's Front Runner), the DMU is inherently more efficient per seat-mile and also, when load factor is considered, per passenger-mile. Thus, where possible under FRA waivers, when starting up a new commuter rail service, it may be more energy efficient to use more frequent DMU service to build ridership before implementing longer, locomotive-hauled trains with greater capacity.

This result differs from the work of Messa (2006), who, from an emissions perspective, concluded that DMUs or trains of double-deck DMUs pulling trailers would always produce fewer emissions than locomotive-hauled trains and would be competitive with the emissions from electric power generation for electric trainsets. The data presented by Messa suggest that DMUs consume 450 Btu per seat-mile. Because no operator currently using DMUs has been able to achieve this level of efficiency, this value may be somewhat idealized and may not account for true operating conditions.

The weighted-average intensity of the two systems using electric propulsion exclusively is 1,196 Btu per passenger-mile and 291 Btu per seat-mile (Table 2-15). Both systems exhibit very efficient operations in this meter-to-wheels analysis. If these values were adjusted upwards to account for regional generation efficiencies, they might increase by as much as three times, and the electrified systems would not be as efficient as several of the commuter systems that use DMUs and diesel-electric locomotives.

The weighted-average intensity of the five systems that use a mix of electric and diesel-electric propulsion is 1,462 Btu per passenger-mile and 405 Btu per seat-mile (Table 2-16). These five systems are among the largest in the United States; they have very high ridership, and they operate some of the longest trains. Comparison to diesel-electric and DMU systems is clouded, however, by the nature of the purchased electricity. Considering the regional generation mix will increase the electric portion of the energy consumed by as much as three times. Doing this will have a varying impact on the efficiency of each system, depending on its proportion of electrified train-miles.

Table 2-15. Energy intensity of electrified commuter rail systems in 2011.

State	System	Energy Intensity (Btu/pass-mi)	Possible Energy Intensity (Btu/seat-mi)
IN	Northern Indiana Commuter Transit District—South Shore	819	211
PA	Southeastern Pennsylvania Transit Authority	1,271	306
	Passenger-mile-weighted Average	1,196	291

Table 2-16. Energy intensity of mixed electric and diesel commuter rail systems in 2011.

State	System	Energy Intensity (Btu/pass-mi)	Possible Energy Intensity (Btu/seat-mi)
IL	Northeast Illinois Regional Commuter Rail Corporation—Metra	2,150	562
MD	Maryland Transit Administration—MARC	2,031	618
NJ	New Jersey Transit Corporation	1,670	380
NY	MTA Metro—North Commuter Railroad Company	977	349
NY	MTA Long Island Rail Road	1,261	339
	Passenger-mile-weighted Average	1,462	405

For all of the data expressed in Table 2-13 through Table 2-16, standing passengers during peak periods may allow the actual energy intensity in Btu per passenger-mile for a specific trip to be lower than the possible energy intensity expressed in the tables as Btu per seat-mile.

2.3.2 Conventional Regional and Long-Distance Intercity Rail

Table 2-1 presented the national average energy intensity for Amtrak service as 1,628 Btu per passenger-mile. This value is comparable to the average value for commuter systems that, like Amtrak, use a mixture of electric and diesel-electric propulsion.

Disaggregating this national average to obtain data on specific services and routes is difficult because Amtrak does not routinely directly track fuel consumption for specific train runs. Instead, Amtrak monitors fuel purchases and deliveries at their fueling points around the system, and a spreadsheet tool is used to allocate this fuel to different train services based on train size, operating speed and grade profile on the route. The situation is more complicated for the Northeast Corridor, where the electricity consumed by different Amtrak services is mixed within the pool of power supplied to different commuter rail services. Amtrak does not have meters on each locomotive that report power consumption data to a central database for management purposes.

Collection of route-specific fuel consumption is complicated by the lack of reliable and accurate fuel gauges on locomotives. Regular locomotive fuel gauges often are unreliable, with University of Illinois students involved in Amtrak fuel studies reporting that locomotive fuel tank gauges would often show more fuel in the tank at the end of a run than at the start. Amtrak fuel studies on specific routes utilize a locomotive equipped with special fuel monitoring equipment.

The NTD includes information for two state-supported Amtrak intercity corridors: the Downeaster from Boston, MA to Portland, ME, and the Pennsylvania DOT's Pennsylvanian and Keystone Service, operating between Pittsburgh, Harrisburg, and Philadelphia, PA, and New York City. A test of biodiesel fuel on the Heartland Flyer between Fort Worth, TX, and Oklahoma City, OK, provided information on annual fuel consumption for that regional intercity route (Smith and Shurland 2013). The NCRRP Project 02-01 study team attempted to obtain fuel consumption data for other specific state-supported regional intercity services from public data. State rail plans and passenger rail budgets were consulted, but in most cases the fuel costs were lumped together with crew and other operating expenses.

Table 2-17. Energy intensity of selected Amtrak corridors.

Corridor	Energy Intensity (Btu/pass-mi)	Possible Energy Intensity (Btu/seat-mi)	Source
Amtrak (national average)	1,628	--	BTS (2011)
Northeast Corridor Regional Train (AEM7 and 6 coaches)	--	226	Lombardi (1994)
NC DOT Piedmont	3,125	1,505	Frey and Graver (2012)
Downeaster	2,510	921	NTD (2001)
PennDOT Keystone and Pennsylvanian	2,703	859	NTD (2011)
Heartland Flyer	--	574	Smith and Shurland (2013)

The three corridors for which data are available per passenger-mile exhibit lower efficiency than the Amtrak national average (Table 2-17). The Piedmont has higher energy intensity per seat-mile than the other corridors. This may be partially due to the short train consist on the Piedmont, which has only two revenue coaches to offset the resistance of the café-lounge car and the locomotive. Trains on the other two eastern corridors average five or six revenue coaches plus a café car and locomotive. The Heartland Flyer consists of three bi-level coaches, a locomotive and a non-powered control unit.

Several international benchmarks of conventional passenger train performance in regional and long-distance intercity service are available. To provide a global context, these benchmarks and others obtained from the literature are compiled with the results showing significant variation (Table 2-18).

Oum and Yu (1994) explained international variation in passenger rail efficiency as being the result of various organizational, policy, societal, service and financial objectives of each national

Table 2-18. International benchmarks of conventional passenger rail service.

Country	Service	Propulsion	Energy Intensity (Btu/pass-mi)	Source
Canada	VIA Corridor	Diesel	1,699	English et al. (2007)
Spain	Intercity	Electric	1,427	Alvarez (2010)
Sweden	Conventional (8-car train)	Electric	590	Andersson and Lukaszewicz (2006)
	Conventional (4-car train)	Electric	650	
	OTU* Multiple-unit	Electric	379	
Norway	Signatur Long Distance	Electric	434	
UK	InterCity	Diesel	1,081	Dincer and Elbir (2007)
Turkey	Intercity	Diesel	1,560	
Italy	Intercity	Electric	274	Federici et al. (2008)
Denmark	InterCity	Diesel	790	Jorgensen and Sorenson (1997)
	Regional	Diesel	1,370	

* Öresund Train Unit

passenger rail network. The authors developed an index to measure the overall efficiency of passenger rail operations and determined that the leading nations at the time were Japan, the United Kingdom, Sweden and the Netherlands, followed closely by Denmark and Finland. The least efficient nations were Greece and Belgium.

Andersson and Lukaszewicz benchmarked the energy intensity of conventional Swedish passenger trains at 590 Btu per passenger-mile for electrified locomotive-hauled eight-car trains and 650 Btu per passenger-mile for electrified locomotive-hauled four-car trains. The authors also presented the energy intensity of several higher-speed electric trainsets operating in Norway (Signatur) and between Sweden and Denmark (Öresund train unit [OTU] multiple unit). Dincer and Elbir (2007) benchmarked the efficiency of passenger rail service in Turkey at 1,560 Btu per passenger-mile and in the UK at 1,081 Btu per passenger-mile. Federici et al. (2008) benchmarked the electrified intercity passenger rail service in Italy at an energy intensity of 274 Btu per passenger-mile. Jorgensen and Sorenson (1997) reported that diesel passenger trains in Denmark have energy intensities ranging from 790 Btu to 1,370 Btu per passenger-mile, depending on the load factor of the region and type of service. Comparing these values to the values given in Table 2-17, there is clearly room for improvement of domestic passenger train efficiency.

2.3.3 High-Speed Rail

Currently no domestic operations meet the International Union of Railways (UIC) definition of true HSR of 250 kmh (155 mph) over extended distances on dedicated lines, and only the Amtrak Acela meets the definition of 200 kmh (124 mph) for specially upgraded lines. Because Amtrak does not track the energy consumption of specific trains on the Northeast Corridor, no data are available to provide a benchmark for domestic electric high-speed train energy consumption.

Several researchers, including Levinson et al. (1997) and Chester and Horvath (2008, 2010), have examined the case of true HSR and its associated energy consumption and emissions. These studies take a full lifecycle approach, so their treatment of energy consumption is at a high level and is based on averages of various European HSR systems. The authors conclude, however, that California HSR will need to achieve, at a minimum, medium load factors in order to achieve better energy efficiency and emissions reductions than competing modes.

Von Rozycki et al. (2003) conducted a unique assessment of the energy consumed by the high-speed ICE service, designed to operate at 250 kmh, between Hanover and Würzburg in Germany. The authors calculated that the ICE train consumed 22.5 kWh of electricity per train-kilometer for traction and that an additional 1.35 kWh per train-kilometer were consumed by train on-board functions and amenities (Table 2-19). The authors also determined an amount of "overhead energy"—1.20 kWh per train-mile—consumed in servicing, maintaining and making up the train. Finally, the authors considered access to the station by car, with an energy consumption of 0.945 liters of petrol per passenger. The authors also considered the ICE train load factor to determine the energy consumption per passenger-km and adjusted this value to reflect the generation efficiency of traction power supply. The access mode trip makes up about 18% of the energy consumed in the HSR passenger trip.

As noted by Bosquet et al. (2013), special considerations are required to model the energy consumption of high-speed trains. Energy consumption increases rapidly with increasing speed as illustrated by SYSTRA (2011) simulation results for energy consumed at the wheels for two different trainsets (Table 2-20). At higher speeds, considerable increases in energy consumption are required for small improvements in travel time. To cut the base (200 kmh) travel time in half, energy consumption more than triples. However, as noted by Garcia (2010),

Table 2-19. Energy consumption of German HSR Hanover–Würzburg ICE corridor (Von Rozycki et al. [2003]).

Component	Consumption (kWh/train-km)	(kWh/train-mi)	(kWh/pkm)	(kWh/pmi)	Energy Intensity (kJ/pkm)	(Btu/pmi)
Traction	22.5	36.2	0.0731	0.1176	755	1,152
On-board Services	1.35	2.2	0.0044	0.0071	33.5	51
Train Make-up	1.20	1.9	0.0039	0.0063	25.1	38
Passenger Automobile Access	**(L/pass)**	**(gal./pass)**	**(g/pkm)**	**(gal./pmi)**		--
	0.945	0.25	4.2	0.0024	184	281
Total					998	1,522

pkm = passenger-kilometer; pmi = passenger-mile; U.S. units derived from the metric units

reducing travel time decreases the total energy consumed by on-board train services and amenities. The two trainsets considered in Table 2-20 are the French TGV-Réseau, with 375 seats, and the 11-car AGV-11, with 460 seats. The AGV-11, with its distributed power configuration, is more efficient than the TGV-Réseau, with its concentrated locomotive power. When the number of seats per train is considered, the AGV-11 becomes even more energy efficient than the TGV-Réseau.

With railway operation in Europe divided between rail infrastructure companies and train operating companies that pay for track access and traction energy, the energy consumption of individual trains is monitored much more closely than it is in North America. Thus, actual measured energy consumption of high-speed trains over particular route segments is more prevalent in the literature. Jorgensen and Sorenson (1997) presented measured energy consumption of German ICE and French TGV train runs (Table 2-21). Although the consumed energy largely parallels the average speed, it is also influenced by the number of intermediate stops on the segment, the grade profile and the exact model of train in use on the route.

As part of the New Lines Program, Network Rail in the UK conducted a study in 2009 analyzing the relative environmental impacts of conventional rail and HSR. This study has supplied many efficiency and emissions benchmarks for existing HSR systems around the world (Table 2-22).

Table 2-20. Simulated energy consumption of two high-speed trainsets at different speeds (SYSTRA [2011]).

Speed (kmh)	Speed (mph)	Time to Cover 100 km (min)	TGV-Réseau Consumption* (kWh/tkm)	TGV-Réseau Consumption* (kWh/tmi)	AGV-11 Consumption* (kWh/tkm)	AGV-11 Consumption* (kWh/tmi)
200	124	30	8.25	13.3	7.31	11.8
250	155	24	11.19	18.0	10.52	16.9
300	186	20	16.25	26.2	14.36	23.1
350	217	17	21.31	34.3	18.83	30.3
400	249	15	27.08	43.6	23.92	38.5

tkm = train-kilometers; tmi = train-miles

*The authors indicate that "calculation estimates energy at the wheel, neglecting transmission and rolling stock losses, hotel power, and so forth; the assumed infrastructure is perfectly flat and straight, with no wind. Acceleration and braking are not taken into account."

Table 2-21. Measured energy consumption of different high-speed line segments (Jorgensen and Sorenson 1997).

Service	Segment	Segment Length (km)	Segment Length (mi)	Average Speed (kmh)	Average Speed (mph)	Energy Consumption (kWh/tkm)	Energy Consumption (kWh/tmi)
ICE	Hamburg–Hanover	178	111	146	91	20.8	33.5
	Hanover–Göttingen	100	62	190	118	26.0	41.9
	Göttingen–Kassel–Wilhelmshöhe	45	28	138	86	32.4	52.1
	Kassel–Wilhelmshöhe–Fulda	89	55	178	111	32.9	52.9
	Fulda–Frankfurt	104	65	114	71	22.3	35.9
	Frankfurt–Mannheim	78	48	114	71	23.1	37.1
	Mannheim–Stuttgart	107	66	160	99	25.7	41.4
	Stuttgart–Ulm	93	58	95	59	19.6	31.5
	Ulm–Augsburg	86	53	129	80	19.5	31.3
	München–Augsburg	61	38	118	73	26.4	42.4
	Average					24.1	38.8
TGV Sud Est	Paris–Lyon (2 stops)	427	265	214	133	17.4	27.9
	Paris–Lyon (3 stops)	427	265	200	124	17.7	28.5
TGV Atlantique	Paris–St Pierre des Corps	221	137	240	149	22.0	35.4
	St Pierre des Corps–Bordeaux	348	216	144	89	13.2	21.2
TGV-Réseau	Paris–Lille	226	140	229	142	18.8	30.2
TGV Duplex	Paris–Lyon (2 stops)	427	265	270	168	17.7	28.4
	Paris–Lyon (3 stops)	427	265	270	168	18.0	29.0
	Paris–Lille	226	140	229	142	19.0	30.5

tkm = train-kilometers; tmi = train-miles

Janic (2003) benchmarked both German and French HSR energy efficiency at 0.044 kWh per seat-kilometer for the TGV and 0.058 kWh per seat-kilometer for the German ICE. Andersson and Lukaszewicz (2006) benchmarked the Swedish X2000 high-speed passenger trains with energy intensity of 0.042 kWh per seat-kilometer and 0.077 kWh per passenger-kilometer. The energy intensity of high-speed trains in Spain was quantified as 0.051 kWh per seat-kilometer by Jorgensen and Sorenson (1997) and 0.190 kWh per passenger-kilometer by Alvarez (2010). Le Maout (2012) reported on the efficiency of several routes in Japan and France in terms of kWh per passenger-kilometer.

Table 2-22. International benchmarks of HSR passenger service.

Country	Train/Service	Seats	*Speed* (kmh)	(mph)	*Energy Intensity* (kWh/skm)	(kWh/smi)	*Energy Intensity* (kWh/pkm)	(kWh/pmi)	Source
UK	Class 91 InterCity 225	536	200	124	0.035	0.056	--		1
UK	Class 390 Pendolino	439	225	140	0.033	0.053	--		1
UK	Hitachi Super Express	649	200	124	0.028	0.045	--		1
UK	Class 373 Eurostar	750	300	186	0.041	0.066	--		1
France	TGV Sud Est	347	300	186	0.044	0.071	--		2
France	TGV-Réseau	377	300	186	0.039	0.063	--		1
France	TGV Duplex	545	300	186	0.037	0.060	--		1
France	AGV	650	300	186	0.033	0.053	--		1
Germany	ICE-1	743	250	155	0.058	0.093	0.073	0.117	2
Spain	AVE Series 1	329	270	168	0.051	0.082	0.190	0.306	3
Spain	AVE Series 103 Velaro	545	300	186	0.039	0.063	--		1
Japan	Tokaido 700	1,323	270	168	0.028	0.045	0.028	0.045	4
Japan	Tokaido N700	1,323	300	186	--	--	0.023	0.037	4
Japan	Tohoku E2	815	275	171	--	--	0.026	0.042	4
Japan	Tohoku E5	731	320	199	--	--	0.026	0.042	4
Sweden	SJ2000	320	210	130	0.042	0.068	0.077	0.124	5

pkm = passenger-kilometers; pmi = passenger-miles; skm = seat-kilometers; smi = seat-miles

Sources: Network Rail (2009); Janic (2003); Alvarez (2010); Le Maout (2012); Andersson and Lukaszewicz (2006)

CHAPTER 3

Simulation Methodology: The Multi-Modal Passenger Simulation Tool

Traditionally, gross annual average energy consumption metrics have been used to quantify the energy efficiency of passenger rail operations. However, as shown in Chapter 2, passenger rail energy efficiency varies significantly among routes that have different operating speeds and train consist configurations, and is greatly influenced by load factor. That being the case, averages are not useful in analyzing the energy efficiency of individual passenger train runs.

To move away from simple averages, the project team developed the Multi-Modal Passenger Simulation Tool (MMPASSIM), a Microsoft® Excel-based simulation model that quantifies energy consumption and GHG emissions of passenger rail transportation and competing passenger modes for door-to-door passenger trips. MMPASSIM has four primary applications, which are illustrated through case studies in later chapters of this report:

- **single-train simulation,** to determine the energy and GHG emissions intensities of a passenger rail trip on the rail modal leg from departure to arrival station;
- **technology evaluation,** to determine the sensitivity of rail modal leg energy and GHG emissions intensities to changes in rail equipment, operating and infrastructure parameters;
- **single-train simulation with access modes,** to determine the energy and GHG emissions intensities of a complete door-to-door passenger rail trip from origin to destination, including access to the departure station and egress from the arrival station; and
- **modal comparison,** to benchmark the energy and GHG emissions intensities of a complete door-to-door passenger rail trip against light-duty vehicle (LDV), bus and air travel modes.

Accomplishing all of the above tasks requires a flexible energy model of each passenger transportation mode, and a particularly robust set of parameters to describe the rail mode. Given its complexity, the internal workings of MMPASSIM are not fully explained here; rather, they are detailed in a companion User Guide for the simulation tool. NCRRP Web-Only Document 1 provides the technical details of the simulation model—MMPASSIM—as well as the User Guide. Both documents also appear in CRP-CD 176, which accompanies this report.

To provide some context for the analysis in subsequent chapters, the remainder of this chapter provides a high-level description of each module, simulation inputs and simulation outputs.

3.1 Rail Module and Required Inputs

The following sections provide an overview of MMPASSIM and the principal inputs/outputs involved.

MMPASSIM simulates the energy consumption of rail movements using a simplified train performance calculator based on traditional train energy and resistance methodology. It differs from more detailed train performance calculators by aggregating gradient and curvature along a route into a distribution, rather than simulating the train movement over a specific elevation profile and geometric alignment.

Basic train resistance is calculated for each segment. Kinetic energy from acceleration of the train is calculated and used to find the braking energy (either regenerated or dissipated as heat in friction or dynamic brakes). Additional energy components related to the gradients and curvature along the route, braking used to maintain speed limits on down grades, and head-end power (HEP) are calculated. The output energy consumption values are separated into totals of inherent resistance, brake dissipation, track curvature/grade resistance, and HEP.

Simulations of electric traction systems use regional electricity generation intensities to create like-for-like comparisons with conventional diesel-electric traction. This is achieved by adding to the output values the incremental energy consumed in the generation of the electricity used by the train.

The rail module requires the following sets of inputs:

- passenger rolling stock characteristics;
- route characteristics;
- trip characteristics (e.g., load factor, schedule time); and
- access and egress modes.

3.1.1 Passenger Rolling Stock Characteristics

MMPASSIM can use detailed train consist information, resistance coefficients, HEP configuration, traction power and other inputs in the calculation of energy consumption.

Estimates for several common train consists were developed for use with the model (Appendix A). Because most domestic passenger rolling stock does not have published or publicly available train resistance coefficients, they must be estimated based on the CN Train Resistance Model and the size and weight of each locomotive and railcar. Information on railcar and locomotive size and operating weight is most easily obtained from manufacturer websites or the *Official Railway Equipment Register*. MMPASSIM also is capable of using user-defined train consists if practitioners have access to more detailed equipment characteristics.

More-specific groups of rolling stock input parameters are:

- number of locomotives/power cars and number of railcars or unpowered units;
- number of seats (Seating configurations can be obtained from equipment manufacturer or operator websites.);
- total train weight and consist length;
- train resistance coefficients (a) N, (b) N/kmh and (c) N/(kmh)^2, where N = Newtons and kmh = kilometers per hour, input from known equipment specifications or tests, or derived via empirical formulas that calculate each coefficient based on the train weight;
- transmission efficiency coefficients;
- propulsion and fuel types;
- nominal traction power of the power unit;
- prime mover energy consumption;
- dynamic braking characteristics, including regeneration and wayside storage; and
- HEP configuration.

Table 3-1 gives an example of a partial set of rolling stock and route input parameters for a single-train simulation. Details of grade, curve and speed are not shown in the example.

Table 3-1. Partial sample of rail inputs for single-train simulation.

Rail Equipment Parameters

Parameter	Value	Notes
Consist Description	1 MP36PH Locomotive, 4 Bi-level Coaches	Assumed as typical operations
Total Loaded Mass (kg)	441,444	Literature review
Total Length (m)	124.35	Literature review
a (N)	3,468	Literature review
b (N/kmh)	39.27	Literature review
c $[N/(kmh)^2]$	0.673	Literature review
Nominal Traction Power (kW)	2,685	Literature review
Primary Fuel Type	U.S. Conventional Diesel	Assumed for locomotive type
Hotel Power Provision Code	2 (PTO* Fixed-speed Main Engine)	Assumed for locomotive type
Energy Recovery Type	0 (None)	Assumed for locomotive type

Rail Route Parameters

<table>
<tr><th>Parameter</th><th colspan="4">Value</th><th>Notes</th></tr>
<tr><td>Scheduled Stops</td><td colspan="4">7</td><td>Metro Transit Northstar Route 888 Schedule</td></tr>
<tr><td rowspan="3">Average Expected Speed Reductions per One-Way</td><td>Number</td><td>Speed (mph)</td><td colspan="2">Length (mi)</td><td rowspan="3">Assumptions based on engineering judgment</td></tr>
<tr><td>0.2</td><td>25</td><td colspan="2">0.2</td></tr>
<tr><td>0.4</td><td>40</td><td colspan="2">0.1</td></tr>
<tr><td rowspan="2">Average Expected Unscheduled Stops per One-Way</td><td>Number</td><td>Speed (mph)</td><td>Length (mi)</td><td>Duration (min)</td><td rowspan="2">Assumptions based on engineering judgment</td></tr>
<tr><td>1</td><td>25</td><td>0.5</td><td>2.4</td></tr>
</table>

* Power take-off

3.1.2 Route Characteristics

To provide route-specific energy consumption and GHG emissions analyses, MMPASSIM requires information on the station stopping pattern, maximum authorized passenger train speed, gradient and curvature along the route of interest. Station stopping patterns can be obtained from posted train schedules and operator websites. Speed, curvature and gradient data can be obtained from a combination of employee timetables and railway track charts. If these documents are not available to practitioners, various GIS approaches can be used to estimate curve and grade profiles along the route. Grade, curve and speed data for specific routes also was published in Volume 1 (covering baseline data) of the *Improved Passenger Equipment Evaluation Program—Train System Review Report* (Bachman et al. 1978). The MMPASSIM tool contains a pre-processor to convert gradient, curvature and speed data by milepost into the format required by the model.

More-specific groups of rail route input parameters are as follows:

- Grade profile
- Curvature
- Speed limits, including special restrictions for conventional and tilt-body railcars

- Location of station stops
- Presence of wayside storage at each station
- Speed limit in sidings
- Expected number of speed restrictions and unplanned stops
- Extra idle time and non-revenue miles
- Boundaries of fuel-energy use for dual-mode locomotives

With regard to the expected speed restrictions and unplanned stops, unless a specific train with a known speed profile or event recorder data is being simulated, these values are subject to the judgment of the user. These parameters can be adjusted to reflect the amount of traffic on the route, the number of tracks and the relative priority of the train being modeled. Idealized results also can be obtained by eliminating speed restrictions and unplanned stops.

3.1.3 Load Factor

Calculation of energy efficiency and GHG emissions per passenger-mile requires information on the ridership of each evaluated passenger rail service. Ideally, the ridership load factor (percent of seats occupied) would correspond to specific train runs. Ridership information is of particular importance for commuter rail systems, for which the load factor can vary considerably throughout the day. MMPASSIM allows the user to input specific load factor information if the user has the data for their system.

For users who do not have access to proprietary data, published information for most passenger rail operations only provides gross annual average ridership and load factor data. These data must be used to consider average ridership, with the per seat-mile values serving as a proxy for periods of peak ridership when most seats are full and efficiency is maximized.

Analysis of the National Transit Database (NTD) in 2011, combined with passenger railcar seating data compiled by the project team, suggests that commuter rail services operate with average load factors between 20% and 40%.

For intercity service, the published Amtrak system-wide average load factor is 0.47. Chester and Horvath (2010) indicate that Amtrak regional intercity passenger service operates with a 35% load factor on average. This suggests that Amtrak trains in the Northeast Corridor operate at higher load factor.

Jorgensen and Sorenson (1997) indicate that the high-speed rail (HSR) systems in France and Germany operate with load factors between 45% and 65% on average. Network Rail (2009) determines that certain routes in Spain and France operate at load factors between 70% and 80%. Levinson at. al. (1997) recognize that load factor will fluctuate greatly over the course of the day, reaching 90% during the peak morning and evening travel periods but dropping as low as 10% to 20% during off-peak times of low demand.

Load factors for the case study routes are discussed in more detail in the summary and ridership section in Chapter 4.

3.1.4 Access and Egress Modes

When modeling a door-to-door trip, MMPASSIM requires information on the transportation modes and distances traveled between (a) the trip origin and the departure station and (b) the arrival station and trip destination.

Access and egress modes and distances can be specified by a user who is modeling a specific passenger trip. Multiple access and egress modes can be selected (e.g., walking to the subway).

Dwell time is defined as the idle wait time between modal leg trips or between access and egress legs. Dwell time is included in the results for each case study as a component of the total travel time, calculated as the sum of the total dwell time and the run time of each main travel and access mode segment.

Absent information on specific access and egress mode or providing a composite measure of passengers using different modes, default access and egress modal distributions have been developed for MMPASSIM (Appendix B). Based on public data released in operator annual reports and other ridership studies, commuter, regional intercity, long-distance intercity and HSR services all have distinct patterns of transportation modes used at either end of the rail portion of the trip.

In calculating the door-to-door energy use and GHG emissions of the passenger rail trip, MMPASSIM does not simulate the energy consumption of access and egress modes in detail. Instead, the model uses average values of energy intensity for these modes. The Technical Document included on CRP-CD 176 and in NCRRP WOD 1 includes a section on access and egress modes characterization that presents additional discussion of the assumptions made in developing average energy and GHG emissions intensities for the various access and egress modes.

3.2 Highway Module and Required Inputs

Main travel segments using automobile LDVs are defined in MMPASSIM by the chosen route (with associated distance, grade and congestion characteristics), number of travelers, time of day, season and vehicle characteristics (available seats, vehicle type and fuel type). Data for vehicle types include averages of the purchased and driven fleets for recent years, or data for specific types of automobiles, such as sedan, truck, sport-utility vehicle, and so forth. The automobile engine fuel map is particularly important in calculating energy efficiency and GHG emissions (Appendix C).

Highway gradient and traffic congestion can have a significant effect on the energy consumption of autos and buses. Therefore, MMPASSIM provides the user with the ability to specify the gradient and congestion distributions on the highway route (Appendix D). GIS techniques were used to create highway gradient distributions from digital elevation models along the case study routes simulated in this study. Gradient does not have as significant an influence on energy intensity of the highway modes as congestion does, and MMPASSIM users can, in most cases, select one of the gradient profiles derived for the case study locations that are included with the model. Congestion is more varied, and the user might wish to generate a specific congestion profile or modify the case study congestion profiles. The American Transportation Research Institute has developed a National Corridors Analysis and Speed Tool (N-CAST) that can be used to infer the level of traffic congestion on a particular route at a given time of day for many major highways.

On extended intercity trips, the effects of congestion vary along the route as the highway user moves through urban areas. This variability affects urban centers—those at the start and end of a trip along with any congested areas encountered along the route. In MMPASSIM, extended trips also include an allowance for a reasonable number of stops for rest, food and fuel. Additional miles of congested vehicle travel are shifted from open freeway speed profiles to more congested profiles to account for intermediate congested areas on long-distance trips.

Table 3-2 shows a partial example set of highway input parameters for a modal comparison (details of grade not shown).

Table 3-2. Sample auto, bus and air inputs for modal comparison.

Auto Route Parameters

Parameter	Value		Notes
Description	I-35 to I-35W		Google Maps route choice
Urban Freeway Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion
	8	37	
Urban Arterial Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion
	3	1	
Intercity Freeway Distance (mi)	154		Determined by total trip distance minus urban distances
Wayside Stops (Engine Idle)	Number	Duration (min)	General assumption
	1	2	

Bus Route Parameters

Parameter	Value		Notes
Description	I-35 to I-35W		Google Maps route choice
Urban Freeway Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion; intercity freeway distance shifted to urban freeway distance to account for congestion around stops
	16	73	
Urban Arterial Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion; intercity freeway distance shifted to urban freeway distance to account for congestion around stops
	3	1	
Intercity Freeway Distance (mi)	110		Determined by total trip distance minus urban distances
Intermediate Urban Arterial and Bypass (mi)	26		Additional 7 km per stop
Wayside Stops	Number	Duration (min)	Greyhound Bus schedule
	6	5	

Air Parameters

Parameter	Value				Notes
Airports	OKC		DFW		OpenFlights Airport Database
Latitude/Longitude	35.39	-97.60	32.90	-97.04	OpenFlights Airport Database

Bus alternatives are defined by the chosen route (with associated distance, grade and congestion characteristics), number of travelers, time of day, season, passenger load factor and vehicle characteristics (available seats, bus type and fuel type). Bus trips also can include access and egress modes.

Bus trips can be modeled as non-stop express services but will usually include scheduled stops with additional miles of travel as appropriate. As with automobile trips, allowances are made for a reasonable number of extended rest, food and fuel stops. At each stop, an additional distance on arterial roads is added to account for the bus traveling from the main freeway to the appropriate station. Five minutes of additional idle time at each stop was included in the case study simulations to account for driver breaks and station dwell time.

3.3 Air Module and Required Inputs

Air mode alternatives are defined in MMPASSIM by the chosen airport pair (airport latitude and longitude coordinates), number of travelers, passenger load factor, time of day, season and aircraft characteristics. MMPASSIM calculates the great circle (GC) distance of the flight based on the specified airport coordinates. The user can specify either non-stop flights or hub-and-spoke flights with up to two intermediate stops for a trip.

By default, MMPASSIM simulates a distribution of aircraft types representative of the national average mix of aircraft in scheduled commercial passenger service in the United States (Table 3-3). The user can, however, define specific distributions to more accurately represent the aircraft types in use between certain origin-destination pairs or the specific aircraft type of those available on a route that the user selects (e.g., a regional jet rather than a turboprop).

In most cases, the user will specify direct air service using non-stop flights. Previous research has shown that the additional take-off and landing cycles required for stops to change aircraft greatly degrade aircraft energy and GHG emissions performance metrics for a given trip. Nonetheless, some travelers on long intercity trips involving smaller local communities combine local feeder service flights at the end points with a long intercity flight between the major cities, and the model allows these trip scenarios to be simulated.

Like the rail module, the air module includes access and egress modes between the origin and departure airport and between the arrival airport and final destination. To account for travel to and from the airport, appropriate energy and GHG emissions data are added to the air trip according to the selected access/egress modes.

3.4 MMPASSIM Outputs

MMPASSIM calculates the energy consumed by the main modal travel segments and the access and egress modes (where applicable). Energy consumption is reported in either U.S. or metric units, as specified by the user. With metric chosen, the energy consumption outputs are:

- kJ per round trip,
- kJ per seat-mile, and
- kJ per passenger-mile.

Depending on the type of fuel consumed or the regional electric generation profile, the energy consumed by the passenger trip is reported as an equivalent amount of CO_2 emissions. The CO_2

Table 3-3. Default aircraft distribution.

	% seat-miles by aircraft type for different great circle (GC) distance ranges						
Lower-distance (km)	0	402	805	1207	1609	2414	3219
Lower-distance (mi)	0	250	500	750	1000	1500	2000
Segment Number	1	2	3	4	5	6	7
Turboprop	81.5%	6.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Small Regional Jet	16.5%	6.1%	0.0%	0.0%	0.0%	0.0%	0.0%
Regional Jet	1.9%	80.0%	22.0%	4.5%	0.0%	0.0%	0.0%
Narrow-body Jet	0.1%	8.0%	78.0%	94.9%	92.1%	77.7%	0.0%
Wide-body Jet	0.0%	0.0%	0.0%	0.6%	7.9%	22.3%	100.0%

equivalent (CO_2e) measure applies the relative global warming potential of other greenhouse gases (GHG) in proportion to their thermal impact. On a unit-mass basis, methane (CH_4) has 25 times the impact of CO_2, and nitrous oxide (N_2O) has 298 times the impact of CO_2. Thus, combined GHG emissions are calculated as

$$CO_2e = 1 \times CO_2 + 25 \times CH_4 + 298 \times N_2O. \qquad (1)$$

The CO_2e of the various fuel types used by MMPASSIM are summarized in Table 3-4. With metric chosen, GHG emissions are reported as:

- kg of CO_2e per round trip,
- kg of CO_2e per seat-mile, and
- kg of CO_2e per passenger-mile.

Upstream emissions (alternatively called *indirect* or *well-to-pump* emissions) are calculated by multiplying the quantity of a fuel consumed by an emission factor. The Argonne National Laboratory GREET model was used to derive the energy content, fuel density, upstream energy use and upstream emissions of CO_2, CH_4 and nitrous oxide (N_2O) gases in providing fuels for direct consumption at the pump. The GREET model was also used to derive upstream energy use and emission factors in the provision of electricity for transportation use in various regions of the United States. These default data are provided in tables located in the Energy-Emission worksheet of the MMPASSIM spreadsheet tool.

Direct GHG emissions are those produced by the consumption of fuel or energy while operating a vehicle. MMPASSIM calculates direct GHG emissions by multiplying the fuel quantity consumed by the direct emission factor associated with a vehicle type and fuel. The direct emission factors are derived from multiple sources, depending on the transportation mode, and are tabulated in the Energy-Emission worksheet to the right of the respective upstream emission factors. Table 3-4 summarizes these direct CO_2e emission factors.

In the Energy-Emission worksheet, comments are provided in the relevant cells to identify the source of the data values used. For the rail mode, EPA-published values of CO_2, CH_4 and N_2O emission factors for direct consumption of diesel and biofuels in railroad transportation have been used. EPA's published emission factors for GHG inventories can be found online by

Table 3-4. CO_2e for various fuels.

Fuel	CO_2e	Unit
Locomotive Diesel	10.31	kg/gal.
Locomotive Biodiesel	9.54	kg/gal.
Locomotive LNG	6.10	kg/gal.
Locomotive CNG	1.71	kg/lb
Electricity U.S. Northeast Mix	0.40	(kg/kWh)
Electricity U.S. South Mix	0.61	(kg/kWh)
Electricity U.S. Midwest Mix	0.73	(kg/kWh)
Electricity U.S. West Mix	0.42	(kg/kWh)
Electricity Continental U.S. Mix	0.58	(kg/kWh)
Bus Diesel	10.29	kg/gal.
Jet Fuel	9.84	kg/gal.
Automotive Gasoline	8.83	kg/gal.
E05–LS Gasoline	8.71	kg/gal.
E10–LS Gasoline	8.58	kg/gal.
Automotive Diesel	10.46	kg/gal.

searching on www.epa.gov. Emission factors for methane (CH_4) and nitrous oxide (N_2O) when rail locomotives burn liquefied natural gas (LNG) are estimated from test results of an Energy Conversions Inc.'s conversion of a SD40-2 locomotive (BNSF Railway Company et al. 2007) while the default EPA value for CO_2 emissions from direct consumption of LNG was used. Factors for compressed natural gas (CNG) emissions were inferred from the LNG values, because both fuels are in the same state when burned.

For the bus mode, Canadian default emission factors for CO_2, CH_4 and N_2O are used (Climate Registry Default Emission Factors 2012). The default emission factors in the Canadian registry are expressed in terms of the quantity of fuel consumed, whereas default EPA values for CH_4 and N_2O emissions from on-road diesel fuel consumption are expressed per mile of travel of an assumed national average vehicle.

EPA does provide a CO_2 emissions factor for on-road diesel consumption, but the Canadian value is used for consistency (and the Canadian value used is within 0.29% of the U.S. default value). Comments provided with the individual cells of the Energy-Emission worksheet identify the source tables for the data elements.

For air transportation, EPA-published default values for CO_2, CH_4 and N_2O emissions per gallon of jet fuel consumed are used. As discussed in the section on the air mode analytic framework in NCRRP WOD 1, air emissions at high altitudes have a higher global warming effect, and MMPASSIM scales emissions for this portion of jet aircraft trips.

For automobiles and LDVs, direct CO_2 emissions are estimated from EPA-published values. CH_4 and N_2O emissions intensities vary with a vehicle's age, however, and the LDV model includes characterizations of a range of average vehicle types as well as yearly fleet average vehicles, which are estimated using data published by EPA. Additional details are provided in NCRRP WOD 1 in the section on adjustment of LDV characteristics to reflect driving conditions.

MMPASSIM reports energy and GHG emissions intensity metrics in three tables that correspond to different levels of analysis, as illustrated in Table 3-5. For modal comparisons, the MMPASSIM output includes both raw metrics and values indexed to rail. When indexed to rail, values greater than 1 indicate modes that consume more energy and produce more GHG emissions than rail as quantified by that particular metric. For a given mode, the values indexed to rail vary between metrics and analysis levels based on ridership load factor, the specific travel distance on each mode (i.e., route circuitry), fuels consumed, regional electricity generation profile and access/egress modes.

In Table 3-5, part (a) shows the analysis of *modal leg direct activity*, which includes the energy and GHG emissions of a passenger trip on the main modal travel segment from departure to arrival station/airport. For auto trips, this encompasses the entire trip from origin to destination. For electric propulsion, these values include energy consumed and GHG emissions produced in the generation of electricity.

Part (b) shows the analysis of *door-to-door direct activity*, which adds direct energy and GHG emissions of access and egress trip segments to the modal leg direct activity where appropriate. Since auto trips are assumed to be a single segment from origin to destination, there is no change from the modal leg direct activity values reported in the first group.

Part (c) shows the analysis of door-to-door activity *including indirect well-to-pump consumption/emissions*, which adds upstream energy and GHG emissions required for exploration, recovery, transportation, and refinement of the fuels consumed by internal combustion and electricity generation. These values do not include energy and GHG emissions associated with station/airport services, infrastructure construction or vehicle manufacturing. The NCRRP study team adopted E05 (5% corn-based ethanol) as the representative LDV fuel. When considering

Table 3-5. Example modal comparison output.

(a) Modal Intensity Comparison (modal leg only, direct activity only)

Category		Intensity Measures*						Service Metrics
Divisor		per round trip		per seat-mi		per passenger-mi		Travel Time
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(hrs)
Rail	Value	560,903	99	681	0.120	1,621	0.287	7.3
Auto/ LDV#	Value	1,851,994	318	1,345	0.231	5,380	0.922	6.8
	indexed to rail	3.30	3.20	1.98	1.91	3.32	3.22	0.93
Air	Value	1,458,278	269	4,020	0.741	5,627	1.037	4.5
	indexed to rail	2.60	2.71	5.90	6.15	3.47	3.62	0.62
Bus	Value	321,330	57	483	0.085	848	0.150	7.6
	indexed to rail	0.57	0.57	0.71	0.71	0.52	0.52	1.04

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

(b) Modal Intensity Comparison (door-to-door, direct activity only)

Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	654,050	115	1,811	0.318
Auto/LDV#	Value	1,851,994	318	5,380	0.922
	indexed to rail	2.83	2.76	2.97	2.90
Air	Value	1,964,079	354	6,325	1.139
	indexed to rail	3.00	3.08	3.49	3.58
Bus	Value	449,195	78	1,147	0.200
	indexed to rail	0.69	0.68	0.63	0.63

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

(c) Modal Intensity Comparison (door-to-door, including indirect well-to-pump consumption)

Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	785,017	144	2,173	0.397
Auto/LDV#	Value	2,387,049	414	6,934	1.202
	indexed to rail	3.04	2.88	3.19	3.02
Air	Value	2,288,689	448	7,370	1.444
	indexed to rail	2.92	3.12	3.39	3.63
Bus	Value	539,194	98	1,377	0.250
	indexed to rail	0.69	0.68	0.63	0.63

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

Table 3-6. Reported and simulated energy intensity on validation corridors.

Corridor	Source	Reported Energy Intensity (kJ/skm)	Reported Energy Intensity (Btu/smi)	Simulated Energy Intensity (kJ/skm)	Simulated Energy Intensity (Btu/smi)	Percent Deviation
Amtrak Heartland Flyer	Smith and Shurland (2013)	377	574	382	583	+1.5
Minneapolis Metro Transit Northstar	NTD (2011)	405	618	363	554	-10.4

skm = seat-kilometers; smi = seat-miles

upstream LDV emissions, ethanol can include an offsetting credit for the growth of corn; however, there are differing opinions on the validity of taking this credit for a crop that would be grown anyway. The study team shows LDV-E05 upstream GHG emissions without the credit but indicates in a table footnote what the difference in GHG emissions would be if the credit were included.

3.5 Rail Model Validation

Energy data are available on which to build a model for both air mode and the automobile/LDV mode. The model's validation for the air and auto data is discussed in NCRRP WOD 1. Rail mode has less data available from operators, but data for resistance coefficients and locomotive efficiency performance are publicly available. To validate the MMPASSIM output, reported energy intensity of specific passenger services identified during the literature review were compared to results of MMPASSIM single-train simulations of the same services. Based on data availability, data quality and consistency of operations, the Amtrak Heartland Flyer between Fort Worth, TX, and Oklahoma City, OK, was selected as the regional intercity validation route. The Minneapolis Metro Transit Northstar was selected as the commuter rail validation route.

MMPASSIM single-train simulation inputs were set to reflect the route, equipment and operating characteristics of each validation route (detailed in Chapter 4 of this report). Given the assumptions involved in conducting the simulation and approximating train resistance coefficients with the CN model, the MMPASSIM "Modal Leg Direct Activity" output in kJ/seat-kilometer and Btu/seat-mile compare favorably with the reported energy intensity for each validation service (Table 3-6).

MMPASSIM also provides results that compare well with another simulation of a high-speed rail trainset (AGV) once the outputs have been adjusted to be a like-for-like measure (see the section on HSR in Chapter 4).

CHAPTER 4

Single-Train Simulation of Passenger Rail Energy Efficiency

This chapter presents a discussion of MMPASSIM models of the energy consumption and GHG emissions of selected passenger rail services in the United States. The services selected for the case studies represent the variety of commuter, regional intercity and long-distance intercity passenger rail operations found across the country. Single-train simulations were conducted to provide baseline energy consumption and GHG emissions values for each case study service and illustrate the variation in these metrics across different types of passenger rail operations.

For each passenger rail service developed as a case study, information about the rail route (e.g., vertical grade profile, horizontal curvature, station stops and timetable speed limits) was collected from railroad track charts or publicly available datasets and publications. Baseline energy intensity, GHG emissions and performance metrics for each case study service were established by simulating an appropriate train consist on each route under typical operating conditions.

4.1 Passenger Rail Systems and Services Evaluated

As indicated by previous research and the published benchmarks of passenger rail energy efficiency summarized in Chapter 2, rail mode efficiency varies according to the type of service, length of route, average speed and train consist. To capture this potential range of efficiency across passenger rail service in the United States, a spectrum of commuter, regional intercity, long-distance intercity and high-speed rail (HSR) services were selected for evaluation. Selection of case studies was also influenced by

- key corridors for ridership and train density;
- operations that had recently received upgrades or improvement projects; and
- systems with sufficient data available from publicly available sources.

Five commuter rail systems, nine regional intercity systems, two long-distance intercity systems, and one HSR system are analyzed via MMPASSIM single-train simulation case studies.

4.1.1 Commuter Rail Services

The five commuter rail case study services analyzed are primarily diesel-electric systems that use bi-level coaches characterized by high seating density. Operating characteristics for the commuter rail systems were obtained from annual reports to the National Transit Database (NTD) and train schedules published on operator websites.

4.1.1.1 Minneapolis: Metro Transit Northstar

Metro Transit in Minneapolis, MN, operates the Northstar commuter service over a distance of 40 miles between Big Lake, MN, and Minneapolis. This service uses diesel-electric locomotives and bi-level coaches with high seating density. A typical train consists of one locomotive and three passenger coaches with a total of 426 seats. As a new-start operation serving 10 stations, trains operate only during peak periods and in the dominant direction of commuter traffic (Metro Transit 2014). Route data for the Metro Transit Northstar was obtained from BNSF track charts (BNSF 2005).

4.1.1.2 Chicago: Metra BNSF

The Metropolitan Rail Corporation (Metra) is the commuter rail division of the Regional Transportation Authority in Chicago, IL. Metra serves 241 stations on 11 different commuter rail lines (Metra 2014). For this study, the 38-mile BNSF commuter rail line between Aurora, IL, and Chicago's Union Station was selected for analysis. Metra BNSF service operates with bi-level coaches and two different models of diesel-electric locomotives. One of the busiest Metra lines, this service operates frequently during peak and non-peak hours, using express scheduling patterns over different zones where trains only make stops at designated blocks of stations. The selected train schedule is an inbound morning peak run that includes seven station stops (Metra 2012). Local trains operate with a single locomotive, but some express trains operate with two locomotives. The case study train consist includes one locomotive and six passenger coaches with a total of 870 seats. Route data for the Metra BNSF line was obtained from BNSF track charts (BNSF 2005).

4.1.1.3 Seattle: Sounder South

Sound Transit in Seattle, WA, operates its Sounder commuter rail route between Seattle, WA, and Tacoma, WA, covering 40 miles with seven stops (Sound Transit 2014). This service operates with diesel-electric locomotives and bi-level coaches with high seating density. A typical train consists of one locomotive and four passenger coaches with a total of 568 seats. This service operates only during peak periods and mostly in the dominant direction of commuting traffic. Route data for the Sounder South line was obtained from BNSF track charts and FRA Improved Passenger Equipment Evaluation Program (IPEEP) report route tables (Bachman et al. 1978).

4.1.1.4 Los Angeles: Metrolink Orange

Metrolink, the Southern California Regional Rail Authority, operates the Orange commuter rail line from the greater Los Angeles region south through Orange County, CA. This service operates during peak and non-peak periods with diesel-electric locomotives and bi-level coaches. A typical train consists of one locomotive and four passenger coaches with a total of 568 seats. This service makes 15 station stops on the 86 miles between Oceanside and Los Angeles, CA (Metrolink 2014). The same route is also simulated with a Pacific Surfliner train consist (as described in the section on regional intercity rail services) that makes nine station stops over the same route segment. Route data for the Metrolink Orange Line was obtained from Union Pacific track charts, BNSF track charts and FRA IPEEP route table data (Bachman et al. 1978).

4.1.1.5 Washington, DC: MARC Penn Line

Maryland Area Regional Commuter (MARC) operates the Penn Line service in the Washington, DC and Baltimore, MD, metropolitan areas. The Penn Line serves 13 stations over 77 miles, using both diesel-electric and electric locomotives on a portion of Amtrak's Northeast Corridor (Maryland Transit Administration 2013). Diesel-electric locomotives are limited to 79 miles per hour, whereas electric locomotives can travel at 125 miles per hour. Bi-level coaches with high seating density are used on both diesel and electric services. Two different case study train consists were examined; both use five passenger coaches with a total of 650 seats, but one uses an electric locomotive and the other uses a diesel-electric locomotive. Route data for the MARC Penn Line was obtained from FRA IPEEP route tables and updated with more recent timetable speed data (Bachman et al. 1978; Amtrak 2008).

4.1.2 Regional Intercity Rail Services

The nine regional intercity passenger rail service case study routes range from approximately 125 miles to 450 miles in length and cover various regions of the United States. Operating characteristics for each route were obtained from public Amtrak train schedules.

4.1.2.1 Oklahoma City, OK–Fort Worth, TX: Heartland Flyer

Amtrak operates the Heartland Flyer service over a distance of 206 miles between Oklahoma City, OK, and Fort Worth, TX. The route has seven station stops. The service typically operates using one diesel-electric locomotive and three bi-level coaches with a total of 252 seats. Amtrak has tested alternative biodiesel fuels on this route, using a retrofitted diesel-electric locomotive (Shurland et al. 2012). Route data for the Heartland Flyer was obtained from BNSF track charts (BNSF 2005). In the past, the service has operated in a push-pull configuration with a non-powered control unit (NPCU). The service now sometimes uses a single locomotive and no NPCU, requiring extra distance at the terminals (3.5 miles total) to turn the train consist at a nearby wye.

4.1.2.2 Charlotte–Raleigh, NC: Piedmont

The North Carolina Department of Transportation (NC DOT), in cooperation with Amtrak, operates the 173-mile Piedmont service between Charlotte and Raleigh, NC. A typical train includes one diesel-electric locomotive and four single-level coaches with a total of 336 seats. This service operates two round trips daily with nine station stops. Route data for the Piedmont was obtained from Norfolk Southern track charts (Norfolk Southern 2002).

4.1.2.3 San Jose–Auburn, CA: Capitol Corridor

The Capitol Corridor Joint Powers Authority, in partnership with Amtrak, operates the Capitol Corridor service between Auburn and San Jose, CA. This service uses diesel-electric locomotives and bi-level coaches to offer seven round trips daily on the 168-mile, 17-station route. A typical train consists of one locomotive and four passenger coaches with a total of 360 seats. Route data for the Capitol Corridor was obtained from Union Pacific track charts.

4.1.2.4 New York City–Buffalo, NY: Empire Service

Amtrak operates the Empire Service between New York City and Albany, NY, with some of the 18 daily round trips extending to Buffalo, NY. This route has recently been upgraded to emerging HSR service, with trains operating at a maximum of 110 miles per hour on portions of the route (FRA 2009). The Empire Service uses dual-mode locomotives with diesel-electric and electric traction capabilities. Third-rail electric traction is used when entering tunnels to access New York Penn Station. The case study for NCRRP Project 02-01 considers a train covering 438 miles and serving 15 stations between New York City and Buffalo. The study train includes one dual-mode locomotive and five single-level passenger coaches with a total of 416 seats. Route data for the Empire Service was obtained from FRA IPEEP route tables and updated with more recent timetable speed data (Bachman et al. 1978; New York State DOT 2014).

4.1.2.5 Chicago, IL–Detroit, MI: Wolverine

Amtrak operates the Wolverine service over a distance of 258 miles and covering 14 stations between Chicago, IL, and Detroit, MI. This service uses diesel-electric locomotives with single-level coaches. A typical train includes one locomotive, four coaches with a total of 336 seats, and a baggage car. This route has recently been improved to support three round trips daily at 110 miles per hour; however, accurate speed limit and track chart data reflecting recent track speed upgrades were not available for use in *NCRRP Report 3.* Route data for the Wolverine service was obtained from FRA IPEEP route tables (Bachman et al. 1978).

4.1.2.6 Portland, OR–Seattle, WA: Cascades

Amtrak's Cascades service between Eugene, OR, and Vancouver, British Columbia, includes service between Portland, OR, and Seattle, WA. This service uses lightweight, tilting, single-axle, articulated single-level Talgo 12-car trainsets with a diesel-electric locomotive and control cab car. Each trainset has 340 seats. The case study examined for *NCRRP Report 3* considers a train covering 343 miles and serving eight stations between Portland, OR, and Seattle, WA. Route data for the Cascades was obtained from FRA IPEEP route tables and BNSF track charts and updated with more recent timetable speed data (Bachman et al. 1978).

4.1.2.7 Los Angeles–San Diego, CA: Pacific Surfliner

Amtrak operates the Pacific Surfliner service between San Luis Obispo and San Diego, CA, which includes a 127-mile segment between Los Angeles and San Diego. This portion of the route has 15 stations. The service runs 12 daily round trips using diesel-electric locomotives and bi-level coaches. A typical train consists of one locomotive and four passenger coaches with a total of 336 seats. Route data for the Pacific Surfliner was obtained from Union Pacific track charts, BNSF track charts and FRA IPEEP route tables (Bachman et al. 1978).

4.1.2.8 Chicago–Quincy, IL: Illinois Zephyr

Amtrak's Illinois Zephyr service operates over a distance of 258 miles between Chicago and Quincy, IL. This service uses diesel-electric locomotives and single-level coaches, operating two round trips daily and serving 10 stations. A typical train consists of one locomotive, four coaches with a total of 336 seats, and a baggage car. Route data for the Illinois Zephyr was obtained from BNSF track charts.

4.1.2.9 New York City–Washington, DC: Northeast Regional

Amtrak operates the Northeast Regional, a higher-speed rail service on the Northeast Corridor, using electric locomotives and single-level coaches and traveling at a maximum speed of 125 miles per hour. This service offers 18 round trips per day between Boston, MA and Washington, DC. The case study examined for *NCRRP Report 3* considers one of the trains covering the 226 miles between New York City's Penn Station and Washington DC, serving 10 stations. The case study train includes one electric locomotive and six single-level passenger coaches with a total of 504 seats. Route data for the Northeast Corridor was obtained from FRA IPEEP route tables and updated with more recent timetable speed data (Bachman et al. 1978; Amtrak 2008).

4.1.3 Long-Distance Intercity Rail Services

Long-distance intercity passenger rail services are operated on a limited number of routes by Amtrak. Two different long-distance intercity services were developed as case study routes. Operating characteristics for both services were obtained from public train schedules and route guides published by Amtrak.

4.1.3.1 Chicago, IL–Los Angeles, CA: Southwest Chief

Amtrak operates daily Southwest Chief service, covering the distance of 2,251 miles between Chicago, IL, and Los Angeles, CA, with 33 station stops. The service typically operates using two diesel-electric locomotives and eight bi-level passenger railcars, including coaches, sleeping cars, a lounge and a dining car. Given that some of the railcars do not have revenue seats and the sleeping cars have limited occupancy, the train carries a maximum of 364 passengers. Route data for the Southwest Chief was obtained from BNSF track charts (BNSF 2005).

4.1.3.2 Chicago, IL–Denver, CO: California Zephyr

Amtrak operates daily California Zephyr service between Chicago, IL, and Emeryville, CA (just outside San Francisco). The service typically operates using two diesel-electric locomotives and eight bi-level passenger railcars, including coaches, sleeping cars, a lounge and a dining car. Given that some of the railcars do not have revenue seats and the sleeping cars have limited occupancy, the train carries a maximum of 364 passengers. This case study considers the portion of the route covering the 1,038 miles between Chicago, IL, and Denver, CO, and serving 16 stations. Route data for the California Zephyr was obtained from BNSF track charts.

4.1.4 High-Speed Rail Services

Currently, the only HSR services in the United States operate on the Northeast Corridor and do not exceed 150 mph for extended periods of time. Thus, simulation of the Amtrak Acela does not offer the best illustration of HSR energy efficiency for comparison to benchmarked HSR systems in Europe and Asia. Also, the research team was unable to obtain train resistance coefficients appropriate for the Acela. Although similar in overall appearance and shape to other HSR trainsets with known train resistance coefficients, the higher tare weight of the Acela compared to European and Asian trainsets does not allow these coefficients to be translated directly to the Acela service.

4.1.4.1 Los Angeles–Fresno, CA: California HSR

A new, dedicated high-speed (220-mph) rail service between San Francisco and Los Angeles, CA, is currently being developed. This service will use electric multiple-unit trainsets with high-capacity single-level coaches, similar to European HSR equipment with known train resistance characteristics. Preliminary horizontal and vertical geometry data for the 292-mile section between Fresno and Los Angeles, CA, was made available in technical memorandums released during the planning stages of the project (CHSRA 2010; CHSRA 2012). Using this information, the Fresno–Los Angeles segment of the proposed California High-Speed Rail (CAHSR) route was developed into a hypothetical case study to illustrate the HSR capabilities of the MMPASSIM tool. The CAHSR route is assumed to operate with an 11-vehicle electric trainset using distributed power with 446 seats, serving three stations in express service (i.e., with one intermediate stop).

4.1.5 Summary and Ridership

Although many of the services developed as single-train case studies may operate different train consists on a daily and seasonal basis, the baseline configurations (Table 4-1) were developed with public data to represent average service conditions on each route. The number of stops listed in Table 4-1 includes the origin and terminating stations for the train run. Average speed is calculated as a final output of MMPASSIM and considers posted passenger train speed, dwell at station stops, and delay for train meets and other unscheduled stops specified in the case study input data. Additional detail on MMPASSIM input parameters for each case study is provided in Appendix E.

Ridership and load factor data are required for each case study service to calculate energy and GHG emissions intensities per passenger-mile and passenger trip (Table 4-2). Load factors for the commuter rail system are based on analysis of the 2012 NTD. Amtrak operations are assigned average load factors (provided by Amtrak) based on the type of service provided. The load factor for CAHSR matches the higher load factor commonly used to study the feasibility of HSR systems.

4.2 Baseline Single-Train Simulation Results

This section presents baseline single-train simulations of the passenger rail case studies for NCRRP Project 02-01 that were completed using the MMPASSIM spreadsheet tool. Results of each simulation describe the energy intensity and GHG emissions intensity of one round-trip

Table 4-1. Characteristics of passenger rail service case study routes.

Route	Origin—Destination	Locomotive(s)	Trailing Railcars	Seats[a]	Stations[b]	Average Speed (mph)
Commuter Rail						
Metro Transit Northstar	Big Lake–Minneapolis, MN	1 x 3,600 hp Diesel	3 bi-level	426	10	40
Metra BNSF	Aurora–Chicago, IL	1 x 3,150 hp Diesel	6 bi-level	870	7	22
Sounder South	Seattle—Tacoma, WA	1 x 3,600 hp Diesel	4 bi-level	568	7	39
Metrolink Orange	Oceanside–Los Angeles, CA	1 x 3,600 hp Diesel	4 bi-level	568	15	37
Pacific Surfliner[c]	Oceanside–Los Angeles, CA	1 x 3,600 hp Diesel	4 bi-level	336	9	41
MARC Penn Line	Perryville, MD–Washington, DC	1 x 3,100 hp Diesel	5 bi-level	650	13	43
MARC Penn Line[d]	Perryville, MD–Washington, DC	1 x 3,221 kW Electric	5 bi-level	650	13	50
Regional Intercity						
Heartland Flyer + NPCU	Oklahoma City, OK—Fort Worth, TX	1 x 4,100 hp Diesel	3 bi-level	252	7	42
Heartland Flyer	Oklahoma City, OK—Fort Worth, TX	1 x 4,100 hp Diesel	3 bi-level	252	7	43
Piedmont	Charlotte—Raleigh, NC	1 x 3,600 hp Diesel	4 single-level	336	9	47
Capitol Corridor	Auburn—San Jose, CA	1 x 3,600 hp Diesel	4 bi-level	360	17	41
Empire	New York—Buffalo, NY	1 x 4,100 hp Dual-mode[e]	5 single-level	416	15	58
Wolverine	Chicago, IL—Detroit, MI	1 x 4,100 hp Diesel	4 single-level, 1 baggage	336	14	57
Cascades	Portland, OR—Seattle, WA	1 x 3,600 hp Diesel	12-car Talgo, 1 cab car	340	8	47
Pacific Surfliner	Los Angeles—San Diego, CA	1 x 3,600 hp Diesel	4 bi-level	336	15	40
Illinois Zephyr	Chicago—Quincy, IL	1 x 4,100 hp Diesel	4 single-level, 1 baggage	336	10	62
Northeast Regional	New York City—Washington, DC	1 x 3,221 kW Electric	6 single-level	504	10	68
Long-Distance Intercity						
Southwest Chief	Chicago, IL—Los Angeles, CA	2 x 4,100 hp kW Diesel	8 bi-level	364	33	53
California Zephyr	Chicago, IL—Denver, CO	2 x 4,100 hp Diesel	8 bi-level	364	16	65
High-Speed Rail						
California HSR	Fresno—Los Angeles, CA	1 x 9,266 kW EMU[f]	11-car trainset	446	3	179

[a]Assumed as typical operations and consist configuration for each case.
[b]Citations for this column can be found in each route's respective entry in Appendix E.
[c]Pacific Surfliner intercity train used as a commuter service.
[d]MARC Penn Line service uses both diesel-electric and electric consists.
[e]Dual-mode refers to dual propulsion—a diesel-electric locomotive that can also draw electricity from third-rail or overhead electricity supply lines.
[f]Electric multiple-unit.

Table 4-2. Ridership assumptions for evaluated passenger rail services.

Route	Load Factor
Metro Transit Northstar	0.24
Metra BNSF	0.27
Sounder South	0.29
Metrolink Orange	0.25
MARC Penn Line	0.30
Amtrak Regional/State-Supported	0.42
Amtrak Northeast Regional	0.53
Amtrak Long-Distance	0.63
California HSR (CAHSR)	0.60

rail movement of the specified train consist. Round-trip simulations were used to average out any directional bias with respect to differences in origin and destination elevation, track profile gradient and relative sequence of speed restrictions and station stops on each route.

The results of the single-train simulations consider the passenger rail mode in isolation; the output metrics include only the energy consumed and GHG emissions produced by the passenger rail trip and associated fuel and energy production. Later chapters of this report incorporate the energy consumption and GHG emissions of the access and egress legs of passenger rail trips into the analysis.

Although the simulated case study services represent typical train consists and operating patterns on each route to provide average energy consumption and GHG emissions metrics, one round trip cannot capture the performance of all train movements occurring as part of each passenger rail service. For any given service, certain trains may operate with longer or shorter train lengths and may potentially make a different number of station stops. Wind direction can alter train resistance and resulting performance. Crew members' differing operating styles can alter throttle settings and locomotive duty cycles. Interference from other rail traffic may vary daily, weekly or seasonally. Small differences in the output metrics are not as important as their relative order of magnitude.

Ridership also fluctuates with time of day and day of the week. Because the results expressed per passenger-mile are calculated on the basis of average load factors, actual trains with higher or lower ridership will exhibit varying energy intensity and GHG emissions performance. The seat-mile statistics present a practical maximum best-case performance as if all available seats on the train were occupied.

4.2.1 Commuter Rail

The results of the baseline single-train simulations for the commuter rail services (Table 4-3) are comparable to the energy intensities of diesel-electric locomotive-hauled commuter rail systems analyzed in the literature review. In 2011, the energy intensity of similar systems ranged from 423 to 578 Btu per seat-mile, with an average of 486 Btu per seat-mile.

Because of their low average load factor, the commuter rail systems exhibit a great disparity between the per seat-mile and per passenger-mile metrics. With the majority of ridership concentrated during peak hours and traveling at much higher load factors, however, the typical passenger commuting by rail is likely to experience lower energy intensity and GHG emissions intensity, approaching the per seat-mile values for their respective train run. Commuter rail

Table 4-3. Baseline single-train simulations of commuter rail services.

Route	/seat-mi (Btu)	/seat-mi (lb-GHG)	/passenger-mi (Btu)	/passenger-mi (lb-GHG)	Travel Time (hrs)	Average Speed (mph)
Metro Transit Northstar	554	0.098	2,308	0.408	2.02	40
Metra BNSF	423	0.075	1,511	0.267	3.44	22
Sounder South	435	0.077	1,740	0.308	2.07	39
Metrolink Orange	366	0.065	1,462	0.259	4.72	36
Pacific Surfliner*	578	0.102	1,377	0.244	4.24	41
MARC Penn Line	478	0.085	1,593	0.282	3.62	43
MARC Penn Line (electric)	565	0.091	1,883	0.302	3.05	50

*Pacific Surfliner intercity train used as a commuter service between Oceanside and Los Angeles, CA.

operations that allow standing passengers can even perform at per passenger intensity levels below the per seat-mile statistics during peak periods.

Two interesting sub-comparisons can be made between particular pairs of simulated operations. The first is between the Metrolink Orange and the Pacific Surfliner. Although the Amtrak Pacific Surfliner regional intercity service is targeted toward longer-distance travelers, a passenger commuting between Oceanside, CA, and Los Angeles, CA, can potentially use the Pacific Surfliner as an alternative to the Metrolink Orange commuter rail service. Interestingly, although the higher seating density of the Metrolink commuter train allows it to achieve lower energy consumption and GHG emissions per seat-mile for this trip, the higher average load factor of the Pacific Surfliner allows the intercity service to achieve lower energy and GHG emissions intensities per passenger.

The MARC Penn Line was simulated with both electric and diesel-electric propulsion. Because the electric train can travel at 125 miles per hour whereas the diesel-electric train is limited to 79 miles per hour, the electric train consist has higher energy consumption and GHG emissions metrics than the diesel-electric train.

4.2.2 Regional Intercity Rail

The baseline simulation results for regional intercity services (Table 4-4) are generally more energy efficient and less GHG emissions intense than many of the benchmarks collected during the literature review for this study. Analysis of the NTD found the energy intensity of the regional Downeaster and Keystone/Pennsylvanian services to be 921 and 859 Btu per seat-mile, respectively. The Amtrak short-haul services also are more efficient than the VIA Rail corridors east and west of Toronto, at 1,046 and 1,156 Btu per seat-mile, respectively (see Table 2-6). The VIA Rail corridors use single-level coaches exclusively, however, and operate at higher speeds than do many of the Amtrak routes. These operating conditions may contribute to the VIA trains' higher energy and GHG emissions intensities compared to the simulated regional intercity corridors.

The results of the Heartland Flyer simulations offer a comparison between operation with and without an NPCU. The NPCU adds weight and train resistance without increasing ridership or the number of seats, which results in a 19% increase in energy intensity and an 18% increase in GHG emissions.

Table 4-4. Baseline single-train simulations of regional intercity rail services.

Route	/seat-mi (Btu)	/seat-mi (lb-GHG)	/passenger-mi (Btu)	/passenger-mi (lb-GHG)	Travel Time (hrs)	Average Speed (mph)
Heartland Flyer with NPCU	583	0.103	1,388	0.246	9.74	42
Heartland Flyer	488	0.086	1,162	0.206	9.67	43
Piedmont	681	0.120	1,621	0.287	7.33	47
Capitol Corridor	561	0.099	1,335	0.236	8.14	41
Wolverine	431	0.076	918	0.162	9.07	57
Cascades	585	0.103	1,393	0.246	14.46	47
Empire	380	0.067	904	0.160	15.11	58
Pacific Surfliner	613	0.109	1,461	0.258	6.42	40
Illinois Zephyr	431	0.076	916	0.162	8.27	62
Northeast Regional	512	0.064	966	0.121	6.60	68

Table 4-5. Baseline single-train simulations of long-distance intercity rail services.

Route	/seat-mi (Btu)	/seat-mi (lb-GHG)	/passenger-mi (Btu)	/passenger-mi (lb-GHG)	Travel Time (hrs)	Average Speed (mph)
Southwest Chief	864	0.153	1372	0.243	84.8	53
California Zephyr	711	0.126	1128	0.200	31.7	65

4.2.3 Long-Distance Intercity Rail

Results of baseline simulation results for long-distance intercity services (Table 4-5) are comparable to the intercity averages from Mittal of 1,000 Btu per seat-mile. The results are slightly lower than the long-distance averages of VIA Rail Canada services (1,717 and 1,431 Btu per seat-mile for Eastern and Western services, respectively). However, the VIA routes operate with single-level railcars and with more sleeping, lounge and food-service cars than the simulated Amtrak long-distance intercity services.

Despite the benefit of bi-level passenger coaches, the presence of food-service and sleeping cars necessitates an additional locomotive that increases energy and GHG emissions intensities per seat-mile compared to regional intercity and commuter rail service.

Both the Southwest Chief and California Zephyr were simulated with identical train consists. Thus, the differences in their energy intensity and GHG emissions intensity metrics illustrate the amount of variation that can be created by different route speed profiles, track geometry and station stopping patterns.

4.2.4 High-Speed Rail

The baseline simulation results for the California HSR simulation (Table 4-6) far exceed the range of energy intensity values for international HSR services collected during the literature review. It is important to reiterate that, in MMPASSIM, the energy reported for electric locomotives includes the regional fuel mix consumed in generating electricity, whereas most operators report the metered kWh consumed by trains and do not include the fuel used to generate that electricity. To compare operator reports against an MMPASSIM prediction, the referenced SYSTRA number must be adjusted to allow for the locomotive losses from wheel to pantograph, the on-board hotel power consumption, the acceleration/braking profile and the gradient profile, and include the fuel consumed in generating the electricity.

The research team took the number of 14.36 kWh/train-kilometer (or 245 kJ/seat-mile) from Table 2 in a SYSTRA desk study of carbon impacts (SYSTRA 2011). This number represents the energy consumed at the wheels for a constant speed of 300 kmh, and estimated what it would be if it included other losses and fuel consumed in electricity generation. First, applying the California fuel mix would bring the SYSTRA number of 245 kJ/seat-mile to 421 Btu/seat-mile, which is 72% of the simulation output in Table 4-6. The SYSTRA report also indicates results from a full simulation of the TGV-Réseau (SYSTRA 2011, p. 24) as being 22 kWh/train-kilometers and

Table 4-6. Baseline single-train simulations of an intercity HSR service.

Route	/seat-mi (Btu)	/seat-mi (lb-GHG)	/passenger-mi (Btu)	/passenger-mi (lb-GHG)	Travel Time (hrs)	Average Speed (mph)
California HSR	585	0.050	975	0.084	3.3	179

also compares the resistive energy at the wheels (SYSTRA 2011, p.10) for the TGV-Réseau as being 16.25 kWh/train-kilometers (as indicated in comparison with the AGV-11 in Table 2-20 of this report).

This ratio of 16.5/22 = 75% is close to the 72% ratio between our simulation of the AGV and the SYSTRA report's energy at the wheels scaled to include fuel consumption. It does not validate the AGV parameters we estimated, but does indicate that MMPASSIM's simulation results are close to those of other simulations when adjusted to provide a like-for-like comparison.

On a per passenger-mile basis, the simulated California HSR compares favorably to all but the most energy-efficient simulated regional intercity passenger rail services while simultaneously increasing average speed by a factor of three to four.

Given its use of relatively clean electricity generation sources in California, the simulated California HSR route has the lowest GHG emissions intensity of all simulated passenger rail services per seat-mile and passenger-mile.

4.2.5 Discussion

Ranking the simulated passenger rail services by energy intensity per passenger-mile highlights the influence of load factor on the results (see Figure 4-1). Although the possible energy intensity of the passenger rail services clusters around 500 kJ/seat-mile, the energy intensity per passenger-mile ranges from under 1,000 Btu to about 2,300 Btu depending on the service's load factor. The commuter rail services, which have the lowest average load factor, exhibit the highest energy intensity. As will be further demonstrated in subsequent chapters, combinations of high load factor, stop spacing and train length make several of the regional intercity passenger services the most efficient passenger rail operations.

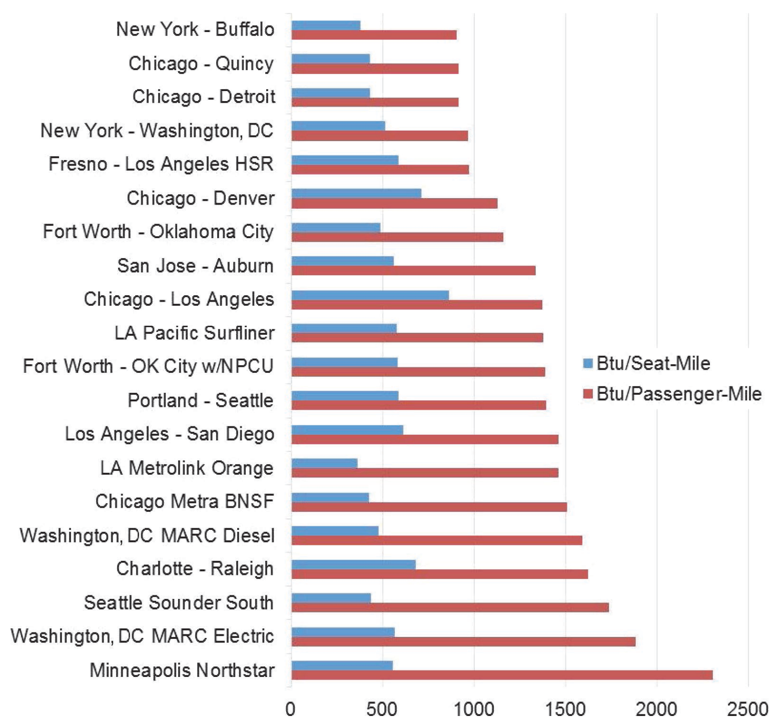

Figure 4-1. Energy intensity of simulated passenger rail services (Btu).

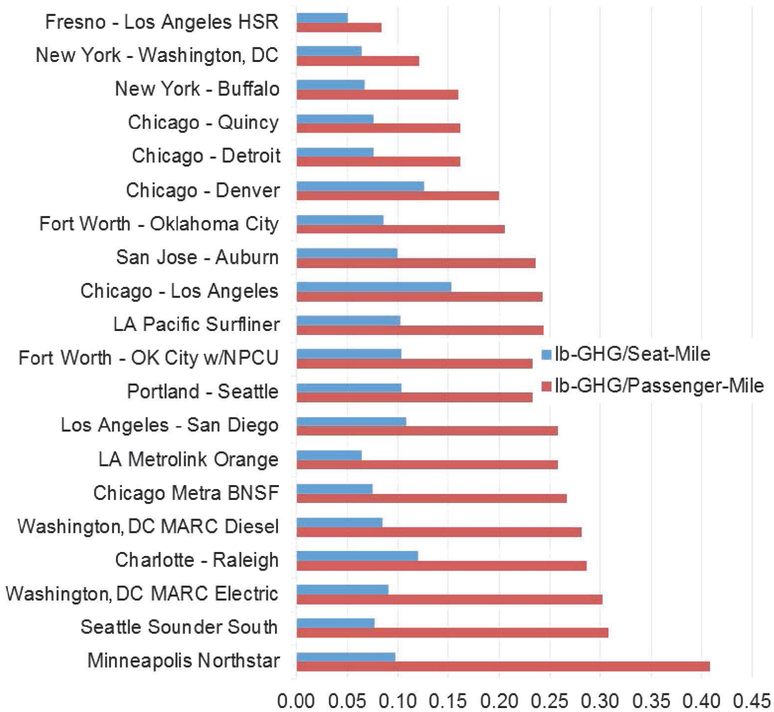

Figure 4-2. GHG emissions intensity of simulated passenger rail services (lb-GHG).

The GHG emissions intensity per passenger-mile exhibits similar trends (Figure 4-2). Wider variation is seen in the per seat-mile metric, however, because of the electrified operations on several routes. The top two routes in terms of pounds of greenhouse gas (lb-GHG) per passenger-mile are both electrified routes, and the system that ranks third uses dual-mode operation.

The California HSR case study route ranks at the top for GHG emissions and near the top for energy intensity on a per passenger-mile basis. Lightweight equipment, optimized alignment design, high load factor and relatively clean sources of electricity all combine to offset the increased energy demands of operation at speeds near 200 mph.

The ratio of GHG emissions to energy consumed for each simulated route is relatively constant for all diesel locomotive-powered case studies, as exhibited by the linear form of the plot in Figure 4-3. This result is expected, given that the diesel locomotive combustion process that

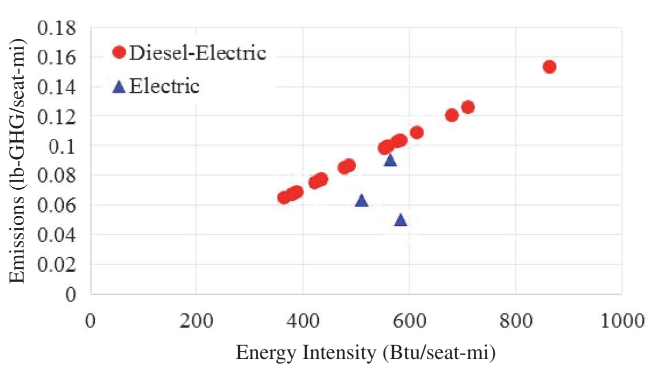

Figure 4-3. Ratio of GHG emissions to energy consumed by simulated passenger rail services.

controls the emissions per unit of energy produced is essentially the same for all case study routes using diesel propulsion. The electric traction case studies fall below this relationship, however, because their emissions are controlled by the source generation of electricity. The dual-mode New York–Buffalo (Empire Service) route falls very near the diesel-electric trend because the majority of the trip is spent in diesel mode. The other two electric cases are farther below the diesel-electric trend, indicating that they involve cleaner sources of electricity and produce less overall GHG emissions per unit of energy consumed than diesel-electric traction.

CHAPTER 5

Technologies to Improve Passenger Rail Energy Efficiency

Fuel and electrical energy costs are among the largest expenses for passenger rail operations. To reduce the cost of passenger rail transportation and meet operating budget constraints, passenger rail operators increasingly strive to improve energy efficiency. At the same time, many rail operators, particularly those in non-attainment areas, have incentives to reduce GHG emissions through improved energy efficiency or use of new sources of energy.

Stodolsky (2002) provided a roadmap for railroad and locomotive technology research and development as part of a 2001 effort between the U.S. Department of Energy and industry partners to improve rail energy efficiency 25% by 2010 and 50% by 2020. Stodolsky's report provides a roadmap for future research and development efforts to improve rail transportation energy efficiency and reduce emissions. Similarly, Barton and McWha (2012) conducted a scan of available technologies to reduce emissions in North America on behalf of the Transportation Development Centre of Transport Canada. The energy- and emissions-saving technologies and strategies discussed in these reports can be broadly grouped into four categories:

- operational strategies,
- railcar design and utilization,
- motive power and fuels, and
- alternative energy sources.

Although these reports discuss the potential of various approaches to reduce rail energy consumption and emissions, the discussions are mainly qualitative in nature and focus on freight rail transportation.

MMPASSIM provides industry practitioners with the ability to assess the effectiveness of specific strategies or technologies in saving energy and reducing GHG emissions of specific passenger rail operations. This capability gives passenger rail operators an approach for evaluating the benefits and drawbacks of multiple improvement strategies and technologies. For example, the results of MMPASSIM simulation of alternative technology scenarios can be useful inputs for economic cost-benefit analysis to justify investment in new technologies or operating strategies.

This chapter evaluates the effectiveness of various operational, equipment, and infrastructure changes on reducing energy consumption and GHG emissions of passenger rail. The chapter introduces several energy-saving technologies and presents data from MMPASSIM simulations that apply these technologies to selected combinations of the passenger rail systems described in Chapter 4. The energy-saving technologies were represented in the MMPASSIM model by either changing the train consist input parameters or by using features built into the MMPASSIM tool to model the capability of a specific new technology.

When a technology is applied in MMPASSIM, the simulation results quantify the corresponding changes in energy and GHG emissions intensities of direct activity associated with passenger rail operations on the simulated route. This direct activity includes movement of the train, idling in stations and terminals, and the energy used to generate electricity (for electric traction systems). Comparing the results from the original case studies with the results obtained by applying different technologies to each respective baseline single-train case study illustrates the effectiveness of the technology strategies at reducing energy consumption and GHG emissions across a range of passenger rail service routes and operating conditions.

5.1 Operational Strategies

Operational strategies attempt to optimize the energy consumption and GHG emissions of existing rolling stock without investment in new equipment or infrastructure. Operational strategies for reducing energy consumption and GHG emissions include:

- driver advisory systems and optimal coasting;
- alternative station stopping patterns;
- elimination of unplanned stops and speed restrictions; and
- changing the maximum operating speed.

The balance of this section presents discussions of operational strategies that demonstrate the effect of each approach on passenger rail energy efficiency and GHG emissions of selected case study routes. Unless otherwise noted, the baseline conditions match those described in Chapter 4.

5.1.1 Driver Advisory Systems and Optimal Coasting

Improving the train-handling behavior of the driver can be one of the most inexpensive yet effective actions taken to improve fuel efficiency of passenger railroads. Optimization of speed fluctuation, coasting, braking and powering ratios can lead to estimated reductions in energy consumption as great as 10%–15% (Lukaszewicz 2006). Improved driver training and education on energy recovery techniques can capture some of these optimized-system savings and driver performance monitoring/feedback can improve the driver-acceptance ratio for installed optimization systems.

Optimal coasting is one train-handling approach to reduce energy consumption through better management of available schedule slack time. When trains are ahead of schedule, or when a station has buffer time, the train driver can be instructed by an on-board driver advisory system to coast down to lower speeds in order to reduce energy consumption while meeting schedule constraints. Because they have the most frequent station stops, optimal coasting is most likely to improve the energy efficiency and GHG emissions of commuter rail systems.

With the optimal coasting simulation feature enabled in MMPASSIM, coasting advice is calculated and implemented at each scheduled stop. The case studies were assumed to have 90 seconds of schedule slack, and the driver was assumed to follow the coasting advice of the driver advisory system at a rate of 65%.

Optimal coasting was simulated on two commuter rail systems with substantial reductions in both energy consumption and missions (Table 5-1). The electrified MARC Penn Line commuter service exhibits a greater reduction because of its larger number of station stops and higher average speed between stations compared to the Metro Transit Northstar commuter route.

5.1.2 Alternative Station Stopping Patterns

To better serve passengers with decreased travel time during peak periods, rather than have every train stop at every station in local service, larger commuter rail operations often incorporate

Table 5-1. Optimal coasting—changes in energy and GHG emissions intensities.

Route	Baseline (per seat-mi)		Optimal Coasting (per seat-mi)			
	(Btu)	(lb-GHG)	(Btu)	Reduction	(lb-GHG)	Reduction
Metro Transit Northstar	554	0.098	457	18%	0.081	18%
MARC Penn Line (electric)[a]	565	0.091	402	29%	0.064	29%

[a]The baseline case has an electric consist used in service at a maximum speed of 125 mph.

skip-stop trains that serve every second station and zonal trains that eliminate large groups of adjacent stops. The design of these more complex timetables focuses largely on demand-related constraints, distributing schedule slack optimally, and minimizing travel time while maintaining connectivity between stations. By increasing the distance between stops and reducing the number of acceleration and braking cycles, however, train schedules that skip stops also have the potential to reduce energy consumption and GHG emissions.

Three hypothetical examples were simulated using the Metra BNSF route between Aurora, IL, and Union Station in Chicago: (1) a local train, making all stops; (2) a zonal train, stopping at the farthest five stations on the line (beginning with Aurora),then running direct to Chicago Union Station; and (3) a skip-stop train, stopping at 10 stations (beginning in Aurora and stopping every 2–3 stations, or roughly every 3 miles) between Aurora and Chicago (Table 5-2).

Relative to the local train pattern, the zonal pattern reduces both energy intensity and GHG emissions intensity by 27%, whereas the skip-stop pattern has a reduction of 12%.

5.1.3 Elimination of Unplanned Stops and Speed Reductions

For a passenger rail operation on track shared with freight operations, unplanned stops and speed reductions may occur as a result of conflicts with freight movements: meets, passes, trains entering yards, local industrial switching and so forth. Other causes of unplanned stops or speed reductions include slow orders due to track maintenance or poor track geometry. Reducing the frequency of unplanned stops and speed reductions through preventive maintenance, infrastructure investment or better coordination of operations can have a positive impact on energy intensity and travel time.

MMPASSIM accounts for unplanned stops and speed reductions via an expected frequency of occurrence input by the user. To analyze the effect of the unplanned stops and speed reductions on both energy intensity and GHG emissions intensity, the baseline frequencies were reduced to zero unplanned stops and speed reductions and increased by factors of two and three in additional MMPASSIM simulations of the BNSF Metra commuter rail route. All three train stopping patterns (local, zonal, and skip-stop) were considered in these simulations.

Table 5-2. Station stopping patterns—changes in energy and GHG emissions intensities.

Route	Station Stopping Patterns (per seat-mi)			
	(Btu)	Reduction	(lb-GHG)	Reduction
Metra BNSF (Local)	421	--	0.075	--
Metra BNSF (Zonal)	309	27%	0.055	27%
Metra BNSF (Skip-stop)	371	12%	0.066	12%

Table 5-3. Unplanned stops and speed reductions—changes in energy intensity.

Schedule Pattern	Baseline (per seat-mi) (Btu)	Unplanned Stops and Speed Reductions (per seat-mi)					
		Eliminate		Double		Triple	
		(Btu)	Reduction	(Btu)	Reduction	(Btu)	Reduction
Metra BNSF (Local)	421	409	3%	433	-3%	445	-6%
Metra BNSF (Zonal)	309	296	4%	321	-4%	333	-8%
Metra BNSF (Skip-stop)	371	362	3%	383	-3%	395	-6%

Eliminating the unplanned stops and speed reductions reduced energy intensity and travel time by an average of 3% (Table 5-3 and Table 5-4). GHG emissions intensity was reduced by a similar amount. Doubling the frequency of such events increased energy consumption and travel time by an average of 3%. Tripling the frequency of these events increased energy consumption by an average of 7% and increased travel time by an average of 6%.

The zonal station stopping pattern, with its longer continuous run at speed between stations, is more sensitive to unplanned stops and speed reductions than the other two station stopping patterns. The local and skip-stop trains already make frequent acceleration and braking cycles for closely spaced station stops and thus have fewer sustained cruising periods to be interrupted by additional unplanned stops and speed reductions.

5.1.4 Operating Speed on Emerging Higher-Speed Rail Corridors

Changes in energy consumption and GHG emissions stemming from changes in operating speed on an emerging higher-speed rail corridor were evaluated by examining additional case studies of the regional intercity passenger rail route from New York City to Buffalo, NY. MMPASSIM was used to simulate the energy and GHG emissions intensities of passenger rail operations on the route under three different operating speed scenarios: (1) conventional speeds only (with no 110-mph sections), (2) the current operations (which incorporate some 110-mph segments) and (3) the current operations with additional segments of 110-mph service. The extent of each segment increased to the 110-mph speed limit was determined by assuming that all current speed limits of 79 mph or above would be upgraded to 110 mph (Table 5-5).

The results of the analysis indicate that energy intensity and GHG emissions intensity increase with speed (Table 5-6). This change reflects a trade-off between reduced travel time (achieved through increased speeds) and energy intensity.

Table 5-4. Unplanned stops and speed reductions—changes in service metrics.

Schedule Pattern	Travel Time (hr)	Average Speed (mph)	Unplanned Stops and Speed Reductions					
			Eliminate		Double		Triple	
			(hr)	(mph)	(hr)	(mph)	(hr)	(mph)
Metra BNSF (Local)	3.44	22	3.36	23	3.51	22	3.58	21
Metra BNSF (Zonal)	1.74	44	1.67	46	1.82	42	1.89	41
Metra BNSF (Skip-stop)	2.14	36	2.07	37	2.21	35	2.28	34

Table 5-5. Speed limit distributions of the emerging higher-speed rail case studies.

Case Study Route	% of Route <79 mph	 79–95 mph	 95–109 mph	 110 mph
Conventional Speeds (max. 79 mph)	30%	70%	0%	0%
Current Operations	30%	49%	14%	7%
Extended 110 mph	30%	0%	0%	70%

5.2 Railcar Design and Utilization

Railcar design can be optimized further to reduce resistance and therefore reduce the energy consumption and GHG emissions of the vehicle. An energy-efficient passenger coach is lightweight and aerodynamic. Passenger coaches are constantly improving in these areas, with high-speed trains in Europe and Asia substantially decreasing axle loads and adding aerodynamic features to support higher-speed operations. On a per passenger-mile basis, however, the most important factor in energy efficiency is the seating density and, eventually, ridership of each coach, assuming that energy consumption does not increase significantly with the added weight of additional passengers. Space on a passenger coach should be optimized to include a maximum number of seats to move the most passengers as possible per unit of energy.

Railcar design and utilization strategies for reducing energy consumption and GHG emissions considered in NCRRP Project 02-01 include:

- reducing tare weight,
- increasing seating density,
- altering the train consist configuration,
- increasing train length, and
- reducing aerodynamic resistance.

The rest of this section presents a discussion of the effect that each of these approaches had on passenger rail energy efficiency and GHG emissions in simulations of selected case study routes. Unless otherwise noted, the baseline conditions match those described in Chapter 4.

5.2.1 Tare Weight Reduction

Unlike freight rail operations, for which the freight being transported can make up the majority of the weight of a train, the weight of passengers on board a passenger train is insignificant compared to the tare weight of the rolling stock. Thus, reducing the tare weight of passenger coaches has the potential to reduce train resistance and improve energy efficiency.

Table 5-6. Operating speed—changes in energy and GHG emissions intensities.

Route	Operating Speed (per seat-mi) (Btu)	 Reduction*	 (lb-GHG)	 Reduction*
Conventional Speeds (max. 79 mph)	359	--	0.063	--
Current Speeds	380	-6%	0.067	-6%
Extended (110 mph)	425	-19%	0.075	-19%

*A negative percentage in the “Reduction” column indicates an increase in intensity. For example, a reduction of -6% indicates an increase in intensity of 6%.

Table 5-7. Tare weight reduction—changes in energy and GHG emissions intensities.

Route	Baseline (per seat-mi)		With Tare Weight Reduction (per seat-mi)			
	(Btu)	(lb-GHG)	(Btu)	Reduction	(lb-GHG)	Reduction
Metro Transit Northstar*	554	0.098	544	2%	0.096	2%
Sounder South*	435	0.077	427	2%	0.076	2%
Southwest Chief*	864	0.153	843	2%	0.149	2%
Cascades (without NPCU)#	585	0.103	535	8%	0.095	8%

*For purposes of the simulation, these trains were assumed to realize a 10% weight reduction to each coach, but an unchanged locomotive weight.
#The Cascades train already has lightweight cars, but the consist normally includes a ballasted shell locomotive as an NPCU. For this simulation the NPCU was eliminated, thereby reducing the train's total tare weight by about 12% and also reducing aerodynamic drag.

Four passenger rail services were simulated with a 10% reduction in passenger coach tare weight (Table 5-7). Each consist was altered by reducing the tare weight of all passenger coaches by 10% but maintaining the same locomotive unit weights.

Reducing railcar tare weight by 10% did not reduce energy intensity and GHG emissions intensity by a similar percentage for three of the four services, including the Southwest Chief route (which traverses Raton Pass and has the steepest active mainline grade in the United States). Reductions in tare weight do not reduce energy consumed overcoming aerodynamic resistance or in providing on-board hotel power services. Also, for shorter trains, the locomotive can provide the majority of the train weight and resistance, which limits the influence of passenger railcar tare weight. Reducing the weight of the locomotive is often impractical because of axle load limits and/or the relationship between locomotive weight on powered axles, adhesion, tractive effort and train performance.

The Cascades service, which already employs an aerodynamic lightweight Talgo trainset, was assessed without a non-powered control unit (NPCU), which reduced aerodynamic drag as well as tare weight, yielding more significant reductions of 8% in both energy intensity and GHG emissions intensity. The alternate case inherently assumes either a nearby Y exists to turn the train or the collision requirements that lead to the use of a locomotive based NPCU are replaced by a positive train control system to mitigate collision events.

5.2.2 Increased Seating Density

Adding more seats to each passenger coach divides the train resistance and the corresponding energy and GHG emissions over additional seats, increasing efficiency per seat-mile.

Train consists with increased seating density were simulated for three passenger rail services (Table 5-8). For the Sounder South and Heartland Flyer routes, seating density on the bi-level

Table 5-8. Increased seating density—changes in energy and GHG emissions intensities.

Route	Baseline (per seat-mi)		With Increase in Seating Density (per seat-mi)			
	(Btu)	(lb-GHG)	(Btu)	Reduction	(lb-GHG)	Reduction
Sounder South	435	0.077	396	9%	0.070	9%
Heartland Flyer (with NPCU)	583	0.103	530	9%	0.094	9%
Heartland Flyer (without NPCU)	488	0.086	444	9%	0.079	9%

coaches was increased by 10% to reflect practical upgrades achievable by better space utilization and removal of convenience items such as tables between facing seats. The changes were applied to the Heartland Flyer case both with and without the NPCU. Because the overall weight of the equipment did not change, the results of increasing seating density by 10% resulted only in a 9% reduction in both energy intensity and GHG emissions. MMPASSIM also could be used to conduct a more complex evaluation of options for increasing seating density that alter the tare weight of the passenger rail equipment.

5.2.3 Altering the Train Consist Configuration

Regional intercity and long-distance trains typically have passenger accommodations such as snack, lounge, or sleeping cars to increase convenience and comfort. However, the extra weight and resistance of additional railcars in the train are not offset by additional passenger seats, which creates a negative impact on energy intensity and GHG emissions intensity.

The baseline Southwest Chief consist with 364 seats assumes two standard coaches, one lounge car, one dining car, two sleeper cars, one transition sleeper car and one baggage car. To quantify the effect of the passenger amenities on energy and GHG emissions intensities, the Southwest Chief consist was altered in MMPASSIM to include seven standard coaches with 84 passenger seats each (588 total) plus a baggage car. This change decreased energy intensity and GHG emissions intensity significantly (Table 5-9). Next, the baseline consist was modified by adding coaches to match the 588 seats in the previous comparison, but retaining the passenger accommodations. This change reduced energy intensity and GHG emissions per seat-mile compared to the baseline, but by less than the previous rearrangement.

As explained in Chapter 4, the Heartland Flyer service was previously run with an NPCU to allow for push-pull operation and avoid turning the train via wyes near each end terminal. When operating without the NPCU, the train travels an additional 3.5 miles total to make the required turning movements. MMPASSIM simulations of the heavier NPCU consist over the baseline route and the lighter non-NPCU consist over the extended route indicate that the service without an NPCU is 16% less energy and GHG emissions intense (Table 5-10). The reduced weight of the train over the entire route more than compensates for the additional movements required to turn the train at each end terminal.

Table 5-10 also shows that adding a snack car with no revenue seats to the non-NPCU train consist causes a 19% increase in both energy intensity and GHG emissions intensity. Energy and GHG emissions intensities are both reduced by 6% when the current bi-level Superliner coaches are replaced by single-level Amfleet coaches. The single-level coaches are 18% lighter than the bi-level Superliner coaches, but they have the same number of seats (84) per railcar. A comparison between the current, 84-seat, bi-level Superliner coaches with the lighter, 142-seat,

Table 5-9. Altered Southwest Chief consist—changes in energy and GHG emissions intensities.

Route	Baseline (per seat-mi)		With Altered Consist (per seat-mi)			
	(Btu)	(lb-GHG)	(Btu)	Reduction	(lb-GHG)	Reduction
Southwest Chief (replace accommodations with seats—588 seats total)	864	0.153	538	38%	0.095	38%
Southwest Chief (add equivalent number of seats to 588 total; retain accommodations)	864	0.153	629	27%	0.111	27%

Table 5-10. Altered Heartland Flyer consist—changes in energy and GHG emissions intensities.

Route	Baseline (per seat-mi) (Btu)	Baseline (per seat-mi) (lb-GHG)	With Altered Consist (per seat-mi) (Btu)	Reduction	(lb-GHG)	Reduction
NPCU vs. Non-NPCU	583	0.103	488	16%	0.086	16%
Addition of Snack Car	488	0.086	581	-19%	0.103	-19%
Superliner vs. Amfleet	488	0.086	459	6%	0.081	6%
Superliner vs. Commuter Bi-level	488	0.086	267	45%	0.047	45%

"commuter" bi-level coaches also is shown. The reduction in coach weight and increase in seating density afforded by the commuter bi-level coaches reduce both energy intensity and GHG emissions intensity per seat-mile by 45%.

The commuter rail services analyzed in this project all use high-capacity bi-level coaches. If the services were to exchange the bi-level coaches for single-level coaches (such as the Amfleet series), more single-level coaches would be required to provide the same number of seats as the bi-level commuter coaches. For example, on the Metra BNSF service, the baseline train uses six bi-level coaches with 145 seats each, for a total of 870 seats. If single-level coaches with 84 seats each were used, 10 railcars would be required to provide 840 seats. The weight of the four additional single-level coaches would cause a 43% increase in energy intensity and GHG emissions intensity per seat-mile (Table 5-11).

5.2.4 Increasing Train Length

Manipulation of train length can affect the energy efficiency of passenger train operations (Stodolsky 2002). Analysis of commuter railroad energy data reported to the National Transit Database (NTD) shows a small fuel savings per train-mile for longer train consists. Also, the length of trains can be optimized to improve the load factor of passenger trains during peak and off-peak periods.

To investigate the relationship between train length and energy intensity per seat-mile, the Metra BNSF train consist was iteratively simulated in MMPASSIM with one bi-level coach added to the train per iteration up to a total train length of 20 coaches. This process of incrementing train length was completed with a single locomotive. However, as the power-to-weight ratio of the train decreased with the addition of railcars, the round-trip running time eventually became unacceptably long.

To avoid violating schedule requirements as the train length increased, the process of incrementing train length was repeated in another series of simulations in which locomotives were added to the train. If the round-trip travel time exceeded the threshold of 3.5 hours, an additional locomotive was added to the train to improve running time to a minimum level of service.

Table 5-11. Altered Metra BNSF consist—changes in energy and GHG emissions intensities.

Route	Baseline (per seat-mi) (Btu)	Baseline (per seat-mi) (lb-GHG)	With Altered Consist (per seat-mi) (Btu)	Reduction	(lb-GHG)	Reduction
Metra BNSF Bi-level vs. Single-level	421	0.075	604	-43%	0.107	-43%

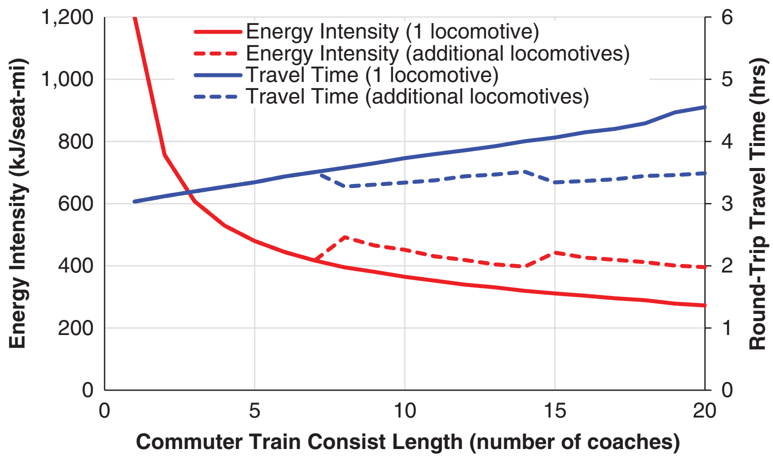

Figure 5-1. Metra BNSF commuter service—consist length, energy intensity and travel time.

Each locomotive had a fixed resistance that was distributed among all the seats in the train consist. Each additional bi-level passenger coach increased the resistance of the train but also increased the number of seats over which the fixed resistance of the locomotive was distributed.

In the case with one locomotive, the energy intensity decreased according to an inverse function, with the horizontal asymptote approaching the fixed energy intensity (resistance) of a single railcar (Figure 5-1). The quality-of-service limit of 3.5 hours was reached with one locomotive and seven coaches, so another locomotive was added to the train as it was increased to eight coaches in length. The addition of the second locomotive increased the energy intensity per seat-mile but reduced the round-trip travel time to acceptable levels. As additional coaches were added beyond this point, energy intensity declined again but remained above that of an equivalent train with a single locomotive. When the train reached 15 coaches in length, a third locomotive was added to meet the quality-of-service constraint. The addition of locomotives to meet schedule requirements effectively limited the potential economy of scale and set a lower bound on the energy efficiency per seat-mile even as the commuter train became very long.

The same analysis was conducted on the Heartland Flyer regional intercity service with a non-NPCU consist (Figure 5-2). Coaches were added to the train incrementally, and a locomotive was added when the round-trip travel time exceeded a threshold of 9.9 hours. The results were similar to those for the commuter train. The energy intensity (per seat-mile) decreased with each additional coach as the fixed energy associated with the locomotive was distributed to more seats. Additional locomotives caused an increase in energy intensity that subsequently decreased as more coaches were added. Because fewer acceleration and deceleration events occurred on the regional intercity route compared to the commuter route, however, each added railcar had less impact on the overall travel time of the regional intercity train than on the commuter train. Similarly, for each locomotive added to the train, the travel time savings were smaller for the regional intercity train than for the commuter train.

5.2.5 Reduced Aerodynamic Resistance

Reduced aerodynamic drag decreases train resistance and corresponding energy consumption and GHG emissions. Three simulations were run involving two trains: the Heartland Flyer (both with and without the NPCU) and the Sounder South. In these simulations the aerodynamic resistance coefficient—N/(kmh)^2 in MMPASSIM—was reduced by 10% (Table 5-12). For both trains, the decrease in energy consumption and emissions was modest. With its frequent

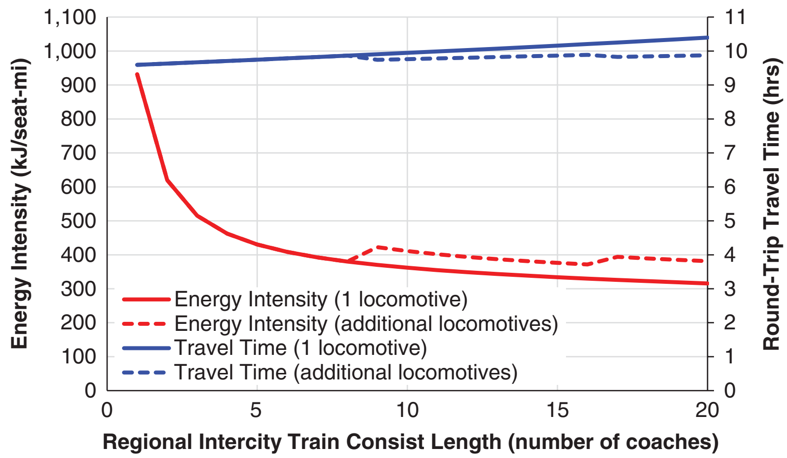

Figure 5-2. Heartland Flyer regional intercity service—consist length, energy intensity and travel time.

stops, the Sounder South service does not spend enough time at high speeds to benefit from aerodynamic improvements. Although operating at faster speeds on a longer route, the energy required to overcome the basic rolling resistance and accelerate the mass of the train consist far exceeds the total aerodynamic resistance experienced by the Heartland Flyer. This limits the effectiveness of aerodynamic improvements.

5.3 Motive Power and Fuels

Various changes to the passenger rail motive power may improve energy efficiency and GHG emissions. Locomotive improvements require significant equipment investments to be successfully implemented in large-scale passenger service. Motive power and fuel technologies for reducing energy consumption and emissions include:

- on-board storage of traction energy;
- head-end power (HEP) hotel configuration;
- upgraded locomotives;
- ultra-low sulfur diesel fuel;
- biodiesel fuel; and
- natural gas fuel.

The balance of this section demonstrates the effects of each of these approaches on passenger rail energy efficiency and GHG emissions as simulated using selected case study routes. Unless otherwise noted, the baseline conditions match those described in Chapter 4.

Table 5-12. Reduced aerodynamic resistance—changes in energy and GHG emissions intensities.

Route	Baseline (per seat-mi)		With 10% Reduction in Aerodynamic Resistance (per seat-mi)			
	(Btu)	(lb-GHG)	(Btu)	Reduction	(lb-GHG)	Reduction
Sounder South	435	0.077	431	1%	0.076	1%
Heartland Flyer (with NPCU)	583	0.103	573	2%	0.101	2%
Heartland Flyer (without NPCU)	488	0.086	478	2%	0.085	2%

5.3.1 On-Board Storage of Traction Energy

A moving train possesses significant amounts of kinetic energy, much of which is generally lost to heat in brake applications. This is especially true in downhill situations for which the energy required to maintain train speed is supplied by gravitational acceleration. Diesel-electric locomotives presently capture some of this kinetic energy through dynamic braking, which enables the locomotive traction motor to generate electricity that is dissipated in the locomotive resistors rather than as heat at the brakes (Stodolsky 2002).

It would be beneficial to capture this lost energy for use later, when the train requires acceleration, but doing so is currently limited by the lack of on-board energy storage options (Stodolsky 2002). Recovered or surplus energy also can be used for auxiliary power loads (e.g., HEP) or, in the case of electric traction, can be returned to the power supply infrastructure for simultaneous use by following accelerating trains. If there is no simultaneous use for the energy surplus, the energy may be dissipated in the resistors of the locomotive (Gonzalez-Gil et al. 2013). In European passenger rail systems that are commonly electrified, emissions have been reportedly reduced by 10%–20% (Barton and McWha 2012).

To save energy for later use, diesel-electric locomotives require high-density energy storage options such as electrochemical batteries, ultracapacitors and electric flywheels (Stodolsky 2002). GE is developing a diesel-electric locomotive model called the Evolution Hybrid for freight operations. The Evolution Hybrid reportedly reduces fuel consumption by up to 15% (Barton and McWha 2012).

Although they are being tested, wayside energy storage options do not currently meet the requirements of affordable, high-density high-rate energy storage. Should research and development improve wayside energy storage in these areas, the possible energy efficiency improvements are significant (Stodolsky 2002).

The effectiveness of traction energy storage systems is highly dependent on locomotive duty cycle, having the greatest potential for systems that have frequent acceleration and deceleration events involving higher speeds. Thus, traction energy storage is best suited for application to commuter rail operations. An MMPASSIM case study was created for a MARC diesel-electric consist with the assumed capability to store 500 kWh of energy and deliver 1.5 MW of power at the wheels from storage (Table 5-13). In this commuter route case study, on-board storage of traction energy reduced both energy intensity and GHG emissions intensity by 8%.

5.3.2 Hotel Power Configuration

Power take-off (PTO) refers to the direct diversion of energy from the main traction engine. PTO decreases the engine horsepower available for traction. The engines of passenger rail locomotives supply the electrical hotel power that provides lighting, heating, ventilation, air conditioning, and other passenger amenities to the trailing passenger railcars. For diesel-electric locomotives, hotel power is configured using one of three common schemes: inverter PTO, fixed-speed main engine PTO, and diesel-generator sets.

Table 5-13. On-board storage of traction energy—changes in energy and GHG emissions intensities.

	Baseline (per seat-mi)		With on-Board Energy Storage (per seat-mi)			
Route	(Btu)	(lb-GHG)	(Btu)	Reduction	(lb-GHG)	Reduction
MARC Penn Line	478	0.085	442	8%	0.078	8%

Table 5-14. Hotel power configuration—changes in energy and GHG emissions intensities.

Route	Baseline (per seat-mi)		With Hotel Power Improvements (per seat-mi)			
	(Btu)	(lb-GHG)	(Btu)	Reduction	(lb-GHG)	Reduction
MARC Penn Line	478	0.085	483	-1%	0.086	-1%
Southwest Chief	864	0.153	888	-3%	0.157	-3%

To provide alternating current electricity at a constant frequency, a fixed-speed main engine PTO requires that the hotel power be provided directly from the engine, running at a constant engine speed (usually 900 rpm). This requirement leads to higher friction losses at low power demands, and limits total traction engine power to that attainable at 900 rpm. Fuel economy and acceleration performance both suffer.

An inverter PTO setup supplies hotel power via a static inverter, which provides a fixed-frequency hotel power supply while allowing the traction engine to use optimal engine speeds for the total power demanded. The static inverter allows the engine to attain higher power levels consistent with engine speeds above 900 rpm. It also allows the engine speed to be reduced under decreased traction energy demand. This feature realizes a significant reduction in energy consumption when the train is stopped and the engine is only supplying hotel power.

With a diesel-generator setup, a small, independent diesel engine drives a separate generator at a constant speed to provide the necessary electricity for hotel power. The small diesel engine and generator set can be designed to operate most efficiently at the speed and power required for hotel power generation. Separating the hotel power from the main traction system also increases the power available for traction from the main engine, allowing faster acceleration and allowing for more coaches per train.

For NCRRP Project 02-01, two passenger rail services were simulated with different hotel power configurations (Table 5-14). On the MARC Penn Line, the diesel-electric hotel power configuration was changed from a fixed-speed PTO to a diesel-generator set. On the Southwest Chief, the hotel power configuration was changed from an inverter PTO to a diesel-generator set.

With both trains, the energy consumption and GHG emissions of the passenger rail services actually increased, but only by a small amount. By providing a separate diesel-generator set for hotel power, additional power was available for traction. The trains used this extra power to accelerate faster and sustain higher operating speeds, increasing overall energy consumption. On routes where trains spend a greater portion of their time idling in hotel power mode and do not accelerate to higher track speeds (i.e., maintain their original speed profile), the diesel-generator set may reduce energy consumption and GHG emissions.

5.3.3 Upgraded Locomotives

In addition to incorporating different hotel power configurations, newly manufactured or upgraded locomotives are more fuel efficient because of technology such as microprocessor control and electronic fuel injection. Two passenger rail services were simulated with upgrades to modern high-horsepower locomotives (Table 5-15). The Heartland Flyer locomotive was changed from a 4,100 horsepower unit with a variable-speed (inverter PTO) hotel power configuration to a 3,200 horsepower unit with a diesel-generator set hotel power configuration. The changes were applied to the Heartland Flyer case study route with and without the NPCU. These changes resulted in a slight increase in energy intensity.

Table 5-15. Upgraded locomotives—changes in energy and GHG emissions intensities.

Route	Baseline (per seat-mi)		With Motive Power Upgrade (per seat-mi)			
	(Btu)	(lb-GHG)	(Btu)	Reduction	(lb-GHG)	Reduction
Heartland Flyer (with NPCU)	583	0.103	587	-1%	0.104	-1%
Heartland Flyer (without NPCU)	488	0.086	509	-4%	0.090	-4%
Piedmont	681	0.120	595	0.126	0.105	13%

The Piedmont locomotive was changed from a 4,100 horsepower unit with a variable-speed (inverter PTO) hotel power configuration to a 3,600 horsepower unit with a variable-speed (inverter PTO) hotel power configuration. This reduction in nominal horsepower resulted in a reduction in energy intensity with no significant impact on travel time or average speed.

5.3.4 Ultra-Low Sulfur Diesel Fuel

Currently, the United States and Canada have placed regulations on the sulfur content of diesel fuels used in locomotives, effectively requiring all diesel locomotives to conform to the ultra-low sulfur diesel (ULSD) standard of 15 ppm sulfur content (Barton and McWha 2012). Emissions testing on diesel fuel containing 50 ppm and 3,190 ppm sulfur content in 2000 reveal reductions in hydrocarbon (HC) emissions by 9%; carbon monoxide (CO), by 10%; nitrogen oxides (NOx), by 8%; and particulate matter (PM), by 24%, associated with the 50 ppm sulfur content fuel. A 1% increase in fuel consumption also has been reported (Barton and McWha 2012). Unlike other alternative energy sources, use of ULSD does not require significant modifications to the locomotive engines or refueling infrastructure (Stodolsky 2002). ULSD was not simulated with MMPASSIM.

5.3.5 Biodiesel Fuel

Biodiesel is a fuel blend that mixes standard, petroleum-based diesel fuel with fuel made from natural, renewable sources (e.g., vegetable oils or animal fats). Biodiesel has different formulations, but the formula most commonly used with conventional diesel engines—B20—is made up of one part (20%) biodiesel to four parts (80%) petroleum-based diesel.

Biodiesel was not simulated with MMPASSIM. However, Frey and Graver (2012) conducted testing on biodiesel versus ULSD on conventional passenger equipment from the North Carolina Department of Transportation (NC DOT) fleet. The testing by Frey and Graver showed a 1% decrease in fuel consumption, 6.4% increase in NOx emissions, 16.5% increase in HC emissions, and 8% increase in PM emissions, while CO emissions remained the same.

The advantage in using biodiesel comes from the renewable sources used in the refining process. However, it appears that biodiesel is not a favorable energy source for significantly improving the energy efficiency and reducing the emissions of rail transportation. Also, concerns remain about the limited number of producers, the distribution infrastructure and other elements of the production/distribution process. Long-term studies could identify problems associated with using biodiesel without engine modifications and could properly quantify the fuel and emissions savings associated with its uses at varying ratios of biodiesel to diesel fuel (Barton and McWha 2012). Unlike other alternative energy sources, use of ULSD does not require significant modifications to the locomotive engines or refueling infrastructure (Stodolsky 2002).

5.3.6 Natural Gas Fuel

Although first demonstrated in test service on revenue freight trains more than 20 years ago, natural gas has not been adopted as a locomotive fuel for a variety of economic and practical factors. Natural gas has a lower energy density per unit volume than diesel fuel, which effectively limits the amount of chemical energy that can be stored in a locomotive fuel tank. To maintain operating range, liquefied natural gas (LNG) or compressed natural gas (CNG) must be supplied from a tender. Use of natural gas as an alternative fuel source for internal combustion motive power requires substantial modifications to the locomotive engine and refueling infrastructure compared to current diesel operations (Stodolsky 2002).

Because of its lower NOx and PM emissions, natural gas could prove to be an advantageous fuel source in the face of stringent regulations from the EPA (Stodolsky 2002). The recent boom in natural gas extraction by means of hydraulic fracturing has made it apparent that natural gas is one of the most abundant fuel sources in the United States. The domestic supply surplus can make natural gas more cost effective than diesel motive power during times of high oil prices, with some estimates suggesting a 55% fuel cost reduction in commuter rail applications (Barton and McWha 2012; Cook 2014). Fuel cost savings come directly from the relative price of natural gas and diesel fuel, and are not intrinsic elements of the fuel itself.

Given the relative prices of natural gas and diesel fuel in recent years, interest in natural gas as a locomotive fuel has been renewed, and several prototypes are in freight test service. A passenger excursion train in Napa, CA, also has been converted to operate on CNG.

MMPASSIM was used to run simulations with LNG and CNG propulsion on the Southwest Chief long-distance intercity passenger rail route. The CNG operation was assumed to require a separate fuel tender car weighing 45,000 kg, whereas the LNG operation was assumed to require an incremental 5,000 kg tank that could be accommodated on the locomotive and baggage car. GHG emissions from the natural gas locomotives were based on tests conducted by BNSF et al. (2007), which showed that a higher methane (CH_4) component overrode the decreased carbon dioxide (CO_2) component when compared with diesel fuel. As a consequence, both types of natural gas operation increased direct GHG emissions (Table 5-16). The upstream processing energy of LNG is higher than that of diesel fuel, whereas that of CNG is lower. GHG emissions are exacerbated with the inclusion of indirect emissions for both LNG and CNG.

The NCRRP research team notes that the railway tests found the original diesel compression engine suffered a 9% efficiency penalty with natural gas fuel. The research team assumed equal efficiency with diesel fuel in the analysis, based on the premise that a compression engine could be developed to attain diesel-equivalent efficiency if it were seen as a fuel of choice justifying engine tuning/development for natural gas fuel properties. The research team also notes that the higher emissions found in the 2007 engine tests might also be reduced with engine development. Future engine tests of natural gas locomotive fuel should be monitored for potential improvements in both energy efficiency and emissions performance.

Table 5-16. Natural gas—changes in energy and GHG emissions intensities.

	Energy and Emissions (per seat-mi)							
	Direct				Direct Plus Upstream			
Fuel	(Btu)	Saving	(lb-GHG)	Saving	(Btu)	Saving	(lb-GHG)	Saving
Baseline Diesel	864	N/A	0.153	N/A	1037	N/A	0.191	N/A
LNG	866	0%	0.156	-2%	1052	-1%	0.206	-8%
CNG	921	-7%	0.171	-12%	1083	-4%	0.224	-15%

One of the main environmental arguments for using natural gas is that it is "clean" from the perspective of criteria air contaminants (CAC) that contribute to smog, and thus offers air quality benefits in urban areas. Depending on the level of air quality concern in urban areas, even without improvements in GHG emissions, the lower CAC emissions of natural gas might offset the higher GHG emissions in an environmental impact assessment for urban commuter services.

5.4 Alternative Energy Sources

Alternative energy sources are improvements that require significant equipment and energy supply infrastructure investments to be successfully implemented in large-scale passenger service. Some technologies also face significant technological challenges before large-scale implementation can be considered; however, each technology discussed has great potential to significantly reduce the energy consumption and/or emissions of passenger rail transportation. Alternative energy sources examined as part of this study include:

- electrification,
- renewable electricity generation,
- regenerative braking,
- dual-mode locomotives, and
- fuel cells.

The balance of this section demonstrates the effect of each of these approaches on passenger rail energy efficiency and GHG emissions on the selected case study routes. Unless otherwise noted, the baseline conditions match those described in Chapter 4.

5.4.1 Electrification

Electrification of passenger rail lines and equipment is a well-established use of technology to reduce local CAC emissions. Electrification consolidates the energy conversion process at a single location, potentially improving overall system efficiency and allowing for better control of emissions from combustion or the use of renewable energy sources that do not produce emissions.

Electric traction requires infrastructure over the entirety of the line to supply power to the traction system, principally by an overhead contact system or an electrified third rail. In North America, electric traction is widely used on systems that require rapid acceleration or where the infrastructure is already in place (i.e., rapid transit, some commuter systems, and intercity trains on the Northeast Corridor). Most intercity and commuter rail systems in North America share infrastructure with freight railroads, however, and currently it is not economically feasible for freight railroads to electrify operations (Barton and McWha 2012). This situation limits the use of electrification until (1) the costs of electrification are lowered, (2) diesel fuel prices increase to a level that justifies the necessary investments, or (3) emissions standards dictate electrification.

MMPASSIM was used to simulate the performance of electric traction locomotives in place of diesel-electric locomotives on the Metrolink Orange Line and MARC Penn Line case study routes (Table 5-17). The "direct" results, presented on the left side of the table, include the energy used in the train movement and the energy used to generate the electricity, but exclude the upstream energy and GHG emissions associated with fuel distribution. The "direct plus upstream" results, presented on the right side of the table, include both direct and upstream energy and GHG emissions. In the Metrolink simulation, the AEM7 train consist was limited to the current speed limits of the line, and both energy intensity and GHG emissions intensity were substantially decreased. In the MARC Penn Line simulation, however, the AEM7 was allowed to reach a maximum speed of 125 mph, whereas the baseline diesel-electric train was limited to 79 mph because

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Table 5-17. Electrification—changes in energy and GHG emissions intensities.

Route	Fuel	Energy and Emissions (per seat-mi) Direct (Btu)	Saving	(lb-GHG)	Saving	Direct Plus Upstream (Btu)	Saving	(lb-GHG)	Saving
Metrolink Orange	Diesel	366	N/A	0.065	N/A	439	N/A	0.081	N/A
	(AEM7)	252	31%	0.034	47%	273	38%	0.038	52%
MARC Penn Line	Diesel	478	N/A	0.085	N/A	574	N/A	0.105	N/A
	(AEM7)	565	-18%	0.091	-7%	580	-1%	0.107	-1%
Metra BNSF	Diesel	421	N/A	0.075	N/A	506	N/A	0.093	N/A
	(AEM7)	396	6%	0.074	1%	424	16%	0.079	15%
	Highliner (EMU)	380	10%	0.071	5%	408	19%	0.076	18%

of equipment speed restrictions. This speed increase was responsible for the overall increase in energy consumption on the MARC train. GHG emissions also increased because of the increased energy consumption. Including upstream activity improves the performance of electric relative to diesel in all cases.

On the Metra BNSF case study route, two different electrified trains were simulated with MMPASSIM. The first was a conventional six-car bi-level train powered by an AEM7 electric locomotive. The second was a Highliner electric multiple-unit (EMU) trainset used on the Metra Electric district. Both Metra BNSF simulations operated at the same speed limits as the baseline diesel-electric train consist. Use of the EMUs reduced energy and GHG emissions intensities more than did use of the consist with the electric locomotive. Although the EMUs were heavier than the baseline bi-level coaches (because of the addition of traction motors and other electric equipment on each coach), the incremental weight was less than the additional weight of the electric locomotive. Thus the EMUs achieved a greater reduction in energy intensity.

This effect of electrification was amplified in the Metrolink case study, because the electricity mix in California contains a large proportion of renewable and/or non-carbon energy sources. Thus, the decrease in emissions for Metrolink was disproportionately large compared to the decrease in energy consumption provided by electrification. This illustrates the differences in energy intensity and GHG emissions intensity reductions due to the regional electricity generation mix.

5.4.2 Regenerative Braking and Renewable Electricity Generation

Like on-board storage via batteries, regenerative braking allows a train consist to accept electrical energy generated from braking events and reuse it for traction. Instead of being supplied from on-board storage, the regenerated energy is supplied from other trains via the overhead catenary. The effectiveness of these systems is highly dependent on locomotive duty cycle and the relative timing of acceleration and braking events by different trains. The greatest potential is on systems with frequent acceleration and deceleration events involving higher speeds and a high train density.

For the MMPASSIM case studies of regenerative braking, the study team assumed that the train could accept the regenerated energy or the grid could accept the returned energy during 65% of the braking events. On both of the electrified intercity passenger rail operations simulated in MMPASSIM, regenerative braking reduced energy consumption and GHG emissions by slightly more than 10% (Table 5-18). The two electrified case studies were simulated in MMPASSIM using electricity generated with 100% renewable wind energy (see Table 5-18). Both the baseline and wind-generated electricity cases had regenerative braking at an acceptance rate of 65%. Wind

Table 5-18. Regenerative brake energy and renewable wind-power impacts.

Route	Fuel	Energy and GHG Emissions (per seat-mi) Direct (Btu)	Saving	(lb-GHG)	Saving	Direct Plus Upstream (Btu)	Saving	(lb-GHG)	Saving
Northeast Regional	Regional Mix	512	N/A	0.064	N/A	570	N/A	0.075	N/A
	With Regen. Braking	439	14%	0.055	14%	489	14%	0.064	14%
	100% Wind	268	48%	0.000	100%	275	52%	0.000	100%
California HSR	Regional Mix	585	N/A	0.050	N/A	660	N/A	0.066	N/A
	With Regen. Braking	522	11%	0.045	11%	589	11%	0.059	11%
	100% Wind	308	47%	0.000	100%	317	52%	0.000	100%

energy was used to illustrate the substantial reductions achievable by generating electricity from wind with no additional input energy and effectively zero emissions. The logistics of delivering the energy required by higher-speed or high-speed train services from constantly varying wind energy supplies was not considered in this analysis. Rather, a scenario is envisioned similar to that proposed by the California High-Speed Rail (CAHSR) project, in which the energy used by the system is offset by an equal amount of renewable, zero-emission energy.

Values seen on the left side of Table 5-18 reflect only the direct activity (energy used in train movements and electricity generation), while values on the right side include upstream indirect energy use and GHG emissions. Because the same source fuels are used for each alternative within the two regions, the percent listed under "Saving" remains unchanged even though the absolute values increase.

5.4.3 Dual-Mode Locomotives

Dual-mode locomotives provide motive power from both electric traction infrastructure and diesel-electric traction systems. This technology allows passenger trains to take advantage of efficient electric traction where the infrastructure is available and continue operations across non-electrified territory when necessary. Dual-powered locomotives lend themselves to electrification upgrades in smaller, incremental steps without disturbing operations (Vitins 2012).

This technology also allows for incorporation of power regeneration technologies wherever electric traction infrastructure has been installed, possibly leading to further energy savings. Dual-mode locomotives have been used for many years, but previous dual-mode locomotives have been subject to performance limitations when operating in electrified mode. Moreover, these locomotives can only be implemented in areas in which partial electrification has been implemented or planned, which limits the utility of this technology to certain regions. The first true dual-mode passenger locomotives in North America with equivalent performance in electric and diesel-electric modes are the ALP 45DP locomotives now in service with New Jersey Transit (Vitins 2012).

MMPASSIM has the capability to consider extended operation with dual-mode locomotives; however, dual-mode locomotives were not simulated in this study beyond the New York City–Buffalo, NY, case study described in Chapter 4.

5.4.4 Fuel Cells

According to Stodolsky (2002), fuel cells are regarded as having the highest potential for replacing the internal combustion engine on rail vehicles. Fuel cell technology converts chemical energy into electricity by means of chemical reactions. In the case of hydrogen fuel cells, hydrogen is used as fuel and oxygen acts as an oxidizer to produce an electric current (Barton and McWha 2012). Research on fuel cell technologies has been increasing due to the emergence of electronic or electrically operated devices and consumers' need for high-performance batteries. Currently, the fuel cell technologies cited as providing the most potential for rail transportation are the proton-exchange-membrane fuel cell (PEMFC), solid-oxide fuel cell (SOFC), phosphoric acid fuel cell (PAFC), molten-carbonate fuel cell (MCFC) and alkaline fuel cell (AFC) (Stodolsky 2002).

Implementation of fuel cells in passenger rail transportation would mean significantly lower GHG emissions. However, the thermal efficiencies of fuel cells are roughly equivalent to modern diesel engines. To be considered feasible for rail transportation, several barriers to fuel cell implementation must be overcome. Infrastructure to produce, store and transport hydrocarbon fuel sources for fuel cells must be available to produce service quality that is similar to or improved beyond that of the current infrastructure. Also, research must be continued to increase the power output of fuel cells to accommodate the power-intensive traction requirements of rail transportation. Notably, the BNSF railroad has tested hydrogen fuel cell technology in a switching locomotive with reported success (Barton and McWha 2012).

Because of a lack of working prototypes that could serve as a basis for a case study, fuel cell locomotives were not simulated in MMPASSIM.

5.5 Conclusions

MMPASSIM offers practitioners the ability to assess the potential benefits of alternative technologies and approaches to reduce the energy and GHG emissions intensities of passenger rail. Technologies and strategies can include changes to operations, rolling stock, motive power, fuel and source of energy. Certain technologies are better suited to commuter rail operations that experience more frequent acceleration and braking events. A different set of technologies are required for intercity service, where trains travel at maximum track speed for extended periods.

Although the research for NCRRP Project 02-01 was not intended to be a comprehensive investigation of the potential benefits of specific technologies and strategies across all passenger rail systems, in demonstrating MMPASSIM capabilities through simulation of energy-saving approaches on certain case study routes, certain trends are evident:

- The operating strategy of optimal coasting potentially offers substantial efficiency improvement for diesel-powered commuter rail systems.
- Across all simulated passenger rail operations, improvements to the equipment (tare weight reduction, seating density increase and consist rearrangement) offer the greatest potential reduction in energy consumption and GHG emissions.
- When single-level railcars are replaced by a smaller number of bi-level railcars to maintain the number of seats per train, commuter rail energy efficiency can increase by more than 40%.
- Provided that ridership can maintain a constant load factor, increasing train length increases efficiency but degrades running-time performance, with the result that the need for additional locomotives to maintain running-time performance sets a lower bound on energy intensity as train length is increased.
- Electrification can reduce energy intensity and GHG emissions intensity but is dependent on the regional electricity generation profile and requires significant capital investment.

- Electrification with higher-horsepower locomotives can facilitate higher operating speeds and more rapid acceleration that increase direct energy consumption and potentially offset GHG emissions gains.
- For an equivalent number of seats, using an EMU is more energy efficient than using an electric locomotive-hauled trainset.
- Under ideal conditions, regenerative braking and on-board storage reduced energy consumption by 8% to 14% for the simulated case study services.
- The simulated systems are largely insensitive to HEP hotel power configuration, aerodynamic improvements, and changes in unplanned stops and speed reductions. Hence any uncertainty in assumed MMPASSIM inputs for these parameters will not substantially alter provided performance metrics.

These conclusions are specific to the case study routes considered in this chapter. Depending on their exact characteristics, certain routes and operations may see more or less benefit from a particular approach to reducing the energy and GHG emissions intensities of passenger rail. For example, the hotel power supply simulation cases were based on a modest amount of layover idle. Provision of hotel power for long idling periods would be more favorable for locomotives that use a separate diesel-generator for hotel power. Similarly, electric and diesel-electric locomotives with higher traction power and separate hotel power will have greater capacity to haul more coaches on a fixed schedule as a commuter system grows.

CHAPTER 6

Barriers to Passenger Rail Energy Efficiency Innovation

To date in the passenger rail industry, decisions about train types and operating patterns have not been strongly influenced by energy use and efficiency concerns. Instead, many technology and operations decisions have been motivated primarily by safety concerns, the ability to use proven equipment designs, initial implementation costs and the need to work within existing operating and infrastructure constraints. In contrast, competing modes may be moving more aggressively to reduce energy consumption.

A 2014 paper finds that, although U.S. commuter rail ridership has grown over the past 15 years, energy efficiency on a passenger-mile basis has not improved (DiDomenico and Dick 2014). The research in NCRRP Project 02-01, together with other research by Brecher et al. (2014), documents that technologies are available to improve passenger rail energy efficiency; yet, on average, passenger rail operators have not improved their energy efficiency.

Chapter 6 addresses the following questions:

- What are barriers to energy efficiency improvements in the passenger rail industry?
- How can the identified barriers be addressed?

The first part of this chapter discusses methodology and limitations. The next section identifies several possible barriers to improving passenger rail energy efficiency, and the third section discusses possible approaches to reduce or eliminate these barriers.

6.1 Methodology and Limitations

The research team prepared this chapter primarily through consultation with passenger rail operators, rolling stock manufacturers, researchers and government agencies over a 4-week period between July 14 and August 12, 2014. Each practitioner interview followed a different progression of topics depending on the expertise of the respondent. As appropriate, the interviewer posed questions related to the technologies listed in Appendix F.

In total, 20 individuals were interviewed. Eight respondents were from commuter rail operators, two respondents were from intercity rail operators, two respondents held research positions at U.S. DOT (including one from FRA), one respondent was from a state government multi-modal planning office, three respondents were from industry associations, three respondents were consultants and one respondent was from a rolling stock manufacturer.

Of these 20 individuals, 15 respondents were from the United States (representing 13 different entities) and five respondents were from Canada (representing three different entities).

Respondents included individuals specializing in vehicle design, transit operations, energy efficiency, and transportation planning. Individuals from operating companies held positions including sustainability director, maintenance supervisor, chief engineer, rail operations supervisor, and rolling stock engineer. (Generic names have been used to describe these titles.)

In general, the persons interviewed provided a representative view of barriers to energy efficiency improvements.

6.2 Barriers to Improving Passenger Rail Energy Efficiency

6.2.1 Cost of Energy Efficiency Upgrades, Constrained Funding and Uncertainty

Multiple respondents indicated that the high upfront capital cost of some energy efficiency upgrades relative to available funding levels is a barrier to investing in energy efficiency improvements. Because of constrained funding for passenger rail transportation in the United States, many investments focus on achieving a "state of good repair" (SOGR) or on system preservation. A company or an agency may have a focus on sustainability, but to be considered, energy efficiency improvements often need to align with planned SOGR investment.

Similarly, some respondents indicated that, because of constrained funding levels, an energy efficiency investment would need to have a short financial payback period if it were to be implemented. In the case of energy efficiency improvements, the payback period is the length of time until the ongoing operational cost savings from decreased energy use equals the initial capital investment.

One respondent noted that the high capital cost of new equipment, combined with the constrained funding environment, means that passenger rail operators do not have many spare locomotives. The lack of spares makes it difficult to take locomotives out of service for equipment overhauls without lowering service capacity or quality. When major maintenance is performed less frequently (the respondent suggested), locomotives are less likely to run at their original manufacturer's specifications, and are thus less likely to be performing at their optimal energy efficiency. When locomotives are highly utilized, there is potentially less flexibility to make improvements in energy efficiency. Implicitly, the respondent highlighted the trade-offs between improving energy efficiency, providing reliable service, and cost.

Respondents also suggested that *uncertainty* in future funding levels potentially limits energy efficiency improvements by reducing the ability of passenger rail operators to effectively plan future capital investments. One respondent argued that it is difficult to conduct strategic planning in the absence of predictable funding levels and noted progressively shorter transportation funding authorizations as one challenge. U.S. federal surface transportation funding authorizations have decreased from six-year terms in the 1990s with ISTEA and TEA-21 to four-year terms in the late 2000s with SAFETEA-LU to, most recently, two-year terms with MAP-21 (Transportation for America 2011). Uncertainty over reauthorization continues as of June 2015. The federal authorization bill for intercity passenger rail funding—the Passenger Rail Investment and Improvement Act of 2008 (PRIIA)—also had not been reauthorized as of August 2014. This respondent was concerned that these progressively shorter authorization periods made it difficult to plan capital purchases.

Similarly, another respondent expressed concern that rolling stock purchases may not be made as part of a longer-term vision for a corridor, resulting in potentially higher long-term costs and slowing down adoption of new technology. The useful life of locomotives and passenger coaches depends on the condition of the rolling stock and whether investments have been made in the stock over time; however, as a general estimate, the useful life of a locomotive can be upwards of 30 years, and that of a passenger coach can exceed 40 years (Amtrak 2012a). Given this longevity, rolling stock purchases can have lasting impacts on energy efficiency. The respondent noted that, in the absence of effective strategic planning for the future, the choice of propulsion technology may be driven by funding availability, rather than by longer-term needs, and cited the 2012 procurement of new diesel-electric locomotives in Illinois as an example (*Progressive Railroading* March 2013). In Illinois, rolling stock is being procured to offer 110-mph service on the Chicago-St. Louis corridor. However, 220-mph fully electrified HSR also is under study (University of Illinois 2013). If the desired result is an electrified corridor, were funding more certain, different locomotive technology may have been selected. In this manner, funding uncertainty may be slowing down implementation of energy-efficient technology, with lasting implications.

6.2.2 Internal Accounting Structures and Employee Incentives

The internal accounting structure of passenger rail operators may not incentivize actions to improve energy efficiency. Specifically, an accounting structure that assigns the capital cost of an energy efficiency improvement to one department and operational savings to another department can limit incentives for managers to make energy efficiency improvements. For example, locomotive purchases or upgrades may be charged to the mechanical department (encouraging employees in the department to be frugal with capital purchases) while potential ongoing operational savings are received by the transportation/operations department. Purchasing fuel-efficient locomotives—which are more expensive in terms of up-front capital cost—may benefit an organization overall, but the internal accounting structure of the company may discourage making the purchase.

One respondent noted that individual train operators may not be incentivized to take energy-efficient actions such as handling trainsets in a fuel-efficient manner or connecting trainsets to wayside hotel electric power for maintenance instead of idling the locomotive. It may not be possible to measure fuel use with sufficient precision to attribute any efficiency gains to an individual operator, which makes it difficult to provide positive incentives. If a train is ever inoperable or late, however (e.g., because it did not start after a layover shutdown or because the engineer attempted to use fuel-efficient train-handling techniques), the negative impact on customer service could be attributed to an individual. Further, as one reviewer pointed out, the stakes are higher when dealing with a train as compared to a light-duty vehicle (LDV). With a train, a malfunction could affect hundreds or thousands of passengers, whereas with an LDV a malfunction likely would affect a small number of people. At the individual-level, risk-taking to improve efficiency offers limited upside benefits but strong downside consequences, thus disincentivizing deviations from current practice.

Similarly, individuals with decision-making authority may be reluctant to implement new technology if it has not been "service-proven" (a term mentioned by respondents). Unless the technology is service-proven, individuals would be concerned that the technology might not function as intended, thus threatening service capacity or quality. Again, it may be difficult to attribute energy efficiency gains from new technologies to decision-makers (particularly in the short term), but it may be easy to trace service issues back to their decisions.

The lack of detailed data at a micro-level (e.g., trip-level) is one barrier to improving energy efficiency. Respondents noted several possible data collection issues, such as the lack of station-level passenger boarding figures (because of open-boarding stations often used on commuter rail lines) and difficulty measuring fuel use at the locomotive or substation level (because of imprecise gauges on diesel equipment and inconsistent electricity metering). While one respondent noted that electricity usage can be measured on board a train, it is not collected or recorded on an ongoing basis. As a result, it is difficult to provide feedback on their energy efficiency performance to field staff (e.g., locomotive engineers and maintenance staff), and it is challenging to identify potential opportunities to reduce energy consumption on an ongoing basis. However, one respondent indicated that if a particular technology investment is being contemplated, it would likely be possible to manually collect the necessary baseline data in the field. Ultimately, the energy efficiency improvements facilitated by enhanced data collection technology or through field work must outweigh their costs.

6.2.3 Conservatism and the Trade-off between Customer Service and Efficiency

Some respondents noted that "conservatism" exists in the industry with respect to adopting new technologies, slowing down innovation. This apparent conservatism can be attributed to several interrelated factors mentioned by respondents, including:

- relatively infrequent opportunities to develop and adopt new technology, such as during major procurements;
- an incentive structure that promotes a risk-averse culture in relation to "non-service-proven" technologies; and
- a focus on safety and service quality rather than energy efficiency.

Major opportunities to develop and adopt new technologies in the passenger rail industry are relatively infrequent given the long useful life of rolling stock and the resulting infrequency of large rolling stock procurements. As a result, operators may have few opportunities to adopt new technologies. A single agency may also be reluctant to divert funds from procurement to research and development to improve the fuel efficiency. Operators often must select from existing designs, and the cycle perpetuates itself, slowing the pace of innovation.

Passenger rail operators often prioritize service quality over energy efficiency. Interview respondents indicated that the highest priority for passenger operators, after safety and security, usually is ensuring good customer service. Respondents differed on the particular actions taken to improve customer service (e.g., initiatives for improving reliability, travel time and passenger comfort), but all of them suggested that ensuring high levels of customer service was a key goal of their organizations. One respondent noted that ensuring a high level of service is a key factor for attracting customers to the service, raising load factors, and thus improving energy efficiency on a per passenger-mile basis.

Some respondents indicated that a trade-off exists between improving customer service (e.g., reliability, travel time and passenger comfort) with the aim of increasing passenger demand, load factors and energy efficiency on a per passenger-mile basis, and improving energy efficiency on a per seat-mile basis. Respondents noted, for example, that adding customer amenities such as Wi-Fi or more spacious seating adds weight to the coach and draws additional energy, decreasing energy efficiency per seat-mile.

Respondents also indicated that rail operators focus on maintaining or improving travel time by using maximum possible acceleration and deceleration to ensure the lowest possible runtime over a route. Similarly, one respondent noted that because of the limit on available rolling stock, his agency operates its equipment with the "pedal to the metal"—that is, as quickly as possible—to maintain minimum headways between trains. Because locomotives are used closer to their maximum output, this focus on improving service quality reduces energy efficiency on a per seat-mile basis, although it potentially raises energy efficiency on a per passenger-mile basis through increased ridership and load factor. One respondent noted that his agency's recent rolling stock procurement resulted in no net change in energy efficiency. To maintain passenger comfort, there is a desired upper limit to the load factor on any given train run, resulting in an upper limit to energy efficiency on a per passenger-mile basis. To ensure a minimum level of customer comfort, operators may set this upper limit at a load factor beneath the maximum possible load factor (i.e., crush load), the point at which no other standing passengers can board (Kittelson and Associates 2003). One commuter rail operator said, "We offer a service that must be attractive enough to the public that they choose us rather than drive. Therefore, high passenger densities [i.e., crush-loading standees] cannot be tolerated as the norm."

Because the agency self-imposes a maximum tolerable load factor lower than the maximum possible (crush) load on train runs during the peak period, the average load factor and average energy efficiency on a per passenger-mile basis are less than what they could be were crush loads regularly permitted. Even if crush loads are permitted during peak periods, there is a limit to the impact on average load factor, and consequent improvement in energy efficiency will be limited by the extent that the service is operated at low load factors during off-peak periods. Off-peak operations are discussed in the next section.

6.2.4 Barriers to Improving Off-Peak/Backhaul Load Factors

One challenge to improving energy efficiency is matching capacity with the variation between peak demand and off-peak demand. For commuter railroads, peak-demand usually occurs twice a day, with a morning peak on trips carrying passengers from the suburbs toward a central business district (CBD) and with an afternoon or evening peak on trips carrying passengers from the CBD back toward the suburbs. Sizing train capacity to peak demand usually results in low load factors during off-peak periods (including any backhaul in the direction opposite peak travel demand). As a result, train runs operating in the off-peak period often have poor energy efficiency on a per passenger-mile basis because a similar amount of energy is expended to move fewer people. From an energy efficiency perspective, avoiding off-peak runs or better matching the number of railcars in the consist to the number of passengers on the train would be beneficial.

Some barriers to improving energy efficiency during off-peak periods might be agency-specific. For example, one respondent noted that their infrastructure configuration does not permit a layover for all trains at the downtown station or nearby yards; thus, trains need to return to an origin station during off-peak periods. If additional trains could layover at the downtown station, inefficient off-peak runs could be avoided. Another respondent noted that the agency has sufficient yard and siding tracks spaced throughout the system to allow for some trains to layover during off-peak periods.

Another approach to improving the energy efficiency of off-peak runs is to reduce the number of railcars in each train consist, thus improving load factors. In a separate, unrelated discussion, one respondent noted that energy costs were less than 10% of total expenditures, but labor costs were approximately 70% of expenditures at the agency in question.

Respondents cited the operational (labor) cost of changing train length between runs as one of the key barriers. An online post by an advocacy group for improved commuter service notes that "changing train length is a laborious and time consuming operation (BayRail Alliance 2013)." This comment is consistent with statements from multiple interview respondents. One respondent also cited as a barrier the potential risk of a malfunction during the uncoupling/coupling process. With spare rolling stock in short supply (as observed by a separate respondent), the risk that a malfunction would not allow a train to operate in its schedule slot appears to outweigh the potential benefits of energy savings.

One respondent speculated that the coupling technology used on commuter rail services in North America, which involves separate brake air lines, may be one of the technical barriers. (European and Japanese-style couplers have integrated air lines for braking that do not need to be connected manually when railcars are coupled.) This comment was neither corroborated nor discounted in other interviews, however.

Another respondent noted that, although their load factors are lower in the off-peak, their equipment is utilized to the point that undertaking the uncoupling/coupling process could disrupt operations. This last comment reinforces a point made in the discussion of the cost of energy efficiency upgrades regarding operators' ability to take equipment out of service for maintenance: When assets are highly utilized, there is potentially less flexibility to make operational decisions that improve energy efficiency.

6.2.5 Market Size and Regulations Specific to North America

When the interviewer raised the issue of the effect of North American regulations on rolling stock tare weight, respondents usually indicated that regulations in the United States governing buff-strength of passenger cars makes some North American equipment heavier than foreign (notably European) equipment. Respondents were referencing the provisions of 49 CFR 238.203, known as the "static end strength" requirements, which state that ". . . on or after November 8, 1999, all passenger equipment shall resist a minimum static end load of 800,000 lb applied on the line of draft without permanent deformation of the body structure."

One respondent familiar with railcar design stated that there is potential for weight reduction using electric multiple-unit/diesel multiple-unit (EMU/DMU) equipment designed to standards incorporating crash-energy management (CEM) currently being integrated into a future FRA Notice of Proposed Rulemaking (NPRM). The same respondent also indicated that any weight savings in comparison to more traditional locomotive-hauled trainsets would be limited, however, because other design requirements govern the weight of this equipment. Although a long process was anticipated before any regulatory changes are made, respondents were hopeful that this future NPRM would clearly describe the design requirements for using EMU/DMU equipment in North America.

One respondent from a rolling stock manufacturer commented that the small size of the passenger rail market in North America relative to the European market also contributes to the impact of North American design standards on rolling stock availability and design innovation. For example, the company had considered the business case for developing FRA-compliant DMUs, but decided that the market size would be too small. (The respondent further noted that DMUs generally serve high-frequency lower-ridership markets that are a subset of the already small North American passenger rail market.) Another respondent noted that one of the pushes for developing the NPRM came from passenger rail operators seeking to increase the number of bidders during rolling stock procurements. Having a more flexible design standard could allow rolling stock manufacturers to bring additional service-proven designs from abroad instead of being forced to develop a unique design solely for North America. As noted, developing a unique design for a limited market often is uneconomical for the manufacturer, who cannot distribute the design and development costs over a large number of purchases. As a result, the barrier to innovation is not only the existence of the unique North American design standards but the fact that the unique standards isolate the North American market from the rest of the global market.

Heretofore, operators could apply for a FRA waiver to implement non-FRA-compliant vehicles on corridors shared by transit and railroad lines. However, "[t]he waiver process puts the applicant [train operators] at the whim of authorities that may identify additional requirements due to unforeseen local circumstances or new lessons learned from novel accident scenarios" (Booz Allen Hamilton et al. 2009). Though there have been successful waiver applications, respondents, echoing this quote, generally noted that the waiver process is time consuming and introduces a barrier by creating uncertainty over the acceptability of certain equipment. Although the current North American safety regulations are not an absolute barrier to procuring alternative rolling stock designs, each exception must go through a unique waiver process, which increases the challenge to procuring equipment tailored to the unique circumstances. The waiver process is described in *TCRP Report 130: Shared Use of Railroad Infrastructure with Noncompliant Public Transit Rail Vehicles: A Practitioner's Guide.*

The interview responses suggest that current FRA design standards result in some heavier rolling stock. Whether these regulations are or are not appropriate given the North American context for passenger rail operations (notably, heavy freight use as compared to elsewhere in the world) is not considered by this research. However, the responses suggest that one barrier to innovation is that, without appropriate flexibility to consider alternative design approaches, the North American regulations can isolate the relatively small North American passenger rail market from the larger global market. Moreover, the lack of a standardized process for approving alternative designs in the appropriate circumstances potentially limits innovation.

6.2.6 Barriers to Implementing the Use of Alternative Fuels

Several of the respondents were asked if their company or agency were considering the use of alternative fuels to power their rolling stock. In the case of technologies that use liquefied natural gas (LNG) and fuel cells, respondents suggested that the major barrier to implementation is the limited availability of mature technology for passenger rail. One respondent suggested that the infrastructure requirements for fueling also represent a barrier, particularly for Amtrak, because its operations are nationwide and Amtrak does not own most of its infrastructure.

Respondents mentioned successful Amtrak trials of a 20% biodiesel blend (B20) in 2010, but noted that the scope of this study was limited to assessing the impact of biodiesel on the diesel locomotive prime mover. These trials were facilitated by a $274,000 grant from FRA (Amtrak 2011). No subsequent tests were planned. A Volpe Center/FRA report highlighted some recent tests of alternative fuel locomotives (Brecher et al. 2014); however, few respondents were able to provide concrete examples of an alternative fuel that they are closely following, which suggests that the technology is not mature enough for implementation.

Electrification of infrastructure was the main "alternative fuel" discussed. Apart from the high capital cost, other technical barriers to electrification were suggested by respondents. One respondent noted that some electrical utilities are wary of allowing energy from regenerative braking from locomotives back into the electrical grid; however, this concern appears localized to certain regions. Amtrak, for example, highlights that it expects $300 million in energy to be returned to the Northeast United States power grid through the use of its new Siemens locomotives that entered service in 2014 (Amtrak 2012b).

Some respondents suggested that shared track with freight railroads is a barrier to implementing electrification in a corridor. One respondent cited as a technical barrier the high overhead clearance requirements for double-stack containers that may necessitate a longer pantograph. Other respondents commented that freight railroads are reluctant to reduce their operational flexibility by adding additional infrastructure (e.g., a second track) with overhead catenary. Further research into this issue could be helpful in the context of shared corridors research programs.

6.3 Approaches to Address Barriers

6.3.1 Improved Asset Management, Lifecycle Maintenance and Data Collection

As discussed in the section on the cost of energy efficiency upgrades, addressing the SOGR backlog at passenger rail operators is a major challenge to providing capital funding for some energy efficiency improvements. Respondents were hopeful that the introduction of improved asset management strategies and increased use of lifecycle maintenance techniques in their operations could improve energy efficiency by:

- improving energy efficiency directly through improved equipment performance;
- improving reliability, allowing operators to enhance the service level provided to customers and thus improve load factor; and
- freeing up capital funding over the longer term for use on energy efficiency improvements.

MAP-21 includes requirements for transit operators (i.e., commuter railroads) to implement asset management strategies overseen by FTA (FTA Fact Sheet n.d.). Following these requirements, transit agencies must catalog their assets and their condition using FTA's definition of SOGR. One respondent indicated that the process of developing a SOGR database at the agency already helped justify additional capital funding. Another respondent indicated that the database would create a "level-playing field" to address the worst SOGR issues across agencies.

One respondent familiar with rolling stock maintenance was also hopeful that improved lifecycle maintenance standards being implemented with the contract operator would improve the energy efficiency of the fleet. The respondent indicated that the contract included provisions to require "original equipment manufacturer" maintenance standards to help ensure that equipment would run closer to specification and with improved energy efficiency.

As noted in the section on internal accounting structures, the incentive structure perceived by individual employees can be a barrier to taking actions that improve energy efficiency. Seeking opportunities to leverage existing data or implement technologies to collect new data can help overcome this barrier. One respondent noted that, in the course of efforts to conserve the useful life of their equipment, the agency learned that it could generate daily excessive idling reports using the locomotives' on-board computers. This information allowed maintenance supervisors to address excessive idling reports directly with a small group of maintenance staff by monitoring whether maintenance staff members were plugging in equipment during layovers. Similarly, VIA Rail Canada, the Canadian intercity passenger rail operator, is implementing technology to measure the diesel consumption on individual train runs (Pinsonneault 2014). The system being implemented allows locomotive operational data to be transmitted through the same system that runs on-board Wi-Fi for passengers (Via Rail Canada 2014). VIA Rail Canada is using this technology to train and encourage locomotive engineers to adopt energy-efficient train-handling approaches.

6.3.2 Emissions Regulations as a Driver of Energy Efficiency Improvements

Many respondents noted that EPA's non-road diesel engine emission standards are a major driver of energy efficiency improvements. Demarcated as "tiers," these progressively stricter standards regulate the amount of pollutants that can be emitted from locomotive engines (EPA 2012). The current standard is "Tier 4." Although a 2014 Volpe/FRA report notes that there is almost no energy efficiency gain from upgrading a Tier-3-compliant locomotive to become Tier-4-compliant because of the extra equipment weight involved (Brecher et al. 2014), going from an old, pre-tier-system locomotive to a new locomotive can result in significant energy efficiency improvements. Respondents generally cited the EPA requirements as the major driver of passenger rail energy efficiency improvements.

Respondents also noted other EPA actions related to air quality and emissions as driving energy efficiency improvements. For example, respondents cited the 2010 consent decree signed by the Massachusetts Bay Transportation Authority (MBTA) and the Massachusetts Bay Commuter Railroad Company (MBCR) with EPA and the U.S. Department of Justice to install plug-in stations for electrical power at layover facilities. As discussed in the section on internal accounting structures, these facilities provide hotel electric power from the wayside rather than from idling locomotives. This decree was signed in response to the MBTA/MBCR's violation of a Massachusetts anti-locomotive-idling law that was federally enforceable under the Clean Air Act (EPA 2010).

State regulations made under the federal Clean Air Act can thus potentially drive energy efficiency improvements. The Massachusetts locomotive anti-idling regulation (310 CMR 7.11) is an EPA-approved regulation in the Massachusetts Clean Air Act State Implementation Plan (EPA 2014). As such, it is federally enforceable by the EPA. Other states, including Rhode Island, include similar provisions as part of their state implementation plans (Massachusetts Department of Environmental Protection 2014). Combined with EPA oversight, these regulations have encouraged energy efficiency improvement.

6.3.3 Efficiency Improvement Grants and Alternative Funding & Financing

Respondents highlighted grants and other funding and financing mechanisms focused on energy efficiency improvements and reductions of emissions as one way to overcome the financial barrier to improving energy efficiency. The most frequently noted grant was the TIGGER (Transit Investments for Greenhouse Gas and Energy Reduction) program, a discretionary grant initiated under the American Recovery and Reinvestment Act of 2009 (ARRA) and administered by FTA. Transit proposals for this (very oversubscribed) grant were evaluated primarily on the ability of the proposed action to decrease GHG emissions or increase energy efficiency, as well as the innovativeness of the proposal (FTA 2012). Though the grant was only offered to transit projects and not specifically commuter rail, the grant funded some innovative projects, including the implementation of wayside energy storage on subway systems (Brecher et al. 2014). Based on discussions with respondents, however, this grant is no longer offered.

One agency uses Energy Efficiency Companies (ESCOs) to finance energy efficiency upgrades (SEPTA 2012). In these arrangements, the agency contracts with the ESCO to provide energy efficiency upgrades, an up-front capital expense. The agency then pays the ESCO out of the energy efficiency savings from the capital upgrades. In Pennsylvania, these arrangements must be "budget neutral" under state law: the ESCO has to guarantee the savings over time. The use of ESCPs is one innovative financing mechanism raised in the interviews that allowed an agency to pursue infrastructure upgrades that improve energy efficiency.

Other potential alternative funding and financing mechanisms can be considered to fund energy efficiency improvements. One reviewer noted that California is allocating $250 million in revenue from the state's carbon cap-and-trade program to constructing HSR alignment in the state (Taylor 2014). *NCRRP Report 1: Alternative Funding and Financing Mechanisms for Passenger and Freight Rail Projects* identifies and describes several such mechanisms in more detail (CPCS 2015).

6.3.4 Leveraging the Growth of "Reverse Commuting"

The growth of reverse commuting, by which a passenger travels from the city center to the suburbs in the morning for work and returns to the city center at night, has the potential to improve load factors during off-peak "backhaul" periods. Reverse commuting appears to be on the rise in certain urban areas. In the San Francisco Bay Area, the Peninsula Corridor Electrification Project Draft Environmental Impact Report notes that "there has been a substantial increase in 'reverse commute' trips from San Francisco to Peninsula and South Bay locations over the past decade" (Caltrain 2014). In New York, around 300,000 people live in New York City and commute to work in the suburbs (Fessenden 2008). Comments received during the interviews suggest that changing demographics (e.g., young people desiring to live in the city) and employment centers (e.g., employers relocating from the city center to the suburbs) are contributing to this trend.

Further study could be undertaken to consider how rail operators can leverage this trend to raise load factors in off-peak periods (including on the backhaul). Some participants were asked if their agency offers any time-of-day pricing (i.e., charging a premium during peak periods) and whether such approach has an impact on off-peak ridership. Respondents generally did not believe that time-of-day pricing was a significant driver of whether individuals traveled in the off-peak or on the backhaul. Corroborating these comments, studies have generally shown that transit ridership is generally insensitive (i.e., inelastic) with respect to changes in fares (Litman 2004). (Inelastic demand means that a 1% increase [decrease] in fare will produce less than a 1% decrease [increase] in demand, respectively.) Should pricing become more of an issue, however, differentiated peak/off-peak fares could still potentially be used to even out demand.

6.3.5 Need for Interdepartmental and Interdisciplinary Groups

One respondent noted that improving energy efficiency often required the participation of many individuals from across an organization. As discussed in the section on internal accounting structures and employee incentives, some agencies and companies may have an accounting structure that does not encourage a department to take actions by itself to improve energy efficiency. One respondent noted that her organization has been increasing the success of energy efficiency improvements by identifying an interdepartmental project team as soon as an initiative is proposed. Doing so ensures that all potential issues are identified and addressed as soon as possible. Often, a company executive position is created to oversee sustainability initiatives and identify and organize such a project team. One reviewer indicated that having this direction at a high level within an organization is crucial for the success of any energy efficiency initiative.

6.3.6 Promoting a Culture of Being "Good Neighbors"

Several respondents noted that their motivation to be "good neighbors" to communities surrounding their operations motivated them to initiate energy efficiency improvements. Usually, the primary goal of such improvements was to reduce air emissions rather than to increase energy efficiency. Operators recognized, however, that members of the surrounding community are important indirect stakeholders—the term "customers" was often mentioned—who can influence the political process, and thus the goals of the rail operator.

Implicit is the assumption that by being a good neighbor, rail operators are more likely to achieve their energy efficiency goals. For example, sometimes the impetus to be a good neighbor started when a new service was being contemplated and public concern over emissions was raised.

6.3.7 Increasing Standardization of Alternative Design Criteria

As discussed in the section on regulations and market size specific to North America, some respondents indicated that buff-strength requirements in North America are one barrier to improving the energy efficiency of some rolling stock, notably EMUs/DMUs. Respondents were hopeful that ongoing development of design standards that allow use of CEM approaches in the design of North American rolling stock would allow for lighter-weight equipment in certain cases. More importantly, respondents were hopeful that having a well-defined standard would allow operators procuring equipment to draw from a larger pool of international suppliers, thus increasing the possibility for innovation.

One respondent cautioned, however, that drawing from a larger pool of international suppliers also would require the development of a North American supply chain to complement the use of international designs. The respondent was familiar with one instance in which rail service on a commuter line was affected because of the lack of available spare parts in North America.

6.4 Summary of Findings

From a methodological perspective, the research team found it easier to solicit best practices for energy efficiency improvements than barriers to energy efficiency improvements. Respondents spoke more freely about energy efficiency improvements. Starting an interview with a discussion of best practices facilitated a transition into a discussion about possible barriers.

An overarching takeaway from this research is that energy efficiency improvements compete with other, higher, priorities of passenger rail operations. For example, the need to address agency SOGR backlogs was highlighted as a key challenge to improving energy efficiency given the constrained (and uncertain) funding available to passenger rail operators. Additionally, some respondents noted that, even though improving energy efficiency is a priority at their company or agency, improving customer service (e.g., travel time, reliability and passenger comfort) is of greater concern. Implicitly, the higher priority of passenger rail operators is to increase their market (modal) share of transportation system users rather than to improve energy efficiency. Although improving customer service hopefully increases ridership (and thus load factors and energy efficiency on a per passenger-mile basis), such improvements also can retard efficiency gains by adding equipment weight or increasing energy draw. Failing to take into consideration these competing priorities can reduce the effectiveness of energy efficiency improvements.

Specific actions that passenger rail operators can take to address these and other barriers to energy efficiency include:

1. Implementing (or continuing to implement) improved asset management strategies and life-cycle maintenance techniques to reduce SOGR backlog, improve investment justification, and ensure that equipment runs at its highest possible efficiency;
2. Seeking opportunities to leverage existing data, such as on-board locomotive reports, or implementing technologies to collect new data on an ongoing basis, such as trip fuel efficiency monitors;
3. Creating a department and executive position responsible for coordinating investments in energy efficiency improvements to ensure that all possible company-wide or agency-wide benefits and costs are considered during financial and economic evaluations;
4. Seeking opportunities for energy efficiency improvement that reduce both operational costs and the impacts of transportation on the surrounding community;
5. Understanding and responding to potential demographic trends, such as the growth of reverse commuting (by which a passenger travels from the city center to the suburbs in the

morning for work and returns to the city center at night) by making service and pricing changes; and

6. Identifying alternative funding and financing mechanisms for energy efficiency improvements, such as those described in *NCRRP Report 1: Alternative Funding and Financing Mechanisms for Passenger and Freight Rail Projects.*

It is also clear from the research that regulatory agencies have an important role to play in terms of energy efficiency and environmental improvements. Many respondents noted that EPA's non-road diesel engine emission standards are a major driver of energy efficiency improvements. Incorporating alternative rolling stock design criteria based on CEM approaches into FRA regulations—as opposed to considering them through the waiver process—also has the potential to reduce the weight of certain rolling stock.

CHAPTER 7

Modal Comparisons of Energy Consumption and GHG Emissions

This chapter describes case studies for which MMPASSIM was used to model the energy consumption of specific door-to-door passenger trips using passenger rail and the competing passenger travel modes available in each region. The constructed case studies represent very specific individual commuter, regional intercity, long-distance intercity and high-speed rail (HSR) round trips between a defined origin and a particular destination. Besides indexing the energy and emissions performance of other passenger modes to passenger rail, the case studies also provide insight into how the following factors influence the modal energy and emissions comparison:

- congestion and peak/off-peak load factor;
- commuter versus regional intercity trainsets;
- electric versus diesel-electric operations;
- push-pull operation with a cab car, compared to turning the trainset;
- snack cars and other passenger amenities;
- access and egress distance; and
- choice of access and egress mode.

7.1 Methodology

For each case study, the energy intensities of door-to-door round trips (as defined by the specific origin-destination pairs) were calculated for the equivalent rail, auto, air and bus trips via MMPASSIM. Chapter 3 provides an overview of MMPASSIM. Additional detail is available in *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* (NCRRP WOD 1), which provides detailed guidance for each module in the spreadsheet tool. CRP-CD 176, which is bound in with this report, also contains copies of the Technical Document and User Guide, together with the MMPASSIM spreadsheet files. The MMPASSIM and User Guide files also can be downloaded from the report's web page at www.trb.org (search for "NCRRP Report 3").

The balance of this chapter highlights important assumptions of the modal comparison and introduces some unique aspects of the MMPASSIM modal comparison methodology that have not yet been discussed.

7.1.1 Definitions of Competing Modes

In the case studies for NCRRP Project 02-01, competing *passenger travel modes* refer to passenger rail; personal automobile (including light-duty vehicles [LDVs], trucks, vans, etc.); intercity bus; and air transportation. Specific characteristics of each mode varied across case studies based on service availability, regional differences and trip characteristics. The *competing mode* of a trip was defined by the mode of travel used for the main travel segment of the door-to-door trip.

Competing modes were simulated using MMPASSIM as described in Chapter 3. Using GIS, highway gradient profiles and distributions of traffic congestion in urban areas were created for the highway routes corresponding to each rail case study. Thus, these factors were considered in the calculation of auto/LDV and bus energy intensity and emissions. Unless specified in the case study description, air trips used the default aircraft distribution (shown in Table 3-3).

7.1.2 Access and Egress Modes

Access and egress modes for each trip included walking, bicycling, rapid transit, bus, automobile, taxi, carpool and so forth. In MMPASSIM, multiple access and egress modes can be selected for each modal alternative (i.e., walking to the subway to access the airport). Access and egress distances for each case study trip were developed using publicly available online mapping software. First, selections of a specific origin address and destination address were made for each round trip. Using these addresses, distances to the terminals of the main travel segment (i.e., railway station, airport or bus station) were calculated. Access and egress modes were selected to reflect reasonable traveler behavior considering several factors: regional availability, trip time (including transfer dwell time), number of travelers, time of day, season, and access and egress distance.

Dwell time, the idle wait time between modal leg trips or access and egress legs, is included in the results of each MMPASSIM case study as a component of the total travel time output. The total travel time of each trip is calculated as the sum of the total dwell time and the run time of each main travel and access mode segment. Dwell time assumptions for the case studies include two different dwell times for the air mode (Table 7-1). The short (80-minute) access dwell applies to flights originating at smaller regional airports with fewer flights and congestion. The long (120-minute) access dwell applies to major airports and hubs that are more congested and have a greater chance of extended waits for security clearance.

Various access and egress modes were selected for the set of case studies, both to illustrate the effects of each mode on total trip energy consumption and trip time and to illustrate the full capabilities of the MMPASSIM tool. Auto/LDV trips were assumed to proceed directly from origin to destination without any access or egress legs.

7.1.3 Ridership and Vehicle Occupancy

In addition to total per-trip energy consumption and emissions, the results of each modal comparison case study are presented on both a per seat-mile and a per passenger-mile basis. Calculation of energy efficiency and emissions per passenger-mile requires information on the

Table 7-1. Dwell time assumptions.

Modal Leg	Access Dwell Assumption (min)	Egress Dwell Assumption (min)
Commuter Rail	10	1
Rail	20	5
Auto	--	--
Air	80 (short), 120 (long)	20
Intercity Bus	20	5
Subway (transfer)	5–10	--

ridership of each evaluated passenger service and also highway-vehicle occupancy. Ideally, the ridership load factor (percent of seats occupied) would correspond to specific train runs, flights and highway vehicle-trips. Rail load factor assumptions for the case study routes are discussed in the summary and ridership section in Chapter 4.

The default auto/LDV simulation was for a vehicle with a single occupant. Although most of the case studies involved a single traveler, selected case studies involved multiple people traveling together. In these instances, the vehicle occupancy rate of the highway mode was adjusted accordingly.

7.1.4 Load Factor Sensitivity Charts

Energy intensity comparisons per passenger-mile at specific load factors or using the per seat-mile metric are useful to compare the efficiency of each mode under specific operating conditions. However, over the course of daily operations, each mode often experiences a range of load factors between 0 and 1.0, depending on the demand at different times of the day. To broaden the MMPASSIM modal comparison results over a wider range of ridership conditions, load factor sensitivity charts were developed for each case study.

Load factor sensitivity charts provide a quick graphical method for assessing the relative per passenger-mile energy intensity of competing modes relative to rail at any combination of load factors, not just those selected in the case study description. An example load factor sensitivity chart (Figure 7-1) plots a line of equal energy intensity along varying rail (vertical axis) and competing mode (horizontal axis) load factors. Combinations of rail and competing mode load factors that fall on this line indicate that—for that particular combination of load factors—the two modes being compared have equal energy intensity per passenger-mile. For example, if rail has a load factor of 0.5, to match its energy intensity, the competing mode must have a load factor of 0.45. Because the competing mode load factor is less than the rail load factor for equal energy intensity, the competing mode is the inherently more energy-efficient mode. Although automobile travel is normally characterized in terms of the number of occupants rather than by a load factor, for purposes of the MMPASSIM the research team defined all LDVs to have 4 seats and characterized the mode with a load factor to be consistent with the other modes. Thus, an LDV load factor of 0.25 has one occupant, and an LDV load factor of 1.0 has four occupants.

In Figure 7-1, for specific pairs of load factors, if the coordinate point falls above the line of equal energy intensity, rail is the more energy-efficient mode; if the point falls below the line,

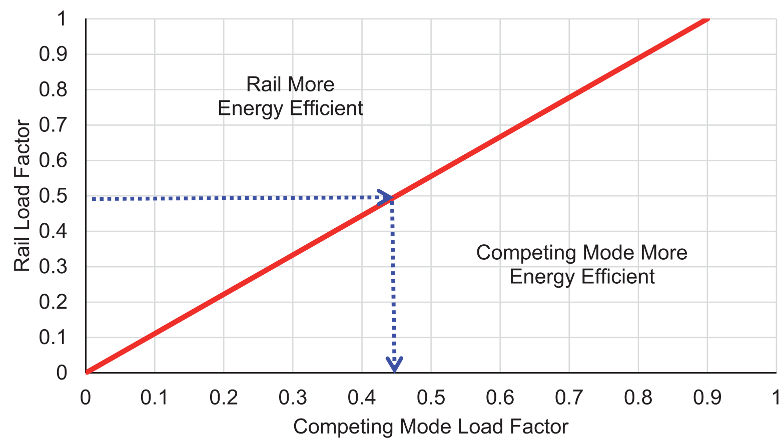


Figure 7-1. Example load factor sensitivity chart.

the competing mode is more energy efficient. In general, the area above the line of equal energy intensity corresponds to load factor pairs for which rail is the less energy intense (more energy-efficient) mode. Conversely, the area below the line represents load factor pairs for which the competing mode is the less energy intense (more energy-efficient) mode. The relative size of each area corresponds to the range of load factor combinations in which a particular mode is more efficient; the larger the area, the more inherently efficient the mode.

Where the line of equal energy intensity intersects the top or right portion of the chart also is significant. If the line intersects the top of the chart, as in Figure 7-1, there exists a certain competing mode load factor above which the competing mode will always be more energy efficient than rail, regardless of rail ridership (unless standing passengers are allowed to produce a load factor above 1.0). If the line intersects the right-hand side of the chart, there exists a rail load factor at which rail will always be more energy efficient, regardless of competing mode ridership.

The research team developed load factor sensitivity charts for each of the door-to-door modal comparisons and considered the access/egress and upstream energy consumption for each mode when plotting the line of equal energy intensity. Similar plots were developed showing emissions for selected case studies, and their interpretation follows that described in this section.

7.1.5 Sensitivity Analysis

The selected case studies described in this chapter cover a wide spectrum of trips using various combinations of rail services, competing modes and access and egress patterns; but they are not comprehensive, given the infinite possibilities for different trip plans along a single route. To help generalize the results and better illustrate the effect of certain factors, additional simulations were conducted beyond the trip-specific modal comparison case studies. The first experiment was a more controlled analysis of the effect of access distances on door-to-door trip energy intensity. In this analysis, for one case study route, the access and egress distances were varied radially around the main travel segment termini with a constant access mode. Similarly, a controlled analysis of the choice of access and egress mode on total trip energy consumption was conducted by varying the access and egress mode choice for one of the case study routes with fixed access and egress distances. The results of these additional simulations are discussed after all of the case study route modal comparisons.

7.2 Evaluated Passenger Rail Services

The review of previous research and data collection on the subject of passenger rail energy efficiency indicated that rail mode performance varies according to the type of service, length of route, average speed and train consist. To capture this range of performance, the project team selected four commuter rail systems, five regional intercity systems, one long-distance intercity service, and one HSR system for modal comparison (Table 7-2). The selected case study routes are a subset of those described in detail in the first part of Chapter 4.

The results of the door-to-door round-trip modal comparison case studies are presented in the balance of this chapter. Each case study is presented in three parts.

The first part describes the specifics of the trip, including access and egress modes and distances. This descriptive information is summarized in a single case description table. Additional details on case study inputs can be found in Appendix G.

The second part of each case study presents the results of the modal comparison simulation in three tables, which are arranged similarly to the example MMPASSIM modal comparisons output table presented in Chapter 3 (Table 3-5).The first table, labeled “(a),” summarizes the

Table 7-2. Characteristics of passenger rail services for modal comparison.

Route	Origin-Destination	Locomotive(s)	Trailing Railcars[a]	Seats[a]	Number of Stops[b]	Average Speed (mph)
Commuter Rail						
Metro Transit Northstar	Big Lake–Minneapolis, MN	1 x 3,600 hp Diesel	3 Bi-level	426	10	40
Metra BNSF	Aurora–Chicago, IL	1 x 3,150 hp Diesel	6 Bi-level	870	26	22
Metrolink Orange	Oceanside–Los Angeles, CA	1 x 3,600 hp Diesel	4 Bi-level	568	15	37
Pacific Surfliner[c]	Oceanside–Los Angeles, CA	1 x 3,600 hp Diesel	4 Bi-level	336	9	41
MARC Penn Line	Perryville, MD–Washington, DC	1 x 3,100 hp Diesel	5 Bi-level	650	13	43
MARC Penn Line[d]	Perryville, MD–Washington, DC	1 x 3,221 kW Electric	5 Bi-level	650	13	50
Regional Intercity						
Heartland Flyer (with NPCU)	Oklahoma City, OK–Fort Worth, TX	1 x 4,100 hp Diesel	3 Bi-level	252	7	42
Heartland Flyer (without NPCU)	Oklahoma City, OK–Fort Worth, TX	1 x 4,100 hp Diesel	3 Bi-level	252	7	43
Piedmont	Charlotte–Raleigh, NC	1 x 3,600 hp Diesel	4 Single-level	336	9	47
Empire	New York City–Buffalo, NY	1 x 4,100 hp Dual-mode	5 Single-level	416	15	58
Cascades	Portland, OR–Vancouver, BC	1 x 3,600 hp Diesel	12-car Talgo, 1 Cab Car	340	8	47
Northeast Regional	New York City–Washington, DC	1 x 3,221 kW Electric	6 Single-level	504	10	68
Long-Distance Intercity						
Southwest Chief	Chicago, IL–Los Angeles, CA	2 x 4,100 hp Diesel	8 bi-level	364	8 of 33	53
High-Speed Rail						
California HSR (CAHSR)	Fresno–Los Angeles, CA	1 x 9,266 kW Electric	11-car Trainset, Distributed Power	446	3	179

[a] Assumed as typical operations and consist configuration for each case.
[b] Citations for this column can be found in each route's respective entry in Appendix C.
[c] Pacific Surfliner service is compared to the Metrolink Orange as an alternative commuter service between Oceanside and Los Angeles, CA.
[d] MARC Penn Line is compared to competing modes using a diesel-electric locomotive and electric consists.

direct energy efficiency and emissions of the main travel segment in isolation. These values are presented per trip, per seat-mile, and per passenger-mile. The second table, labeled "(b)," includes the direct energy and emissions of the access and egress travel segments per trip and per passenger-mile. The third and final table, labeled "(c)," summarizes the total direct and upstream source energy consumption and emissions of all travel segments.

The third part of each case study includes the load factor sensitivity chart for energy intensity between rail and competing modes. Additional charts for emissions or other comparisons of interest also are included to make specific comparisons of interest.

7.3 Commuter Rail Modal Comparisons

Four commuter rail services were selected for comparison to automobiles for specific door-to-door trips in urban areas. Trip lengths ranged from approximately 40 to 100 miles.

7.3.1 Big Lake–Minneapolis, MN

The Big Lake, MN, to Minneapolis, MN, case study is designed to represent typical commuter travel behavior with a party of one traveling from a smaller suburban city in the metro area to a

Table 7-3. Case study: Big Lake–Minneapolis, MN.

Mode	Modal Leg Service/ Vehicle	Modal Leg Distance (mi)	Load Factor	Access Leg 1 Mode	Access Leg 1 Distance (mi)	Access Leg 2 Mode	Access Leg 2 Distance (mi)	Egress Leg 1 Mode	Egress Leg 1 Distance (mi)
Rail	Metro Transit Northstar	39.9	0.25	Auto	2.3	--	--	Walk	0.7
Auto	2013 Driven Fleet	36.9	0.25	--	--	--	--	--	--

An automobile load factor of 1.0 = four occupants; a load factor of 0.25 = one occupant.

downtown center over a distance of approximately 40 miles (Table 7-3). The rail trip, using Minneapolis Metro Transit Northstar service, involves access by auto and egress by walking to the final destination. The automobile alternative uses the 2013 Driven Fleet vehicle characteristics with seating for four occupants.

Results indicate that the door-to-door rail trip is less energy intense than the automobile trip when analyzing the modal leg only, the door-to-door trip in its entirety, and the door-to-door trip including upstream consumption (Table 7-4). This is the case despite the rail travel segment being 3 miles longer than the highway route. Inclusion of the auto access trip decreases

Table 7-4. Modal comparison: Big Lake–Minneapolis, MN.

(a) Modal Intensity Comparison (modal leg only, direct activity only)

Category		Intensity Measures*						Service Metrics
Divisor		per round trip		per seat-mi		per passenger-mi		Travel Time
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(hrs)
Rail	Value	184,355	33	554	0.098	2,308	0.408	2.0
Auto/LDV#	Value	486,841	84	1,649	0.283	6,597	1.132	3.1
	indexed to rail	2.64	2.56	2.98	2.89	2.86	2.77	1.56

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

(b) Modal Intensity Comparison (door-to-door, direct activity only)

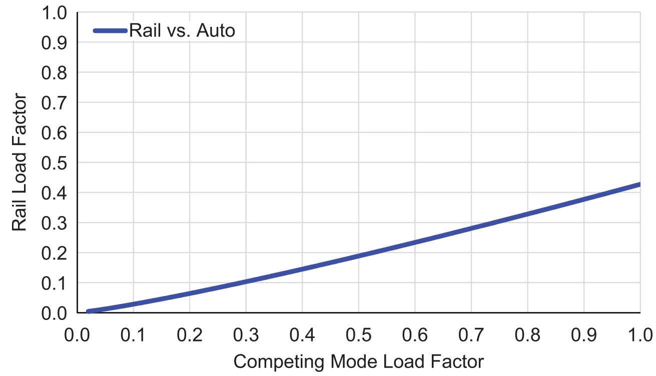
Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	210,402	37	2,450	0.431
Auto/LDV#	Value	486,841	84	6,597	1.132
	indexed to rail	2.31	2.26	2.69	2.63

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

(c) Modal Intensity Comparison (door-to-door, including indirect well-to-pump consumption)

Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	252,530	46	2,941	0.538
Auto/LDV#	Value	627,492	109	8,503	1.474
	indexed to rail	2.48	2.35	2.89	2.74

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.



An automobile load factor of 1.0 = four occupants; a load factor of 0.25 = one occupant.

Figure 7-2. Big Lake–Minneapolis, MN, energy intensity load factor sensitivity chart (including access/egress and upstream energy).

the advantage of the rail option, and longer auto access distances would increase this effect. The automobile trip time is 1.5 times longer than the equivalent rail trip because of the congestion on the highway route during the peak commuting hours. The results also show that the auto trip is more emissions intense from all perspectives.

The load factor sensitivity chart for the Big Lake to Minneapolis modal comparison (Figure 7-2) shows rail with a larger area of the chart above the line of equal energy intensity. This suggests that rail is more efficient than the automobile over a majority of load factor combinations. To be as energy efficient as the commuter rail service at the average rail load factor of 0.25, the automobile must have a load factor of 0.65 (i.e., more than two passengers in the four-passenger 2013 Driven Fleet average vehicle).

7.3.2 Aurora–Chicago, IL

The Aurora, IL, to Chicago, IL case study is designed to illustrate a typical commuter trip for a party of one on the busiest Metra rail service in the suburban Chicago area. The trip covers approximately 42 to 47 miles depending on the selected travel mode (rail or auto). Rail commuters use the Metra BNSF service, accessing the suburban Aurora station by automobile and egressing at Chicago Union Station by walking (Table 7-5). The particular train considered in this case study stops at all 24 stations between Aurora and Chicago Union Station. The alternative mode describes an automobile trip taken using the average vehicle performance of the 2013 Driven Fleet in a vehicle with four seats.

The rail trip is less energy intense than the automobile alternative when considering the modal leg only, the entire door-to-door trip, and the entire door-to-door trip including upstream

Table 7-5. Case study: Aurora–Chicago, IL.

	Modal Leg			Access Leg 1		Access Leg 2		Egress Leg 1	
Mode	Service/ Vehicle	Distance (mi)	Load Factor	Mode	Distance (mi)	Mode	Distance (mi)	Mode	Distance (mi)
Rail	Metra BNSF	41.9	0.28	Auto	3	--	--	Walk	0.8
Auto	2013 Driven Fleet	46.8	0.25	--	--	--	--	--	--

An automobile load factor of 1.0 = four occupants; a load factor of 0.25 = one occupant.

energy consumption (Table 7-6). The energy intensity of the rail trip increases by approximately 30% after 3 miles of auto access is included in the analysis.

The automobile trip time is 36% lower than the rail trip time because the rail trip stops at every station along the route. If the rail trip was following a zonal schedule, running as an express after a block of stations near Aurora, the rail energy intensity, emissions and travel time would all be lower. The results also show that the auto trip is more emissions intense in all cases analyzed.

It must be stressed that this comparison uses average load factors to perform calculations on a passenger-mile basis. Only when more than three commuters carpool in the same vehicle do the auto energy and emission metrics approach those of the rail trip (Figure 7-3). At the average rail load factor of 0.28, the automobile must be loaded with four passengers (in the four-passenger 2013 Driven Fleet average vehicle) to be as energy efficient. Including the access/egress and upstream energy, rail has a larger area of the chart above the line of equal energy intensity. This suggests that rail is more efficient than the automobile over a majority of load factor combinations.

During peak periods, when automobile trips are subject to the most congestion, Metra is likely to be operating at or near capacity. When driving alone, the automobile user consumes 12 times as much energy per trip as a rail passenger on a Metra train with a load factor of 0.75.

On rail trips where the load factor exceeds 0.3, the auto mode will always be less efficient than the equivalent rail trip, regardless of the number of passengers in the automobile. These

Table 7-6. Modal comparison: Aurora–Chicago, IL.

(a) Modal Intensity Comparison (modal leg only, direct activity only)

Category		Intensity Measures*						Service Metrics
Divisor		per round trip		per seat-mi		per passenger-mi		Travel Time
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(hrs)
Rail	Value	115,544	20	421	0.075	1,504	0.266	3.4
Auto/LDV#	Value	427,237	73	1,516	0.260	6,063	1.040	2.2
	indexed to rail	3.70	3.59	3.60	3.49	4.03	3.91	0.64

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

(b) Modal Intensity Comparison (door-to-door, direct activity only)

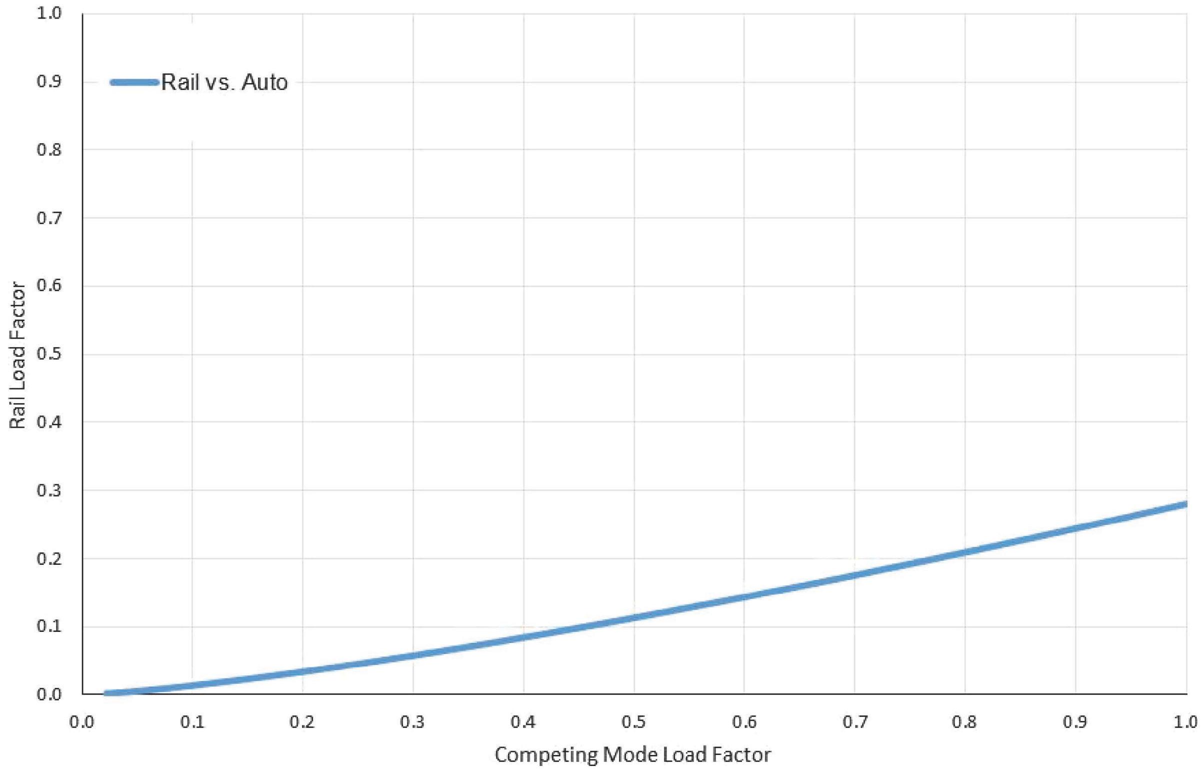
Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	149,518	26	1,772	0.310
Auto/LDV#	Value	427,237	73	6,063	1.040
	indexed to rail	2.86	2.80	3.42	3.36

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

(c) Modal Intensity Comparison (door-to-door, including indirect well-to-pump consumption)

Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	179,468	33	2,126	0.387
Auto/LDV#	Value	550,669	95	7,815	1.355
	indexed to rail	3.07	2.92	3.68	3.50

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.



An automobile load factor of 1.0 = four occupants; a load factor of 0.25 = one occupant.

Figure 7-3. Aurora–Chicago, IL, energy intensity load factor intensity sensitivity chart (including access/egress and upstream energy).

comparisons have been made for a local train; a zonal train with improved energy efficiency would perform even better when compared to the automobile trip.

7.3.3 Oceanside–Los Angeles, CA

This case study illustrates a longer commuter trip for a party of one between Oceanside, CA, and the larger downtown metropolitan area of Los Angeles, CA (Table 7-7). The trip covers 86 to 95 miles depending on the selected transportation mode (Rail or Auto). The rail commuter uses the Metrolink Orange Line, with automobile as the access mode and walking as the egress mode. For this case study, an alternative rail trip using the Pacific Surfliner regional intercity

Table 7-7. Case study: Oceanside–Los Angeles, CA.

Modal Leg				Access Leg 1		Access Leg 2		Egress Leg 1	
Mode	Service/ Vehicle	Distance (mi)	Load Factor	Mode	Distance (mi)	Mode	Distance (mi)	Mode	Distance (mi)
Rail	Metrolink Orange	85.9	0.25	Auto	5.4	--	--	Walk	1.5
Auto	2013 Driven Fleet	95.2	0.25	--	--	--	--	--	--
Rail	Pacific Surfliner (commuter)	85.9	0.42	Auto	5.4	--	--	Walk	1.5

An automobile load factor of 1.0 = four occupants; a load factor of 0.25 = one occupant.

train as a commuter service with the same access/egress legs is also compared to the Metrolink commuter rail trip. The automobile trip uses the performance average of the 2013 Driven Fleet with seating for four occupants. On this route, the rail trip has the added benefit of a more direct route, saving 10 miles compared to the equivalent automobile (highway) trip, not including access/egress distance.

The Metrolink rail trip is less energy intense than the automobile trip when considering the modal leg only, the entire door-to-door trip, and the door-to-door trip including the upstream energy consumption (Table 7-8). The automobile trip has a required travel time 3% less than that of the rail trip. The results also show that the auto trip is more emissions intense in all cases analyzed.

Table 7-8. Modal comparison: Oceanside–Los Angeles, CA.

(a) Modal Intensity Comparison (modal leg only, direct activity only)

Category		Intensity Measures*						Service Metrics
Divisor		per round trip		per seat-mi		per passenger-mi		Travel Time
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(hrs)
Metrolink	Value	251,300	44	366	0.065	1,462	0.259	4.7
Auto/ LDV#	Value	1,066,785	183	1,397	0.240	5,588	0.958	4.6
	indexed to rail	4.25	4.12	3.82	3.70	3.82	3.70	0.97
Surfliner	Value	409,531	72	417	0.074	994	0.176	9.3
	indexed to rail	1.63	1.63	1.14	1.14	0.68	0.68	1.97

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

(b) Modal Intensity Comparison (door-to-door, direct activity only)

Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	312,455	55	1,683	0.295
Auto/LDV#	Value	1,066,785	183	5,588	0.958
	indexed to rail	3.41	3.34	3.32	3.25
Surfliner	Value	409,531	72	962	0.170
	indexed to rail	1.31	1.32	0.57	0.58

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

(c) Modal Intensity Comparison (door-to-door, including indirect well-to-pump consumption)

Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	375,034	68	2,020	0.369
Auto/LDV#	Value	1,374,988	238	7,203	1.248
	indexed to rail	3.67	3.48	3.57	3.39
Surfliner	Value	491,487	90	1,154	0.212
	indexed to rail	1.31	1.32	0.57	0.58

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

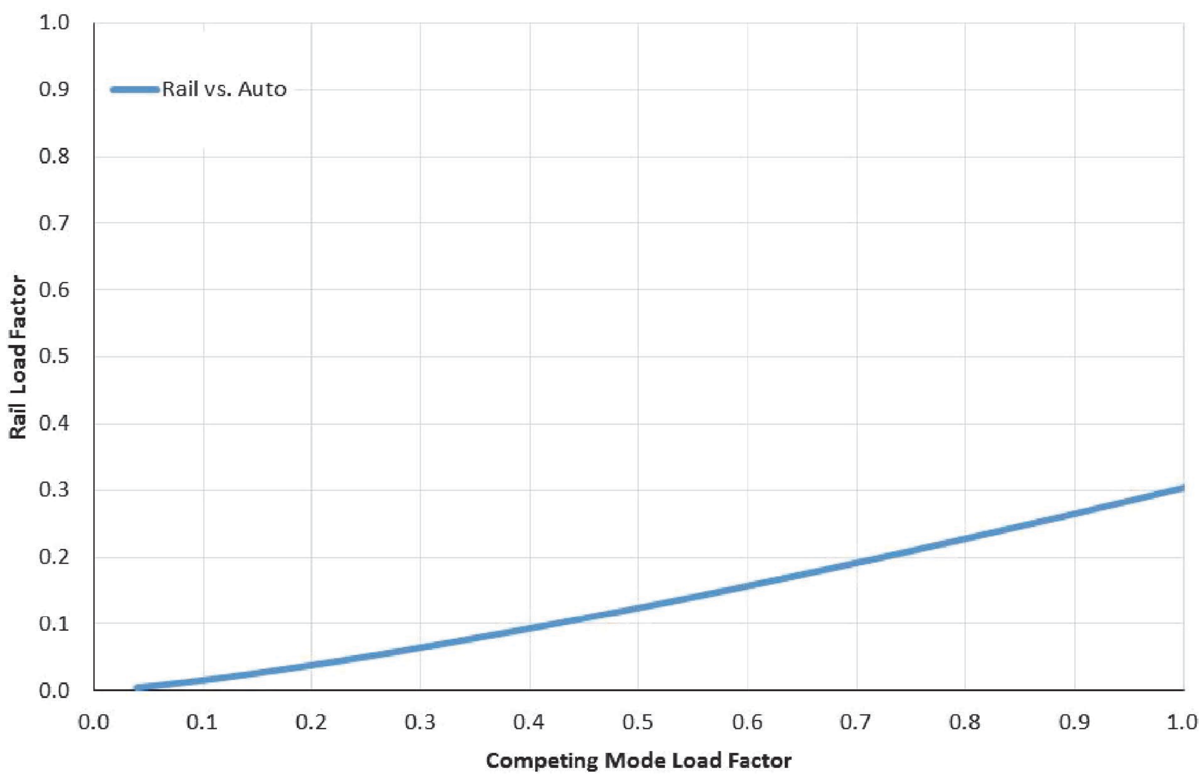
Compared to the Pacific Surfliner regional intercity train functioning in commuter service, the Metrolink trip has lower direct energy and emissions intensities per seat-mile, slightly mitigated for door-to-door trips with and without including upstream energy. Although the Surfliner trip has a higher average load factor and fewer stops than the Metrolink, it has heavier passenger cars with less seating. This end result is that the Surfliner has lower energy and emissions intensities on a per passenger-miles basis.

An average 3.4 person carpool (85% load factor) is required for the automobile to match the energy and emissions performance of commuter rail under average load factors (Figure 7-4). Under peak commuter rail load factors, the train will still be three to four times more efficient than the automobile with four occupants, and commuter rail is an order of magnitude more efficient than the automobile with a single occupant.

The Metrolink commuter train is inherently more efficient than the Pacific Surfliner regional intercity train used as a commuter service (Figure 7-5). When the Metrolink commuter rail is at an average load factor of 0.25, the Surfliner needs to achieve a load factor of 0.52 (slightly above average) to equal or outperform the commuter train. During peak periods, however, if the Metrolink consist can achieve a load factor of 0.6 or above, the Surfliner will be unable to achieve higher energy efficiency than the Metrolink trip regardless of Pacific Surfliner ridership.

7.3.4 Perryville, MD–Washington, DC

This case study demonstrates a typical commuting trip for a party of one from Perryville, MD, to Washington, DC, a distance of approximately 73 to 77 miles (Table 7-9). The rail commuter



An automobile load factor of 1.0 = four occupants; a load factor of 0.25 = one occupant.

Figure 7-4. Oceanside–Los Angeles, CA, energy intensity load factor sensitivity chart (including access/egress and upstream energy).

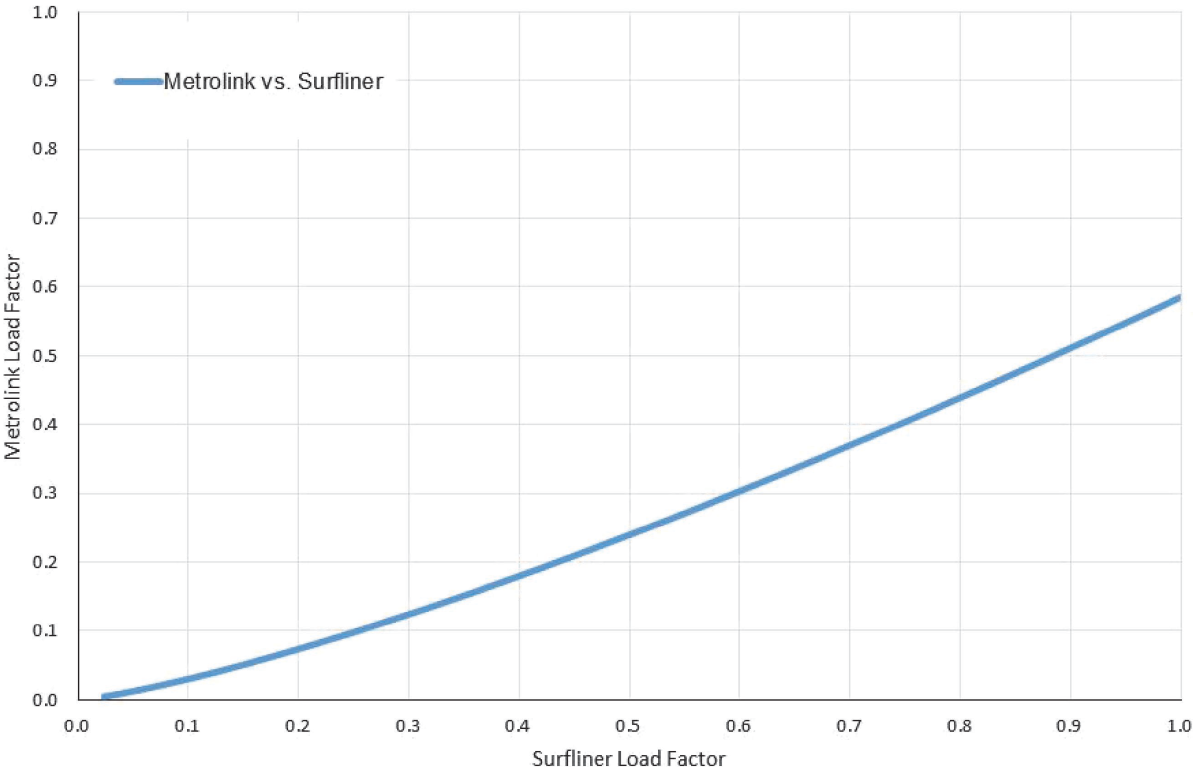


Figure 7-5. Oceanside–Los Angeles, CA, energy intensity load factor sensitivity chart (Metrolink vs. Surfliner, including access/egress and upstream energy).

in this case uses the MARC Penn Line service with a diesel-electric locomotive on the Amtrak Northeast Corridor, accessing the origin station by automobile and egressing at Washington Union Station by subway. The baseline rail trip also is compared to the same service but with an electric locomotive along the same route and with the same access/egress legs. The automobile alternative uses the vehicle performance of the 2013 Driven Fleet with seating for four occupants.

The diesel-electric rail alternative is less energy intense than the auto alternative when analyzing the modal leg only, the entire door-to-door trip, and the door-to-door trip including upstream energy consumption (Table 7-10). The automobile trip requires 53% more time due to peak-period highway congestion. The results also show that the auto trip is more emissions intense in all cases analyzed.

Table 7-9. Case study: Perryville, MD–Washington, DC.

Modal Leg				Access Leg 1		Access Leg 2		Egress Leg 1	
Mode	Service/ Vehicle	Distance (mi)	Load Factor	Mode	Distance (mi)	Mode	Distance (mi)	Mode	Distance (mi)
Rail	MARC Penn Line	77.0	0.30	Auto	2.3	--	--	Subway	2.4
Auto	2013 Driven Fleet	72.9	0.25	--	--	--	--	--	--
Rail	MARC Penn Line (electrified)	77.0	0.30	Auto	2.3	--	--	Subway	2.4

Table 7-10. Modal comparison: Perryville, MD–Washington, DC.

(a) Modal Intensity Comparison (modal leg only, direct activity only)

Category		Intensity Measures*						Service Metrics
Divisor		per round trip		per seat-mi		per passenger-mi		Travel Time
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(hrs)
Diesel-electric	Value	245,331	43	478	0.085	1,593	0.282	3.6
Auto/LDV#	Value	971,940	167	1,523	0.261	6,092	1.045	5.5
	indexed to rail	3.96	3.84	3.19	3.09	3.82	3.71	1.53
Electric	Value	290,028	47	565	0.091	1,883	0.302	3.1
	indexed to rail	1.18	1.07	1.18	1.07	1.18	1.07	0.84

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

(b) Modal Intensity Comparison (door-to-door, direct activity only)

Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	287,635	50	1,760	0.308
Auto/LDV#	Value	971,940	167	6,092	1.045
	indexed to rail	3.38	3.31	3.46	3.39
Electric	Value	290,028	47	1,775	0.285
	indexed to rail	1.01	0.92	1.01	0.92

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

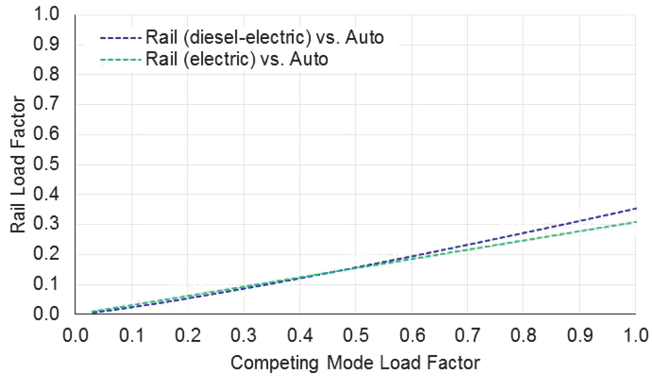
(c) Modal Intensity Comparison (door-to-door, including indirect well-to-pump consumption)

Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	343,731	63	2,104	0.383
Auto/LDV#	Value	1,252,740	217	7,852	1.361
	indexed to rail	3.64	3.47	3.73	3.55
Electric	Value	322,232	52	1,972	0.318
	indexed to rail	0.94	0.83	0.94	0.83

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

Compared to the case with the electric locomotive, the diesel-electric trip is less energy and emissions intense for the modal leg and door-to-door trips. This is because of the increased speed of the electric train (125 mph maximum speed versus 79 mph maximum speed for the diesel-electric train). When upstream energy and emissions are included in the door-to-door comparison, the electric trip is still slightly more energy intense but slightly less emissions intense. This is because of the lower upstream emissions associated with the generation of electricity in the region relative to emissions from diesel fuel.

The results of this case study are consistent with those of the commuter rail cases in the cities of Chicago and Los Angeles in that a three- to four-person carpool is required to equal the performance of the commuter train under average load factors (Figure 7-6). Under peak commuter rail load factors (1.0), the energy and emissions results of the automobile with a single occupant are an order of magnitude worse than those of the commuter train trip. When comparing the emissions intensity of the diesel-electric and electric trains to the auto trip (Figure 7-7), a slight improvement in emissions results from using the electric consist.



An automobile load factor of 1.0 = four occupants; a load factor of 0.25 = one occupant.

Figure 7-6. Perryville, MD–Washington, DC, energy intensity load factor sensitivity chart (including access/egress and upstream energy).

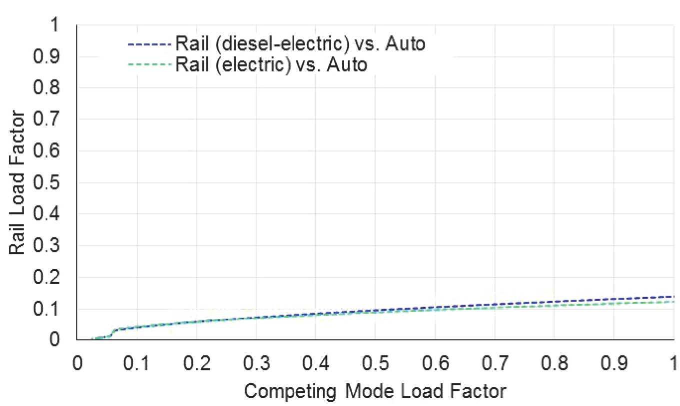
Figure 7-8 shows that the electric service can outperform the diesel-electric (1) in emissions, if the electric train has a 0.67 load factor to match a fully loaded diesel-electric train, and (2) in energy intensity, if the all-electric train has a 0.75 load factor to match a fully loaded diesel-electric train.

7.4 Regional Intercity Rail Modal Comparisons

Five regional intercity rail services were selected for comparison to automobile, air and bus modes for selected door-to-door trips between urban areas. Trip lengths in these case studies range from approximately 150 to 450 miles.

7.4.1 Oklahoma City, OK–Fort Worth, TX

This case study represents an approximately 200-mile regional intercity trip from Oklahoma City, OK, to Fort Worth, TX, for a party of one (Table 7-11). The rail alternative uses Amtrak's



An automobile load factor of 1.0 = four occupants; a load factor of 0.25 = one occupant.

Figure 7-7. Perryville, MD–Washington, DC, emissions intensity load factor sensitivity chart (including access/egress and upstream emissions).

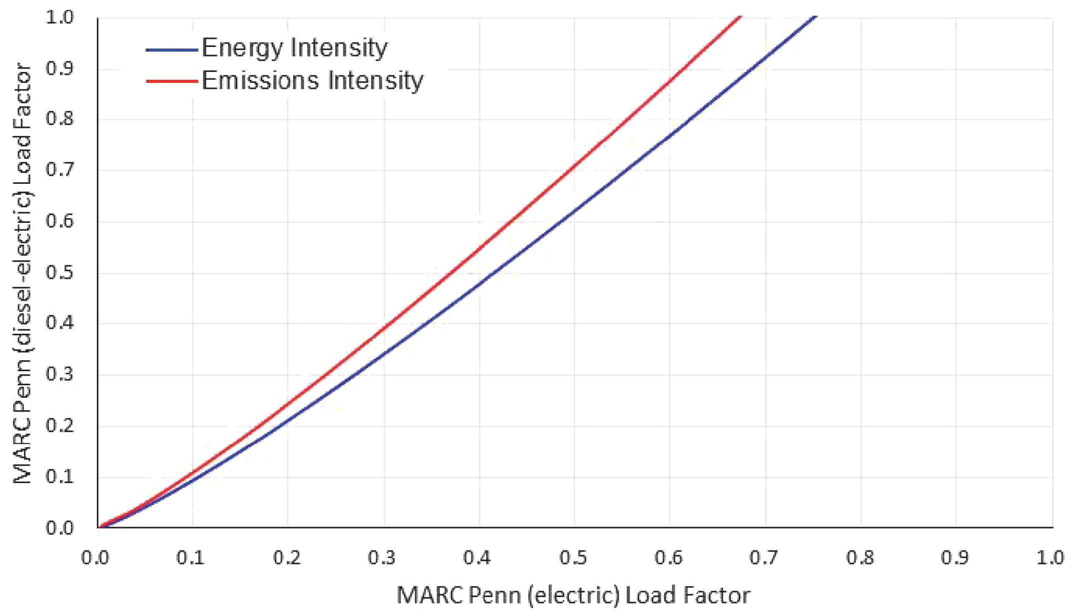


Figure 7-8. Perryville, MD–Washington, DC, load factor sensitivity chart (diesel-electric vs. electric, including access/egress and upstream energy and emissions).

Heartland Flyer service with the push-pull NPCU consist and both access and egress via automobile. The automobile alternative uses the performance characteristics of the 2013 Driven Fleet with seating for four occupants. The air trip is a direct flight and uses an aircraft distribution of 95% narrow-body jet (NBJ) and 5% regional jet (RJ). Airport access and egress is by automobile. Finally, the bus trip uses a 45-ft. coach with 56 seats, with access and egress by automobile.

The bus trip is the least energy intense and emissions intense alternative when analyzed by modal leg only, the entire door-to-door trip, and the door-to-door trip including upstream energy consumption (Table 7-12). When analyzing the door-to-door trip including upstream energy consumption, the bus mode is the least energy intense per passenger-mile, followed by rail, auto and air. However, the air alternative has the shortest travel time, followed by auto, bus, and rail. It is apparent that a compromise exists between energy intensity and trip time.

As seen from Figure 7-9, an automobile must have a load factor of 0.9 (average of 3.6 occupants) to match the energy efficiency and emissions performance of the rail trip. A full air trip (load factor of 1.0) can only match the energy efficiency and emissions of a rail trip at a load factor of 0.17. Conversely, the bus with a load factor of 0.82 exceeds the energy efficiency of a full train.

Table 7-11. Case study: Oklahoma City, OK–Fort Worth, TX.

Mode	Modal Leg Service/ Vehicle	Distance (mi)	Load Factor	Access Leg 1 Mode	Access Leg 1 Distance (mi)	Access Leg 2 Mode	Access Leg 2 Distance (mi)	Egress Leg 1 Mode	Egress Leg 1 Distance (mi)
Rail	Heartland Flyer (NPCU)	206	0.42	Auto	3.6	--	--	Auto	3.4
Auto	2013 Driven Fleet	203	0.25	--	--	--	--	--	--
Air	95% NBJ, 5% RJ	175	0.71	Auto	13.5	--	--	Auto	31.5
Bus	45-foot Coach	229	0.57	Auto	1.5	--	--	Auto	3.4

An automobile load factor of 1.0 = four occupants; a load factor of 0.25 = one occupant.

Table 7-12. Modal comparison: Oklahoma City, OK–Fort Worth, TX.

(a) Modal Intensity Comparison (modal leg only, direct activity only)

Category		Intensity Measures*						Service Metrics
Divisor		per round trip		per seat-mi		per passenger-mi		Travel Time
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(hrs)
Rail	Value	571,760	101	583	0.103	1,388	0.246	9.7
Auto/LDV#	Value	2,198,353	377	1,352	0.232	5,409	0.927	6.7
	indexed to rail	3.84	3.73	2.32	2.25	3.90	3.78	0.68
Air	Value	1,352,187	277	3,196	0.654	3,853	0.789	4.7
	indexed to rail	2.36	2.74	5.48	6.35	2.78	3.21	0.48
Bus	Value	364,439	64	453	0.080	795	0.140	9.4
	indexed to rail	0.64	0.64	0.78	0.78	0.57	0.57	0.97

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

(b) Modal Intensity Comparison (door-to-door, direct activity only)

Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	662,668	116.4	1,556	0.273
Auto/LDV#	Value	2,198,353	376.9	5,409	0.927
	indexed to rail	3.32	3.24	3.48	3.39
Air	Value	2,161,061	412.5	4,901	0.936
	indexed to rail	3.26	3.54	3.15	3.42
Bus	Value	434,550	76.1	928	0.162
	indexed to rail	0.66	0.65	0.60	0.59

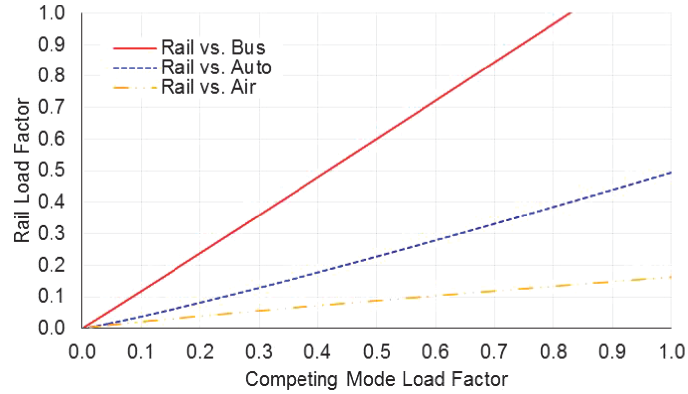
*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

(c) Modal Intensity Comparison (door-to-door, including indirect well-to-pump consumption)

Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	795,357	145	1,867	0.341
Auto/LDV#	Value	2,833,474	491	6,972	1.208
	indexed to rail	3.56	3.38	3.73	3.54
Air	Value	2,530,350	523	5,739	1.185
	indexed to rail	3.18	3.59	3.07	3.47
Bus	Value	521,572	95	1,114	0.203
	indexed to rail	0.66	0.65	0.60	0.59

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

Using a Heartland Flyer consist without an NPCU produces an interesting effect on the modal comparison. Because there is no NPCU to facilitate push-pull operation, this consist requires an extra distance of 3.5 miles to turn the train around, but the train doesn't have the extra resistance of the control unit. As shown in the technology evaluations, the non-NPCU consist has reduced energy and emissions intensities relative to the NPCU consist. This difference causes a more favorable comparison with other modes (Table 7-13). The change is minor, however, and the relative energy intensity and emissions rankings of the modes are the same (Figure 7-10). Compared to Figure 7-9, the lines of equal energy intensity for the non-NPCU consist in Figure 7-10



An automobile load factor of 1.0 = four occupants; a load factor of 0.25 = one occupant.

Figure 7-9. Oklahoma City, OK–Fort Worth, TX (NPCU consist), energy intensity load factor sensitivity chart (including access/egress and upstream energy).

Table 7-13. Modal comparison: Oklahoma City, OK–Fort Worth, TX (non-NPCU).

(a) Modal Intensity Comparison (modal leg only, direct activity only)

Category		Intensity Measures*						Service Metrics
Divisor		per round trip		per seat-mi		per passenger-mi		Travel Time
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(hrs)
Rail	Value	478,855	85	488	0.086	1,162	0.206	9.7
Auto/ LDV#	Value	2,198,353	377	1,352	0.232	5,409	0.927	6.7
	indexed to rail	4.59	4.45	2.77	2.68	4.65	4.51	0.69
Air	Value	1,352,187	277	3,196	0.654	3,853	0.789	4.7
	indexed to rail	2.82	3.27	6.55	7.58	3.32	3.84	0.49
Bus	Value	364,439	64	453	0.080	795	0.140	9.4
	indexed to rail	0.76	0.76	0.93	0.93	0.68	0.68	0.98

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

(b) Modal Intensity Comparison (door-to-door, direct activity only)

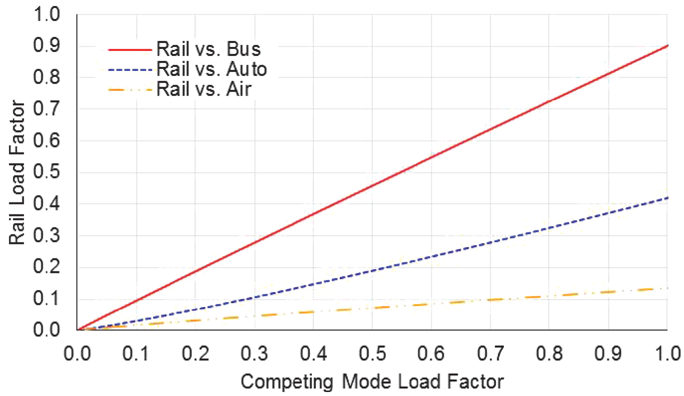
Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	569,763	100	1,337	0.235
Auto/LDV#	Value	2,198,353	377	5,409	0.927
	indexed to rail	3.86	3.77	4.04	3.95
Air	Value	2,161,061	412	4,901	0.936
	indexed to rail	3.79	4.13	3.66	3.99
Bus	Value	478,910	84	1,013	0.177
	indexed to rail	0.84	0.84	0.76	0.75

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

(c) Modal Intensity Comparison (door-to-door, including indirect well-to-pump consumption)

Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	683,860	125	1,605	0.293
Auto/LDV#	Value	2,833,474	491	6,972	1.208
	indexed to rail	4.14	3.93	4.34	4.12
Air	Value	2,530,350	523	5,739	1.185
	indexed to rail	3.70	4.18	3.58	4.04
Bus	Value	574,845	105	1,216	0.221
	indexed to rail	0.84	0.84	0.76	0.75

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.



An automobile load factor of 1.0 = four occupants; a load factor of 0.25 = one occupant.

Figure 7-10. Oklahoma City, OK–Fort Worth, TX (non-NPCU), energy intensity load factor sensitivity chart (including access/egress and upstream energy).

have shifted down and to the right, increasing the amount of area above each line. This indicates that, even with the extra travel distance to turn the train, the non-NPCU consist is inherently more efficient than the NPCU consist and is even less energy and emissions intense than auto mode or air mode. The non-NPCU consist can equal the performance of bus mode at a lower load factor than the NPCU consist.

7.4.2 Charlotte–Raleigh, NC

This case study demonstrates a shorter regional trip from Charlotte, NC, to Raleigh, NC, approximately 170 miles, for a party of one (Table 7-14). The rail alternative uses Amtrak's Piedmont service, with both access and egress via automobile. The automobile alternative uses the performance characteristics of the 2013 Driven Fleet with four passenger seats. The air alternative uses the default distribution of aircraft with the corresponding load factors, and uses auto as the access and egress mode. The bus alternative uses a 45-ft. coach with 56 passenger seats. Access and egress for the bus alternative is via automobile.

The bus alternative is the least energy intense and emissions intense, not only for the modal leg but also for the door-to-door trip and the door-to-door trip including the upstream energy consumption (Table 7-15). Analysis of the door-to-door trip including upstream consumption shows that the bus alternative is the least energy intense per passenger-mile, with rail, auto, and

Table 7-14. Case study: Charlotte–Raleigh, NC.

Modal Leg				Access Leg 1		Access Leg 2		Egress Leg 1	
Mode	Service/Vehicle	Distance (mi)	Load Factor	Mode	Distance (mi)	Mode	Distance (mi)	Mode	Distance (mi)
Rail	Piedmont	173	0.42	Auto	5.6	--	--	Auto	2.0
Auto	2013 Driven Fleet	172	0.25	--	--	--	--	--	--
Air	Default	129	0.71	Auto	9.4	--	--	Auto	16.3
Bus	45-foot Coach	185	0.57	Auto	4.9	--	--	Auto	1.4

An automobile load factor of 1.0 = four occupants; a load factor of 0.25 = one occupant.

Table 7-15. Modal comparison: Charlotte–Raleigh, NC.

(a) Modal Intensity Comparison (modal leg only, direct activity only)

Category		Intensity Measures*						Service Metrics
Divisor		per round trip		per seat-mi		per passenger-mi		Travel Time
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(hrs)
Rail	Value	560,903	99	681	0.120	1,621	0.287	7.3
Auto/ LDV#	Value	1,851,994	318	1,345	0.231	5,380	0.922	6.8
	indexed to rail	3.30	3.20	1.98	1.91	3.32	3.22	0.93
Air	Value	1,458,278	269	4,020	0.741	5,627	1.037	4.5
	indexed to rail	2.60	2.71	5.90	6.15	3.47	3.62	0.62
Bus	Value	321,330	57	483	0.085	848	0.150	7.6
	indexed to rail	0.57	0.57	0.71	0.71	0.52	0.52	1.04

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

(b) Modal Intensity Comparison (door-to-door, direct activity only)

Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	654,050	115	1,811	0.318
Auto/LDV#	Value	1,851,994	318	5,380	0.922
	indexed to rail	2.83	2.76	2.97	2.90
Air	Value	1,964,079	354	6,325	1.139
	indexed to rail	3.00	3.08	3.49	3.58
Bus	Value	449,195	78	1,147	0.200
	indexed to rail	0.69	0.68	0.63	0.63

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

(c) Modal Intensity Comparison (door-to-door, including indirect well-to-pump consumption)

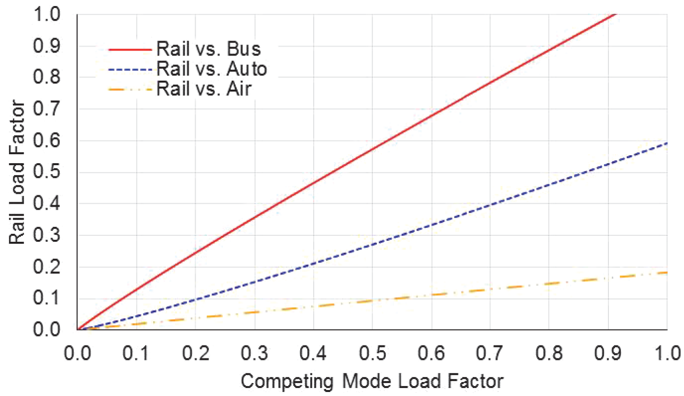
Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	785,017	144	2,173	0.397
Auto/LDV#	Value	2,387,049	414	6,934	1.202
	indexed to rail	3.04	2.88	3.19	3.02
Air	Value	2,288,689	448	7,370	1.444
	indexed to rail	2.92	3.12	3.39	3.63
Bus	Value	539,194	98	1,377	0.250
	indexed to rail	0.69	0.68	0.63	0.63

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

air following. For the case study load factors, the energy intensity and GHG emissions intensity of regional intercity rail is roughly three times less than that of air or automobile trips.

On this route and with the given rail equipment, the bus mode offers clear efficiencies compared to rail despite having a longer route. Only when the train runs at a load factor above 0.65 does it become less energy and GHG emissions intense than the bus operating with a 57% load factor (Figure 7-11).

A full, four-person automobile is only as efficient as a rail trip with a load factor of 0.59 (slightly higher than average). A full trip by air mode (load factor of 1.0) can only match the energy efficiency and emissions of a rail trip at a load factor of 0.18. Conversely, the bus requires a load factor of 0.91 to exceed the energy efficiency of a full train.



An automobile load factor of 1.0 = four occupants; a load factor of 0.25 = one occupant.

Figure 7-11. Charlotte–Raleigh, NC, energy intensity load factor sensitivity chart (including access/egress and upstream energy).

7.4.3 New York City–Buffalo, NY

This case study illustrates the regional trip from New York City to Buffalo, NY, for a party of one. A large disparity exists in potential trip distance depending on the selected mode (Table 7-16). The rail route via Albany is far less direct than the options for modes that take a more direct course between the two terminal cities. The rail trip uses the Amtrak Empire service, with access by subway and egress by automobile. The rail trip includes a brief portion of dual-mode electric operation outside Penn Station in New York City and some sections of 110-mph service. The automobile trip uses the average performance of the 2013 Driven Fleet with seating for four occupants. The air trip uses the default aircraft distribution and corresponding load factors, with access by shuttle van to LaGuardia Airport and egress by city bus. The bus trip uses a 45-ft. coach with 56 passenger seats, with access by subway and egress by taxi. Congestion on the highway mode is assumed to extend for 27 miles outside New York City.

The bus alternative is the least energy- and emissions intense mode per passenger-mile on the modal leg, the door-to-door trip, and the door-to-door trip including the upstream energy consumption; however, rail has the least energy intensity per seat-mile for the intercity (prime-modal) leg of the trip (Table 7-17). Thus, a full train may outperform the other modes, including bus, when operating at their average load factors. Analysis of the door-to-door trip including upstream consumption shows that the bus alternative is the least energy intense mode per passenger-mile, with rail, air and auto following.

Table 7-16. Case study: New York City–Buffalo, NY.

	Modal Leg			Access Leg 1		Access Leg 2		Egress Leg 1	
Mode	Service/ Vehicle	Distance (mi)	Load Factor	Mode	Distance (mi)	Mode	Distance (mi)	Mode	Distance (mi)
Rail	Empire Service	437	0.42	Subway	7.0	--	--	Auto	4.6
Auto	2013 Driven Fleet	333	0.25	--	--	--	--	--	--
Air	Default	291	0.78	Van/ Shuttle	9.5	--	--	Bus	7.0
Bus	45-foot Coach	363	0.57	Subway	7.4	--	--	Taxi	4.1

An automobile load factor of 1.0 = four occupants; a load factor of 0.25 = one occupant.

Table 7-17. Modal comparison: New York City–Buffalo, NY.

(a) Modal Intensity Comparison (modal leg only, direct activity only)

Category		Intensity Measures*						Service Metrics
Divisor		per round trip		per seat-mi		per passenger-mi		Travel Time
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(hrs)
Rail	Value	792,916	140.04	380	0.067	904	0.160	15.1
Auto/LDV#	Value	4,029,282	690.79	1,268	0.217	5,074	0.870	14.8
	indexed to rail	5.08	4.93	3.34	3.24	5.61	5.45	0.98
Air	Value	2,432,485	530.86	3,253	0.710	4,176	0.911	5.2
	indexed to rail	3.07	3.79	8.57	10.59	4.62	5.71	0.35
Bus	Value	625,347	110.41	413	0.073	724	0.128	17.2
	indexed to rail	0.79	0.79	1.09	1.09	0.80	0.80	1.14

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

(b) Modal Intensity Comparison (door-to-door, direct activity only)

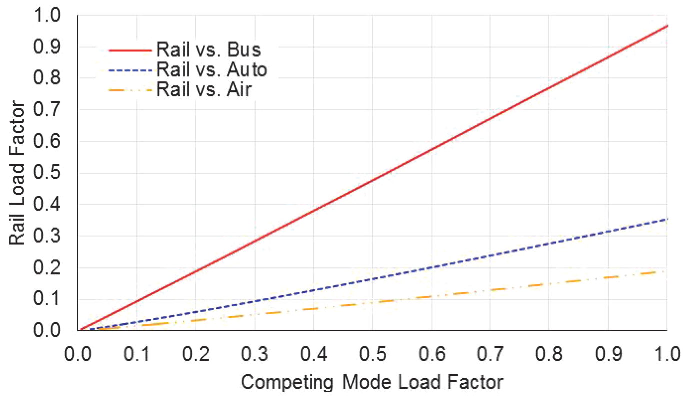
Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	905,252	159	1,005	0.176
Auto/LDV#	Value	4,029,282	691	5,074	0.870
	indexed to rail	4.45	4.36	5.05	4.94
Air	Value	2,524,141	547	4,101	0.888
	indexed to rail	2.79	3.45	4.08	5.04
Bus	Value	725,641	127	818	0.143
	indexed to rail	0.80	0.80	0.81	0.81

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

(c) Modal Intensity Comparison (door-to-door, including indirect well-to-pump consumption)

Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	1,081,732	197	1,201	0.219
Auto/LDV#	Value	5,193,372	900	6,540	1.133
	indexed to rail	4.80	4.57	5.44	5.18
Air	Value	2,914,449	694	4,735	1.127
	indexed to rail	2.69	3.52	3.94	5.15
Bus	Value	866,312	157	977	0.178
	indexed to rail	0.80	0.80	0.81	0.81

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.



An automobile load factor of 1.0 = four occupants; a load factor of 0.25 = one occupant.

Figure 7-12. New York City–Buffalo, NY, energy intensity load factor sensitivity chart (including access/egress and upstream energy).

Comparing per-trip metrics including access and upstream consumption to the rail trip, the bus saves 20% on energy and emissions. This performance difference can be largely attributed to the rail route being 20% longer than the bus route. A less circuitous rail route would perform within 10% of the bus under average load factors. If the more direct route were to capture additional ridership, the rail trip could outperform the bus trip on a passenger-mile basis.

Despite a circuity penalty of approximately 30% compared to the automobile mode, the train trip outperforms the automobile with a single occupant by a factor of four to five on a per-trip basis (Figure 7-12). An automobile with four occupants is still unable to match the energy and GHG emissions performance of the rail trip under average load factors. A full air trip (load factor of 1.0) can only match the energy efficiency and emissions of a rail trip at a load factor of 0.2.

7.4.4 Portland, OR–Seattle, WA

This case study illustrates the regional trip on the 170-mile corridor from Portland, OR, to Seattle, WA, for a party of one (Table 7-18). The rail trip uses the Amtrak Cascades service operating with a Talgo trainset. Rail station access is by automobile, and egress is by taxi. The auto trip uses the average performance of the 2013 Driven Fleet with seating for four occupants. The air trip uses the default aircraft distribution and corresponding load factors, with access by auto and egress by taxi. The bus trip uses a 45-ft. coach with 56 passenger seats, with access by auto and egress by taxi.

Table 7-18. Case study: Portland, OR–Seattle, WA.

	Modal Leg			Access Leg 1		Access Leg 2		Egress Leg 1	
Mode	Service/ Vehicle	Distance (mi)	Load Factor	Mode	Distance (mi)	Mode	Distance (mi)	Mode	Distance (mi)
Rail	Cascades	184	0.42	Auto	2.1	--	--	Taxi	3.6
Auto	Driven Fleet	173	0.25	--	--	--	--	--	--
Air	Default	129	0.71	Auto	14.8	--	--	Taxi	17.1
Bus	45-foot Coach	195	0.57	Auto	2.1	--	--	Auto	3.2

An automobile load factor of 1.0 = four occupants; a load factor of 0.25 = one occupant.

The bus alternative is the least energy intense and emissions intense mode for the modal leg simulation, the door-to-door trip, and the door-to-door trip including the upstream energy consumption (Table 7-19). Analysis of the door-to-door trip including upstream consumption shows that the bus alternative is the least energy intense mode per passenger-mile, with rail, auto and air following.

This case study result follows a pattern similar to that of the North Carolina case study. Even when fully loaded, the train cannot match the energy and emissions performance of the bus under a load factor of 0.65; however, the rail trip is still nearly three times more efficient than the automobile with one occupant (Figure 7-13). An automobile with one occupant is as efficient as

Table 7-19. Modal comparison: Portland, OR–Seattle, WA.

(a) Modal Intensity Comparison (modal leg only, direct activity only)

Category		Intensity Measures*						Service Metrics
Divisor		per round trip		per seat-mi		per passenger-mi		Travel Time
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(hrs)
Rail	Value	688,721	122	783	0.139	1,864	0.330	6.8
Auto/ LDV#	Value	1,843,921	316	1,329	0.228	5,318	0.912	7.5
	indexed to rail	2.68	2.59	1.70	1.65	2.85	2.76	1.11
Air	Value	1,409,403	259	3,894	0.717	5,452	1.003	4.5
	indexed to rail	2.05	2.13	4.97	5.17	2.92	3.04	0.67
Bus	Value	300,138	53	448	0.079	787	0.139	7.6
	indexed to rail	0.44	0.43	0.57	0.57	0.42	0.42	1.13

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

(b) Modal Intensity Comparison (door-to-door, direct activity only)

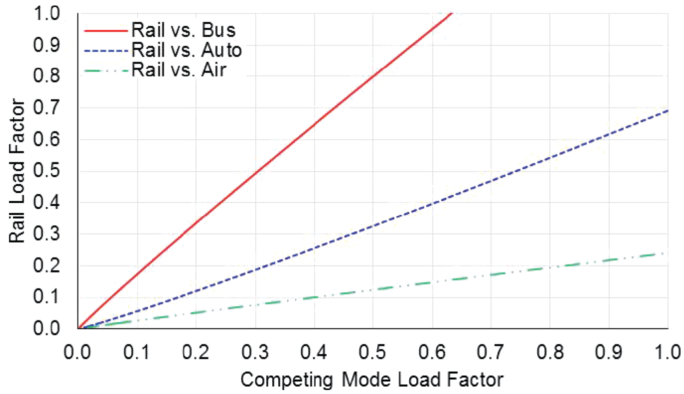
Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	766,013	135	2,012	0.354
Auto/LDV#	Value	1,843,921	316	5,318	0.912
	indexed to rail	2.41	2.35	2.64	2.58
Air	Value	1,831,183	330	5,681	1.024
	indexed to rail	2.39	2.45	2.82	2.89
Bus	Value	379,438	66	968	0.169
	indexed to rail	0.50	0.49	0.48	0.48

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

(c) Modal Intensity Comparison (door-to-door, including indirect well-to-pump consumption)

Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	919,374	168	2,414	0.442
Auto/LDV#	Value	2,376,644	412	6,854	1.188
	indexed to rail	2.59	2.45	2.84	2.69
Air	Value	2,131,436	419	6,613	1.299
	indexed to rail	2.32	2.49	2.74	2.94
Bus	Value	455,437	83	1,161	0.211
	indexed to rail	0.50	0.49	0.48	0.48

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.



An automobile load factor of 1.0 = four occupants; a load factor of 0.25 = one occupant.

Figure 7-13. Portland, OR–Seattle, WA, energy intensity load factor sensitivity chart (including access/egress and upstream energy).

a rail trip at a low load factor of approximately 0.15. An automobile with four occupants is still unable to match the energy and emissions performance of the rail trip when the rail load factor exceeds 0.69.

The air trip is more competitive with rail on this corridor. The air trip is only approximately 2.5 times more energy intense and three times more emissions intense than the rail trip at the average load factors. The energy intensity of a full flight can be matched by the performance of a train with a load factor of 0.23.

7.4.5 Bethesda, MD–New York City

This case study illustrates the higher-speed electrified intercity rail trip from Bethesda, MD (a suburb of Washington, DC) to New York City for a party of one (Table 7-20). The rail trip uses the electrified Amtrak Northeast Regional service at higher speeds of 125 mph, with access and egress by walking and subway. The automobile trip uses the average performance of the 2013 Driven Fleet with seating for four occupants. The air trip uses the default aircraft distribution and corresponding load factors, with access and egress by subway. The bus trip uses a 45-ft. coach with 56 passenger seats, with access and egress by subway. Congestion on the auto (highway) mode is assumed to extend for the entire length of the corridor from New York City to Washington, DC.

Table 7-20. Case study: Bethesda, MD–New York City.

	Modal Leg			Access Leg 1		Access Leg 2		Egress Leg 1	
Mode	Service/ Vehicle	Distance (mi)	Load Factor	Mode	Distance (mi)	Mode	Distance (mi)	Mode	Distance (mi)
Rail	Northeast Regional	226	0.53	Walk	0.7	Subway	10.0	Subway	8.0
Auto	2013 Driven Fleet	233	0.25	--	--	--	--	--	--
Air	Default	214	0.71	Subway	7.0	Subway	4.0	Taxi	10.0
Bus	45-foot Coach	242	0.57	Subway	10.0	--	--	Subway	7.6

An automobile load factor of 1.0 = four occupants; a load factor of 0.25 = one occupant.

The bus alternative is the least energy intense mode for the modal leg, the door-to-door trip, and the door-to-door trip including the upstream energy consumption (Table 7-21). From the final upstream perspective, the rail and bus modes are essentially equal in terms of energy consumption, in part due to the higher rail load factor obtained through higher-speed and higher-frequency service on the Northeast Corridor. Unlike the previous cases, the rail alternative has the lowest emissions intensity from each perspective because of the electric traction and source generation mixture along the corridor. Analysis of the door-to-door trip including upstream consumption shows that the bus alternative is the least energy intense per passenger-mile, with rail, air and auto following.

The rail trip with average load factor is six times more energy efficient than the automobile with a single occupant given the combination of electric traction, higher load factor, and highway congestion. Even a full automobile with four passengers is only as energy efficient as a rail trip with a below average load factor of 0.4 (Figure 7-14).

A similar comparison is made for the emissions of each mode (Figure 7-15). At the simulated load factors, compared to rail, auto is approximately seven times as emissions intense; air is over six times as emissions intense, and bus is roughly 25% more emissions intense. The emissions intensity of a full aircraft trip can be matched by a train with a very low load factor of 0.09. The emissions intensity of a full bus can be matched by a train with a load factor of 0.58.

In this case study, the air trip time is the lowest, taking 75% of the rail trip time. Compared to the previous case studies, however, the rail alternative for this trip offers much more competitive travel time due to the higher-speed service.

7.5 Long-Distance Intercity Case Study: Chicago, IL–Los Angeles, CA

A single long-distance intercity rail service case study was developed for comparison to automobile, air and bus modes for a door-to-door trip between Chicago, IL, and Los Angeles, CA. The trip traverses over 2,100 miles and is made by a party of two travelers (Table 7-22). The rail trip uses the Amtrak Southwest Chief service, with access to Chicago Union Station by walking and subway and egress in Los Angeles by taxi. The train consist includes a number of food-service, lounge and sleeping cars. Because of the large number of rail station stops, the MMPASSIM input data was set with most stops shown as "unscheduled stops"; the impact is the same. The automobile trip uses the average performance of the 2013 Driven Fleet with seating for four occupants. The auto trip has 11 stops scheduled with an average of 20 minutes per stop, which accounts for several stops for gasoline and food. Also, the trip time has an additional 8 hours per one-way trip to account for overnight stops. The auto and bus follow the same route, which is a more southerly course than the rail trip, passing through St. Louis and Oklahoma City. The air trip is a direct flight from Chicago O'Hare International Airport (ORD) to Los Angeles International Airport (LAX). The air trip uses the default aircraft distribution and corresponding load factors, with access by walking and subway and egress by taxi. The bus trip uses a 45-ft. coach with 56 passenger seats, with access and egress by subway.

The bus alternative is the least energy- and emissions intense mode for the modal leg only, the door-to-door trip, and the door-to-door trip including the upstream energy consumption (Table 7-23). Analysis of the door-to-door trip including upstream consumption shows that the bus alternative is the least energy intense per passenger-mile, with rail, air and auto following. In this case, the air round-trip time is the lowest, at 13% of the rail round-trip time.

Because of the long distance and the extra weight required to provide rail passengers with meal service and other on-board amenities, the rail trip has relatively poor energy and emissions

Table 7-21. Modal comparison: Bethesda, MD–New York City.

(a) Modal Intensity Comparison (modal leg only, direct activity only)

Category		Intensity Measures*						Service Metrics
Divisor		per round trip		per seat-mi		per passenger-mi		Travel Time
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(hrs)
Rail	Value	438,499	55	514	0.064	970	0.122	6.6
Auto/ LDV#	Value	2,493,349	427	1,336	0.229	5,345	0.916	9.7
	indexed to rail	5.69	7.77	2.60	3.55	5.51	7.53	1.46
Air	Value	2,009,342	377	3,349	0.628	4,689	0.879	5.0
	indexed to rail	4.58	6.85	6.52	9.74	4.84	7.23	0.75
Bus	Value	397,881	70	478	0.084	838	0.148	11.1
	indexed to rail	0.91	1.28	0.93	1.31	0.86	1.22	1.68

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

(b) Modal Intensity Comparison (door-to-door, direct activity only)

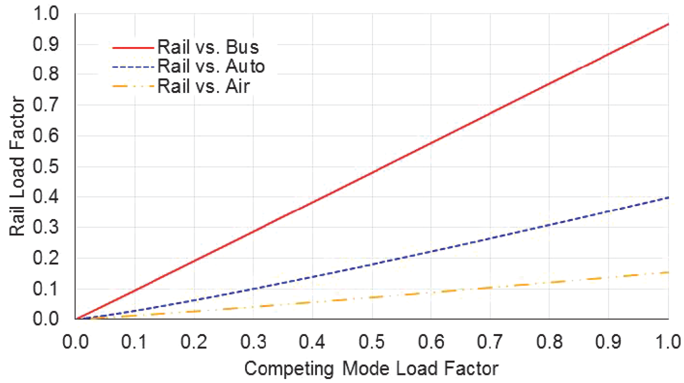
Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	551,545	73	1,126	0.149
Auto/LDV#	Value	2,493,349	427	5,345	0.916
	indexed to rail	4.52	5.85	4.74	6.13
Air	Value	2,209,692	410	4,697	0.871
	indexed to rail	4.01	5.60	4.17	5.83
Bus	Value	508,415	88	997	0.173
	indexed to rail	0.92	1.20	0.89	1.15

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

(c) Modal Intensity Comparison (door-to-door, including indirect well-to-pump consumption)

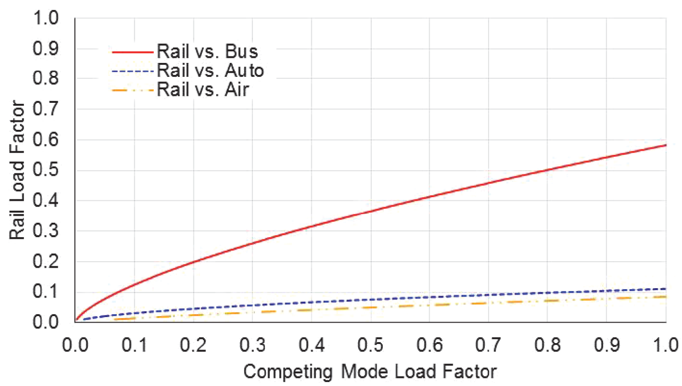
Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	612,906	84	1,252	0.172
Auto/LDV#	Value	3,213,697	557	6,889	1.194
	indexed to rail	5.24	6.60	5.50	6.93
Air	Value	2,550,301	519	5,421	1.102
	indexed to rail	4.16	6.15	4.33	6.40
Bus	Value	599,243	107	1,175	0.211
	indexed to rail	0.98	1.27	0.94	1.22

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.



An automobile load factor of 1.0 = four occupants; a load factor of 0.25 = one occupant.

Figure 7-14. Bethesda, MD–New York City, energy intensity load factor sensitivity chart (including access/egress and upstream energy).



An automobile load factor of 1.0 = four occupants; a load factor of 0.25 = one occupant.

Figure 7-15. Bethesda, MD–New York City, emissions intensity load factor sensitivity chart (including access/egress and upstream emissions).

Table 7-22. Case study: Chicago, IL–Los Angeles, CA.

	Modal Leg			Access Leg 1		Access Leg 2		Egress Leg 1	
Mode	**Service/ Vehicle**	**Distance (mi)**	**Load Factor**	**Mode**	**Distance (mi)**	**Mode**	**Distance (mi)**	**Mode**	**Distance (mi)**
Rail	Southwest Chief (full amenities)	2,251	0.63	Walk	0.8	Subway	5.5	Taxi	12.0
Auto	2013 Driven Fleet	2,120	0.50	--	--	--	--	--	--
Air	Default	1,742	Default	Walk	0.8	Subway	12.4	Taxi	30.0
Bus	45-ft. Coach	2,122	0.57	Subway	10.0	--	--	Subway	7.6

An automobile load factor of 1.0 = four occupants; a load factor of 0.5 = two occupants.

Table 7-23. Modal comparison: Chicago, IL–Los Angeles, CA.

(a) Modal Intensity Comparison (modal leg only, direct activity only)

Category		Intensity Measures*						Service Metrics
Divisor		per round trip		per seat-mi		per passenger-mi		Travel Time
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(hrs)
Rail	Value	6,176,851	1,093	864	0.153	1,372	0.243	84.8
Auto/ LDV#	Value	10,679,535	1,831	1,259	0.216	2,519	0.432	62.9
	indexed to rail	1.73	1.68	1.46	1.41	1.84	1.78	0.74
Air	Value	7,036,161	1,762	1,697	0.425	2,021	0.506	10.8
	indexed to rail	1.14	1.61	1.96	2.78	1.47	2.09	0.13
Bus	Value	3,225,677	570	434	0.077	761	0.134	65.5
	indexed to rail	0.52	0.52	0.50	0.50	0.55	0.55	0.77

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

(b) Modal Intensity Comparison (door-to-door, direct activity only)

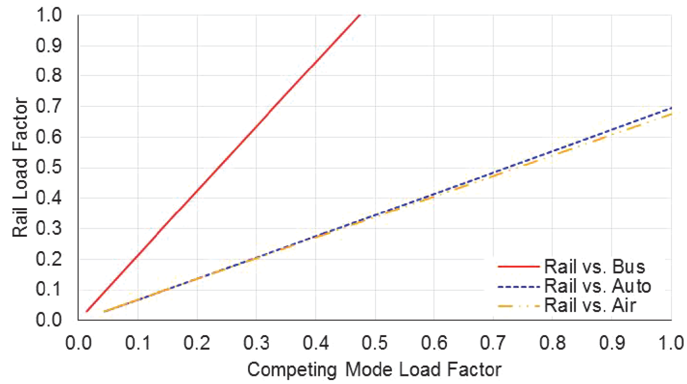
Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	6,317,950	1116	1,392	0.246
Auto/LDV#	Value	10,679,535	1831	2,519	0.432
	indexed to rail	1.69	1.64	1.81	1.76
Air	Value	7,310,935	1808	2,049	0.507
	indexed to rail	1.16	1.62	1.47	2.06
Bus	Value	3,336,211	587	780	0.137
	indexed to rail	0.53	0.53	0.56	0.56

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

(c) Modal Intensity Comparison (door-to-door, including indirect well-to-pump consumption)

Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	7,578,994	1392	1,670	0.307
Auto/LDV#	Value	13,764,935	2385	3,246	0.562
	indexed to rail	1.82	1.71	1.94	1.83
Air	Value	8,434,230	2294	2,364	0.643
	indexed to rail	1.11	1.65	1.42	2.10
Bus	Value	3,992,947	731	934	0.171
	indexed to rail	0.53	0.52	0.56	0.56

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.



An automobile load factor of 1.0 = four occupants; a load factor of 0.25 = one occupant.

Figure 7-16. Chicago, IL, to Los Angeles, CA (full-amenity consist), energy intensity load factor sensitivity chart (including access/egress and upstream energy).

performance given the load factor of 0.63. At the average rail load factor, a full automobile with four passengers can be more energy efficient than the rail trip (Figure 7-16), whereas in other cases, a full automobile could not match the rail efficiency at typical load factors.

Interestingly for this case, because of the long distance involved, the per-trip air energy consumption becomes competitive with the rail trip energy consumption. At these distances, air load factors are higher and there are improved economies in distributing the fixed take-off and landing cycle over a long cruise distance. Combined with the low seating density of the train with sleeping accommodations, air nearly matches rail's energy consumption. Per trip, however, air mode emissions are still 65% higher than rail when upstream emissions are included.

It is interesting to analyze the effect on the modal comparison of altering the train consist by removing dining, sleeping, and lounge cars and replacing them with additional coaches with seats. The rearranged consist has reduced energy and GHG emissions intensities relative to the original consist. This change causes a more favorable comparison with the competing modes, but the *relative* energy intensity and emissions intensity rankings of the modes is the same (Table 7-24). With the "all-coach" consist, the auto mode is once again approximately three times more energy and emissions intense compared to the rail trip.

The load factor sensitivity of this configuration (Figure 7-17) illustrates the improved efficiency of the rail trip by the reduced slope of the lines of equal energy intensity compared to Figure 7-16.

7.6 HSR Case Study: Fresno, CA–Los Angeles, CA

A single high-speed intercity rail service case study was developed for comparison to automobile, air and bus modes for a selected door-to-door trip between urban areas. The HSR case study illustrates a regional intercity trip from Fresno, CA, to Los Angeles, CA, for a party of one (Table 7-25). The rail trip uses the planned California High-Speed Rail (CAHSR) service, with access by auto and egress by taxi. Given the constraints of HSR geometry, availability of right-of-way corridors and desire to serve certain online communities, the rail route suffers from a nearly 50% circuity penalty compared to the more direct routes taken by the other modes. The CAHSR system uses electrified trainsets. The automobile trip uses the average performance of the 2013 Driven Fleet with seating for four occupants. The air trip uses the default aircraft distribution

Table 7-24. Modal comparison: Chicago, IL–Los Angeles, CA (all-coach).

(a) Modal Intensity Comparison (modal leg only, direct activity only)

Category		Intensity Measures*						Service Metrics
Divisor		per round trip		per seat-mi		per passenger-mi		Travel Time
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(hrs)
Rail	Value	3,844,072	680	538	0.095	854	0.151	84.9
Auto/LDV #	Value	10,676,612	1833	1,259	0.216	2,518	0.432	62.9
	indexed to rail	2.78	2.70	2.34	2.27	2.95	2.86	0.74
Air	Value	7,036,161	1762	1,697	0.425	2,021	0.506	10.8
	indexed to rail	1.83	2.59	3.16	4.47	2.37	3.35	0.13
Bus	Value	3,225,677	570	434	0.077	761	0.134	65.5
	indexed to rail	0.84	0.84	0.81	0.80	0.89	0.89	0.77

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

(b) Modal Intensity Comparison (door-to-door, direct activity only)

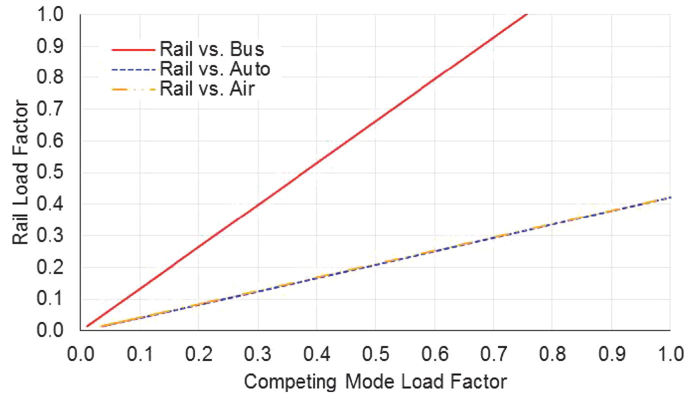
Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	3,985,171	703	878	0.155
Auto/LDV #	Value	10,676,612	1833	2,518	0.432
	indexed to rail	2.68	2.61	2.87	2.79
Air	Value	7,310,935	1808	2,049	0.507
	indexed to rail	1.83	2.57	2.33	3.27
Bus	Value	3,336,211	587	780	0.137
	indexed to rail	0.84	0.83	0.89	0.89

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

(c) Modal Intensity Comparison (door-to-door, including indirect well-to-pump consumption)

Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	4,779,372	877	1,053	0.193
Auto/LDV #	Value	14,186,085	2426	3,346	0.572
	indexed to rail	2.97	2.77	3.18	2.96
Air	Value	8,434,230	2294	2,364	0.643
	indexed to rail	1.76	2.61	2.24	3.33
Bus	Value	3,992,947	731	934	0.171
	indexed to rail	0.84	0.83	0.89	0.88

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.



An automobile load factor of 1.0 = four occupants; a load factor of 0.25 = one occupant.

Figure 7-17. Chicago, IL–Los Angeles, CA (all-coach consist), energy intensity load factor sensitivity chart (including access/egress and upstream energy).

and corresponding load factors, with access by auto and egress by taxi at LAX. The bus trip uses a 45-ft. coach with 56 passenger seats, with access by auto and egress by taxi.

The bus alternative is the least energy intense mode in the analyses of the modal leg, the door-to-door trip and the door-to-door trip including the upstream energy consumption; however, the HSR alternative has the lowest emissions intensity in each of these analyses because of the electricity generation mixture along the corridor and the fact that the CAHSR trainset includes regenerative braking at an assumed 65% acceptance rate (Table 7-26).

Analysis of the door-to-door trip including upstream consumption shows that the bus alternative is the least energy intense per passenger-mile, with rail, air and auto following. In this case, the rail trip time is the lowest, with air round-trip time at 151% of the HSR round-trip time. This result can be attributed to an airport dwell time of 80 minutes required each way, compared to 20 minutes of dwell time required for the rail alternative. Compared to the previous case studies, the rail alternative for this trip is much more competitive with regard to trip time because of the higher-speed service.

Like most of the other cases, the rail trip is approximately three to four times more energy efficient than an automobile trip with a single occupant (Figure 7-18). Thus, given average rail load factors, an automobile with three or four occupants is required to match the energy and emission performance of the HSR trip. A full automobile is as efficient as a rail trip with a load

Table 7-25. Case study: Fresno–Los Angeles, CA.

	Modal Leg			Access Leg 1		Access Leg 2		Egress Leg 1	
Mode	Service/ Vehicle	Distance (mi)	Load Factor	Mode	Distance (mi)	Mode	Distance (mi)	Mode	Distance (mi)
Rail	California HSR	292	0.6	Auto	12.0	--	--	Taxi	5.0
Auto	2013 Driven Fleet	219	0.25	--	--	--	--	--	--
Air	Default	209	Default	Auto	30.0	--	--	Taxi	5.0
Bus	45-ft. Coach	223	0.57	Auto	12.0	--	--	Taxi	5.0

An automobile load factor of 1.0 = four occupants; a load factor of 0.25 = one occupant.

Table 7-26. Modal comparison: Fresno–Los Angeles, CA.

(a) Modal Intensity Comparison (modal leg only, direct activity only)

Category		Intensity Measures*						Service Metrics
Divisor		per round trip		per seat-mi		per passenger-mi		Travel Time
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(Btu)	(lb-GHG)	(hrs)
Rail	Value	508,225	44	522	0.045	870	0.075	3.3
Auto/ LDV#	Value	2,433,549	417	1,387	0.238	5,547	0.951	7.8
	indexed to rail	4.79	9.52	2.66	5.28	6.37	12.68	2.38
Air	Value	1,976,890	370	3,374	0.632	4,724	0.885	4.9
	indexed to rail	3.89	8.45	6.46	14.04	5.43	11.80	1.51
Bus	Value	364,455	64	464	0.082	815	0.144	8.0
	indexed to rail	0.72	1.47	0.89	1.82	0.94	1.92	2.46

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

(b) Modal Intensity Comparison (door-to-door, direct activity only)

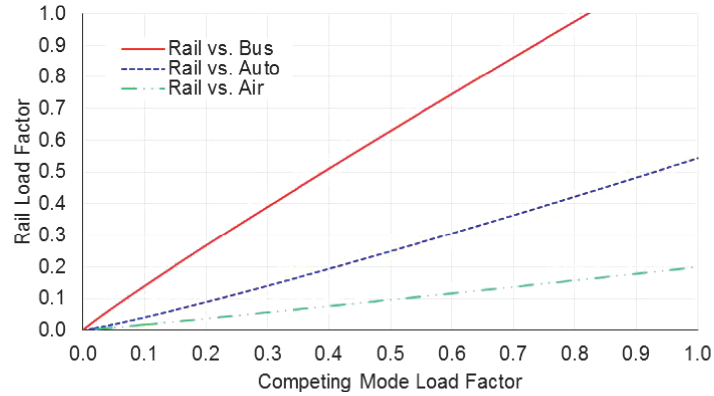
Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	621,730	63	1,006	0.102
Auto/LDV#	Value	2,433,549	417	5,547	0.951
	indexed to rail	3.91	6.64	5.51	9.35
Air	Value	2,276,098	421	4,659	0.861
	indexed to rail	3.66	6.69	4.63	8.47
Bus	Value	503,828	88	1,047	0.182
	indexed to rail	0.81	1.40	1.04	1.79

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.

(c) Modal Intensity Comparison (door-to-door, including indirect well-to-pump consumption)

Category		Intensity Measures*			
Divisor		per trip		per passenger-mi	
Units of Measure		(Btu)	(lb-GHG)	(Btu)	(lb-GHG)
Rail	Value	709,756	81	1,148	0.131
Auto/LDV#	Value	3,136,620	544	7,150	1.239
	indexed to rail	4.42	6.71	6.23	9.45
Air	Value	2,638,491	534	5,401	1.093
	indexed to rail	3.72	6.59	4.70	8.34
Bus	Value	604,770	110	1,256	0.228
	indexed to rail	0.85	1.36	1.09	1.74

*GHG is measured in lb of CO_2e.
#LDV GHG is E05 without credit for corn growth; with credit, the GHG is reduced by 2.5%.



An automobile load factor of 1.0 = four occupants; a load factor of 0.25 = one occupant.

Figure 7-18. Fresno–Los Angeles, CA, load factor sensitivity chart (including access/egress and upstream energy).

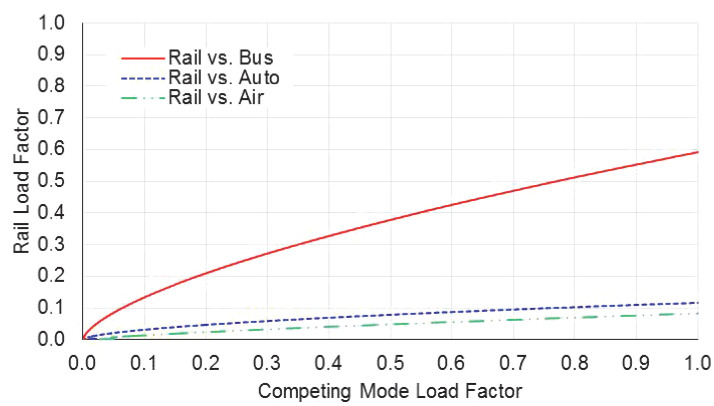
factor of 0.54. Auto and air trips produce seven times the emissions of a trip by CAHSR at the simulated load factors. Compared to a bus trip at a load factor of 1.0, the rail trip can achieve an equal emissions intensity operating at a load factor of 0.59 (Figure 7-19).

7.7 Summary Comparisons

To better illustrate the variation in the energy and GHG emissions performance of each competing mode relative to rail across the full range of case studies, the results have been summarized in a series of single-mode comparisons in the balance of this section.

7.7.1 Auto and Rail

Figure 7-20 shows the auto energy and GHG emissions intensities per trip, including access and upstream energy, indexed to rail values and plotted across all case study routes. In all cases, the rail trips outperform their equivalent auto trips. The greatest disparity between the auto



An automobile load factor of 1.0 = four occupants; a load factor of 0.25 = one occupant.

Figure 7-19. Fresno–Los Angeles, CA, emissions intensity load factor sensitivity chart (including access/egress and upstream emissions).

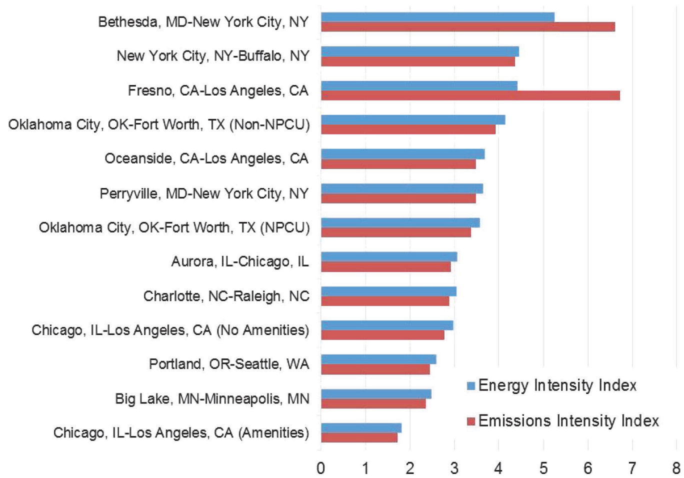


Figure 7-20. Auto energy and GHG emissions intensities indexed to rail values.

and rail mode is observed for the electrified passenger rail operation on the Northeast Corridor between Bethesda, MD, and New York City and, despite its circuitous route, the California HSR trip between Fresno and Los Angeles. For most of the diesel-electric routes, auto trip energy intensity is two to four times rail trip energy intensity.

7.7.2 Air and Rail

Figure 7-21 shows the air trip energy and GHG emissions intensities per trip, including access and upstream energy, indexed to rail values and plotted across all case study routes where air service is an option. In all cases, the rail trips outperform their equivalent air trips. For the long-distance trip from Chicago, IL, to Los Angeles, CA, however, the air trip nearly equals the performance of the rail mode. As was seen with the comparison between auto and rail, the best relative rail performance is observed on the Northeast Corridor and the California HSR.

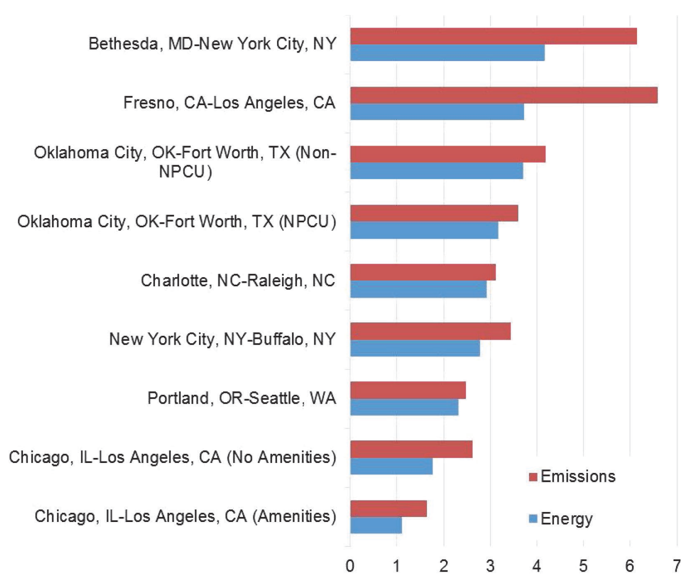


Figure 7-21. Air energy and GHG emissions intensities indexed to rail values.

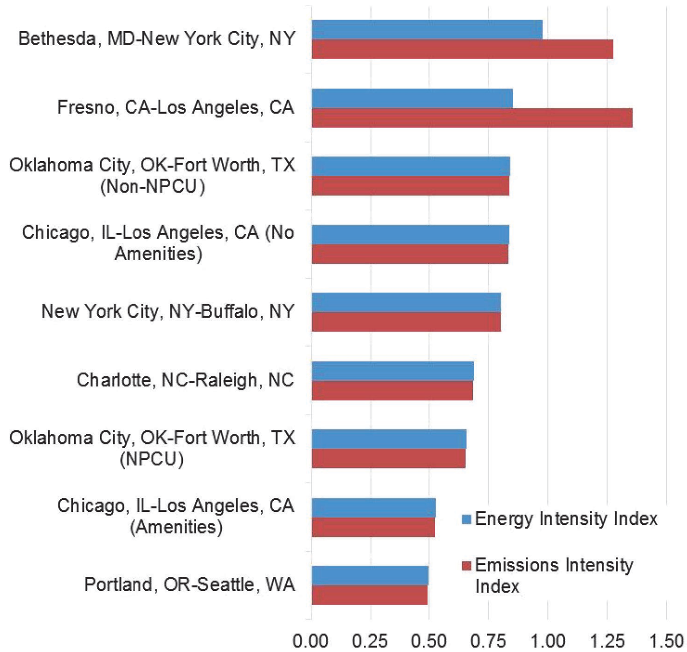


Figure 7-22. Bus energy and GHG emissions intensities indexed to rail values.

7.7.3 Bus and Rail

Figure 7-22 shows the bus mode energy and GHG emissions intensities per trip, including access and upstream energy, indexed to rail values and plotted across all case study routes where bus service is an option. To better show the data, this plot has been prepared on a different scale than the previous two figures. In nearly all cases, the rail trips are outperformed by their equivalent bus trips. The only exceptions are the emissions performance of the electrified passenger rail operations on the Northeast Corridor and California HSR. The regional intercity route from Portland, OR, to Seattle, WA, has the worst performance relative to the bus.

7.8 Sensitivity Analysis

The results presented in the summary comparisons as illustrated by Figure 7-20 through Figure 7-22 cover a wide range of trips using different combinations of rail services, competing modes and access and egress patterns. To help generalize the results and better illustrate the effects of certain factors, the NCRRP Project 02-01 research team conducted additional simulations beyond the trip-specific modal comparison case studies. The first experiment considered the effect of access and egress distances on door-to-door trip energy intensity. The second experiment examined the influence of access and egress mode choice on total trip energy consumption.

7.8.1 Access and Egress Distance

To investigate the effect of access/egress distances on total trip energy intensity, experiments were conducted using modified versions of two case study routes (one commuter and one regional intercity). Two scenarios were developed that follow a similar progression to increase the access and egress distances from the terminal rail stations, with corresponding adjustments to the auto trip length (Figure 7-23).

Figure 7-23. Methodology for increasing access/egress distances.

The first experiment, Scenario A, involved increasing the access and egress distances in diverging directions away from the terminals such that the overall distance for the equivalent auto trip alternative increased. The second experiment, Scenario B, increased the access and egress distances in converging directions between the rail terminals to decrease the overall distance for the equivalent auto trip alternative. At some point, increasing the access and egress distance in Scenario B may result in an auto trip short enough that the total trip energy consumption or emissions per passenger is less than the alternative rail trip (including access legs). The access and egress mode for both scenarios is auto with one occupant (the driver).

The results of this approach as applied to the Metrolink Orange Line case study from Oceanside, CA, to Los Angeles, CA appear in Figure 7-24. In this case, rail stations are spaced 9 miles apart. In comparison to the original case, access and egress distances were increased from 1 mile to 4.5 miles (in both directions A and B). When the station access trip distance reached 4.5 miles, the rational traveler would have the option to use the next closest station at a shorter overall distance. Distances greater than 4.5 miles were not investigated. For this long commuter route, at average load factor, the results indicate the rail alternative is still less energy intense than the auto trip, even if it requires driving in the opposite direction of the general trip to access and egress the rail terminals.

The same approach was applied to the Cascades case study route from Portland, OR, to Seattle, WA (Figure 7-25). The access and egress distances were increased (in directions A and B) from 1 mile to 30 miles. In this case, the adjacent stations are less than 15 miles away, so the rational traveler would choose to use the closer adjacent stations once the access distance exceeds 7.5 miles. For the purpose of this analysis, however, the distances were further increased to find the point where the equivalent alternative auto trip would become less energy intense than the combination of the rail trip between terminals and the access and egress legs.

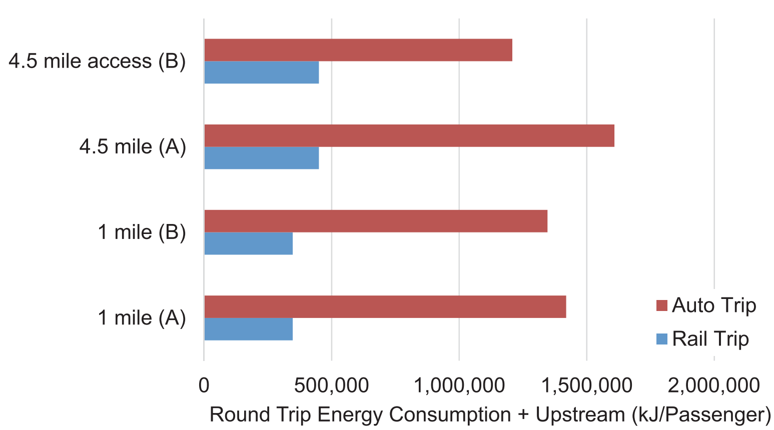


Figure 7-24. Results with access and egress distance changes on Metrolink Orange Line.

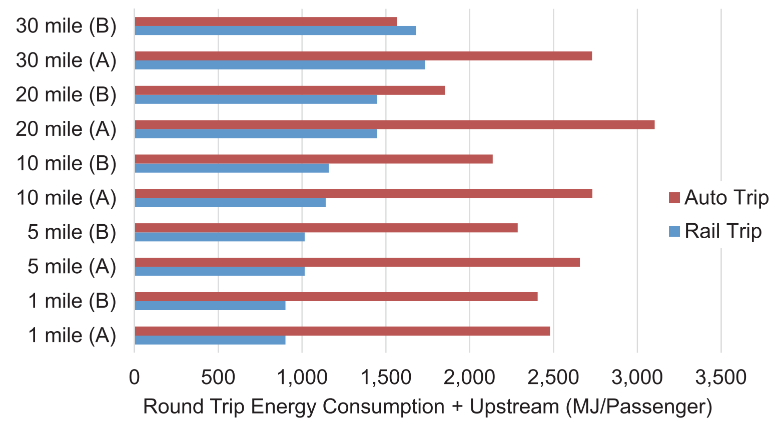


Figure 7-25. Results with access and egress distance changes on Cascades route.

The results of this experiment indicate that the auto alternative becomes less energy intense than rail after increasing the access and egress distances in the direction B nearly 30 miles for each of the access and egress stations. At this point, the auto trip is only 120 miles long, whereas the rail trip consists of 180 miles via rail plus a 30-mile auto access leg and a 30-mile auto egress leg, for a total trip of 240 miles. The results also show that—as would be expected–increasing the access and egress trip in either direction increases the energy intensity of the rail trip.

7.8.2 Access Mode Choice

The influence of access and egress mode choice on total rail trip energy consumption was investigated for both a commuter rail case study and a regional intercity case study.

The total trip energy consumption per person for the Metrolink Orange Line commuter rail case study and Cascades regional intercity case study were simulated with different access mode assumptions. For both case studies in this experiment, the access mode was altered while the egress mode at the opposite end was held constant. For the Metrolink commuter case study, egress by walking was held constant whereas egress by streetcar/light rail was held constant for the Cascades regional intercity case study.

First, consider the alternative access modes to commuter rail as the prime mode (Figure 7-26). Relative to the case with 5.4 miles of auto access (driving alone), choosing bus as the access mode yields a reduction in round-trip energy consumption per person of 6%. Similarly, choosing light rail (electric) or branching commuter rail (diesel) lines as access modes yields an 11% reduction, and choosing bicycle as the access mode yields a 20% reduction.

Second, consider the alternative access modes to the regional intercity rail as the prime mode (Figure 7-27). Relative to the case with 2.1 miles of auto (driving alone) as the access mode, selecting bus as the access mode reduces round-trip energy consumption per person by 1%. Choosing light rail (electric) and commuter rail (diesel) as the access mode yields a reduction of 2%, whereas choosing bicycle as the access mode yields a reduction of 3%.

In both of the situations described, light rail (electric) and commuter rail (diesel) access modes yield similar reductions in energy consumption. This indicates that both are lower than single-occupant auto access but very similar to each other in energy consumption. As expected, given that the prime mode trip contributes a larger share of the total trip energy for the longer regional intercity trip (i.e., Cascades), that service is less sensitive to changes in access mode

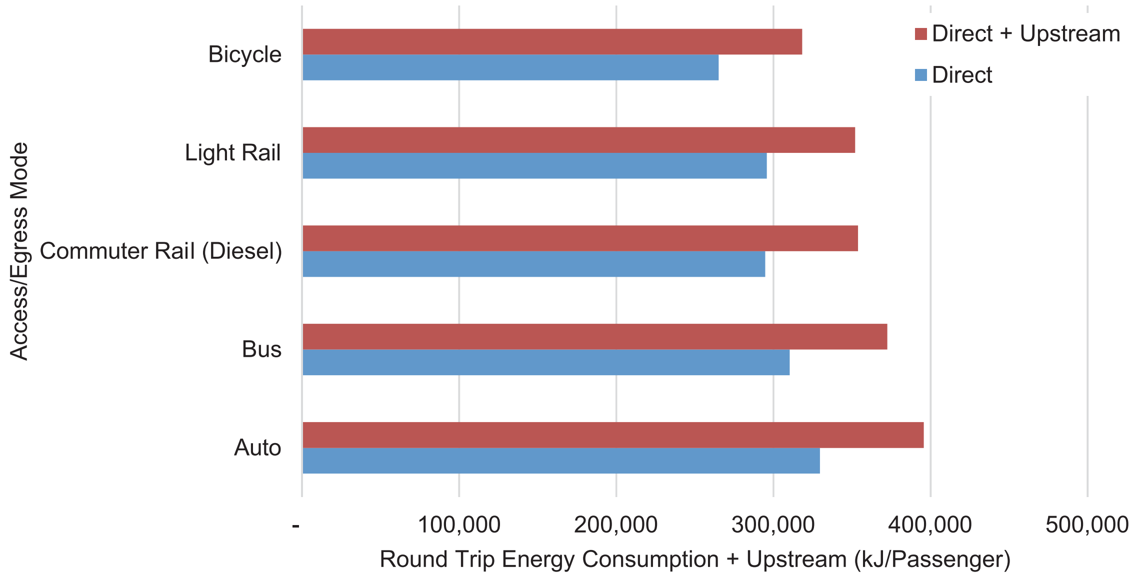


Figure 7-26. Effect of access mode choice on Metrolink Orange Line.

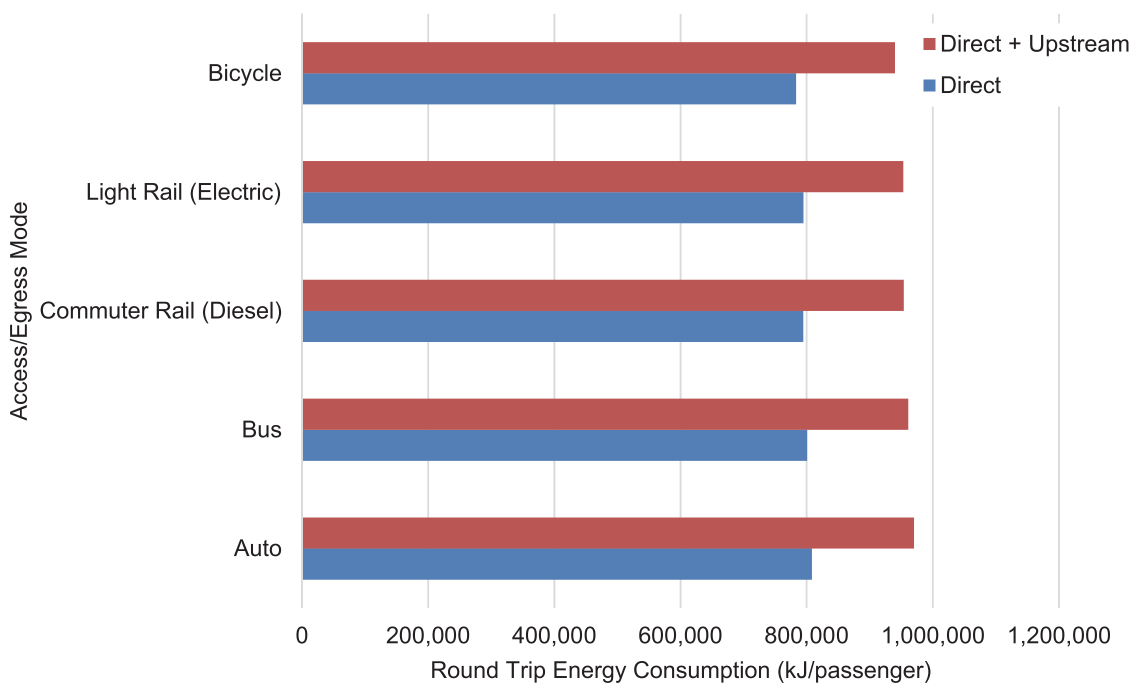


Figure 7-27. Effect of access mode choice on Cascades route.

changes. Although only access modes were assessed in this experiment, the findings would be equally applicable to egress modes if the egress trip length were similar to the access trip length.

7.9 Conclusions

In this study, energy consumption and GHG emissions for selected commuter, regional intercity, long-distance intercity and HSR trips were compared to those of comparable auto, bus and air mode trips via MMPASSIM simulation. The examined case studies compared energy use and GHG emissions under a variety of infrastructure, equipment and operating conditions for each of the modes. Analysis revealed several general trends, despite differences between individual case study conditions.

An overarching takeaway is the reinforcement that modal load factor strongly influences the relative energy and GHG emissions intensities of any of the modes studied. Driving alone is inefficient, and no other travel mode operates efficiently if the load factor is low, with few passengers and many empty seats. Differences in the inherent efficiency of each mode are sufficiently large, however, to prevent the mode with the highest load factor from always being the most efficient. Although a full aircraft or automobile is much more competitive with rail in terms of energy efficiency, many rail operating and ridership scenarios exist for which a below-capacity train will still be more energy and GHG emissions efficient than air mode or auto mode for an equivalent trip. Some data limitations prevented a wider range of comparisons in this study. The research team did not have characterization data for Amtrak's Acela trainset, which has a higher load factor than the other Northeast Regional services that were included among the simulations. Also, even though the researchers had some region-specific load factor data for Amtrak services, only system-wide average load factors were available for bus, and it is reasonable to expect that the bus mode would see the same types of variations in load factor with population density as is experienced by rail. A final observation for automobile users is that, from a marginal impact perspective, it is always more energy and GHG emissions efficient to take a scheduled carrier than it is to drive. A scheduled train or bus will make the trip anyway, and additional passengers will have a minimal incremental fuel impact on that scheduled trip.

In general, for the majority of case studies relative to auto:

- Auto is three to four times more energy and GHG emissions intense than rail under average load factors.
- An automobile with four passengers approaches the performance of regional intercity trains but cannot match the energy and GHG emissions performance of commuter trains under average load factors.
- During peak periods, when the majority of commuting trips take place, roadways are congested and rail operates at higher load factors, commuter rail can be over 10 times more efficient than driving alone.

Commuter rail stations are spaced at close enough intervals that the length of the auto access and egress legs of the commuter's trip does not substantially alter the comparison between rail and auto. This is the case even when the commuter must drive in the "wrong" direction to access and egress commuter rail, effectively lengthening the rail trip and shortening the competing auto trip.

On regional intercity rail routes with larger intervals between stations, access distance can have a greater influence on the modal comparison. On the case study regional intercity route, adding 20 miles of access/egress distance to the rail trip and subtracting 20 miles from the length of the competing auto trip cut the energy and GHG emissions advantage of rail to 2:1. Adding 60 miles of access/egress distance to the rail trip and subtracting 60 miles from the competing auto trip resulted in the auto being slightly more energy efficient for the door-to-door trip under average load factors. This extreme case is unlikely in practice, however, as most regional intercity lines feature stations spaced less than 60 miles apart.

Choice of access and egress mode is more important for commuter rail trips. For one case study route, under an average load factor, switching from auto to bicycle access decreased round-trip energy consumption by 20%. Given the amount of energy consumed by the modal leg travel segment, choice of access mode has less influence on regional intercity rail. In either case, the difference in energy intensity and GHG emissions intensity is unlikely to change the relative results in modal comparisons to auto and air.

Electricity consumption often is reported at the locomotive input location in kWh, which can make an electric locomotive appear more efficient than a diesel-electric locomotive. To compare the energy intensity on an equal footing, the research team included the fuel energy consumed in electricity generation to compare the performance of electric locomotives with diesel-electric locomotives and the other modes with on-board engines. The additional upstream (well-to-pump) energy/emissions are unique to each type of fuel delivered and were also considered in the modal comparison case studies and rail alternative fuel case studies. When direct and upstream energy consumption are considered together, electrification does not generally improve passenger rail energy efficiency unless the regional generation profile contains a substantial amount of renewable power generation. When combined with track upgrades, implementation of higher-horsepower electric locomotives may facilitate more rapid acceleration and higher operating speeds that actually increase energy consumption. As discussed in Chapter 5, however, electric multiple-unit (EMU) trainsets can offer energy efficiency benefits through electrification.

The GHG emissions benefits of electrification are highly dependent on regional electricity generation profiles. On certain case study routes, auto mode GHG emissions are up to seven times higher than passenger rail GHG emissions under average load factors. When driving alone, a traveler can produce an order of magnitude more GHG emissions than a passenger on a train operating at peak load factor.

The GHG emissions benefits of rail are particularly apparent from the case studies in urban areas, where auto and bus modes experience extensive highway congestion and idling in slow traffic increases their emission intensity. This comparison is of particular importance as it is these same congested urban areas that tend to have air quality concerns and where the environmental benefits of rail are used as one justification for investment in commuter and regional intercity passenger rail, along with urban rail transit.

The modal comparison case studies reinforce the influence of seating density and train consist weight on energy and GHG emissions intensities relative to auto. Three examples from the simulations merit noting here:

- The performance of the Heartland Flyer relative to competing modes increased when the NPCU was removed and additional miles of travel were added to turn the train.
- Despite its higher load factor, the Pacific Surfliner regional intercity train was only slightly more energy efficient than the Metrolink commuter train between the same two stations. The greater seating density of the Metrolink commuter railcars made the service more competitive with the other modes.
- The Southwest Chief case study demonstrated how on-board passenger services and amenities can degrade energy and GHG emissions performance relative to competing modes to the point at which an air trip is competitive with rail energy intensity. Although performance can be improved by removing service cars (and replacing them with coach seats if ridership warrants), these on-board amenities (and the extra comfort offered by the lower seating density on the Pacific Surfliner compared to Metrolink) are required to attract ridership and load factor.

Analysis of the regional and long-distance intercity case study routes relative to air suggests the following:

- A compromise between trip time and energy consumption is apparent. Air alternatives reduce travel time by 25% to 90% relative to the equivalent rail trip, but increase energy intensity per passenger by as much as four times in some cases.
- Air mode can be up to six to seven times more GHG emissions intense than electrified passenger rail services that use relatively clean electricity. This result was particularly evident for the California HSR case study.

The case study simulations indicate that intercity buses tend to be the least energy and GHG emissions intense passenger travel mode, followed by rail. On some routes, bus and passenger rail offer nearly equal energy and emissions performance when operating at the same load factor, whereas bus has clear advantages on other routes. Thus, the disparity between the bus and rail mode is due partly to differences in ridership and load factor between the modes but also due partly to differences in routing and train consists. The bus mode gains some of its advantage by having a higher seating density and not providing on-board passenger amenities required for trips over longer distances. The bus is subject to congestion in urban areas, however, which has a negative impact on its GHG emissions performance on case study routes in urban areas.

Although the intercity bus mode is more efficient than rail, rail's higher comfort—and in some applications higher speeds—make rail more successful than bus at attracting people from the more energy-intensive modes (automobiles and planes). Comfort and speed cost energy but also help attract ridership. The ideal balance of comfort/speed and energy intensity for the rail mode is a candidate topic for future work. From a pragmatic perspective, it can be helpful to view bus and rail not as competitors on the basis of energy efficiency, but rather as complementary components of an integrated network that can provide passenger transportation three to four times more efficiently than auto or air.

CHAPTER 8

Conclusions

Industry practitioners are correct when promoting rail as a "green" alternative to driving or flying. At average load factors, even across different routes with various rolling stock and operating parameters, auto and air are generally three to four times more energy and GHG emissions intense than passenger rail for equivalent door-to-door trips. An automobile with four passengers approaches the performance of regional intercity trains but cannot match the energy and GHG emissions performance of commuter trains under average load factors. During peak periods, when the majority of commuting trips take place, roadways are congested and rail operates at higher load factors, commuter rail can be over 10 times more efficient than driving alone.

This finding echoes the original findings of Mittal (1977) that passenger rail has the potential to be an even more energy-efficient mode if it can attract additional ridership. Thus, as mentioned in the discussion of barriers to energy efficiency improvement, efforts to increase passenger rail ridership and load factor are just as important for improving passenger rail energy efficiency as operational, rolling stock and energy supply innovations. Even on routes without excess seating capacity during peak periods, there is room for improvement if institutional barriers to adopting energy-efficient practices and technologies can be addressed through the findings of this research.

This research for NCRRP Project 02-01 illustrates the capabilities of MMPASSIM to simulate the energy consumption and GHG emissions of specific rail routes, as well as the equivalent auto, bus, and air trips. This tool can be applied by rail industry, government and operating authority practitioners to analyze specific cases of existing and planned passenger rail services. The resulting analyses will better support decisions on regional transportation development, rail service expansion investment, system operating plans and energy and emissions reduction strategies to best meet future demands for passenger rail transportation and public mobility.

The automobile (LDV) and air modules of MMPASSIM are based on detailed energy performance data and are inherently calibrated to those data. The LDV module has a built in capability to update the module with future fleet performance data. The research team suggests that the air mode be updated with analysis of air mode energy data at 5 year intervals.

The rail module is based on limited validation data and a more extensive validation exercise is a candidate for future work. Collection of energy performance data, equipment data and route characterization data for existing operations and/or new technology installations would be an important step in validation, but depend on the cooperation of operators. Further research and industry collaboration can improve MMPASSIM by providing composite fuel efficiency data for the latest generation of passenger rail motive power (and natural gas conversion performance), train resistance coefficients for the Amtrak Acela trainset, and appropriate parameters to describe the new generation of DMUs being deployed on several commuter rail operations. This information could facilitate additional case studies to verify that the trends observed in

NCRRP Project 02-01 extend across even more diverse passenger rail operating environments in North America. The rail module is not intended to be a replacement for detailed time-step simulation models/train performance calculators (TPCs). The rail module can provide screening sensitivities for operations and technology comparisons; however, a TPC analysis can provide more accurate results when detailed track profile data are available. The treatment of gradient profiles in particular is not as refined as can be achieved using confidential route gradient data and time-step simulation models. Enhancement of the rail module to provide a more rigorous treatment of gradient for users with confidential gradient profiles also is a candidate for future work.

MMPASSIM is coded to provide energy and GHG emissions intensities of the passenger modes but could be enhanced in several areas. Full lifecycle GHG emissions for equipment and infrastructure of each passenger mode were not in the scope of this research project, but they can have important differences in energy and GHG emissions intensities. Similarly, land use differs by mode, which also can have significant environmental and community impacts, but this was not in the scope of work. CAC emissions intensity for commuter trips or for the urban areas of intercity trips is a possible enhancement to the model. Comfort and speed cost energy but also help attract ridership; the ideal balance of comfort/speed and energy intensity for the rail mode is not known. MMPASSIM has a framework to support diesel LDVs and all-electric LDVs; however, the model needs more work to be able to accurately simulate these vehicles. Enhancements to address these factors are all candidates for future consideration.

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APPENDIX A

Passenger Rolling Stock Characteristics

The MMPASSIM tool requires default data related to passenger rolling stock energy requirements and utilization. The data summarized in this section has been collected from various sources to provide the user that does not have their own train parameters a library of rolling stock to select from when conducting energy simulations on a passenger rail corridor.

Locomotive Power and Fuel Consumption

The study team approached the primary manufacturers of passenger locomotives for information to support this research. General Electric, Electro-Motive and Brookville Locomotive refused to consider any requests, citing proprietary concerns.

Specific throttle-notch fuel consumption data on some locomotives commonly used in passenger service are available in the literature (Table A-1). Frey and Graver (2012) conducted full-scale yard and in-service tests of the EMD F59PHI, F59PH, and GP40H. Fritz (1994) conducted full-scale tests on the EMD F59PH and GE B32-8WH. Mittal (1977) includes data for several locomotives with the EMD F40PH still being used in service by several commuter operators and the MLW LRC locomotive, although now retired, being representative of light-weight diesel-electric locomotives.

Several widely used locomotives are missing from the published locomotive data. The General Electric P42 series that makes up the majority of the Amtrak regional and long-distance diesel-electric locomotive fleet is the most notable exception. However, it does have similar internal prime mover performance characteristics to the B32-8WH, albeit with greater power. For commuter rail, the common MPXpress series of locomotives from Wabtec subsidiary Motive Power Inc. are not included in the data. The new Brookville BL36PH locomotives being delivered to the South Florida Regional Transportation Authority Tri-Rail commuter service are also not represented.

The study team also lacked data on the new generation of “genset” locomotives that are being developed for passenger service. These locomotives use multiple smaller high-speed diesel engines connected to generators in place of one large diesel prime mover for propulsion. The Midwestern states recently announced that they would order such a design constructed by Siemens using Cummins diesel engines for use on regional intercity passenger routes in the region.

Head-end Hotel Power

Comfort functions include lighting, heating and ventilating coaches for passenger comfort. While this is mainly required during operation there is demand during staging and stored periods for cleaning and maintenance, and to ensure a comfortable temperature when the train begins operation. The exact demand depends greatly on the ambient temperature and intensity of sunlight.

Frey and Graver (2012) indicate that head-end power (HEP) requirements for passenger coaches average 8kW per car for lights and air conditioning. Food-service and sleeping cars may have greater power demands.

Network Rail (2009) suggests that hotel power functions account for around 20 percent of the energy consumption of a train on average. Since power use for on-board services is independent of train speed, a train that travels at higher speed or spends less time stopped and idling between stations will have less hotel power demand per seat-mile than an equivalent train taking more time to cover the route.

For trains hauled by diesel-electric locomotives, different configurations can be used to deliver the HEP, each with their own efficiency. HEP can be drawn off the main locomotive alternator (requiring the prime mover to operate at a fixed RPM), from a static inverter on a locomotive equipped with alternating current traction or from a separate diesel-generator set on the locomotive. Passenger trains with multiple locomotives can be configured such that the HEP load is shared between the locomotives or such that all power is provided by one locomotive while the remaining locomotives are operated in "freight mode" with no HEP functions.

Resistance Characteristics

The weight, length rolling resistance and seating capacity of passenger rolling stock are essential for performing energy calculations. For locomotives and powered trainsets, the maximum power output is also required to conduct the rail energy simulation.

Equations for the rolling resistance of railway equipment take the form:

$$R = A + BV + CV^2,$$

where A, B and C are coefficients specific to a particular piece of rolling stock and position in a train consist and V is the speed of the train. The three terms describe the inherent resistance of the train that is independent of speed, resistances such as flange friction that vary linearly with the speed of the train and finally resistances such as aerodynamic drag that vary with the square of the speed of the train.

The most detailed rolling resistance model for North American passenger equipment is the Canadian National (CN) model, as documented in Chapter 16 of the American Railway and Maintenance-of-Way Association Manual of Railway Engineering. The CN model contains specific aerodynamic factors that apply to different types of passenger rolling stock. Mittal (1977) also suggested several modifications to the coefficients obtain better results from the rolling resistance equations.

The literature contains A, B and C coefficients for specific passenger trainsets, locomotives, passenger cars and specific train consists. Many of these have been recently published as part of the train energy studies conducted by Lukaszewicz (2007), Rochard and Schmid (2000), Pawar (2011), Hoffrichter (2012), Lindgreen (2005) and Bosquet et al. (2013).

Table A-2 summarizes the rolling resistance and other rolling stock data collected to support development of the rail energy simulation tool.

Table A-1. Summary of locomotive data.

Locomotive	EMD F59PH				EMD F59PHI		EMD GP40H		GE B32-8WH		EMD F40PH		MLW LRC	
Prime Mover	12-710G3A		HEP-Genset		12-710G3A		16-645E3		7FDL w/HEP		16-645E3 w/HEP		16-251F w/HEP	
Throttle Notch	Power	Fuel	Output	Fuel	Power	Fuel	Power	Fuel	Power	Fuel	Power	Fuel	Power	Fuel
	hp	gal/hr	kW	gal/hr	hp	gal/hr	hp	gal/hr	hp	gal/hr	hp	gal/hr	hp	gal/hr
8	3,190	151.6	503	38.6	3,003	151.7	3,000	153.8	2,775	131.0	2,300	127	2,700	194
7	2,520	118.0	407	31.7	2,158	107.3	2,400	121.8	2,775	131.0	2,300	127		
6	1,680	80.3	300	25.1	1,601	81.3	1,600	82.5	2,257	108.0				
5	1,380	66.8	255	22.0	1,304	64.9	1,300	67.4	1,773	86.1				
4	1,050	50.4	203	19.0	987	49.4	1,000	52.1	1,021	51.7				
3	708	34.3	154	16.0	672	34.3	675	35.4	712	37.5				
2	366	19.4	105	13.3	328	17.5	345	18.6	431	25.3				
1	209	12.4	N/A	N/A	191	11.5	190	12.3	324	20.6				
Idle-High	14	4.8	N/A	N/A	9	8.1	20	6.3	190	11.5				
Idle-Low	10	2.7	0	7.7	9	3.3	20	6.3	22	2.2				
DB	28	9.8	N/A	N/A	11	6.4	20	22.3	N/A	N/A				
No HEP 8	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	3250	157.1				
Source	Fritz (1995)		Fritz (1995)		Frey (2012)		Frey (2012)		Fritz (1995)		Mittal (1977)		Mittal (1977)	

The EMD F59PHI and GP40H use the same HEP-Genset as the F59PH.

The Rail module of MMPASSIM uses a generic fuel intensity equation fit to the brake specific fuel consumption (bsfc) curve in lb/hp-hr derived from the above data and normalized to the minimum bsfc value. The generic curves are considered to be reasonable estimates for locomotive diesel engines and more efficient engines can be specified by choosing a lower minimum bsfc for the locomotive's characterization data in the 'consist' input data sheet of the model.

Table A-2. Summary of rolling stock data.

Equipment	Country	Propulsion	Power	Weight	Length	Max Speed	F = A + BV + CV2 (N-m-s)			Seats	Reference
			kW	tonnes	m	km/h	A	B	C		
RDC (Leading)	US	Diesel MU	410	51	26	137	697	16.9	5.50	90	AREMA, (CN Model)
RDC (Trailing)	US	Diesel MU	410	51	26	137	697	16.9	1.16	90	AREMA, (CN Model)
EMD F40PH (Leading)	US	Diesel	2,237	118	17	177	1,188	38.8	6.54		AREMA, (CN Model)
EMD F40PH (Trailing)	US	Diesel	2,237	118	17	177	1,188	38.8	1.25		AREMA, (CN Model)
EMD F59PH (Leading)	US	Diesel	2,237	118	18	177	1,188	38.8	6.54		AREMA, (CN Model)
EMD F59PH (Trailing)	US	Diesel	2,237	118	18	177	1,188	38.8	1.25		AREMA, (CN Model)
EMD F59PHI (Leading)	US	Diesel	2,386	120	18	177	1,201	39.4	5.92		AREMA, (CN Model)
EMD F59PHI (Trailing)	US	Diesel	2,386	120	18	177	1,201	39.4	1.09		AREMA, (CN Model)
EMD GP40H (Leading)	US	Diesel	2,237	120	19	124	1,201	39.4	8.55		AREMA, (CN Model)
EMD GP40H (Trailing)	US	Diesel	2,237	120	19	124	1,201	39.4	1.96		AREMA, (CN Model)
GE B32-8WH (Leading)	US	Diesel	2,386	130	20	113	1,274	42.7	8.55		AREMA, (CN Model)
GE B32-8WH (Trailing)	US	Diesel	2,386	130	20	113	1,274	42.7	1.96		AREMA, (CN Model)
MPX PH36-3C (Leading)	US	Diesel	2,685	121	21	174	1,208	39.7	5.92		AREMA, (CN Model)
MPX PH36-3C (Leading)	US	Diesel	2,685	121	21	174	1,208	39.7	1.09		AREMA, (CN Model)
LRC Locomotive (Leading)	Canada	Diesel	2,759	113	20	209	1,154	37.3	4.05		Mittal (1977)
LRC Coach	Canada			48	26		671	15.7	0.54	84	Mittal (1977)
Conventional Single-Level Coach	US			61	26		766	19.9	1.01	64	Mittal (1977)
Amfleet Coach	US			55	26		725	18.1	0.49	84	Mittal (1977)
SJ Rc4 (Amtrak AEM7) and 1 Coach	Sweden/US	Electric	3,623	124	40	201	2,150	8.0	6.90	78	Lukaszewicz (2007)
SJ Rc4 (Amtrak AEM7) and 5 Coach	Sweden/US	Electric	3,623	300	145	201	3,300	28.0	10.80	390	Lukaszewicz (2007)
SJ Rc4 (Amtrak AEM7) and 6 Coach	Sweden/US	Electric	3,623	344	172	201	3,680	34.8	11.20	468	Lukaszewicz (2007)
SJ Rc4 (Amtrak AEM7) and 9 Coach	Sweden/US	Electric	3,623	476	251	201	4,400	48.0	14.70	702	Lukaszewicz (2007)
SJ Rc4 (Amtrak AEM7) + 10 Coach	Sweden/US	Electric	3,623	520	278	201	4,800	55.9	14.90	780	Lukaszewicz (2007)
SJ X2-5 (power unit, 3 cars, power unit)	Sweden	Electric	6,520	300	109	200	1,600	51.6	6.22	203	Lukaszewicz (2007)

(*continued on next page*)

Table A-2. (Continued).

Equipment	Country	Propulsion	Power	Weight	Length	Max Speed	F = A + BV + CV2 (N-m-s)			Seats	Reference
			kW	tonnes	m	km/h	A	B	C		
SJ X2-7 (power unit, 5 cars, p.u.)	Sweden	Electric	6,520	398	159	200	2,300	57.8	7.74	355	Lukaszewicz (2007)
SJ X2 (p.u., 4 cars, driving trailer)	Sweden	Electric	3,260	318	139	200	2,000	40.0	6.90	355	Lukaszewicz (2007)
DB Class 120 and 6 Eurofima Coach	Germany	Electric	5,600	324	175	200	5,115	0.0	10.07	396	Lukaszewicz (2007)
DB Class 120 and 10 Eurofima Coach	Germany	Electric	5,600	484	279	200	6,453	0.0	12.69	660	Lukaszewicz (2007)
Eurostar Class 373 (18 cars, 2 p.u.)	UK	Electric	12,000	867	394	300	6,554	82.0	23.90	750	Rochard et al. (2000)
TGV Duplex	France	Electric	9,280	380	200	320	6,338	1.8	5.75	508	Bosquet et al. (2013)
Bombardier AVE-102	Spain	Electric	8,000	322	200	330	2,245	26.8	5.50	318	Pawar (2011)
Hitachi N700 Shinkansen	Japan	EMU	9,760	356	205	300	5,854	61.0	5.50	1,323	Pawar (2011)
ICE-3	Germany	EMU	8,000	409	200	300	3,494	128.0	6.40	441	Pawar (2011)
Alstom AGV (NGV 11-car Trainset)	France/Italy	Electric*	8,640	410	200	360	6,669	39.0	6.10	446	Pawar (2011)
Composite EMU 1	--	EMU	9,000	445	200	366	4,000	60.0	7.50	450	Pawar (2011)
Composite EMU 2	--	EMU	12,000	400	200	435	4,000	55.0	6.50	450	Pawar (2011)
HST High-Speed Train (8 cars)	UK	Diesel	2,600	498		200	3,221	112.8	7.80	488	Hoffrichter (2012)
Class 390 Pendolino (9 cars)	UK	EMU	5,100	456		225	5,422	69.0	12.10	549	Hoffrichter (2012)
Intercity Express Prog. (8-car EMU)	UK	EMU	3,200	389		200	4,629	58.9	12.10	488	Hoffrichter (2012)
Intercity Exp. Prog. (5-car D/EMU)	UK	Dual-Mode	2,400	256		200	3,044	38.8	12.10	305	Hoffrichter (2012)
Intercity Exp. Prog. (8-car D/EMU)	UK	Dual-Mode	3,200	405		200	4,818	61.3	12.10	488	Hoffrichter (2012)
IC3 (1 Trainset)	Denmark	Diesel MU	1,176	88	59	180	1,620	47.2	4.58	144	Lindgreen (2005)
IC3 (2 Trainsets)	Denmark	Diesel MU	2,352	176	118	180	3,210	78.5	7.23	288	Lindgreen (2005)
IC3 (3 Trainsets)	Denmark	Diesel MU	3,528	264	176	180	4,480	109.4	9.89	432	Lindgreen (2005)
IC3 (5 Trainsets)	Denmark	Diesel MU	5,880	440	294	180	7,958	171.8	15.16	720	Lindgreen (2005)
IC-Electric Regional (1 Trainset)	Denmark	EMU	1,680	121	77	180	2,102	56.6	5.41	230	Lindgreen (2005)
IC-Electric Regional (2 Trainsets)	Denmark	EMU	3,360	241	153	180	4,164	97.2	8.88	460	Lindgreen (2005)
IC-Electric Regional (3 Trainsets)	Denmark	EMU	5,040	362	230	180	6,227	137.7	12.35	690	Lindgreen (2005)
MR-Local (Trainset)	Denmark	Diesel MU	474	63	45	130	2,503	19.9	0.53	132	Lindgreen (2005)

* The AGV has electric locomotives but also uses distributed powered axles beyond the locomotives.

APPENDIX B

Rail Access/Egress Mode Characteristics

The scope of this project includes accounting for the energy consumption of access modes used to reach the passenger rail mode used for the main segment of the trip and egress modes used to reach the final destination after the conclusion of the rail portion of the trip. Chester and Ryerson (2013) find that few studies have considered the beginning and end of line-haul trips, failing to examine how passengers access/egress from competing main travel segment origins and destinations (e.g. airports or train stations). Furthermore, it is noted that the effects of the beginning and ending segments of such trips may have non-negligible effects. To include these portions of the passenger journey in the rail energy simulation model, data is needed on the access and egress modal split for different types of passenger rail service and also for the average efficiency of these access modes.

Modal Split

Information on the modes used to access and egress from different forms of passenger rail transportation is usually obtained via passenger surveys and other marketing tools. The research team was able to obtain data for commuter rail, regional intercity and long-distance intercity passenger operators that describe the modes used to access to and egress from their systems. While this data does provide the share of each mode, additional research is required to determine how the modal share changes with distance from the origin or destination station.

Commuter Rail

Ridership surveys including access and egress mode data were obtained for eight commuter rail operators across the United States. The operations include:

- Metra, Chicago, IL
- Metrolink, Los Angeles, CA
- Metro-North, New York, NY
- Caltrain, San Francisco, CA
- Massachusetts Bay Transportation Authority (MBTA), Boston, MA
- Virginia Railway Express, Washington, DC
- Tri-Rail, Miami, FL
- Altamont Corridor Express, San Jose, CA (access only)

Results of the surveys are included in Table B-1 and Table B-2. The surveys tend to be constructed around a trip during the morning peak. Thus, the access modes are usually those used by commuters to travel to an outlying suburban station in the morning. For the vast majority of commuters, this is usually the automobile mode, either driving alone or being dropped off. The egress mode typically describes how the commuter travels to their workplace after disembarking at the downtown or main system terminal. For many of the systems, the majority of passengers walk to their final destination

Table B-1. Distribution of access modes from commuter rail surveys.

Operator	Metra	Metrolink	Metro-North	Caltrain	MBTA	Virginia Railway Express	Tri-Rail	Altamont Corridor Express
Year	2005	2008	2009	2010	2010	2012	2008	2011
Ridership	68,590,955	8,456,441	79,464,160	10,611,734	36,909,924	4,645,591	3,810,823	718,356
Walked	21%	4%	7%	26%	29%	4%	7%	3%
Drove Alone	52%	70%	72%	29%	51%	81%	45%	69%
Dropped Off	14%	13%	15%	11%	12%	8%	21%	11%
Carpooled as driver	3%	2%	2%	-	-	3%	1%	2%
Carpooled as Passenger	3%	2%	-	2%	-	3%	1%	2%
Local Bus	3%	4%	1%	7%	2%	1%	15%	5%
Rapid Transit	1%	3%	-	11%	5%	-	3%	-
Commuter Rail	-	-	-	1%		-		-
Bicycle	1%	2%	1%	13%	1%	0%	-	6%
Other (Taxi, Shuttle, Etc.)	2%	1%	1%	0%	1%	0%	5%	1%

Source: Synovate, 2005

Table B-2. Distribution of egress modes from commuter rail surveys.

Operator	Metra	Metrolink	Metrolink[1]	Metro-North	Caltrain	MBTA	Virginia Railway Express	Tri-Rail
Year	2005	2008	2008	2009	2010	2010	2012	2008
Ridership	68,590,955	8,456,441		79,464,160	10,611,734	18,454,962	4,645,591	3,810,823
Walked	73%	14%	20%	56%	30%	61%	67%	19%
Drove Alone	3%	13%	17%	6%	22%	3%	3%	13%
Picked Up	2%	6%	11%	3%	10%	1%	1%	1%
Carpool	-	3%	5%	0%	-	-	1%	1%
Shuttle Bus/Van	4%	5%	7%	12%	8%	4%	-	18%
Taxi	3%	-		2%	1%	0%	-	2%
Local Bus	10%	18%	29%	5%	6%	4%	6%	25%
Rapid Transit	3%	38%	7%	14%	13%	24%	22%	15%
Commuter Rail	-	-	-	-	1%	1%	0%	-
Bicycle	-	2%	3%	0%	13%	1%	0%	5%
Other	2%	2%	1%	1%	1%	0%	-	3%

[1] Excluding LA Union Station egress

but there is also a large share that connects to other forms of bus and rapid transit where available. Note that there are some empty cells in the matrix as not all of the systems presented all of the modes in the table as options on their survey.

Regional Intercity

Grengs et al. (2009) conducted such a survey on the regional intercity Amtrak routes under sponsorship from the Michigan Department of Transportation (Michigan DOT). The study included the Blue Water, Pere Marquette, and Wolverine Amtrak services. The majority of passengers are either driving to the station, being dropped off or taking a taxi (Table B-3). Very few are connecting from transit services.

Table B-3. Access and egress modes for Michigan Amtrak regional intercity service.

Access		Egress	
Walked	7%	Walked	6%
Drove Alone	35%	Drove Alone	12%
Dropped off	23%	Picked up	44%
Carpooled as driver	-	Carpool	-
Carpooled as passenger	-	Shuttle Bus/Van	-
Other (taxi, shuttle, etc.)	19%	Taxi	23%
Intercity Bus	1%	Local Bus	4%
Amtrak Thruway Bus	1%	Intercity Bus	1%
Local Bus	4%	Amtrak Thruway Bus	1%
Rapid Transit	-	Rapid Transit	-
Commuter Rail	7%	Commuter Rail	5%
Connecting Amtrak	3%	Connecting Amtrak	2%
Bicycle	0%	Bicycle	0%
-	-	Other	2%

The University Transportation Center for Mobility at Texas A&M University performed a similar study investigating the impacts of passenger rail in intercity corridors on passenger mobility. This research by Sperry and Morgan (2012) contains similar on-board survey data detailing the access/egress mode distribution for the Amtrak Hiawatha service between Chicago and Milwaukee, Wisconsin (Table B-4 and Table B-5). These data contain additional detail on how the modal split changes from the weekday to the weekend as the nature and purpose of the trips change as different passengers utilize the service. The vast majority of travelers access or egress from the Hiawatha trains via automobile, either driving alone or being dropped off/picked up. The exception is Union Station in Chicago where passengers connect to a variety of different modes with the most popular being a taxi or simply walking or riding a bike to the final destination.

From the surveys of these two regional corridors, it is clear that passenger trips on regional intercity passenger rail corridors are almost always linked to travel by automobile.

Table B-4. Access modes for Amtrak Hiawatha regional intercity service.

Travel Mode (Weekday/Weekend)	Milwaukee (Downtown)	Milwaukee (Airport)	Sturtevant	Glenview	Chicago
Drive Car/Truck	46/39	73/60	73/72	51/33	5/3
Dropped off	30/36	14/17	21/24	38/50	7/14
Local Bus	5/8	0/0	0/0	4/0	6/6
Rapid Transit	<1/0	0/0	0/0	0/0	10/17
Commuter Train	<1/0	0/0	0/0	4/4	3/3
Courtesy Shuttle	1/<1	5/6	0/3	0/0	1/<1
Taxi	5/5	1/2	0/0	2/13	22/35
Walk/Bicycle	8/9	1/1	3/0	0/0	34/11
Amtrak Train	1/<1	0/0	1/0	0/0	14/12
Intercity Bus	2/2	0/0	1/0	0/0	1/1
Airplane	1/1	7/14	0/0	0/0	<1/0

Table B-5. Egress modes for Amtrak Hiawatha regional intercity service.

Travel Mode (Weekday/Weekend)	Milwaukee (Downtown)	Milwaukee (Airport)	Sturtevant	Glenview	Chicago
Drive Car/Truck	47/34	68/57	71/64	49/33	4/7
Dropped off	22/35	14/28	21/21	31/45	3/11
Local Bus	3/8	1/1	2/0	0/0	4/3
Rapid Transit	0/1	0/0	0/0	0/0	7/10
Commuter Train	0/<1	0/0	0/0	2/3	3/6
Courtesy Shuttle	0/<1	1/3	0/11	4/0	1/<1
Taxi	12/8	2/4	5/4	9/18	30/37
Walk/Bicycle	14/10	2/1	0/0	4/3	36/16
Amtrak Train	0/<1	0/0	0/0	0/0	10/9
Intercity Bus	1/4	0/0	0/0	0/0	1/1
Airplane	0/0	11/4	0/0	0/0	<1/0

Long-distance Intercity

Amtrak provided average access and egress data for the long-distance intercity trains (Table B-6). This data does not provide insight into individual service characteristics, but rather the averages across all Amtrak long-distance intercity services. Therefore, for specific services, the results could vary significantly. It does not appear that there are many deviations between the national Amtrak data and those obtained for the Michigan and Hiawatha services. Nationally, it appears that fewer passengers are connecting to another Amtrak train than on the Hiawatha service. This is reasonable since the Hiawatha service feeds into an Amtrak hub (Chicago) with many options for connecting trains while the majority of stations do not have options for connections.

Table B-6. Access and egress modes for Amtrak long-distance intercity service.

<table>
<tr><th colspan="2">Access</th><th colspan="2">Egress</th></tr>
<tr><td>Walked</td><td>3%</td><td>Walked</td><td>11%</td></tr>
<tr><td>Drove Alone</td><td rowspan="4">64%</td><td>Drove Alone</td><td rowspan="4">46%</td></tr>
<tr><td>Dropped off</td><td>Picked up</td></tr>
<tr><td>Carpooled as driver</td><td>Carpool</td></tr>
<tr><td>Carpooled as passenger</td><td>Shuttle Bus/Van</td></tr>
<tr><td>Other (taxi, shuttle, etc.)</td><td rowspan="3">8%</td><td>Taxi</td><td>21%</td></tr>
<tr><td>Intercity Bus</td><td>Local Bus</td><td rowspan="3">6%</td></tr>
<tr><td>Amtrak Thruway Bus</td><td>Intercity Bus</td></tr>
<tr><td>Local Bus</td><td>5%</td><td>Amtrak Thruway Bus</td></tr>
<tr><td>Rapid Transit</td><td>12%</td><td>Rapid Transit</td><td>9%</td></tr>
<tr><td>Commuter Rail</td><td rowspan="2">9%</td><td>Commuter Rail</td><td rowspan="2">4%</td></tr>
<tr><td>Connecting Amtrak</td><td>Connecting Amtrak</td></tr>
<tr><td>Bicycle</td><td>-</td><td>Bicycle</td><td>-</td></tr>
<tr><td>-</td><td>-</td><td>Other</td><td>1%</td></tr>
</table>

APPENDIX C

Automobile Fuel Maps

Simulation of automobile fuel consumption requires knowledge of the "engine map", or the amount of fuel injected into the engine to generate various levels of torque. A typical engine map shows the fuel consumption rate as a function of engine speed or torque. Fuel maps for commercially available automobiles are not readily available for use in this research. Also, it is necessary to use a single fuel map to accurately represent many models of light-duty vehicles in MMPASSIM. For these reasons, fuel maps for diesel (Table C-1) and unleaded gasoline (Table C-2) vehicles constructed from measurements of over 400 light-duty automobiles by Hammarstrom et al. (2010) are used in this project. These generic 2004-vintage fuel maps are used in the LDV (light-duty vehicle) module of the MMPASSIM model and improvements in minimum brake specific fuel consumption (bsfc) as well as improvements in drive-train efficiencies are applied as scale factors such that the generic fuel map produces representative fuel economy performance for newer vehicles.

Table C-1. Estimated engine fuel map (G/S) for diesel automobile models 1996–2003 (Hammarstrom et. al., 2010).

Torque (Nm)	Engine Speed (rps)												
	10	15	20	25	30	35	40	45	50	55	60	65	70
-80	-0.242	-0.326	-0.390	-0.435	-0.464	-0.478	-0.477	-0.462	-0.432	-0.385	-0.320	-0.233	-0.118
-60	-0.155	-0.204	-0.234	-0.249	0.250	-0.236	-0.207	-0.164	-0.105	-0.027	0.073	0.199	0.356
-40	-0.072	-0.085	-0.084	-0.069	-0.042	-0.001	0.054	0.125	0.213	0.322	0.456	0.620	0.819
-20	0.009	0.031	0.063	0.106	0.160	0.227	0.308	0.406	0.523	0.663	0.830	1.030	1.270
0	0.088	0.143	0.205	0.276	0.357	0.450	0.557	0.681	0.826	0.996	1.200	1.430	1.720
20	0.166	0.253	0.344	0.443	0.550	0.668	0.801	0.951	1.120	1.320	1.560	1.830	2.160
40	0.241	0.360	0.481	0.607	0.740	0.883	1.040	1.220	1.420	1.650	1.920	2.230	2.590
60	0.316	0.466	0.616	0.769	0.927	1.100	1.280	1.480	1.710	1.970	2.270	2.620	3.030
80	0.389	0.571	0.750	0.929	1.110	1.310	1.510	1.740	2.000	2.290	2.630	3.010	3.460
100	0.462	0.676	0.883	1.090	1.300	1.520	1.750	2.010	2.290	2.610	2.980	3.410	3.900
120	0.535	0.780	1.016	1.250	1.480	1.730	1.990	2.270	2.580	1.940	3.340	3.800	4.340
140	0.609	0.884	1.150	1.410	1.670	1.940	2.230	2.540	2.880	3.260	3.700	4.210	4.790
160	0.682	0.990	1.280	1.570	1.860	2.150	2.470	2.800	3.180	3.600	4.070	4.620	5.250
180	0.757	1.100	1.420	1.740	2.050	2.370	2.710	3.080	3.480	3.940	4.450	5.040	5.710
200	0.833	1.210	1.560	1.900	2.240	2.600	2.960	3.360	3.790	4.280	4.830	5.470	6.190
220	0.910	1.320	1.700	2.070	2.440	2.820	3.220	3.650	4.120	4.640	5.230	5.910	6.690
240	0.990	1.430	1.850	2.250	2.650	3.060	3.480	3.940	4.450	5.010	5.640	6.370	7.200
260	1.070	1.550	2.000	2.430	2.860	3.300	3.760	4.250	4.790	5.390	6.070	6.840	7.730
280	1.160	1.670	2.150	2.620	3.080	3.550	4.040	4.560	5.140	5.780	6.510	7.330	8.280
300	1.240	1.790	2.310	2.810	3.310	3.810	4.330	4.890	5.510	6.190	6.960	7.850	8.860
320	1.330	1.920	2.480	3.010	3.540	4.080	4.640	5.230	5.890	6.620	7.440	8.380	9.460

Table C-2. Estimated engine fuel map (G/S) for gasoline automobile models 1996–2003 (Hammarstrom et. al. 2010).

Torque (Nm)	Engine Speed (rps)									
	10	20	30	40	50	60	70	80	90	100
-60	-0.201	-0.364	-0.487	-0.571	-0.613	-0.611	-0.560	-0.453	-0.278	-0.022
-40	-0.103	-0.177	-0.219	-0.226	-0.194	-0.119	0.006	0.191	0.448	0.793
-20	-0.011	-0.002	0.033	0.099	0.201	0.346	0.544	0.804	1.140	1.580
0	0.076	0.165	0.274	0.409	0.579	0.793	1.060	1.400	1.820	2.340
20	0.159	0.325	0.505	0.709	0.946	1.230	1.570	1.980	2.480	3.100
40	0.241	0.481	0.731	1.000	1.310	1.660	2.070	2.560	3.150	3.860
60	0.321	0.636	0.956	1.290	1.670	2.080	2.570	3.140	3.820	4.640
80	0.402	0.792	1.180	1.590	2.030	2.520	3.080	3.740	4.520	5.450
100	0.485	0.951	1.410	1.890	2.410	2.970	3.620	4.370	5.250	6.300
120	0.570	1.120	1.660	2.210	2.800	3.450	4.180	5.020	6.020	7.200
140	0.660	1.290	1.910	2.540	3.210	3.950	4.780	5.730	6.840	8.160
160	0.755	1.470	2.180	2.900	3.660	4.490	5.410	6.480	7.730	9.210
180	0.857	1.670	2.470	3.280	4.130	5.060	6.110	7.300	8.690	10.340
200	0.967	1.880	2.780	3.690	4.650	5.690	6.850	8.190	9.740	11.570

APPENDIX D

Highway Grade Profiles and Congestion Distributions

Highway gradient and traffic congestion can both have a significant effect on the energy consumption of auto/LDV and bus modes. Therefore, MMPASSIM provides the user with the ability to characterize the gradient and congestion distributions and analyze their effects on modal comparisons. Several predefined highway routes have been included with MMPASSIM, and contain highway gradient and traffic congestion input data. This section describes the process of creating user-defined highway grade and traffic congestion distributions.

Highway Grade Characterization

Although gradient has a smaller effect on highway vehicle energy consumption than it does on the energy consumption of passenger rail equipment, gradient plays a significant role in determining the energy required to complete auto and bus trips. Highway grades were characterized for each of the individual highway trip routes used in the modal comparison case studies. Additional default characterizations for various U.S. regions were also developed for inclusion with the model for use in the absence of route-specific grade data.

ESRI's GIS software, ArcMap, was used to characterize the highway grades on each route. First, the data must be projected into the appropriate projected coordinate system for each region (in the regional cases, NAD 1973 UTM [Universal Transverse Mercator] projection with the zone specific to the highway route being analyzed). However, if possible, it would be ideal to use equidistant projections that are regional specific, rather than transverse Mercator projections, to preserve distance accuracy. In this case, it was assumed that the NAD 1983 UTM zone projections were accurate in the small regions being analyzed. For long-distance routes, such as the highway trip from Chicago to Los Angeles, the North American Equidistant Conic projection was used, due to the large area of the highway route.

In the horizontal plane, ESRI database shapefiles of the U.S. Interstate Highway system centerlines were used to create the initial equivalent highway route for each rail trip. Vertically, Digital Elevation Models (DEM) for each route were obtained from the U.S. Geological Survey (USGS) National Elevation Dataset at varying resolutions ranging from 3 to 10 meters due to data availability. First, the DEMs were processed to combine them into a single layer covering the entire route. Next, the various roadway line segments comprising a specific route are combined to create a continuous line representing the desired highway route. Finally, using the 3D analyst toolkit, elevation information from the DEM along the route centerline is extracted with the Profile Graph tool. This elevation and distance information along the highway route is exported to a separate spreadsheet and used to calculate the slope of small segments of the route.

The raw grade dataset is then preprocessed (in a similar manner as the rail route preprocessing described in the model documentation) to create a simplified highway grade distribution. This highway grade distribution is the direct input required by the 'LDV-Route' sheet in the MMPASSIM model.

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Highway Congestion Characterization

Highway congestion in urban areas can have an impact on door-to-door energy intensity of automobile and bus trips, depending on the severity and length of the congested highway segments. Therefore, the highway segments of each case study were analyzed to characterize the typical severity of congestion in the urban areas of each case. Average traffic speed was used as a proxy for highway congestion, as severely congested segments will have significantly lower average speeds than free-flow conditions.

The American Transportation Research Institute has constructed a GIS tool called the National Corridors Analysis and Speed Tool (N-CAST). This GIS database contains information about the performance of freight-by-truck movements on the U.S. Interstate Highway system. Average speeds of truck movements along the highway routes included in each case study were obtained from this database. These speeds are delineated by time of day (a.m. peak, mid-day, p.m. peak, and overnight).

For this analysis, light-duty vehicle (LDV) speeds are assumed to be equivalent to truck speeds during the congested a.m. peak, mid-day, and p.m. peak periods where the data exhibit average speeds that are less than free-flow speeds. For the overnight period, it is assumed that the trucks are able to travel at free-flow speeds, and the LDV speeds are an average of ten percent higher than the truck speeds.

After the data has been extracted from the N-CAST GIS database, it is preprocessed to correspond to the MMPASSIM user-defined 'LDV-Drive-Schedules' and 'Bus-Drive-Schedules' sheet input format. The congestion distribution created from the preprocessing tool can be stored on the 'LDV-Drive-Schedules' and/or 'Bus-Drive-Schedules' sheet following the same format as the default entries included with MMPASSIM.

APPENDIX E

Single-Train Simulation and Rail Technology Evaluation Input Data

Minneapolis Metro Northstar

Rail Equipment Parameters

Parameter	Value	Notes
Consist Description	1 MP36PH Loco., 3 Bi-level coaches, 426 seats	Assumed as typical operations
Total Loaded Mass (kg)	283,000	Literature Review, Table
Total Length (m)	98.5	Literature Review, Table
a (N)	2,903	Literature Review, Table
b (N/km/h)	32.21	Literature Review, Table
c $(N/(km/h)^2)$	0.619	Literature Review, Table
Nominal Traction Power (kW)	2,685	Literature Review, Table A-1
Primary Fuel Type	U.S. Conventional Diesel	Assumed for loco. type
Hotel Power Provision Code	3 (dg-genset)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Route Parameters

Parameter	Value				Notes
Distance	39.9 miles				(BNSF, 2005)
Scheduled Stops	7				(Metro Transit, 2014)
Average Expected Speed Reductions per One-Way	Num.	Speed (mph)	Length (mi)		Assumptions based on engineering judgement
	0.2	25	0.2		
	0.4	40	0.1		
Average Expected Unscheduled Stops per One-Way	Num.	Speed (mph)	Length (mi)	Duration (min)	Assumptions based on engineering judgement
	1	25	0.5	2.4	

Chicago Metra BNSF

Rail Equipment Parameters

Parameter	Value	Notes
Consist Description	1 F40PH Loco., 6 Bi-level coaches, 870 seats	Assumed as typical operations
Total Loaded Mass (kg)	454,408	Literature Review, Table
Total Length (m)	172.57	Literature Review, Table
a (N)	5,133	Literature Review, Table
b (N/km/h)	0	Literature Review, Table
c (N/(km/h)^2)	0.838	Literature Review, Table
Nominal Traction Power (kW)	2,349	Literature Review, Table A-1
Primary Fuel Type	U.S. Conventional Diesel	Assumed for loco. type
Hotel Power Provision Code	1 (PTO-inverter)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Route Parameters

<table>
<tr><th>Parameter</th><th colspan="4">Value</th><th>Notes</th></tr>
<tr><td>Distance</td><td colspan="4">38.4 miles</td><td>(BNSF, 2005)</td></tr>
<tr><td>Scheduled Stops</td><td>Local: 26</td><td>Zonal: 6</td><td colspan="2">Skip-Stop: 10</td><td>Local: (Metra, 2012), Zonal and Skip-Stop hypothetical</td></tr>
<tr><td rowspan="3">Average Expected Speed Reductions per One-Way</td><td>Num.</td><td>Speed (mph)</td><td colspan="2">Length (mi)</td><td rowspan="3">Assumptions based on engineering judgement</td></tr>
<tr><td>0.05</td><td>25</td><td colspan="2">0.2</td></tr>
<tr><td>0.1</td><td>40</td><td colspan="2">0.1</td></tr>
<tr><td rowspan="2">Average Expected Unscheduled Stops per One-Way</td><td>Num.</td><td>Speed (mph)</td><td>Length (mi)</td><td>Duration (min)</td><td rowspan="2">Assumptions based on engineering judgement</td></tr>
<tr><td>0.5</td><td>25</td><td>0.5</td><td>3</td></tr>
</table>

Seattle Sounder South

Rail Equipment Parameters

Parameter	Value	Notes
Consist Description	1 F59PHI loco., 4 Bi-Level Coaches, 568 seats	Literature Review
Total Loaded Mass (kg)	330,070	Literature Review, Table
Total Length (m)	126	Literature Review, Table
a (N)	3,461	Literature Review, Table
b (N/km/h)	39.184	Literature Review, Table
c $(N/(km/h)^2)$	0.673	Literature Review, Table
Nominal Traction Power (kW)	2,386	Literature Review, Table A-1
Primary Fuel Type	U.S. Conventional Diesel	Assumed for train type
Hotel Power Provision Code	3 (dg-set)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Route Parameters

Parameter	Value				Notes
Distance	40.5 miles				(FRA 1978)
Scheduled Stops	7				(Sound Transit, 2014)
Average Expected Speed Reductions per One-Way	Num.	Speed (mph)	Length (mi)		Assumptions based on engineering judgement
	0.2	25	0.2		
	0.4	40	0.1		
Average Expected Unscheduled Stops per One-Way	Num.	Speed (mph)	Length (mi)	Duration (min)	Assumptions based on engineering judgement
	0.5	25	0.5	2.37	

Los Angeles Metrolink Orange

Rail Equipment Parameters

Parameter	Value	Notes
Consist Description	1 F59PHI Loco., 4 Bi-level coaches, 568 seats	Assumed as typical operations
Total Loaded Mass (kg)	330,070	Literature Review, Table
Total Length (m)	126.64	Literature Review, Table
a (N)	3,461	Literature Review, Table
b (N/km/h)	39.184	Literature Review, Table
c (N/(km/h)^2)	0.673	Literature Review, Table
Nominal Traction Power (kW)	2,386	Literature Review, Table A-1
Primary Fuel Type	U.S. Conventional Diesel	Assumed for loco. type
Hotel Power Provision Code	3 (dg-set)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Route Parameters

Parameter	Value				Notes
Distance	85.9 miles				(Bachman et al., 1978)
Scheduled Stops	15				(Metrolink, 2014)
Average Expected Speed Reductions per One-Way	Num.	Speed (mph)	Length (mi)		Assumptions based on engineering judgement
	0.3	25	0.2		
	0.4	40	0.1		
Average Expected Unscheduled Stops per One-Way	Num.	Speed (mph)	Length (mi)	Duration (min)	Assumptions based on engineering judgement
	1	25	0.5	3	

Washington, DC, MARC Penn Line

Rail Equipment Parameters (electric)

Parameter	Value	Notes
Consist Description	1 AEM7 Loco., 5 Bi-level coaches,, 650 seats	Assumed as typical operations
Total Loaded Mass (kg)	434,575	Literature Review, Table
Total Length (m)	145.08	Literature Review, Table
a (N)	4,687	Literature Review, Table
b (N/km/h)	38.36	Literature Review, Table
c (N/(km/h)^2)	0.729	Literature Review, Table
Nominal Traction Power (kW)	4,320	Literature Review, Table A-1
Primary Fuel Type	Electricity (U.S. South Atlantic)	Assumed region
Hotel Power Provision Code	4 (electric)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Equipment Parameters (diesel-electric)

Parameter	Value	Notes
Consist Description	1 MP36PH Loco., 5 Bi-levels, 650 seats	Assumed as typical operations
Total Loaded Mass (kg)	451,190	Literature Review, Table
Total Length (m)	150.27	Literature Review, Table
a (N)	4,033	Literature Review, Table
b (N/km/h)	46.328	Literature Review, Table
c (N/(km/h)^2)	0.727	Literature Review, Table
Nominal Traction Power (kW)	2,685	Literature Review, Table A-1
Primary Fuel Type	U.S. Conventional Diesel	Assumed for loco. type
Hotel Power Provision Code	2 (PTO-fixed speed main engine)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Route Parameters

Parameter	Value				Notes
Distance	77 miles				(FRA 1978)
Scheduled Stops	13				(Maryland Transit Administration, 2013)
Average Expected Speed Reductions per One-Way	Num.	Speed (mph)	Length (mi)		Assumptions based on engineering judgement
	0.2	25	0.2		
	0.4	40	0.1		
Average Expected Unscheduled Stops per One-Way	Num.	Speed (mph)	Length (mi)	Duration (min)	Assumptions based on engineering judgement
	0.5	25	0.5	1.2	

Oklahoma City, OK–Fort Worth, TX, Heartland Flyer

Rail Equipment Parameters (NPCU)

Parameter	Value	Notes
Consist Description	1 P42 Loco., 3 Bi-level coaches, 1 NPCU, 252 seats	Assumed as typical operations
Total Loaded Mass (kg)	448,392	Literature Review, Table
Total Length (m)	198.12	Literature Review, Table
a (N)	4,133	Literature Review, Table
b (N/km/h)	0	Literature Review, Table
c (N/(km/h)^2)	0.622	Literature Review, Table
Nominal Traction Power (kW)	3,054	Literature Review, Table A-1
Primary Fuel Type	U.S. Conventional Diesel	Assumed for loco. type
Hotel Power Provision Code	1 (PTO-inverter)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Equipment Parameters (Non-NPCU)

Parameter	Value	Notes
Consist Description	1 P42 Loco., 3 Bi-levels, 252 seats	Assumed as typical operations
Total Loaded Mass (kg)	330,392	Literature Review, Table
Total Length (m)	176.8	Literature Review, Table
a (N)	3,382	Literature Review, Table
b (N/km/h)	0	Literature Review, Table
c (N/(km/h)^2)	0.622	Literature Review, Table
Nominal Traction Power (kW)	3,054	Literature Review, Table A-1
Primary Fuel Type	U.S. Conventional Diesel	Assumed for loco. type
Hotel Power Provision Code	1 (PTO-inverter)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Route Parameters

<table>
<tr><th>Parameter</th><th colspan="4">Value</th><th>Notes</th></tr>
<tr><td>Distance</td><td colspan="2">NPCU: 206 miles</td><td colspan="2">Non-NPCU: 209.5 miles</td><td>(BNSF, 2005)</td></tr>
<tr><td>Scheduled Stops</td><td colspan="4">7</td><td>(Amtrak, 2014)</td></tr>
<tr><td rowspan="3">Average Expected Speed Reductions per One-Way</td><td colspan="2">Num.</td><td>Speed (mph)</td><td>Length (mi)</td><td rowspan="3">Assumptions based on engineering judgement</td></tr>
<tr><td colspan="2">1.7</td><td>25</td><td>0.1</td></tr>
<tr><td colspan="2">3.5</td><td>40</td><td>0.1</td></tr>
<tr><td rowspan="2">Average Expected Unscheduled Stops per One-Way</td><td>Num.</td><td>Speed (mph)</td><td>Length (mi)</td><td>Duration (min)</td><td rowspan="2">Assumptions based on engineering judgement</td></tr>
<tr><td>5</td><td>25</td><td>2.1</td><td>6</td></tr>
</table>

Charlotte, NC–Raleigh, NC, Piedmont

Rail Equipment Parameters

Parameter	Value	Notes
Consist Description	1 F59PHI Loco., 4 single-level coaches, 336 seats	Assumed as typical operations
Total Loaded Mass (kg)	349,995	Literature Review, Table
Total Length (m)	126.64	Literature Review, Table
a (N)	4,252	Literature Review, Table
b (N/km/h)	32.889	Literature Review, Table
c (N/(km/h)^2)	0.816	Literature Review, Table
Nominal Traction Power (kW)	2,386	Literature Review, Table A-1
Primary Fuel Type	U.S. Conventional Diesel	Assumed for loco. type
Hotel Power Provision Code	3 (dg-set)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Route Parameters

<table>
<tr><th>Parameter</th><th colspan="4">Value</th><th>Notes</th></tr>
<tr><td>Distance</td><td colspan="4">173 miles</td><td>(Norfolk Southern, 2002)</td></tr>
<tr><td>Scheduled Stops</td><td colspan="4">9</td><td>(Amtrak, 2014)</td></tr>
<tr><td rowspan="3">Average Expected Speed Reductions per One-Way</td><td>Num.</td><td>Speed (mph)</td><td colspan="2">Length (mi)</td><td rowspan="3">Assumptions based on engineering judgement</td></tr>
<tr><td>1.7</td><td>25</td><td colspan="2">0.1</td></tr>
<tr><td>3.5</td><td>40</td><td colspan="2">0.1</td></tr>
<tr><td rowspan="2">Average Expected Unscheduled Stops per One-Way</td><td>Num.</td><td>Speed (mph)</td><td>Length (mi)</td><td>Duration (min)</td><td rowspan="2">Assumptions based on engineering judgement</td></tr>
<tr><td>5</td><td>25</td><td>2.1</td><td>6</td></tr>
</table>

New York, NY–Buffalo, NY, Empire Service

Rail Equipment Parameters

Parameter	Value	Notes
Consist Description	1 P32AC-DM Dual-Mode Loco., 5 single-level coaches, 416 seats	Assumed as typical operations
Total Loaded Mass (kg)	409,851	Literature Review, Table
Total Length (m)	176.784	Literature Review, Table
a (N)	4,528	Literature Review, Table
b (N/km/h)	0	Literature Review, Table
c (N/(km/h)^2)	0.718	Literature Review, Table
Nominal Traction Power (kW)	3,170	Literature Review, Table A-1
Primary Fuel Type	Bimodal (U.S. Conventional Diesel and Electric)	Assumed for loco. type
Hotel Power Provision Code	1 (PTO-inverter)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Route Parameters

<table>
<tr><th>Parameter</th><th colspan="4">Value</th><th>Notes</th></tr>
<tr><td>Distance</td><td colspan="4">437.9</td><td>(Bachman et al., 1978)</td></tr>
<tr><td>Scheduled Stops</td><td colspan="4">15</td><td>(Amtrak, 2014)</td></tr>
<tr><td rowspan="3">Average Expected Speed Reductions per One-Way</td><td>Num.</td><td>Speed (mph)</td><td colspan="2">Length (mi)</td><td rowspan="3">Assumptions based on engineering judgement</td></tr>
<tr><td>1.7</td><td>25</td><td colspan="2">0.1</td></tr>
<tr><td>3.5</td><td>40</td><td colspan="2">0.1</td></tr>
<tr><td rowspan="2">Average Expected Unscheduled Stops per One-Way</td><td>Num.</td><td>Speed (mph)</td><td>Length (mi)</td><td>Duration (min)</td><td rowspan="2">Assumptions based on engineering judgement</td></tr>
<tr><td>5</td><td>25</td><td>2.1</td><td>6</td></tr>
</table>

San Jose, CA–Auburn, CA, Capitol Corridor

Rail Equipment Parameters

Parameter	Value	Notes
Consist Description	1 F59 loco., 4 Bi-Level coaches, 360 seats	Assumed as typical operations
Total Loaded Mass (kg)	340,692	Literature Review, Table
Total Length (m)	126.64	Literature Review, Table
a (N)	3,461	Literature Review, Table
b (N/km/h)	18.789	Literature Review, Table
c $(N/(km/h)^2)$	0.673	Literature Review, Table
Nominal Traction Power (kW)	2,386	Literature Review, Table A-1
Primary Fuel Type	U.S. Conventional Diesel	Assumed for loco. type
Hotel Power Provision Code	3 (dg-set)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Route Parameters

<table>
<tr><th>Parameter</th><th colspan="12">Value</th><th>Notes</th></tr>
<tr><td>Distance</td><td colspan="12">168 miles</td><td>(Union Pacific, 2009)</td></tr>
<tr><td>Scheduled Stops</td><td colspan="12">17</td><td>(Amtrak, 2014)</td></tr>
<tr><td rowspan="3">Average Expected Speed Reductions per One-Way</td><td colspan="4">Num.</td><td colspan="4">Speed (mph)</td><td colspan="4">Length (mi)</td><td rowspan="3">Assumptions based on engineering judgement</td></tr>
<tr><td colspan="4">0.2</td><td colspan="4">25</td><td colspan="4">0.2</td></tr>
<tr><td colspan="4">0.4</td><td colspan="4">40</td><td colspan="4">0.1</td></tr>
<tr><td rowspan="2">Average Expected Unscheduled Stops per One-Way</td><td colspan="3">Num.</td><td colspan="3">Speed (mph)</td><td colspan="3">Length (mi)</td><td colspan="3">Duration (min)</td><td rowspan="2">Assumptions based on engineering judgement</td></tr>
<tr><td colspan="3">2</td><td colspan="3">25</td><td colspan="3">0.5</td><td colspan="3">2.37</td></tr>
</table>

Chicago, IL–Detroit, MI, Wolverine

Rail Equipment Parameters

Parameter	Value	Notes
Consist Description	1P42 Loco., 4 single-level coaches, 1 baggage car, 336 seats	Assumed as typical operations
Total Loaded Mass (kg)	408,423	Literature Review, Table
Total Length (m)	176.8	Literature Review, Table
a (N)	4,519	Literature Review, Table
b (N/km/h)	0	Literature Review, Table
c (N/(km/h)^2)	0.718	Literature Review, Table
Nominal Traction Power (kW)	3,054	Literature Review, Table A-1
Primary Fuel Type	U.S. Conventional Diesel	Assumed for loco. type
Hotel Power Provision Code	1 (PTO-inverter)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Route Parameters

<table>
<tr><th>Parameter</th><th colspan="12">Value</th><th>Notes</th></tr>
<tr><td>Distance</td><td colspan="12">279 miles</td><td>(Bachman et al., 1978)</td></tr>
<tr><td>Scheduled Stops</td><td colspan="12">14</td><td>(Amtrak, 2014)</td></tr>
<tr><td rowspan="3">Average Expected Speed Reductions per One-Way</td><td colspan="4">Num.</td><td colspan="4">Speed (mph)</td><td colspan="4">Length (mi)</td><td rowspan="3">Assumptions based on engineering judgement</td></tr>
<tr><td colspan="4">0.2</td><td colspan="4">25</td><td colspan="4">0.2</td></tr>
<tr><td colspan="4">0.4</td><td colspan="4">40</td><td colspan="4">0.1</td></tr>
<tr><td rowspan="2">Average Expected Unscheduled Stops per One-Way</td><td colspan="3">Num.</td><td colspan="3">Speed (mph)</td><td colspan="3">Length (mi)</td><td colspan="3">Duration (min)</td><td rowspan="2">Assumptions based on engineering judgement</td></tr>
<tr><td colspan="3">2</td><td colspan="3">25</td><td colspan="3">0.5</td><td colspan="3">2.37</td></tr>
</table>

Portland, OR–Seattle, WA, Cascades

Rail Equipment Parameters

Parameter	Value	Notes
Consist Description	1 F59PHI Loco., 12-car Talgo, 1 cab car, 340 seats	Assumed as typical operations
Total Loaded Mass (kg)	402,138	Literature Review, Table
Total Length (m)	192.48	Literature Review, Table
a (N)	4,239	Literature Review, Table
b (N/km/h)	0	Literature Review, Table
c $(N/(km/h)^2)$	0.923	Literature Review, Table
Nominal Traction Power (kW)	2,386	Literature Review, Table A-1
Primary Fuel Type	U.S. Conventional Diesel	Assumed for loco. type
Hotel Power Provision Code	3 (dg-set)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Route Parameters

Parameter	Value				Notes
Distance	342.8 miles				(Bachman et al., 1978)
Scheduled Stops	8				(Amtrak, 2014)
Average Expected Speed Reductions per One-Way	Num.	Speed (mph)	Length (mi)		Assumptions based on engineering judgement
	1.7	25	0.1		
	3.5	40	0.1		
Average Expected Unscheduled Stops per One-Way	Num.	Speed (mph)	Length (mi)	Duration (min)	Assumptions based on engineering judgement
	5	25	2.1	6	

Los Angeles, CA–San Diego, CA, Pacific Surfliner

Rail Equipment Parameters

Parameter	Value	Notes
Consist Description	1 F59PHI Loco., 4 Bi-Level coaches, 336 seats	Assumed as typical operations
Total Loaded Mass (kg)	398,523	Literature Review, Table
Total Length (m)	126.64	Literature Review, Table
a (N)	3,461	Literature Review, Table
b (N/km/h)	18.789	Literature Review, Table
c (N/(km/h)^2)	0.673	Literature Review, Table
Nominal Traction Power (kW)	2,386	Literature Review, Table A-1
Primary Fuel Type	U.S. Conventional Diesel	Assumed for loco. type
Hotel Power Provision Code	3 (dg-set)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Route Parameters

<table>
<tr><th>Parameter</th><th colspan="4">Value</th><th>Notes</th></tr>
<tr><td>Distance</td><td colspan="4">127.4 miles</td><td>(Bachman et al., 1978)</td></tr>
<tr><td>Scheduled Stops</td><td colspan="4">15</td><td>(Amtrak, 2014)</td></tr>
<tr><td rowspan="3">Average Expected Speed Reductions per One-Way</td><td>Num.</td><td>Speed (mph)</td><td colspan="2">Length (mi)</td><td rowspan="3">Assumptions based on engineering judgement</td></tr>
<tr><td>0.2</td><td>25</td><td colspan="2">0.2</td></tr>
<tr><td>0.4</td><td>40</td><td colspan="2">0.1</td></tr>
<tr><td rowspan="2">Average Expected Unscheduled Stops per One-Way</td><td>Num.</td><td>Speed (mph)</td><td>Length (mi)</td><td>Duration (min)</td><td rowspan="2">Assumptions based on engineering judgement</td></tr>
<tr><td>2</td><td>25</td><td>0.5</td><td>2.37</td></tr>
</table>

Chicago, IL–Quincy, IL, Illinois Zephyr

Rail Equipment Parameters

Parameter	Value	Notes
Consist Description	1P42 Loco., 4 single-level coaches, 1 baggage car, 336 seats	Assumed as typical operations
Total Loaded Mass (kg)	408,423	Literature Review, Table
Total Length (m)	176.8	Literature Review, Table
a (N)	4,519	Literature Review, Table
b (N/km/h)	0	Literature Review, Table
c (N/(km/h)^2)	0.718	Literature Review, Table
Nominal Traction Power (kW)	3,054	Literature Review, Table A-1
Primary Fuel Type	U.S. Conventional Diesel	Assumed for loco. type
Hotel Power Provision Code	1 (PTO-inverter)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Route Parameters

Parameter	Value				Notes
Distance	258 miles				(BNSF, 2005)
Scheduled Stops	10				(Amtrak, 2014)
Average Expected Speed Reductions per One-Way	Num.	Speed (mph)	Length (mi)		Assumptions based on engineering judgement
	0.2	25	0.2		
	0.4	40	0.1		
Average Expected Unscheduled Stops per One-Way	Num.	Speed (mph)	Length (mi)	Duration (min)	Assumptions based on engineering judgement
	3	25	0.5	2.37	

Washington, DC–New York, NY, Northeast Regional

Rail Equipment Parameters

Parameter	Value	Notes
Consist Description	1 AEM7 Loco., 6 single-level coaches, 504 seats	Assumed as typical operations
Total Loaded Mass (kg)	564,405	Literature Review, Table
Total Length (m)	170.99	Literature Review, Table
a (N)	3,680	Literature Review, Table
b (N/km/h)	9.667	Literature Review, Table
c $(N/(km/h)^2)$	0.864	Literature Review, Table
Nominal Traction Power (kW)	4,320	Literature Review, Table A-1
Primary Fuel Type	Electricity (U.S. Northeast Mix)	Assumed for loco. type
Hotel Power Provision Code	4 (electric-loco)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Route Parameters

<table>
<tr><th>Parameter</th><th colspan="4">Value</th><th>Notes</th></tr>
<tr><td>Distance</td><td colspan="4">226.1</td><td>(Bachman et al., 1978)</td></tr>
<tr><td>Scheduled Stops</td><td colspan="4">10</td><td>(Amtrak, 2014)</td></tr>
<tr><td rowspan="3">Average Expected Speed Reductions per One-Way</td><td>Num.</td><td>Speed (mph)</td><td colspan="2">Length (mi)</td><td rowspan="3">Assumptions based on engineering judgement</td></tr>
<tr><td>1</td><td>25</td><td colspan="2">0.1</td></tr>
<tr><td>2</td><td>40</td><td colspan="2">0.1</td></tr>
<tr><td rowspan="2">Average Expected Unscheduled Stops per One-Way</td><td>Num.</td><td>Speed (mph)</td><td>Length (mi)</td><td>Duration (min)</td><td rowspan="2">Assumptions based on engineering judgement</td></tr>
<tr><td>3</td><td>25</td><td>2.1</td><td>6</td></tr>
</table>

Chicago, IL–Los Angeles, CA, Southwest Chief

Rail Equipment Parameters (Amenities)

Parameter	Value	Notes
Consist Description	2 P42 loco., 8 Bi-level railcars, 364 seats	Assumed as typical operations
Total Loaded Mass (kg)	504,548	Literature Review, Table
Total Length (m)	249.94	Literature Review, Table
a (N)	6,930	Literature Review, Table
b (N/km/h)	78.37	Literature Review, Table
c $(N/(km/h)^2)$	0.973	Literature Review, Table
Nominal Traction Power (kW)	2x 3,054	Literature Review, Table A-1
Primary Fuel Type	U.S. Conventional Diesel	Assumed for loco. type
Hotel Power Provision Code	1 (PTO-inverter)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Route Parameters

Parameter	Value				Notes
Distance	2,250.9 miles				(BNSF, 2005)
Scheduled Stops	33				(Amtrak, 2014)
Average Expected Speed Reductions per One-Way	Num.	Speed (mph)	Length (mi)		Assumptions based on engineering judgement
	8	25	0.1		
	15	40	0.1		
Average Expected Unscheduled Stops per One-Way	Num.	Speed (mph)	Length (mi)	Duratio n (min)	Assumptions based on engineering judgement
	27	25	2.1	25	

Chicago, IL–Denver, CO, California Zephyr

Rail Equipment Parameters

Parameter	Value	Notes
Consist Description	2 P42 loco., 8 Bi-level railcars, 364 seats	Assumed as typical operations
Total Loaded Mass (kg)	504,548	Literature Review, Table
Total Length (m)	249.94	Literature Review, Table
a (N)	6,930	Literature Review, Table
b (N/km/h)	78.37	Literature Review, Table
c (N/(km/h)^2)	0.973	Literature Review, Table
Nominal Traction Power (kW)	2x 3,054	Literature Review, Table A-1
Primary Fuel Type	U.S. Conventional Diesel	Assumed for loco. type
Hotel Power Provision Code	1 (PTO-inverter)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Route Parameters

<table>
<tr><th>Parameter</th><th colspan="4">Value</th><th>Notes</th></tr>
<tr><td>Distance</td><td colspan="4">1,038 miles</td><td>(BNSF, 2005)</td></tr>
<tr><td>Scheduled Stops</td><td colspan="4">16 (Chicago-Denver)</td><td>(Amtrak, 2014)</td></tr>
<tr><td rowspan="3">Average Expected Speed Reductions per One-Way</td><td>Num.</td><td>Speed (mph)</td><td colspan="2">Length (mi)</td><td rowspan="3">Assumptions based on engineering judgement</td></tr>
<tr><td>8</td><td>25</td><td colspan="2">0.1</td></tr>
<tr><td>15</td><td>40</td><td colspan="2">0.1</td></tr>
<tr><td rowspan="2">Average Expected Unscheduled Stops per One-Way</td><td>Num.</td><td>Speed (mph)</td><td>Length (mi)</td><td>Duratio n (min)</td><td rowspan="2">Assumptions based on engineering judgement</td></tr>
<tr><td>27</td><td>25</td><td>2.1</td><td>25</td></tr>
</table>

Fresno, CA–Los Angeles, CA, California High-Speed Rail

Rail Equipment Parameters

Parameter	Value	Notes
Consist Description	AGV 11 coach trainset, 446 seats	Assumed as trainset chosen for operation
Total Loaded Mass (kg)	432,746	Assumed as trainset chosen for operation
Total Length (m)	200	Assumed as trainset chosen for operation
a (N)	6,669	Assumed as trainset chosen for operation
b (N/km/h)	10.833	Assumed as trainset chosen for operation
c (N/(km/h)^2)	0.471	Assumed as trainset chosen for operation
Nominal Traction Power (kW)	8,640	Assumed as trainset chosen for operation
Primary Fuel Type	Electricity (CA Mix)	Assumed for train type
Hotel Power Provision Code	4 (electric-loco)	Assumed for train type
Energy Recovery Type	3 (electric grid)	Assumed for train type

Rail Route Parameters

<table>
<tr><th>Parameter</th><th colspan="12">Value</th><th>Notes</th></tr>
<tr><td>Distance</td><td colspan="12">292 miles</td><td>(CHSRA, 2010; CHSRA, 2012)</td></tr>
<tr><td>Scheduled Stops</td><td colspan="12">3</td><td>Assumed as express service type</td></tr>
<tr><td rowspan="3">Average Expected Speed Reductions per One-Way</td><td colspan="4">Num.</td><td colspan="4">Speed (mph)</td><td colspan="4">Length (mi)</td><td rowspan="3">Assumptions based on engineering judgement</td></tr>
<tr><td colspan="4">0.2</td><td colspan="4">25</td><td colspan="4">0.2</td></tr>
<tr><td colspan="4">0.4</td><td colspan="4">40</td><td colspan="4">0.1</td></tr>
<tr><td rowspan="2">Average Expected Unscheduled Stops per One-Way</td><td colspan="3">Num.</td><td colspan="3">Speed (mph)</td><td colspan="3">Length (mi)</td><td colspan="3">Duration (min)</td><td rowspan="2">Assumptions based on engineering judgement</td></tr>
<tr><td colspan="3">0.5</td><td colspan="3">40</td><td colspan="3">1.5</td><td colspan="3">2.37</td></tr>
</table>

APPENDIX F

Technologies to Improve Energy Efficiency

Category	Subcategory	Description	Applicable Services		
			Commuter	**Long-Distance Mixed Traffic**	**Medium-Distance High-Speed Rail (HSR) Corridor Services**
Equipment	Coach	Tare weight	Yes	Yes	Yes
		seating density, aerodynamic drag			
		tilt-body	No	Yes, region-specific	Yes, region-specific
	Motive Power/ Alternative Fuels	Diesel-electric/Electric/ hybrid/dual-mode/ SPV/DMU/EMU/	Yes for relevant technologies	Yes for relevant technologies	Yes for relevant technologies
		fuel cell/LNG			
	Hotel Power	PTO vs DG set	Yes	Yes	Yes
Operations	Driver Advisory	Speed and/or coast/braking advice for energy recovery	Yes, coast/braking advice at stops	Yes, Improved Meet Planning	Yes, coast/braking advice at stops
	Idle/shutdown policy		Yes, region-specific	Yes, region-specific	Yes, region-specific
	Passenger Yield Curve	High passenger density cars at lower price and/or defined greenhouse gas credit	Yes, offer some standing-room cars	Yes, offer some cars at bus-type seat-pitch	Yes, offer some cars at bus-type seat-pitch
	Power-to-weight ratio	Trip time versus energy trade-off	Yes	Yes	Yes
Infrastructure	Power provision	Wayside energy storage/recovery	Yes		Yes, region-specific
		Provide Wayside hotel power at layover sites	Yes, region-specific	Yes, region-specific	Yes, region-specific
	Reduce interference stops via Capacity Enhancement	Additional tracks	If relevant	If relevant	If relevant
		Improved Signal System	If relevant	If relevant	If relevant
	Rail Friction	Friction control agents		Yes, region-specific	

PTO = power take off from the traction engine shaft.
DG set = separate diesel generator set for hotel power generation.

APPENDIX G

Modal Comparison Simulation Input Data

Big Lake, MN–Minneapolis, MN, Case Study Description

Rail Equipment Parameters

Parameter	Value	Notes
Consist Description	1 MP36PH Loco., 3 Bi-level coaches, 426 seats	Assumed as typical operations
Total Loaded Mass (kg)	283,000	Literature Review, Table
Total Length (m)	98.5	Literature Review, Table
a (N)	2,903	Literature Review, Table
b (N/km/h)	32.21	Literature Review, Table
c (N/(km/h)^2)	0.619	Literature Review, Table
Nominal Traction Power (kW)	2,685	Literature Review, Table A-1
Primary Fuel Type	U.S. Conventional Diesel	Assumed for loco. type
Hotel Power Provision Code	3 (dg-genset)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Route Parameters

Parameter	Value				Notes
Distance	39.9 miles				(BNSF, 2005)
Scheduled Stops	7				(Metro Transit, 2014)
Average Expected Speed Reductions per One-Way	Num.	Speed (mph)	Length (mi)		Assumptions based on engineering judgement
	0.2	25	0.2		
	0.4	40	0.1		
Average Expected Unscheduled Stops per One-Way	Num.	Speed (mph)	Length (mi)	Duration (min)	Assumptions based on engineering judgement
	1	25	0.5	2.4	

Auto Route Parameters

Parameter	Value		Notes
Description	MN-101 to I-94		Google Maps Route Choice
Urban Freeway Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion
	26	-	
Urban Arterial Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion
	11	-	
Intercity Freeway Distance (mi)	-		Assume entire trip congested
Wayside Stops (Engine Idle)	Number	Duration (min)	General Assumption
	0	-	

Aurora, IL–Chicago, IL, Case Study Description

Rail Equipment Parameters

Parameter	Value	Notes
Consist Description	1 F40PH Loco., 6 Bi-level coaches, 870 seats	Assumed as typical operations
Total Loaded Mass (kg)	454,408	Literature Review, Table
Total Length (m)	172.57	Literature Review, Table
a (N)	5,133	Literature Review, Table
b (N/km/h)	0	Literature Review, Table
c (N/(km/h)^2)	0.838	Literature Review, Table
Nominal Traction Power (kW)	2,349	Literature Review, Table A-1
Primary Fuel Type	U.S. Conventional Diesel	Assumed for loco. type
Hotel Power Provision Code	1 (PTO-inverter)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Route Parameters

Parameter	Value				Notes
Distance	39.9 miles				(BNSF, 2005)
Scheduled Stops	7				(Metro Transit, 2014)
Average Expected Speed Reductions per One-Way	Num.	Speed (mph)	Length (mi)		Assumptions based on engineering judgement
	0.2	25	0.2		
	0.4	40	0.1		
Average Expected Unscheduled Stops per One-Way	Num.	Speed (mph)	Length (mi)	Duration (min)	Assumptions based on engineering judgement
	1	25	0.5	2.4	

Auto Route Parameters

Parameter	Value		Notes
Description	I-88 to I-290		Google Maps Route Choice
Urban Freeway Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion
	44	-	
Urban Arterial Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion
	1	2	
Intercity Freeway Distance (mi)	-		Entire trip assumed to be in congested urban area
Wayside Stops (Engine Idle)	Number	Duration (min)	General Assumption
	0	-	

Oceanside, CA–Los Angeles, CA, Case Study Description

Rail Equipment Parameters

Parameter	Value	Notes
Consist Description	1 F59PHI Loco., 4 Bi-level coaches, 568 seats	Assumed as typical operations
Total Loaded Mass (kg)	330,070	Literature Review, Table
Total Length (m)	126.64	Literature Review, Table
a (N)	3,461	Literature Review, Table
b (N/km/h)	39.184	Literature Review, Table
c $(N/(km/h)^2)$	0.673	Literature Review, Table
Nominal Traction Power (kW)	2,386	Literature Review, Table A-1
Primary Fuel Type	U.S. Conventional Diesel	Assumed for loco. type
Hotel Power Provision Code	3 (dg-set)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Route Parameters

Parameter	Value				Notes
Distance	85.9 miles				(Bachman et al., 1978)
Scheduled Stops	15				(Metrolink, 2014)
Average Expected Speed Reductions per One-Way	Num.	Speed (mph)	Length (mi)		Assumptions based on engineering judgement
	0.3	25	0.2		
	0.4	40	0.1		
Average Expected Unscheduled Stops per One-Way	Num.	Speed (mph)	Length (mi)	Duration (min)	Assumptions based on engineering judgement
	1	25	0.5	3	

Auto Route Parameters

Parameter	Value		Notes
Description	I-5 to I-405 to I-110		Google Maps Route Choice
Urban Freeway Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion
	94	-	
Urban Arterial Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion
	2	0.1	
Intercity Freeway Distance (mi)	-		Entire trip assumed to be in congested urban area
Wayside Stops (Engine Idle)	Number	Duration (min)	General Assumption
	0	-	

Perryville, MD–Washington, DC, Case Study Description

Rail Equipment Parameters (electric)

Parameter	Value	Notes
Consist Description	1 AEM7 Loco., 5 Bi-level coaches, 650 seats	Assumed as typical operations
Total Loaded Mass (kg)	434,575	Literature Review, Table
Total Length (m)	145.08	Literature Review, Table
a (N)	4,687	Literature Review, Table
b (N/km/h)	38.36	Literature Review, Table
c (N/(km/h)^2)	0.729	Literature Review, Table
Nominal Traction Power (kW)	4,320	Literature Review, Table A-1
Primary Fuel Type	U.S. Conventional Diesel	Assumed for loco. type
Hotel Power Provision Code	4 (electric)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Equipment Parameters (diesel-electric)

Parameter	Value	Notes
Consist Description	1 MP36PH Loco., 5 Bi-levels, 650 seats	Assumed as typical operations
Total Loaded Mass (kg)	451,190	Literature Review, Table
Total Length (m)	150.27	Literature Review, Table
a (N)	4,033	Literature Review, Table
b (N/km/h)	46.328	Literature Review, Table
c (N/(km/h)^2)	0.727	Literature Review, Table
Nominal Traction Power (kW)	2,685	Literature Review, Table A-1
Primary Fuel Type	U.S. Conventional Diesel	Assumed for loco. type
Hotel Power Provision Code	2 (PTO-fixed speed main engine)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Route Parameters

<table>
<tr><th>Parameter</th><th colspan="12">Value</th><th>Notes</th></tr>
<tr><td>Distance</td><td colspan="12">77 miles</td><td>(FRA 1978)</td></tr>
<tr><td>Scheduled Stops</td><td colspan="12">13</td><td>(Maryland Transit Administration, 2013)</td></tr>
<tr><td rowspan="3">Average Expected Speed Reductions per One-Way</td><td colspan="4">Num.</td><td colspan="4">Speed (mph)</td><td colspan="4">Length (mi)</td><td rowspan="3">Assumptions based on engineering judgement</td></tr>
<tr><td colspan="4">0.2</td><td colspan="4">25</td><td colspan="4">0.2</td></tr>
<tr><td colspan="4">0.4</td><td colspan="4">40</td><td colspan="4">0.1</td></tr>
<tr><td rowspan="2">Average Expected Unscheduled Stops per One-Way</td><td colspan="3">Num.</td><td colspan="3">Speed (mph)</td><td colspan="3">Length (mi)</td><td colspan="3">Duration (min)</td><td rowspan="2">Assumptions based on engineering judgement</td></tr>
<tr><td colspan="3">0.5</td><td colspan="3">25</td><td colspan="3">0.5</td><td colspan="3">1.2</td></tr>
</table>

Auto Route Parameters

Parameter	Value		Notes
Description	I-95 to I-495		Google Maps Route Choice
Urban Freeway Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion
	63	-	
Urban Arterial Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion
	2	8	
Intercity Freeway Distance (mi)	-		Entire trip assumed to be in congested urban area
Wayside Stops (Engine Idle)	Number	Duration (min)	General Assumption
	0	-	

Oklahoma City, OK–Fort Worth, TX, Case Study Description

Rail Equipment Parameters (NPCU)

Parameter	Value	Notes
Consist Description	1 P42 Loco., 3 Bi-level coaches, 1 NPCU, 252 seats	Assumed as typical operations
Total Loaded Mass (kg)	448,392	Literature Review, Table
Total Length (m)	198.12	Literature Review, Table
a (N)	4,133	Literature Review, Table
b (N/km/h)	0	Literature Review, Table
c (N/(km/h)^2)	0.622	Literature Review, Table
Nominal Traction Power (kW)	3,054	Literature Review, Table A-1
Primary Fuel Type	U.S. Conventional Diesel	Assumed for loco. type
Hotel Power Provision Code	1 (PTO-inverter)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Equipment Parameters (Non-NPCU)

Parameter	Value	Notes
Consist Description	1 P42 Loco., 3 Bi-levels, 252 seats	Assumed as typical operations
Total Loaded Mass (kg)	330,392	Literature Review, Table
Total Length (m)	176.8	Literature Review, Table
a (N)	3,382	Literature Review, Table
b (N/km/h)	0	Literature Review, Table
c (N/(km/h)^2)	0.622	Literature Review, Table
Nominal Traction Power (kW)	3,054	Literature Review, Table A-1
Primary Fuel Type	U.S. Conventional Diesel	Assumed for loco. type
Hotel Power Provision Code	1 (PTO-inverter)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Route Parameters

<table>
<tr><th>Parameter</th><th colspan="4">Value</th><th>Notes</th></tr>
<tr><td>Distance</td><td colspan="2">NPCU: 206 miles</td><td colspan="2">Non-NPCU: 209.5 miles</td><td>(BNSF, 2005)</td></tr>
<tr><td>Scheduled Stops</td><td colspan="4">7</td><td>(Amtrak, 2014)</td></tr>
<tr><td rowspan="3">Average Expected Speed Reductions per One-Way</td><td>Num.</td><td>Speed (mph)</td><td colspan="2">Length (mi)</td><td rowspan="3">Assumptions based on engineering judgement</td></tr>
<tr><td>1.7</td><td>25</td><td colspan="2">0.1</td></tr>
<tr><td>3.5</td><td>40</td><td colspan="2">0.1</td></tr>
<tr><td rowspan="2">Average Expected Unscheduled Stops per One-Way</td><td>Num.</td><td>Speed (mph)</td><td>Length (mi)</td><td>Duration (min)</td><td rowspan="2">Assumptions based on engineering judgement</td></tr>
<tr><td>5</td><td>25</td><td>2.1</td><td>6</td></tr>
</table>

Auto Route Parameters

Parameter	Value		Notes
Description	I-35 to I-35W		Google Maps Route Choice
Urban Freeway Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion
	8	37	
Urban Arterial Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion
	3	1	
Intercity Freeway Distance (mi)	154		Determined by total trip distance minus urban distances
Wayside Stops (Engine Idle)	Number	Duration (min)	General Assumption
	1	2	

Air Parameters

Parameter	Value				Notes
Airports	OKC		DFW		OpenFlights Airport Database
Latitude/Longitude	35.39	-97.60	32.90	-97.04	OpenFlights Airport Database

Bus Route Parameters

Parameter	Value		Notes
Description	I-35 to I-35W		Google Maps Route Choice
Urban Freeway Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion. Intercity freeway distance shifted to urban freeway distance to account for congestion around stops
	16	73	
Urban Arterial Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion. Intercity freeway distance shifted to urban freeway distance to account for congestion around stops
	3	1	
Intercity Freeway Distance (mi)	110		Determined by total trip distance minus urban distances
Intermediate Urban Arterial and Bypass (mi)	26		Additional 7 km per stop
Wayside Stops	Number	Duration (min)	Greyhound Bus Schedule
	6	5	

Charlotte, NC–Raleigh, NC, Case Study Description

Rail Equipment Parameters

Parameter	Value	Notes
Consist Description	1F59PHI Loco., 4 single-level coaches, 336 seats	Assumed as typical operations
Total Loaded Mass (kg)	349,995	Literature Review, Table
Total Length (m)	126.64	Literature Review, Table
a (N)	4,252	Literature Review, Table
b (N/km/h)	32.889	Literature Review, Table
c (N/(km/h)^2)	0.816	Literature Review, Table
Nominal Traction Power (kW)	2,386	Literature Review, Table A-1
Primary Fuel Type	U.S. Conventional Diesel	Assumed for loco. type
Hotel Power Provision Code	3 (dg-set)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Route Parameters

<table>
<tr><th>Parameter</th><th colspan="4">Value</th><th>Notes</th></tr>
<tr><td>Distance</td><td colspan="4">173 miles</td><td>(Norfolk Southern, 2002)</td></tr>
<tr><td>Scheduled Stops</td><td colspan="4">9</td><td>(Amtrak, 2014)</td></tr>
<tr><td rowspan="3">Average Expected Speed Reductions per One-Way</td><td>Num.</td><td>Speed (mph)</td><td colspan="2">Length (mi)</td><td rowspan="3">Assumptions based on engineering judgement</td></tr>
<tr><td>1.7</td><td>25</td><td colspan="2">0.1</td></tr>
<tr><td>3.5</td><td>40</td><td colspan="2">0.1</td></tr>
<tr><td rowspan="2">Average Expected Unscheduled Stops per One-Way</td><td>Num.</td><td>Speed (mph)</td><td>Length (mi)</td><td>Duration (min)</td><td rowspan="2">Assumptions based on engineering judgement</td></tr>
<tr><td>5</td><td>25</td><td>2.1</td><td>6</td></tr>
</table>

Auto Route Parameters

<table>
<tr><th>Parameter</th><th colspan="2">Value</th><th>Notes</th></tr>
<tr><td>Description</td><td colspan="2">I-85/I-40</td><td>Google Maps Route Choice</td></tr>
<tr><td rowspan="2">Urban Freeway Distance (mi)</td><td>Urb-A(1)</td><td>Urb-A(2)</td><td rowspan="2">Urban distances determined by extent of congestion</td></tr>
<tr><td>25</td><td>24</td></tr>
<tr><td rowspan="2">Urban Arterial Distance (mi)</td><td>Urb-A(1)</td><td>Urb-A(2)</td><td rowspan="2">Urban distances determined by extent of congestion</td></tr>
<tr><td>3</td><td>6</td></tr>
<tr><td>Intercity Freeway Distance (mi)</td><td colspan="2">115</td><td>Determined by total trip distance minus urban distances</td></tr>
<tr><td rowspan="2">Wayside Stops (Engine Idle)</td><td>Number</td><td>Duration (min)</td><td rowspan="2">General Assumption</td></tr>
<tr><td>1</td><td>2</td></tr>
</table>

Air Parameters

Parameter	Value				Notes
Airports	CLT		RDU		OpenFlights Airport Database
Latitude/Longitude	35.21	-80.94	35.88	-78.79	OpenFlights Airport Database

Bus Route Parameters

Parameter	Value		Notes
Description	I-85/I-40		Google Maps Choice
Urban Freeway Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion. Intercity freeway distance shifted to urban freeway distance to account for congestion around stops
	52	49	
Urban Arterial Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion. Intercity freeway distance shifted to urban freeway distance to account for congestion around stops
	3	6	
Intercity Freeway Distance (mi)	62		Determined by total trip distance minus urban distances
Intermediate Urban Arterial and Bypass (mi)	13		Additional 7 km per stop
Wayside Stops	Number	Duration (min)	Greyhound Bus Schedule
	3	5	

New York, NY–Buffalo, NY, Case Study Description

Rail Equipment Parameters

Parameter	Value	Notes
Consist Description	1 P32AC-DM Dual-Mode Loco., 5 single-level coaches, 416 seats	Assumed as typical operations
Total Loaded Mass (kg)	409,851	Literature Review, Table
Total Length (m)	176.784	Literature Review, Table
a (N)	4,528	Literature Review, Table
b (N/km/h)	0	Literature Review, Table
c (N/(km/h)^2)	0.718	Literature Review, Table
Nominal Traction Power (kW)	3,170	Literature Review, Table A-1
Primary Fuel Type	Bimodal (U.S. Conventional Diesel and Electric)	Assumed for loco. Type
Hotel Power Provision Code	1 (PTO-inverter)	Assumed for loco. Type
Energy Recovery Type	0 (none)	Assumed for loco. Type

Rail Route Parameters

Parameter	Value				Notes
Distance	437.9				(Bachman et al., 1978)
Scheduled Stops	15				(Amtrak, 2014)
Average Expected Speed Reductions per One-Way	Num.	Speed (mph)	Length (mi)		Assumptions based on engineering judgement
	1.7	25	0.1		
	3.5	40	0.1		
Average Expected Unscheduled Stops per One-Way	Num.	Speed (mph)	Length (mi)	Duration (min)	Assumptions based on engineering judgement
	5	25	2.1	6	

Auto Route Parameters

Parameter	Value		Notes
Description	I-80 to I-380 to I-81 to I-90		Google Maps Route Choice
Urban Freeway Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion
	27	4	
Urban Arterial Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion
	6	4	
Intercity Freeway Distance (mi)	292		Determined by total trip distance minus urban distances
Wayside Stops (Engine Idle)	Number	Duration (min)	General Assumption
	1	2	

Air Parameters

Parameter	Value				Notes
Airports	LGA		BUF		OpenFlights Airport Database
Latitude/Longitude	40.78	-73.87	42.94	-78.73	OpenFlights Airport Database

Bus Route Parameters

Parameter	Value		Notes
Description	I-85/I-40		Google Maps Route choice
Urban Freeway Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion. Intercity freeway distance shifted to urban freeway distance to account for congestion around stops
	60	7	
Urban Arterial Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion. Intercity freeway distance shifted to urban freeway distance to account for congestion around stops
	6	4	
Intercity Freeway Distance (mi)	255		Determined by total trip distance minus urban distances
Intermediate Urban Arterial and Bypass (mi)	30		Additional 7 km per stop
Wayside Stops	Number	Duration (min)	Greyhound Bus Schedule
	8	5	

Portland, OR–Seattle, WA, Case Study Description

Rail Equipment Parameters

Parameter	Value	Notes
Consist Description	1 F59PHI Loco., 12-car Talgo, 1 cab car, 340 seats	Assumed as typical operations
Total Loaded Mass (kg)	402,138	Literature Review, Table
Total Length (m)	192.48	Literature Review, Table
a (N)	4,239	Literature Review, Table
b (N/km/h)	0	Literature Review, Table
c (N/(km/h)^2)	0.923	Literature Review, Table
Nominal Traction Power (kW)	2,386	Literature Review, Table A-1
Primary Fuel Type	U.S. Conventional Diesel	Assumed for loco. type
Hotel Power Provision Code	3 (dg-set)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Route Parameters

Parameter	Value				Notes
Distance	184.7 miles				(Bachman et al., 1978)
Scheduled Stops	8				(Amtrak, 2014)
Average Expected Speed Reductions per One-Way	Num.	Speed (mph)	Length (mi)		Assumptions based on engineering judgement
	1.7	25	0.1		
	3.5	40	0.1		
Average Expected Unscheduled Stops per One-Way	Num.	Speed (mph)	Length (mi)	Duration (min)	Assumptions based on engineering judgement
	5	25	2.1	6	

Auto Route Parameters

Parameter	Value		Notes
Description	I-80 to I-380 to I-81 to I-90		Google Maps Route Choice
Urban Freeway Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion
	14	77	
Urban Arterial Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion
	4	3	
Intercity Freeway Distance (mi)	75		Determined by total trip distance minus urban distances
Wayside Stops (Engine Idle)	Number	Duration (min)	General Assumption
	1	2	

Air Parameters

Parameter	Value				Notes
Airports	PDX		SEA		OpenFlights Airport Database
Latitude/Longitude	45.59	-122.60	47.45	-122.31	OpenFlights Airport Database

Bus Route Parameters

Parameter	Value		Notes
Description	I-85/I-40		Google Maps Route Choice
Urban Freeway Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion. Intercity freeway distance shifted to urban freeway distance to account for congestion around stops
	27	50	
Urban Arterial Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion. Intercity freeway distance shifted to urban freeway distance to account for congestion around stops
	4	3	
Intercity Freeway Distance (mi)	89		Determined by total trip distance minus urban distances
Intermediate Urban Arterial and Bypass (mi)	22		Additional 7 km per stop
Wayside Stops	Number	Duration (min)	Greyhound Bus Schedule
	4	5	

Bethesda, MD–New York, NY, Case Study Description

Rail Equipment Parameters

Parameter	Value	Notes
Consist Description	1 AEM7 Loco., 6 single-level coaches, 504 seats	Assumed as typical operations
Total Loaded Mass (kg)	564,405	Literature Review, Table
Total Length (m)	170.99	Literature Review, Table
a (N)	3,680	Literature Review, Table
b (N/km/h)	9.667	Literature Review, Table
c (N/(km/h)^2)	0.864	Literature Review, Table
Nominal Traction Power (kW)	4,320	Literature Review, Table A-1
Primary Fuel Type	Electricity (U.S. Northeast Mix)	Assumed for loco. type
Hotel Power Provision Code	4 (electric-loco)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Route Parameters

Parameter	Value				Notes
Distance	226.1				(Bachman et al., 1978)
Scheduled Stops	10				(Amtrak, 2014)
Average Expected Speed Reductions per One-Way	Num.	Speed (mph)	Length (mi)		Assumptions based on engineering judgement
	1	25	0.1		
	2	40	0.1		
Average Expected Unscheduled Stops per One-Way	Num.	Speed (mph)	Length (mi)	Duration (min)	Assumptions based on engineering judgement
	3	25	2.1	6	

Auto Route Parameters

Parameter	Value		Notes
Description	I-495 to I-95 to I-295 to I-95 to I-78		Google Maps Route Choice
Urban Freeway Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion
	134	92	
Urban Arterial Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion
	3	4	
Intercity Freeway Distance (mi)	0		Determined by total trip distance minus urban distances
Wayside Stops (Engine Idle)	Number	Duration (min)	General Assumption
	1	2	

Air Parameters

Parameter	Value				Notes
Airports	DCA		LGA		OpenFlights Airport Database
Latitude/Longitude	38.85	-77.04	40.78	-73.87	OpenFlights Airport Database

Bus Route Parameters

Parameter	Value		Notes
Description	I-495 to I-95 to I-295 to I-95 to I-78		Google Maps Route Choice
Urban Freeway Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion. Intercity freeway distance shifted to urban freeway distance to account for congestion around stops
	134	92	
Urban Arterial Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion. Intercity freeway distance shifted to urban freeway distance to account for congestion around stops
	3	4	
Intercity Freeway Distance (mi)	0		Entire route assumed to be congested
Intermediate Urban Arterial and Bypass (mi)	9		Additional 7 km per stop
Wayside Stops	Number	Duration (min)	Greyhound Bus Schedule
	1	5	

Chicago, IL–Los Angeles, CA, Case Study Description

Rail Equipment Parameters (Amenities)

Parameter	Value	Notes
Consist Description	2 P42 loco., 8 Bi-level railcars, 364 seats	Assumed as typical operations
Total Loaded Mass (kg)	504,548	Literature Review, Table
Total Length (m)	249.94	Literature Review, Table
a (N)	6,930	Literature Review, Table
b (N/km/h)	78.37	Literature Review, Table
c (N/(km/h)^2)	0.973	Literature Review, Table
Nominal Traction Power (kW)	2x 3,054	Literature Review, Table A-1
Primary Fuel Type	U.S. Conventional Diesel	Assumed for loco. type
Hotel Power Provision Code	1 (PTO-inverter)	Assumed for loco. type
Energy Recovery Type	0 (none)	Assumed for loco. type

Rail Route Parameters

Parameter	Value				Notes
Distance	2,250.9 miles				(BNSF, 2005)
Scheduled Stops	8				(Amtrak, 2014)
Average Expected Speed Reductions per One-Way	Num.	Speed (mph)	Length (mi)		Assumptions based on engineering judgement
	8	25	0.1		
	15	40	0.1		
Average Expected Unscheduled Stops per One-Way	Num.	Speed (mph)	Length (mi)	Duration (min)	Assumptions based on engineering judgement
	27	25	2.1	25	

Auto Route Parameters

Parameter	Value		Notes
Description	I-55 to I-44 to I-40 to I-15 to I-210 to I-10		Google Maps Route Choice
Urban Freeway Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion
	75	88	
Urban Arterial Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion
	1	2	
Intercity Freeway Distance (mi)	1,955		Determined by total trip distance minus urban distances
Wayside Stops (Engine Idle)	Number	Duration (min)	General Assumption
	11	55	

Air Parameters

Parameter	Value				Notes
Airports	ORD		LAX		OpenFlights Airport Database
Latitude/Longitude	41.98	-87.91	33.94	-118.41	OpenFlights Airport Database

Bus Route Parameters

Parameter	Value		Notes
Description	I-495 to I-95 to I-295 to I-95 to I-78		Google Maps Route Choice
Urban Freeway Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion. Intercity freeway distance shifted to urban freeway distance to account for congestion around stops
	75	88	
Urban Arterial Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion. Intercity freeway distance shifted to urban freeway distance to account for congestion around stops
	1	2	
Intercity Freeway Distance (mi)	1955		Determined by total trip distance minus urban distances
Intermediate Urban Arterial and Bypass (mi)	144		Additional 7 km per stop
Wayside Stops	Number	Duration (min)	Greyhound Bus Schedule
	32	15	

Fresno, CA–Los Angeles, CA, Case Study Description

Rail Equipment Parameters

Parameter	Value	Notes
Consist Description	AGV 11 coach trainset, 446 seats	Assumed as trainset chosen for operation
Total Loaded Mass (kg)	432,746	Assumed as trainset chosen for operation
Total Length (m)	200	Assumed as trainset chosen for operation
a (N)	6,669	Assumed as trainset chosen for operation
b (N/km/h)	10.833	Assumed as trainset chosen for operation
c (N/(km/h)^2)	0.471	Assumed as trainset chosen for operation
Nominal Traction Power (kW)	8,640	Assumed as trainset chosen for operation
Primary Fuel Type	Electricity (CA Mix)	Assumed for train type
Hotel Power Provision Code	4 (electric-loco)	Assumed for train type
Energy Recovery Type	3 (electric grid)	Assumed for train type

Rail Route Parameters

Parameter	Value				Notes
Distance	292 miles				(CHSRA, 2010; CHSRA, 2012)
Scheduled Stops	3				Assumed as express service type
Average Expected Speed Reductions per One-Way	Num.	Speed (mph)	Length (mi)		Assumptions based on engineering judgement
	0.2	25	0.2		
	0.4	40	0.1		
Average Expected Unscheduled Stops per One-Way	Num.	Speed (mph)	Length (mi)	Duration (min)	Assumptions based on engineering judgement
	0.5	40	1.5	2.37	

Auto Route Parameters

Parameter	Value		Notes
Description	I-5 to CA-99		Google Maps Route Choice
Urban Freeway Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion
	25	11	
Urban Arterial Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion
	5	5	
Intercity Freeway Distance (mi)	177		Determined by total trip distance minus urban distances
Wayside Stops (Engine Idle)	Number	Duration (min)	General Assumption
	0	-	

Air Parameters

Parameter	Value				Notes
Airports	LAX		FAT		OpenFlights Airport Database
Latitude/Longitude	33.94	-118.41	36.78	-119.72	OpenFlights Airport Database

Bus Route Parameters

Parameter	Value		Notes
Description	I-495 to I-95 to I-295 to I-95 to I-78		Google Maps Route Choice
Urban Freeway Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion. Intercity freeway distance shifted to urban freeway distance to account for congestion around stops
	25	11	
Urban Arterial Distance (mi)	Urb-A(1)	Urb-A(2)	Urban distances determined by extent of congestion. Intercity freeway distance shifted to urban freeway distance to account for congestion around stops
	3	3	
Intercity Freeway Distance (mi)	176		Determined by total trip distance minus urban distances
Intermediate Urban Arterial and Bypass (mi)	4		Additional 7 km per stop
Wayside Stops	Number	Duration (min)	Greyhound Bus Schedule
	1	5	

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

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