FACTORS AFFECTING COMMUTER RAIL ENERGY EFFICIENCY AND ITS COMPARISON WITH COMPETING PASSENGER TRANSPORTATION MODES

BY

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THESIS

Submitted in partial fulfilment of the requirements
for the degree of Master of Science in Civil Engineering
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2015

Urbana, Illinois

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ABSTRACT

As concerns about the environmental impacts and sustainability of the transportation sector continue to grow, modal energy efficiency is a factor of increasing importance when evaluating benefits and costs of transportation systems and justifying future investment. Poor assumptions on the efficiency of the system can alter the economics of investment in commuter rail. This creates a need to understand the factors affecting commuter rail energy efficiency and the comparison to competing passenger transportation modes to aid operators and decision makers in the development of new commuter rail lines and the improvement of existing services.

This thesis describes analyses to further understand the factors affecting the current energy efficiency of commuter rail systems, how their efficiency may be improved through implementation of various technologies, and how their efficiency compares to competing modes of passenger transportation. After reviewing the literature, it was evident that past studies often conducted energy efficiency analyses and modal comparisons using methods that favored one energy source or competing mode by neglecting losses in the system. Therefore, four methods of energy efficiency analysis were identified and applied to 25 commuter rail systems in the United States using data from the National Transit Database (NTD). Using the same database, an analysis of trends in energy efficiency exhibited by the United States commuter rail systems was conducted.

To understand the effects of congestion, traffic heterogeneity, operational parameters, and infrastructure characteristics on energy efficiency of passenger trains, single and multi-variable analyses were conducted. Simulations in Rail Traffic Controller (RTC) provided energy consumption results that were used in the statistical analyses. The results illustrated the effects of congestion due to increased freight and passenger traffic on a single-track freight-owned railroad.

The effect of alternative scheduling patterns on energy intensity was analyzed through a case study of operations on one existing commuter rail line. Using the Multimodal Passenger Simulation Tool (MMPASSIM), the energy consumption of the current operations and proposed schedules of local, zonal, skip-stop and express train stopping patterns during a weekday peak period were simulated. A trade-off between improved passenger service through reduced travel times and energy consumption was evident in the results. MMPASSIM was also used to simulate the effects of technologies and strategies to increase energy efficiency and improve service levels. Changes such as electrification, driver advisory systems, equipment modifications, and slow zone reductions were evaluated for their effect on energy efficiency and service metrics. Finally, MMPASSIM was used to compare the energy intensity of the same commuter rail service to competing modes of passenger transportation for equivalent commuter trips. The rail service was evaluated under local, zonal, and skip-stop patterns and compared to automobile and bus trips under off-peak and peak highway congestion levels. Load factor sensitivity charts were developed, showing lines of equal energy intensity of rail and competing modes across a range of modal load factors.

ACKNOWLEDGEMENTS

My passion for passenger rail transportation may have ended as a general interest if it weren't for the opportunity to study and conduct research with the Rail Transportation and Engineering Center (RailTEC) at the University of Illinois at Urbana-Champaign. Besides the extensive railroad engineering curriculum and research program, RailTEC is led by faculty and staff that care deeply about students and their success. Not only have I received a world-class education in my time here, but I have been challenged professionally and personally.

This would not have been without the efforts of Dr. Christopher P.L. Barkan and C. Tyler Dick. Dr. Barkan has redeveloped the RailTEC program to be a leader in railroad engineering education and research. C. Tyler Dick, my adviser, has been instrumental in my growth during my time here. He has an analytical mind that is brilliant at conceptualizing trends and cause-and-effect relationships. He has challenged me to work hard, do excellent research, and encouraged me when I made mistakes.

This research was supported financially by the National University Rail (NURail) Center (a US DOT-OST Tier 1 University Transportation Center), the Association of American Railroads (AAR), and the National Cooperative Rail Research Program (NCRRP) of the Transportation Research Board (TRB).

Special thanks are given to Gordon English and Thomas Moynihan at TranSys Research Ltd. for their collaboration and help in using MMPASSIM. I would like to thank Garrett Fullerton, who entered the program with me and continually helped me with my research and navigating graduate school in general. Mei-Cheng Shih and Ivan Atanassov were extremely helpful with the RTC cases. Nao Nishio and Taskin Sehitoglu, Undergraduate Research Assistants, helped conduct several of the analyses in this thesis. Also, my colleagues in Room B-118 (and now 3214) deserve thanks for their friendship and fun times in and out of the office.

My parents (Charles, Loretta, Mardell, and Mark) have been a great support and encouragement during my time in Champaign. I am certain I would not have been able to complete my degree, or this thesis, without their upbringing. Nancy and David, my parents-in-law, have also been a tremendous support after our move to Illinois.

Finally, I owe the greatest of thanks to my wife, Brooke, who has supported me in pursuing my passion daily since we left our friends and newly-planted roots in Colorado and moved to Champaign, Illinois.

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CHAPTER 1: INTRODUCTION

1.1 Purpose

The purpose of this research is to identify and analyze factors affecting commuter rail system energy efficiency and its comparison with competing passenger travel modes.

1.2 Background

As concerns about the environmental impacts and sustainability of the transportation sector continue to grow, modal energy efficiency is increasingly important when evaluating the benefits and costs of future transportation system investment in commuter rail operations. Increased energy efficiency of passenger rail systems compared to other modes is often cited as a justification for new investment. Commuter rail is best characterized as a passenger rail service operating between a downtown area of a major city and the outlying suburban areas on conventional railroad infrastructure. In many metropolitan areas, this trackage may be shared with freight rail operations (Brock & Souleyrette 2013). Commuter rail typically moves riders longer distances within the greater metropolitan area of a city or region, compared to light or heavy rail rapid transit that more typically moves passengers within the city, or intercity passenger rail that covers longer distances between cities and metropolitan regions (Brock & Souleyrette 2013). Environmental concerns of energy efficiency and emissions reductions are integral in regional planning, especially in urban areas where highways and roads can become increasingly congested. Commuter rail in the United States (US) has experienced a renaissance in recent years, with rapid growth both in ridership and the number of systems in operation. Commuter rail ridership increased by 28% between 1997 and 2007 (Federal Railroad Administration 2009) and by nearly 13% between 2008 and 2012 (Federal Transit Administration 2012), for a total combined increase of 49%.

Operating energy consumption is a vital consideration in the economic justification of commuter rail projects, representing a large portion of the long-term system operating expenses. In the planning stages of a commuter rail project, the costs and benefits are often based on national averages. However, as this thesis will demonstrate, operating energy efficiency varies with many factors such as vehicle type, energy source, interference from other trains, service frequency, stopping patterns, average speed, and consist make-up.

1.3 Objective and Scope

This thesis investigates factors affecting commuter rail energy efficiency and its comparison with competing passenger travel modes. To accomplish this, data from the National Transit Database were analyzed to demonstrate various methods of quantifying the energy efficiency of commuter rail systems and to identify trends in commuter rail system energy efficiency in the US. In parallel, statistical analyses of simulation results from Rail Traffic Controller show the effects of several operational and infrastructure parameters on passenger rail energy efficiency. The Multimodal Passenger Simulation (MMPASSIM) tool was used to simulate the movements and energy efficiency of several commuter rail case studies to investigate the influence of alternative patterns of train station stops. This tool was also used to investigate the effects of energy-saving technologies and strategies on the commuter rail case study services, and to compare the results to competing passenger travel modes including automobile and bus.

1.4 Organization

The first section of this thesis identifies previous studies of passenger rail energy efficiency and modal comparisons relevant to the analysis that follows. Next, methods of analyzing commuter rail energy efficiency at various points in the energy supply system were identified and applied to the US commuter rail operations. An analysis of the trends in energy efficiency of commuter rail systems in the US follows. The fifth chapter investigates the effects of several factors, including traffic congestion, on energy efficiency of passenger rail systems using industry-standard train dispatching simulation software. Chapter six introduces the MMPASSIM model in detail, and discusses the methodologies used to create key inputs for use in modal comparisons with highway modes. Chapter seven investigates the effect of scheduling patterns on commuter rail systems using the MMPASSIM tool. Chapters eight and nine apply the MMPASSIM tool to commuter rail case studies to investigate the effects of energy saving technologies/strategies and conduct modal comparison analyses, respectively. Finally, the thesis concludes with discussion of the general findings and recommendations for future research.

CHAPTER 2: LITERATURE REVIEW

Earlier versions of this research appeared in:

TranSys Research Limited, University of Illinois Rail Transportation and Engineering Center (RailTEC), & CPCS. Comparison of Passenger Rail Energy Consumption with Competing Modes. National Cooperative Rail Research Program (NCRRP) Project No. 02-01. Transportation Research Board of the National Academies. Washington, D.C., USA. (In Review).

2.1 Passenger Rail Energy Efficiency Research

In 1970, domestic production of petroleum peaked, followed by a long, steady decline that only ended in the past few years due to development of new extraction technologies. The impact of this decline was amplified by the Organization of the Petroleum Exporting Countries embargo in 1973. These events 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 the demand for energy efficient transportation in the future. Along this theme, the United States Department of Transportation (USDOT) organized a 1974 conference on the “Role of the US Railroads in Meeting the Nation’s Energy Requirements” that highlighted the energy efficiency benefits of the rail mode. Research from this era was mainly concerned 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 primarily developed for freight applications, also allowed for the most detailed simulations of passenger trains to date.

As a scientific consensus began to develop regarding global climate change and possible human-caused factors, more recent research has focused on the potential for reduced greenhouse gas emissions through expanded use of passenger rail. This research has examined technology and alternative energy sources to reduce emissions directly and through improved energy efficiency. Work has also been done to determine the role of passenger rail in reducing highway congestion, leading to improved efficiencies of all modes.

The following sections summarize research on passenger rail energy efficiency, starting with a discussion of different efficiency metrics and raw averages presented in the literature. Next, a summary of more detailed studies into the efficiency of passenger rail, either alone or relative to competing modes, is presented. This is followed by a section detailing the state of strategies to improve energy efficiency of passenger rail, including alternative locomotive technologies and energy sources.

2.2 Measures of Average Passenger Rail Efficiency

2.2.1 Units of Measurement

Several metrics have been used to describe the efficiency of passenger transportation. Energy efficiency quantifies the amount of useful output a system can achieve per unit energy input. In the case of a passenger rail system, the useful output is passenger transportation. This output is often measured in terms of system capacity (seat-miles) or actual passenger trips (passenger-miles), while the input is energy consumed (liquid fuel, electricity, etc.). Where diesel-electric propulsion is used, passenger rail systems can be described using passenger-miles per gallon, seat-miles per gallon, train-miles per gallon, and vehicle-miles per gallon. However, it is more useful to use energy units such as kilowatt-hour (kWh), kilojoule (kJ), or British Thermal Unit (BTU) when analyzing electric-traction vehicles or comparing with systems that do not use liquid fuel.

The energy efficiency of individual passenger trips is described by the number of passenger-miles per unit energy because this metric considers the ridership and load factor (percentage of seats occupied with passengers) of the system. Since the value of passenger-miles dominates in determining this metric, differences in ridership can obscure variations in the inherent base efficiency of different transportation systems. The seat-miles per unit energy metric is independent of ridership and is a measure of the potential per-trip efficiency of the system. However, this metric is heavily influenced by the number of seats per railcar and changes in seating configuration can overshadow the base efficiency of the system.

Train-miles per unit energy describes the energy efficiency of the entire train and is independent of ridership and the number of seats per railcar. However, as will be demonstrated in subsequent chapters, train-miles per unit energy is directly correlated with the length of the train, with longer, heavier trains appearing to be less efficient by this metric. Vehicle-miles per unit energy describes the efficiency of each railcar (vehicle) in a train consist and is independent of ridership and the number of seats. Although it is partially influenced by train length, with longer trains gaining efficiencies of scale and improved aerodynamics, it is probably the best measure of the efficiency of the system rolling stock and infrastructure design and operations.

Depending on the exact comparisons being made, any one of the four different measures of energy efficiency may be most appropriate. When conducting a modal comparison of door-to-door trips on a particular route, passenger-miles per gallon may provide the best comparison for a given ridership. However, when examining the impact of new technologies to improve efficiency, vehicle-miles per gallon may provide the best metric to describe the direct improvements to the inherent efficiency of the system. These concepts will be revisited in the discussion of approaches to measuring rail system efficiency in Chapter 3.

The reciprocal of efficiency is energy intensity, usually described using BTU per passenger-mile (or kJ per passenger-kilometer). Since it allows the efficiency of systems using different energy sources and fuels to be compared with the same units, energy intensity (or units of energy per passenger-distance) is the metric generally used to compare competing passenger transportation modes.

2.2.2 Average Passenger Rail Efficiency

The most widely-available measures of passenger rail energy efficiency are those analyzed on an annual gross average basis. This method uses annual statistics, such as fuel or electric power purchased or consumed and reported passenger-miles, to estimate the energy efficiency and emissions of passenger rail systems per passenger-mile. This method is effective in obtaining a high-level metric of the efficiencies of rail systems and competing travel modes. However, annual gross average efficiencies should not be used to describe individual trains and passenger trips. Each system, route, train, and passenger trip has unique characteristics that can cause the efficiency of that journey to significantly deviate from the annual average. In order to describe individual trip performance, a model of the energy consumption of each passenger mode is necessary to analyze the exact energy consumption and emissions of the passenger vehicle on a specific route.

The USDOT Bureau of Transportation Statistics (BTS) analyzes energy efficiency and emissions of transportation in the US. The annual gross average energy intensity of several passenger modes for 2011, as reported by the BTS in the National Transportation Statistics, is shown in Table 2.1. In 2011, on an annual gross average basis, Amtrak is the least intense (most efficient) mode of passenger transportation. However, the energy intensity figure for Amtrak includes both diesel-electric and electric motive power while the competing modes are all powered by liquid fossil-fuels. The presence of these two energy sources complicates direct comparisons of efficiency metrics between systems and to the highway mode on the "per-gallon" basis familiar to the general public. This will be addressed in detail in Chapter 3.

Table 2.1 Energy Intensity of Passenger Travel Modes in 2011 (USDOT 2013a)

Mode	Energy Intensity (BTU/Passenger-mile)
Air	3,058
Light Duty Vehicle	4,689
Motorcycle	2,669
Transit Bus	3,343
Amtrak	1,628

The fact that electric locomotives are intrinsically more efficient than diesel-electric locomotives further clouds energy efficiency comparisons. A tank or meter to wheels comparison ignores significant losses associated with energy conversion prior to delivery to the electric locomotive. Thermal efficiency of electric locomotives, when measured from the pantograph (or power meter) to the work performed by the wheels at the rails, is about 76-84% (Andersson 2012, Hoffrichter et al. 2012). Meanwhile, diesel-electric locomotive efficiency is between 28-30% (Hoffrichter et al. 2012). This intrinsic difference in the efficiency of electric and diesel-electric propulsion skews simple comparisons of energy efficiency as measured by purchased fuel or electricity. While the conversion of fuel to electricity for traction and associated losses takes place on board the diesel-electric locomotive, electricity is delivered to the electric locomotive after the fuel or source energy is converted to electricity at a remote generating station. Losses associated with generation and transmission of purchased electricity are not accounted for when considering the efficiency of an electric train on this basis. A complete "well-to-wheels" analysis on a per-BTU basis accounts for electric power generation losses to provide a true comparison with internal combustion engines using fossil fuels. However, such comparisons are highly influenced by the generation profile supplying electric power to the commuter rail operator. These challenges are discussed in detail in Chapter 3.

Alternatively, analyses can include life-cycle energy consumption and emissions from vehicle manufacture and disposal, infrastructure raw materials and construction, and source fuel extraction, refining and transportation (as may apply to internal combustion engines or electric power generating stations). Such analyses are useful in analyzing the effect of transportation systems on entire communities, regions, or even nations, but are less useful to transit agencies in understanding energy consumption of daily operations to increase efficiency.

2.3 Previous Studies of Passenger Rail Efficiency

Numerous previous studies have quantified the energy intensity of the passenger rail mode on the basis of analytical models, simulation, and field data collection. To varying degrees, several of these studies make direct comparisons between travel modes for specific routes. The studies also take differing approaches to considering ridership, access modes, time of day, trip purpose, and upstream energy and emissions. Several noteworthy studies are discussed in the following sections.

2.3.1 1975 Hopkins FRA Study

J.B. Hopkins (1975) conducted a Federal Railroad Administration (FRA) study entitled "Railroads and the Environment – Estimation of Fuel Consumption in Rail Transportation". The first volume presents analytical models of fuel consumption for branchline-freight service, line-haul freight service, and passenger service. While the freight analysis presented comparisons to the highway mode, 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 assumes a locomotive fuel consumption rate of 20.9 horsepower-hours per gallon to determine efficiency in terms of seat-miles per gallon:

$$s_{mpg} = \frac{8.16 \times 10^7}{(v \times W_s)}$$

Where:

S_{mpg} = passenger train fuel efficiency in seat-miles per gallon
v = train speed in miles per hour (mph)
W_s = train weight per seat in pounds

The form of the equation indicates that fuel efficiency decreases as train weight per seat and speed increase. The simplified assumption of train resistance in pounds per ton embedded in this equation is taken to be valid for the range of 40 to 80 mph. The derived relationship reinforces the need for lightweight equipment to maintain efficiency as speed increases. Hopkins illustrated that at 60 mph, conventional equipment operated at approximately 180 seat-miles per gallon, while more modern lightweight equipment being developed for high-speed rail operated 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, he did indicate that since the weight of the passenger load is only five to ten percent of train weight, seat-miles per gallon is independent of passenger load and can provide a better metric of the actual efficiency of the passenger train itself than passenger-miles per gallon.

Hopkins acknowledged that besides the two factors included in the equation, passenger train efficiency varies with grade, train length, stop spacing and idle time, and presents 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 because the fixed drag and resistance of the locomotives can be distributed over more cars and seats in a longer train. Station stops and idling can influence efficiency in practice; Hopkins calculated that as much as 15% of the fuel consumed by passenger trains is due to idling time at stops.

Hopkins extended his model for trains designed to operate at cruising speeds between 90 and 160 mph and conducted a comparative analysis of the high-speed rail systems in service or being planned at the time of the study (Table 2.2). Hopkins did this by making the assumption that at the design cruise 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 one mile were converted to gallons of fuel and then the seating capacity used to estimate the seat-miles per gallon. Since the model was based on rated horsepower, the same approach was applied to diesel-electric, turbine, and electric trainsets to allow for comparisons. In the case of electric trains, this represented the equivalent amount of diesel fuel needed to produce the required horsepower in a locomotive diesel prime mover.

The values presented in Table 2.2 are for service on level grade and do not include stops or idling. Also note that some of these designs were still in development in 1975, so the presented values may differ from the final in-service design or those currently in service. This is best exemplified by the Train à Grande Vitesse (TGV) prototype in France that was powered by gas turbines before later redevelopment as an electric train. An interesting comparison is between the US TurboTrain and the longer version placed in service by Canadian National (CN) in Canada. The CN train, with its much greater seating capacity (326 seats versus 144) and lower operating speed (95 mph versus 120 mph) was 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-Miles per Gallon
Metroliner (US)	Electric	110	5,900	246	360	23.9	65 - 95
TurboTrain (US)	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[a]	185	5,000	146	223	34.5	45 - 65
ER200 (USSR)	Electric	125	13,800	872	1,010	15.8	120 - 180

[a]The first TGV prototype was propelled by gas turbines before rising petroleum costs led to development of an all-electric design in 1974.

2.3.2 1977 Mittal USDOT Study

R.K. Mittal of Union College (1977) completed a study in December 1977 for the USDOT FRA entitled “Energy Intensity of Intercity Passenger Rail”. He examined the contemporary and future energy intensity of intercity passenger rail systems, the impact of new technologies and operating characteristics on this 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 the average BTU per passenger-mile for different train services. The analytical method used known physical and engineering relationships of train performance simulation to derive the energy intensity of particular trips. The resistance of particular train consists were used to determine the required rail horsepower for a desired operating speed. After calculating rail horsepower, fuel consumption rates of particular locomotives were used to calculate the energy consumption of the train service. The energy consumption is divided by the number of passengers on the train (expressed as the number of seats multiplied by the load factor) to determine the energy intensity per passenger-mile. To compare electric and diesel-electric trains, Mittal calculated the energy consumed (in BTU) based on the required 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 where the energy intensity of the electric locomotives was based on the energy input to the electrical generating plant based on assumed power generation efficiency of 35% and transmission efficiency of 95%. Consequently, this raised the energy intensity of the electric locomotives by a factor of three; however, the lower traction input values were used more extensively in the report.

Mittal applied the analytical methods in two different manners to answer different research questions. The first is an analysis that calculates the energy intensity of a train consist cruising 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. The second application of the analytical method simulates the operations of trains over actual routes. Mittal used actual operating conditions following normal train driving patterns to determine the energy intensity of diesel-electric consists between Albany and New York, New York and electric train consists between New York City and Washington, D.C.

Common diesel electric locomotives of the time were included in the analysis, namely the General Motors Electro-Motive Division (EMD) E-8, SDP-40F and F-40PH models, General Electric (GE) P30CH model 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 electric multiple-unit trainset, and three different electric locomotives: the GE E60CP, the Alstom CC14500 from France and the Swedish RC4a (that was later adapted to become the Amtrak AEM7). Although several of these locomotive types have been retired, others are still operated in commuter and intercity passenger service today. The railcars considered include refurbished 1950s-era passenger cars, newer Amfleet coaches, and the lightweight coaches and trailer cars appropriate for the LRC and Turboliner trainsets. With the exception of the Turboliner, all of the railcars are still in service. The presence of lounge, snack and meal-service cars in train consists was also considered in calculating energy intensity per seat and passenger-mile.

The Mittal study offers many interesting conclusions. For a given load factor, passenger trains tended to reach their peak efficiency (lowest energy intensity) at cruising speeds in the range of 20 to 30 mph. This was a lower speed than light-duty passenger automobiles that reach peak efficiency at 50 to 60 mph. Thus, to provide competitive service times for intercity service, passenger trains must have operated outside of their most efficient speed range. Mittal confirmed Hopkins' suggestion that the efficiency of passenger trains can be improved by increasing the number of passenger coaches in the train consist. This is particularly important for trains of conventional refurbished passenger cars hauled by heavier diesel-electric locomotives and less important for more modern light weight equipment such as the LRC. Lounge and snack cars could negatively impact the efficiency of a train, but Mittal suggested that such passenger amenities are required to satisfy passenger demand and maintain load factor. At low load factors, passenger rail became very inefficient. Mittal verified Hopkins' assumption that the weight of added passengers has little impact on train fuel consumption rates. Thus, the energy consumption rates on a per train-mile basis were nearly the same under full and partial load factors.

Mittal made an interesting comparison between the analytical energy intensity of the passenger trains at a constant cruising speed of 65 mph and the energy intensity derived from the simulation of actual train operations, including route grade profiles, speed restrictions, and station stops. As shown by Mittal's per seat-mile values (Table 2.3), the real-world operating environment greatly increased the energy intensity of passenger trains compared to steady-state cruising. For the diesel-electric train consists, the energy intensity per seat-mile increased by a factor of 50% to 100% under real operating conditions. Characterized by higher operating speeds and more rapid acceleration, the electric trains were approximately 200% more energy intense under real operating conditions. This finding highlights the need for determination and comparison of passenger train energy efficiency based on actual routes and specific train operations.

Mittal's results can be compared to Hopkins' by comparing Table 2.2 and Table 2.3. Hopkins estimated the efficiency of the LRC as 115 to 170 seat-miles per gallon and the Metroliner as 65 to 95 seat-miles per gallon. This is 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. These values were greater than the in-service values presented by Mittal but given Hopkins' assumptions for operating speed and grade, they appear to offer reasonable agreement. Also note the high energy intensity of the Turboliner compared to the diesel-electric trains and even the higher-speed electric trains. This parallels the low efficiency of the gas turbine TGV prototype from the Hopkins study.

Table 2.3 Comparison of Energy Intensity Between Cruising Mode and Actual Service Operating Cycle (Mittal 1977)

Propulsion	Motive Power	Cruising Energy Intensity (BTU/seat-mile)	Cruising Speed (mph)	Operating[b] Energy Intensity (BTU/seat-mile)	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 energy consumed at the power plant.
[b]NYC-Albany for diesel-electric and gas turbine trains; NYC-Washington DC for electric trains.

Mittal also surveyed the literature to determine appropriate values for the energy intensity of intercity passenger travel by aircraft, automobiles, and buses (Table 2.4). Historical trends of fuel consumption and load factor of each mode were considered. The comparison suggested that passenger rail has the potential to be a very efficient mode of passenger transportation because its energy intensity per seat-mile is lower than that for automobiles and aircraft. However, due to the low passenger rail load factors of the era, the energy intensity of passenger rail per seat-mile was greater than some of the competing modes. Bus became the most efficient passenger transportation mode, followed closely by compact automobiles. Passenger rail simply could not attract enough riders to take advantage of its potential efficiency.

Mittal suggested that the best way to improve the efficiency of passenger rail is to increase the load factor by attracting more ridership. This may be accomplished by reducing travel time through improved track condition and operating speeds, frequency of operation, quality of service, and cost of travel. Mittal recognized that there were complex interactions between these factors and conducts additional analysis to determine the effect of track improvements and reduced travel time on the two corridors considered in the study. While the increase in ridership and load factor resulting from reduced travel time was straightforward, the

Table 2.4 Comparative Analysis of Energy Intensity Values for Intercity Passenger Movement (Mittal 1977)

Mode	Possible Energy Intensity (BTU/seat-mile)	Energy Intensity w/ Load Factor (BTU/passenger-mile)
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

increase in operating speed had a mixed effect on energy intensity. Elimination of speed restrictions and their associated acceleration events in order to create a more uniform speed profile tended to improve the energy efficiency of the trains. However, higher maximum operating speed increased aerodynamic drag and reduced efficiency. For the given routes and their distribution of speed restrictions, these two effects counteracted each other to maintain energy intensity for a given ridership. Thus, when the increased ridership is considered, the track improvements and increased speeds reduced energy intensity per passenger-mile and improved efficiency. Mittal acknowledged that this may not be the case for all corridors, and that if an increase in operating speed did not result in a sufficient ridership increase, the efficiency of the passenger rail operation would ultimately decrease.

It is interesting to compare Mittal's values of BTU/passenger-mile in Table 2.4 to the current national averages presented in 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. Light-duty vehicles, however, appear to be much less efficient than Mittal's estimates. This is surprising given the large advances that have been made in light duty vehicle fuel efficiency since 1977. The result could be due to a combination of the BTS data considering congested city trips that are inherently less efficient than highway travel, and Mittal assuming 2.4 persons per automobile. This occupancy rate is far greater than current statistics that suggest the current vehicle occupancy rate is closer to 1.2 (USDOT 2013a).

2.3.3 1996 Study of Metrolink Commuter Rail in Los Angeles

Barth et al. (1996) presented “Emissions Analysis of Southern California Metrolink Commuter Rail” that estimated and compared the emissions for a morning peak Metrolink commuter rail trip and automobile commute from Riverside to downtown Los Angeles, California. Emissions for the line-haul portion of the commuter rail trip were determined by recording locomotive throttle settings for an actual commuter rail trip and then multiplying by specific throttle-notch emissions factors developed for that model of locomotive during full-scale laboratory testing. The study also included emissions from the station access segment of the commuter rail trip. The access mode was included by using data collected during on board surveys for a morning peak period commuting trip. The surveys 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 to build a distribution of vehicle-trip profiles for rail passenger access to and from Metrolink. A distribution of vehicle emissions characteristics and high-emitting vehicles was collected using remote sensing technology and the resulting automobile emissions were simulated using the California Air Resources Board (CARB) EMFAC7F emissions model. A similar approach was used to determine the emissions of the automobiles required to transport the same number of commuters via highway if they all elected to drive alone in their own vehicles.

The results show that total emissions for the Metrolink commute, including the train trip and access modes, were less than the equivalent automobile commute for this line on a per-passenger basis for the scenario where 300 drivers were compared to 300 train passengers that drive to the Metrolink station. However, not all individual pollutants were reduced (CO and HC emissions were reduced compared to the automobile trip, the Metrolink trip yielded higher NO_x and PM emissions).

Although the original authors were not concerned with energy, the locomotive duty cycle data provided in the paper can be used to deduce the fuel consumption and energy intensity of the Metrolink commuter rail trip. Using the throttle-notch fuel consumption data for the EMD F59PH presented later in the paper, it can be determined that each train consumes 101 gallons of diesel fuel in direct propulsion and, assuming a minimum demand, another 25 gallons for HEP. Thus, the four morning trains carrying a total of 1,100 passengers operate at 94 passenger-miles per gallon or an estimated energy intensity of 1,378 BTU per passenger-mile.

2.3.4 1999 Transport Canada Study

Lake et al. (1999) conducted a study for Transport Canada entitled "Measures to Favour Passenger Modal Shift for GHG Reduction" that characterized the greenhouse gas intensity of passenger travel modes for different origin-destination pairs in Canada. The analysis considered actual travel patterns through load factor and market share for different passenger travel modes. The resulting estimates of Greenhouse Gas (GHG) emissions per passenger trip for some city pairs reflected the general expectation that bus, followed by rail, were the most emission-efficient modes, while the auto and air were the least emission-efficient modes; however, there were some notable exceptions. In the long-distance markets, emissions from rail were the highest or the second highest of all modes due to the need for sleeping and food-service cars on long-distance trains, reducing the number of seats per railcar (and increasing the train weight per seat). On certain routes where bus service has a relatively low load factor, automobile could be the most efficient mode, and rail could exceed bus on routes where rail has a strong ridership and a high load factor.

The appendix to the report presented a detailed methodology for the calculation of the emissions per passenger trip for each mode. Included in the methodology were metrics for average energy efficiency of the different passenger transportation modes on the basis of passenger-miles and seat-miles. These values have been converted to BTU per passenger-mile and seat-mile (Table 2.5). On average, the intercity bus was the most efficient mode. If the trains were operated at capacity, they would be more efficient only on a limited number of routes.

Table 2.5 Energy Intensity of Canadian Passenger Travel Modes in 1996 (Lake et al. 1999)

Mode	Energy Intensity (BTU/ passenger-mile)	Possible Energy Intensity (BTU/seat-mile)
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

2.3.5 2002 German Case Studies

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

Besides considering access modes, the study is noteworthy for its consideration of trip purpose and time of day. The following trip scenarios were considered:

Commuter traffic (leave 8:00 a.m., return 4:30 p.m.),
Shopping traffic (leave 10:00 a.m., return 12:00 p.m.),
Leisure traffic (leave 7:30 p.m., return 10:30 p.m.), and
Sunday leisure traffic (leave 11:00 a.m., return 5:00 p.m.).

Case studies of a typical 20-mile interurban trip for leisure and commuter traffic were examined using different combinations of automobile, transit bus, light rail transit, commuter rail, regional express trains, bike and walking to reflect actual trips.

Direct energy and emissions for automobile and bus transportation were calculated using the German Handbook Emission Factors for Road Transport. This book accounts for parameters such as traffic situation, road grade, motor system, and cubic engine capacity. For rail vehicles, computer simulations were used to calculate energy consumption and emissions. Indirect energy consumption and emissions were broken into three categories and calculated separately: fuel and electricity production and supply; vehicle production, maintenance and disposal; and infrastructure production, maintenance and disposal. Fuel and electricity production and supply were calculated considering the energy mix in production. Vehicle production, maintenance, and disposal considered the energy and emissions used in creating, maintaining, and disposing of the vehicle, and were distributed linearly over the lifetime of the vehicle based on vehicle mileage.

The study concluded that for the case studies analyzed, light-rail transit had the lowest energy consumption and GHG emissions of the passenger travel modes for the 20-mile interurban trip. However, Wacker and Schmid noted that the results depend heavily on the time of day analyzed. For the commuter trips, the trips involving rail were very competitive with the automobile with four passengers. However, for midday leisure trips during off-peak hours, when the rail and public transit modes have a low load factor, the automobile with four passengers (or even one passenger) was more energy efficient and resulted in less emissions than the trips involving the rail and transit mode.

The paper indicated that details of additional long-distance intercity passenger rail studies were available in German-language publications. According to the authors, all of these case studies found that the German ICE high-speed train was more efficient and resulted in less 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 longer-distance rail travel, depending on the exact route and the implemented technology, the passenger rail mode could generate poorer results than an automobile with a single occupant.

2.3.6 2006 Swedish Passenger Train Energy and Modal Comparison Study

Andersson and Lukaszewicz (2006) led a study sponsored by Bombardier Transportation to determine the average energy consumption and emissions of the modern Bombardier trainsets in passenger service in Sweden. The report, entitled "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 (head-end power, HEP), and idling outside of scheduled service. It did not include the energy used in other activities, such as maintenance, operations of fixed installations or heating of facilities. Losses in the power supply system were accounted for in the energy consumption of the electric trainsets by aggregating efficiencies of the power supply systems and applying a scaling factor to the energy consumed at the pantograph. Since electric power is generated at a power generation station rather than on board, the type of power generation used in the region is an important factor for determining the overall energy efficiency and emissions of an electric traction system. This study considered the average emissions, the marginal CO_2 emissions, and the average amount of electricity produced from renewable sources in the estimation of emissions for the electric trains; however, it did not include the efficiencies of the power generation of the region in its energy calculations. Train energy consumption was measured near the pantograph and regenerated energy from the braking of the train was subtracted from this total. Emissions were then calculated using intensity factors and the amount of electric energy consumed by the train.

Average energy consumption and emissions of other modes were not measured. Instead, statistics provided by the Network for Transport and Environment, a Swedish non-profit organization aimed at establishing a common base of values of the environmental performance of other modes of transport, were used.

Comparisons were made for two case studies, Stockholm to Gothenberg (283 miles) using the X2000 trainset and Stockholm to West Aros (66 miles) using the Regina trainset (Tables 2.6 and 2.7). For both routes, passenger rail exhibited the lowest energy intensity when

Table 2.6 Energy Intensity of Passenger Modes from Stockholm to Gothenberg (Andersson & Lukaszewicz 2006)

Mode	Possible Energy Intensity (BTU/seat-mile)	Energy Intensity w/ Load Factor (BTU/ passenger-mile)	CO_2 Emissions (g/passenger-km)	NO_X Emissions (g/passenger-km)
Rail (6-car X2000)	231	423	7	16
Air (Boeing 737-800)	1,757	2,800	130	600
Bus (Euro 3 Emissions)	373	1,098	53	360
Automobile (Mid-size car)	714	1,921	87	40

Table 2.7 Energy Intensity of Passenger Modes from Stockholm to West Aros (Andersson & Lukaszewicz 2006)

Mode	Possible Energy Intensity (BTU/seat-mile)	Energy Intensity w/ Load Factor (BTU/ passenger-mile)	CO_2 Emissions (g/passenger-km)	NO_X Emissions (g/passenger-km)
Rail (3-car Regina)	165	478	8	18
Bus (Euro 3 Emissions)	412	1,208	59	409
Automobile (Mid-size car)	714	2,031	93	43

load factor was considered to calculate the energy intensity. The original energy intensity values in kWh per seat-kilometer and passenger-kilometer presented by the authors have been converted to BTU per seat-mile and passenger-mile for consistency with the other studies presented.

2.3.7 2010 Spanish Passenger Train Energy and Modal Comparison Study

A.G. Alvarez (2010) conducted a study entitled "Energy Consumption and Emissions of High-Speed Trains" that compared the efficiency of conventional rail and high-speed rail to competing modes of transportation on ten different routes in Spain. The comparison was made via analysis of simulations conducted with software calibrated for rail operations in Spain. The analysis considered the actual distance travelled by each mode between a particular origin-destination pair, since 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 in comparing the electrified modes of transportation to other modes and to each other as the emissions factors of power generation systems varied greatly between regions and also have temporal variation within the same region.

The results have been converted from the values of kWh per passenger-kilometer presented in the original paper for consistency with other values reported in this thesis (Table 2.8). On seven of the ten routes analyzed, the high-speed train produced fewer emissions than any other mode. However, in terms of energy efficiency, the bus was the most efficient mode, the high-speed train was second most efficient, and the conventional train was third.

Table 2.8 Energy Intensity of Passenger Modes on Selected Routes in Spain (Alvarez 2010)

	Energy Intensity with Load Factor (BTU/passenger-mile)				
Route	**Auto**	**Bus**	**Air**	**Conv. Rail**	**High-Speed Rail**
Average of 10 Routes	2,635	659	2,965	1,427	1,043

Alvarez's conclusion, that the high-speed train was more energy efficient than the conventional train, is inconsistent with the "square rule" convention that "the energy consumption of the trains would increase with the square of their speed" (Alvarez 2010). Alvarez suggested that this conclusion arises because other factors besides speed vary 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 and have a more homogenous speed profile with fewer stops and curves. The high-speed trainsets were also designed to have less weight per seat and better aerodynamic performance than conventional trains. In Spain, the high-speed trains also operated on a 25kV AC electrification system while the conventional trains operate on a much less efficient 3kV DC system. Finally, the faster running time of high-speed trains reduced the total time and power consumption of HEP and auxiliary power services, increasing energy efficiency.

2.3.8 2012 NCDOT Regional Rail Study and Modal Comparison

Frey and Graver (2012) investigated in-service fuel consumption and emissions rates for the North Carolina Department of Transportation (NCDOT) Rail Division fleet on the Amtrak regional intercity route between Raleigh and Charlotte, North Carolina. The study, summarized in the report entitled "Measurement and Evaluation of Fuels and Technologies for Passenger Rail Service in North Carolina", used actual field measurements to compare 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.

NCDOT's fleet consisted of two EMD F59PHI, four F59PH, and one GP40H locomotive. Each locomotive type had a separate diesel generator set used to provide HEP for train services. All three locomotive types were characterized by a Portable Emissions Measurements Systems (PEMS) used to measure the emissions in the rail yard and during "over-the-rail" testing in service from Raleigh to Charlotte. The results from these measurements were quite extensive, and will not be displayed here. However, these data were useful to understand the range of energy efficiency values obtained using empirical methods.

For comparison with the in-service rail measurements, comparable highway trips were simulated with the EPA Motor Vehicle Emission Simulator (MOVES) software. The average passenger rail and automobile CO_2 emissions and energy intensity over the route derived through the NCDOT study were compared (Table 2.9). Two different rail results were presented, a route average and then a separate peak average for the most efficient segment of the route. The values for passenger rail include fuel and emissions associated with both the locomotive prime mover and the diesel generator set used for HEP functions. On average, the head-end power unit was responsible for roughly eight percent of emissions and energy consumption. The authors also presented two values for automobiles, one for vehicles with a single occupant and one where there were 1.69 persons per vehicle (consistent with US Department of Energy (DOE) assumptions). The results indicated that passenger rail was more efficient than the automobile if it was assumed that each traveler on the highway was in a separate vehicle. For the case where the highway vehicle occupancy was higher, the efficiency of the rail and highway becomes nearly equal. Under these circumstances, the automobile was more efficient on average, but rail was more efficient on certain segments with high ridership. Bus energy efficiency was not considered by the authors.

Table 2.9 Energy Intensity of Passenger Modes in Raleigh-Charlotte Corridor (Frey & Graver 2012)

Mode	Energy Intensity (incl. load factor (BTU/passenger-mile)
Rail (Corridor Average)	3,125
Rail (Greensboro-Charlotte)	2,806
Automobile (1 occupant/vehicle)	4,993
Automobile (1.69 occupants/vehicle)	2,954

The study concluded that travel time is a significant factor in determining the emission factors (thereby energy efficiency) on the in-service trips. For a 5% increase in the scheduled travel time, the emissions rates increased roughly 16% per passenger-mile on the Amtrak Piedmont route. The authors did not consider highway congestion and delay in the analysis but acknowledged that it could improve the comparison in favor of passenger rail.

2.4 Technologies to Improve Energy Efficiency

Fuel or electricity costs are among the largest operating expenses for passenger railroads. Some of these railroads are trying to attract new ridership using marketing campaigns that portray passenger rail as an environmentally-friendly alternative to the automobile or airplane. Recent emphasis on the energy efficiency and emissions of transportation modes highlights the need for increased research and development of energy-saving and emission-reduction strategies and technologies for passenger rail transportation. This section will review the current status of these technologies and the developmental barriers each faces to be considered implementable by passenger railroads. Several of these technologies/strategies will be applied to case studies analyzing the expected impacts on energy efficiency and emissions in Chapter 8.

Stodolsky (2002) provided a roadmap for railroad and locomotive technology research and development as part of a 2001 effort between the US DOE and a number of industry partners to improve energy efficiency 25% by 2010 and 50% by 2020. This report provided a framework for future research and development efforts to improve rail transportation energy efficiency and reduce emissions. In Canada, Barton and McWha (2012) from the Centre for Surface Transportation Technology of the National Research Council reviewed available technologies to reduce emissions in North America. These documents are the main sources of information used for this review, as they aggregate the findings of many other research efforts and analyze the potential of each technology or strategy at its current state.

2.4.1 Alternative Locomotive Power and Energy Sources

Alternative locomotive power and energy sources are improvements that require significant equipment or infrastructure investments for successful, large-scale implementation in passenger service. Some also face significant technological challenges. However, each technology discussed has the potential to substantially reduce the energy consumption and/or emissions of passenger rail transportation.

Electrification

Electrification of passenger rail lines and equipment is a well-established technology to reduce direct emissions and improve energy efficiency. Electric-traction locomotives or electric-multiple units (EMUs) are inherently more efficient than modern diesel-electric traction technology. Thermal efficiency of electric locomotives, when measured from the pantograph power meter to the work performed by the wheels at the rails, is about 76-84% (Andersson 2012, Hoffrichter et al. 2012). Meanwhile, diesel-electric locomotive efficiency is between 28-30% (Hoffrichter et al. 2012). Electric traction requires infrastructure over the entire line to distribute and deliver power to the electric vehicles in the form of either an overhead contact system (OCS) or an electric third rail. Electric traction is already in use on nearly all rapid transit systems, some commuter rail lines, and also on intercity trains on the Northeast Corridor. However, most intercity and commuter rail systems share infrastructure with freight railroads in North America. It is not economically feasible for freight railroads to electrify operations (Barton & McWha 2012). Consequently, new electrification installations are unlikely unless: the costs of electrification are reduced, diesel fuel prices increase relative to electricity to justify investments, or emissions standards require electrification.

Fuel Cells

According to Stodolsky (2002), fuel cells were 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 & McWha, 2012). Research on these technologies has been increasing due to substantially increased demand for electronic or electrically-operated devices and the consequent need for high-performance batteries to power them. Currently, the fuel cell technologies cited as providing the most potential for rail transportation are 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) (Stodlosky 2002). Extensive implementation of fuel cells in rail transportation would substantially reduce emissions; however, energy efficiency would not improve because the thermal efficiency of fuel cells is roughly equivalent to modern diesel engines.

In order to be considered feasible for rail transportation, there are several barriers to overcome. Infrastructure to produce, store, and transport hydrocarbon fuel sources for fuel cells must be available to produce similar or improved service quality compared to 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. The BNSF railroad has tested hydrogen fuel cell technology in a switching locomotive with reported success (Barton & McWha, 2012).

Dual-Mode Locomotives

Dual-mode locomotives provide motive power from both electric traction infrastructure (discussed above) and on-board diesel-electric traction systems. The New Haven Railroad made use of these beginning in 1957 for trains entering New York City, although they had performance limitations (Swanberg 1988). 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). It also allows for power regeneration technologies where electric traction infrastructure has been installed, leading to further energy savings. This technology is readily implementable, with one commuter railroad (NJ Transit in New Jersey) already utilizing ALP 45DP locomotives in revenue service (Vitins 2012). These locomotives perform equally using both the diesel-electric and electric modes and are able to smoothly switch between them. However, these locomotives can only be implemented in areas with partial or planned electrification, limiting the utility of this technology to certain regions.

Regenerative Braking, Energy Storage, and Optimal Coasting

A moving train possesses significant amounts of kinetic energy that is generally lost to heat in brake applications. This is especially true in downhill situations, where all of the energy required to maintain the desired train speed is supplied by gravitational acceleration. At present, in diesel-electric locomotives, some of the kinetic energy is captured by dynamic brakes that transform the locomotive traction motor into an electric generator, producing electricity that is dissipated in the locomotive resistors rather than as heat at the brakes (Stodlosky 2002). Additionally, dynamic brakes require cooling fans powered by the prime mover during braking. It would be beneficial to capture this lost energy and use it later when the train requires acceleration. However, the ability to make use of this energy is currently limited by the lack of energy storage options required to save the energy for acceleration cycles (Stodlosky 2002).

Recovered energy can also be used for auxiliary power loads (head-end power). In the case of electric traction, surplus energy can be returned to the power supply infrastructure for simultaneous use by other trains consuming traction energy. When there is no simultaneous use for the energy surplus, the energy is dissipated in the locomotive resistors, as is the case with the dynamic braking system (Gonzalez-Gil et al. 2013). In European passenger rail systems, which are often electrified, emissions have reportedly been decreased by 10-20% (Barton & McWha 2012), while fuel savings opportunities are very high as well. Diesel-electric locomotives can take advantage of regenerative braking as well. However, since they are not powered by an electric traction supply system, they require high-density energy storage options to store usable amounts of regenerated energy (Barton & McWha 2012).

Storage options include electrochemical batteries, ultracapacitors and electric flywheels (Stodlosky 2002); however, wayside energy storage options do not currently meet the requirements of affordable, high-density, high-power energy storage. Should research and development improve wayside energy storage in these areas, the possible energy efficiency improvements are significant (Stodlosky 2002). GE is currently developing a diesel-electric locomotive model called the Evolution Hybrid for freight operations that reportedly reduces fuel consumption by up to 15% (Barton & McWha 2012).

Driver Advisory systems also exist for rail systems and can be expected to be most effective for commuter operations where frequent stops are encountered. These software-based systems monitor the speed and location of the train. The system calculates coast and brake rates into a scheduled stop and, when schedule slack is available, advises the driver when to optimally initiate coasting and braking. The success of these systems is dependent on the extent that drivers follow the coast advice, the magnitude and distribution of schedule slack in the system, and the number of stops and braking events.

2.4.2 Fuels

Ultra-Low Sulfur Diesel (ULSD)

The use of ultra-low sulfur diesel (ULSD) does not require significant modifications to locomotive diesel prime movers or refueling infrastructure (Stodlosky 2002). The US and Canada have placed regulations on the sulfur content of diesel fuels used in locomotives, effectively requiring all locomotive diesels to conform to the ULSD standard of 15 ppm sulfur content (Barton & McWha 2012). Emissions testing on diesel fuel containing 50 ppm and 3,190 ppm sulfur content in 2000 reveal reductions in HC emissions by 9%, CO by 10%, NOx by 8% and PM by 24% associated with the 50 ppm sulfur content fuel; a 1% increase in fuel consumption was also reported (Barton & McWha 2012).

Biodiesel

Generally speaking, use of diesel-fuel variants (like biodiesel) does not require significant modifications to the locomotive diesel prime movers or refueling infrastructure (Stodlosky 2002). Biodiesel is a fuel made from a mixture of standard petroleum diesel and fuel made from natural, renewable sources (vegetable oils or animal fats), commonly at a ratio of 4:1 petroleum diesel to biodiesel (B20).

Frey and Graver (2012) conducted testing on biodiesel versus ULSD on conventional passenger equipment from the North Carolina Department of Transportation (NCDOT) fleet, showing a 1% reduction 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 of biodiesel is the renewable sources used in its production; however, biodiesel has not been widely accepted by the North American rail industry because of high production costs and availability concerns (Stodolsky 2002, Barton & McWha 2012). Also, concerns remain about the limited number of producers, the distribution infrastructure, and other elements of the production/distribution process. Similarly, long-term studies could identify potential issues associated with using biodiesel in unmodified diesel prime movers. These studies could also properly quantify the fuel and emissions savings associated with its uses at varying ratios of biodiesel to diesel fuel (Barton & McWha 2012).

Natural Gas

Using natural gas as an alternative fuel source for motive power requires substantial modifications to the locomotive prime mover, on-board fuel storage, and refueling infrastructure compared to current diesel operations (Stodlosky 2002). Natural gas can be used in a compressed or liquefied form. It could become useful in the wake of stringent regulations from the USEPA, since it reduces NO_x and PM emissions compared to diesel. Also, the substantial expansion in natural gas production using hydraulic fracturing has reduced its cost, making it one of the most abundant fuel sources in the US. Natural gas may become more economic than diesel fuel (Barton & McWha 2012). Estimates based on oil prices in 2013 suggest a 55% fuel cost reduction in commuter rail applications when using compressed natural gas (Cook 2014).

Although there has been considerable interest in recent years in developing natural gas as a railroad fuel source, the decline in petroleum prices in late 2014 has substantially reduced the relative economic benefit of its use. Fuel cost savings come directly from low natural gas prices, and not intrinsic elements of the fuel itself; liquefied natural gas is significantly less energy-dense, costing about 60% more per BTU than diesel fuel (Stodlosky 2002). However, there is additional concern about the costs of the fuel supply infrastructure, with cost estimates for an LNG fueling station at about $700,000 (Barton & McWha 2012).

2.4.3 Railcar Design

Railcar design can be optimized further to reduce resistance, and therefore, reduce energy consumption and emissions of the vehicle. An energy efficient passenger coach is light weight and aerodynamic. Passenger coaches continue to improve, with high-speed trains in Europe and Asia substantially reducing axle loads and adding aerodynamic features to support higher-speed operations. However, on a per passenger-mile basis, the most important factor in energy efficiency is the seating density and, ultimately, ridership of each coach (assuming that energy consumption does not substantially increase with more passengers). Space in a passenger coach should be optimized to include the maximum number of seats to move the most passengers per unit energy as possible. In the US, passenger coaches should expect to see significant design weight reductions with anticipated revisions of FRA crashworthiness regulations.

2.4.4 Operations

Driving Behavior

Improving the train-handling behavior of the driver can be one of the most inexpensive yet effective actions to improve fuel efficiency of passenger railroads. Optimization of speed fluctuation, coasting, braking and powering ratios can reduce energy consumption as much as 10-15% (Lukaszewicz 2001). Improved driver training and education on energy recovery techniques, driver performance monitoring, and feedback can improve the driver-acceptance ratio and maximize the energy savings of these systems.

Consist Management

The manipulation of train length and locomotive placement can have an impact on the energy efficiency of passenger train operations (Stodlosky 2002). Analysis of commuter railroad energy data reported to the National Transit Database shows a small fuel savings per vehicle-mile for longer consists, as shown in Chapter 4 Section 5. Also, the length of trains can be optimized to improve the load factor of passenger trains during peak and off-peak periods.

2.5 Conclusions

Many different methods of analyzing the energy efficiency of passenger trains have been used over the past four decades. Statistical methods use aggregated annual energy and transportation productivity data to create annual averages of energy efficiency over whole systems or nationwide. Analytical methods use known relationships to model the efficiency of trains under varying parameters. Empirical analyses use field testing and measurement to determine the energy efficiency of in-service passenger trains on specific routes. Furthermore, each of these analyses measures the energy efficiency of operations at different points in the energy supply system. Some studies draw comparisons between traction types or modes with different energy flow paths, thus neglecting losses at some point (such as electricity generation with electric traction systems). Chapter 3 will address this issue by analyzing the energy efficiency of 25 US commuter rail systems at several key points.

CHAPTER 3: METHODS OF ANALYZING AND COMPARING ENERGY EFFICIENCY OF PASSENGER RAIL SYSTEMS

Earlier versions of this research appeared in:

DiDomenico, G.C. & C.T. Dick. 2015. Methods of Analyzing and Comparing Energy Efficiency of Passenger Rail Systems. Accepted: Transportation Research Record: Journal of the Transportation Research Board. Washington, DC, USA.

3.1 Introduction

Recent studies and published reference values have taken various approaches to quantifying the energy efficiency of passenger rail systems. Perhaps most prominent is the National Transportation Statistics publication released annually by the United States Department of Transportation (USDOT) Bureau of Transportation Statistics. This publication collects energy consumption data from the National Railroad Passenger Corporation (Amtrak) and calculates the energy intensity (energy per unit of transportation productivity) of the Amtrak system on a gross annual average basis. The publication also calculates the gross annual average energy intensities of competing passenger transportation modes, such as automobile, bus, and air. According to this publication, Amtrak consumes 1,628 BTU per passenger-mile, while the average energy intensity of the automobile in the United States (US) was 4,689 BTU per passenger-mile (USDOT 2013a).

Due to their influence on policy decisions, it is important that studies of the environmental benefits of transportation investments accurately and fairly describe the energy efficiency of passenger rail systems and competing modes. To do this, researchers must have a clear understanding of the energy flow through each system. Depending on the propulsion method, energy flows through passenger rail systems along different paths with varying degrees of energy conversion, energy loss, and upstream energy consumption. Significant differences between the energy paths occur due to the use of different fuel types, traction power systems, operating equipment types and geographic location. As a result of these differences, energy efficiency comparisons must be made at equivalent points on each energy path to ensure a fair comparison. As will be shown in the review of previous studies (Section 3.3), it is common for energy efficiency comparisons between systems to be drawn at unequal points along the energy path. Conducting a comparison in this manner may neglect inefficiencies in a particular energy conversion process, tending to produce results that inaccurately favor one fuel type, traction power system, or mode. To improve on these comparisons, this research identifies and demonstrates four methodologies for analyzing the energy efficiency of passenger rail systems. These methodologies ensure accurate and fair energy efficiency analyses of passenger rail systems by examining critical and comparable points along the energy path and clearly defining the system boundaries for each analysis.

Energy efficiency quantifies the amount of useful output a system can achieve per unit energy input. In the case of a passenger rail system, the useful output is passenger transportation. This output is often measured in terms of system capacity (seat-miles) or actual passenger trips (passenger-miles), while the input is energy consumed (liquid fuel, electricity, etc.). Energy intensity, the reciprocal of efficiency, quantifies the amount of energy required to achieve one unit of useful output. Both metrics are frequently used to describe the energy consumption of a system. Variations of these metrics are passenger-miles per unit energy, train-miles per unit energy, vehicle-miles per unit energy, and seat-miles per unit energy. Passenger-miles per unit energy describes the energy efficiency of the system considering the ridership and load factor (percentage of seats occupied by passengers) of the system. Seat-miles per unit energy describes efficiency independent of actual ridership, and is a measure of the potential per-trip efficiency of the system under fully-loaded conditions. The reciprocal of each yields the energy intensity.

For the purpose of this chapter, energy efficiency and intensity were analyzed using seat-miles to exclude the effects of system ridership. However, the methods presented in this chapter can be applied when developing any of the energy consumption metrics described above.

3.2 Electric and Diesel-Electric Traction Energy Flow

Intercity and commuter passenger rail systems in the US rely predominantly on diesel-electric traction. However, there are two commuter services that use electric traction exclusively. Amtrak and several other commuter services use a mixture of diesel-electric, electric, or dual-mode traction. These traction power systems exhibit key differences in the steps required to provide the traction motors with electricity. The different steps involved and their relative efficiencies complicate energy comparisons between different traction power systems. Four critical points of the energy path were identified as upstream energy consumption, energy consumed by the energy conversion process, purchased energy, and energy for traction (Figure 3.1).

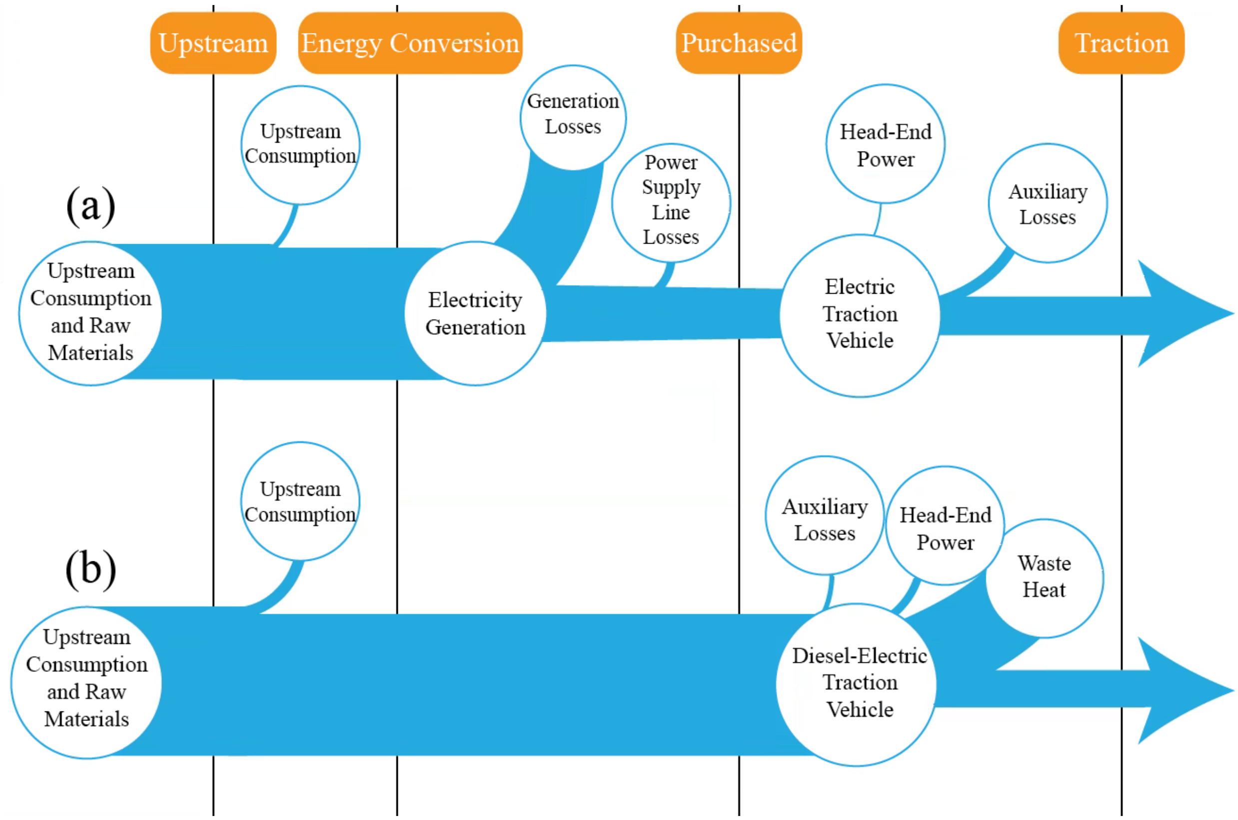


Figure 3.1 Energy path through electric and diesel-electric passenger rail systems. Path (a) represents an electric traction system and path (b) represents a diesel-electric system

For an electric traction system (path a), the *upstream* point includes energy required for exploration, recovery, transportation, refinement of raw materials required for electricity generation, energy used in transmission to the pantograph, as well as the energy content of the raw materials themselves (Wang 2012).

The next point on the path is *energy conversion*, defined as the chemical energy content of the raw materials consumed by electricity generation. Although on a national level, electricity generation in the US is fueled primarily by coal (50%, followed by natural gas at 22%), the source distribution and efficiency of electricity generation can vary significantly by region (Cai et al. 2012). Each method of electricity generation has an associated thermal efficiency, with renewables such as hydroelectricity, solar, and wind being the most efficient. Given the average efficiency of the US generation mix, the useful electrical energy produced by the generation step is only 43% of the total energy consumed during generation. Electricity is then distributed to the pantograph or third-rail collection shoe on the electric train (the *purchased* point) by the traction power supply and distribution system with its associated transmission losses. In Sweden, the efficiency of the traction power supply system from the electrical generating station to the electric train has been estimated to be 85% (Andersson & Lukaszewicz 2006). Finally, before being fed to the traction motors (the *traction* point), electrical energy is subject to the efficiency of the electric rail vehicle itself. For this analysis, the efficiency of an electric locomotive between the *purchased* and *traction* points is assumed to be 76% (Hoffricter et al. 2012). This average value includes the efficiency of the traction motors, internal electronics, transmission, and traction auxiliaries. Note that electric rail vehicle efficiency can vary by specific vehicle models. For example, newer electric high-speed trainsets claim vehicle efficiencies of up to 84% (Andersson 2012). Overall, after combining the losses at each critical point, the total average efficiency from the upstream energy consumption to the traction power at the rails is found to be 27% for the electric traction system.

The energy flow through a system using diesel-electric traction is quite different from the flow through an electric traction system. The upstream point shown on the far left of the diesel-electric traction path in Figure 3.1 (path b) includes energy required for exploration, recovery, transportation, refinement of raw materials, and transporting the refined US diesel fuel to fueling stations. Generation of usable electrical energy occurs on board the diesel-electric vehicle, rather than at an electric generation station. Energy available at the *energy conversion* point, equal to the chemical energy content of the diesel fuel, is the same as the *purchased* energy. The diesel engine drives an electric alternator that produces electricity to power electric traction motors (the *traction* point). Diesel-electric locomotive efficiency between the *purchased* and *traction* points is assumed to be 28% for this analysis, but this can vary between specific locomotive models (Hoffrichter et al. 2012). Overall, after combining the losses at each critical point, the total average efficiency of the system from upstream energy to traction power at the rails is found to be 26% for the diesel-electric traction system. Although the overall efficiency for electric and diesel-electric traction are nearly the same, there can be large discrepancies between the relative efficiency of each traction system at intermediate points along the energy flow path depending on the regional electricity generation mix and specific vehicle models.

3.3 Approaches of Previous Studies

Studies of passenger rail energy efficiency have used varying methodologies, each analyzing the energy efficiency of the system from different points along the energy paths described above. Hopkins (1975) developed a simple equation to calculate passenger train fuel efficiency as a function of train speed and weight per seat with an output in seat-miles per gallon, analyzing between the *purchased* and *traction* points in Figure 3.1. Mittal (1977) determined the energy intensity of passenger rail using statistical (reported annual averages) and analytical (route modeling) methods. Using gross figures for annual fuel consumption and annual passenger-miles to calculate the average BTU per passenger-mile for different train services, Mittal analyzed the national passenger rail system efficiency between the *purchased* point and *traction* points, then compared the results to competing modes.

Barth et al. (1996) estimated emissions for a morning peak commuter rail trip and compared them to an equivalent automobile commute from Riverside, California to downtown Los Angeles. Emissions for the line-haul portion of the commuter rail trip were determined by combining recorded locomotive throttle settings for an actual train with locomotive-specific throttle-notch emissions factors measured with full-scale laboratory testing. The locomotive duty cycle data provided in the paper can be used to deduce the fuel consumption and energy intensity of the Metrolink commuter rail trip between the *purchased* and *traction* points. Frey and Graver (2012) investigated in-service fuel consumption and emissions rates for the Amtrak regional intercity route between Raleigh and Charlotte, North Carolina. They measured direct energy consumption values of in-service trains and calculated the energy efficiency between the *purchased* and *traction* points.

Andersson and Lukaszewicz (2006) conducted a study to compare energy consumption and emissions of modern trainsets to older locomotive-hauled trains and averages for other modes of passenger transportation in Sweden. They analyzed between the *purchased* and *traction* points, thereby ignoring energy consumed in the generation of electricity, resulting in misleading comparisons to modes with on-board internal combustion energy conversion. Garcia (2010) compared the efficiency of conventional rail and high-speed rail to competing modes of transportation on ten different routes in Spain using train simulations to determine the *purchased* energy consumption. The report acknowledged the difficulty in comparing electrified modes of transportation to other modes and each other due to regional and temporal variations of generation. M.J. Bradley & Associates (2014) compared passenger transportation modal energy efficiency and ignored energy used to generate electricity for electric rail modes and electric trolley busses. The author notes that this creates misleading comparisons to modes using gasoline or diesel on-board energy conversion

Messa (2006) conducted an emissions analysis of electric and diesel-multiple unit (DMU) railway vehicles between the *energy conversion* and *traction* points, including the emissions from electricity generation in the comparison. Gbologah et al. (2014) modeled the energy consumption of electric rail transit between the *purchased and traction* points, but calculated emissions using regional emission rates at the *energy conversion* point.

Wacker and Schmid (2002) developed a complete *upstream* energy consumption and emissions model for passenger transportation, including the energy used on a main travel segment, the access/egress of the main segment mode, the energy used in upstream fuel production and supply, and the energy used producing, maintaining, and disposing of transportation vehicles and infrastructure. The study also considers time of day and trip purpose in evaluating passenger trips. Sonnenberg (2010) also employs a full lifecycle assessment, including the upstream and downstream emissions (and implicitly energy consumption) of passenger transportation modes, including US rail operations.

Finally, DiDomenico & Dick (2014) analyzed trends in US commuter rail energy efficiency using purchased diesel volumes and converted purchased electrical energy values, reported in the National Transit Database (NTD), to equivalent volumes of diesel fuel. The conversion process effectively analyzed the efficiency from the *traction* point by accounting for differences in efficiencies and losses between the locomotive tank, traction motors and pantograph. Efficiency is analyzed on a per-gallon basis to facilitate direct comparisons to the highway mode using metrics familiar to the public. This analysis is detailed in Chapter 4.

The inconsistency in methodologies used to analyze energy efficiency has resulted in investigations that make comparisons between passenger rail systems or other modes based on analyses conducted at different points in the energy path. The research described in this chapter presents four standardized methods of analyzing the energy efficiency of passenger rail systems to help researchers and policy-makers conduct and evaluate analyses in a fair and consistent manner.

3.4 Methods of Analyzing Commuter Rail Energy Efficiency

As discussed earlier, energy efficiency of passenger rail systems can be analyzed at four main points along the energy flow path (Figure 3.1). Analysis at each point produces different results, each useful in specific applications. Due to differences in the energy path between electric and diesel-electric systems, it is important to analyze energy efficiency at equivalent points to ensure fair comparisons. To illustrate how this may be accomplished for passenger rail, this section describes four methods of analyzing energy efficiency, one at each of the four main points along the energy flow path. Each method has been applied to a case study of US commuter rail systems using information on purchased diesel fuel, biodiesel fuel, and electricity from the NTD (Federal Transit Administration 2012). However, the methods can be applied to any passenger rail operation and can use other data sources, such as simulation or event recorder data, to establish the duty cycles of passenger rail trips of interest.

3.4.1 Traction Analysis

The traction analysis method considers the energy efficiency of the system at the traction point in Figure 3.1. The *traction analysis* provides a measure of the electric energy used to directly power the wheels and propel the train. This method only considers the energy required to overcome rolling resistance, and is a function of the train consist, system infrastructure and operational characteristics. Therefore, traction analysis provides the most basic measure of the efficiency of passenger rail coaches. It also gives insight into the effect of various infrastructure and operational characteristics, such as grade, curvature, speed profile, and stopping pattern on energy efficiency.

To fairly compare electric and diesel-electric traction systems, electrical energy used by the traction motors must be calculated based on the amount of purchased fuel and electricity (Equation 3.1). In the case of electric traction, energy used by the traction motors is the purchased electrical energy at the pantograph minus the losses and auxiliary loads within the vehicle prior to the traction motors. Traction energy is calculated by multiplying energy purchased from the power supply by the efficiency of the electric locomotive, in this case assumed to be 76% (Andersson & Lukaszewicz 2006). In the case of diesel-electric traction, energy used by the traction motors must be determined from the fuel consumed by the diesel prime mover and any losses and auxiliary power demand within the locomotive between the generator and traction motors. Tests on a calibrated four-axle diesel-electric locomotive with the same diesel prime mover found in the locomotives used on many commuter rail systems have shown that 0.0795 gallons of diesel fuel are consumed per kWh of electricity delivered to the traction motors (Rownd & Newman 1984). This factor has been adjusted for use with systems using biodiesel according to the relative chemical energy content of diesel and B20 biodiesel to yield 0.0753 gallons of B20 per kWh. For systems with dual-mode operation, both calculations are made as appropriate for the amounts of fuel and electricity purchased for the trip. This analysis is modified to use gallons of diesel fuel in Chapter 4 to facilitate comparisons to the highway mode using familiar metrics.

$$E_{Traction} = (E_{Electric} \times C \times e_{Elec.Traction}) + \left[\left(\frac{F_{diesel}}{A_{diesel}} + \frac{F_{B20}}{A_{B20}}\right) \times C\right] \tag{3.1}$$

Where:

$E_{Traction}$ = energy consumed by the traction motors
$E_{electric}$ = purchased electric energy at the catenary (kWh)
$e_{Elec.Traction}$ = efficiency of electric locomotive, assumed to be 0.76
F_{diesel} = diesel fuel consumed (gallons)
F_{B20} = B20 blended biodiesel consumed (gallons)
A_{diesel} = gallons of diesel fuel required to deliver 1 kWh to the traction motors of a diesel-electric vehicle, assumed to be 0.0795 gallons per kWh
A_{B20} = gallons of B20 biodiesel fuel required to deliver 1 kWh to the traction motors of a diesel-electric vehicle, assumed to be 0.0753 gallons per kWh
C = energy unit conversion 3,412 BTU per kWh

Once the traction energy is calculated, energy efficiency and intensity can be calculated (Equations 3.2 and 3.3).

$$Efficiency = \frac{n \times d}{E_{Traction}} \tag{3.2}$$

$$Intensity = \frac{E_{Traction}}{n \times d} \tag{3.3}$$

Where:

n = average number of seats per passenger coach
d = vehicle-miles travelled

3.4.2 Purchased Analysis

The purchased analysis method analyzes energy efficiency between the purchased point and the power at the wheels (Figure 3.1). Purchased energy includes electricity supplied to the traction power supply system and the energy density of the liquid fuel for locomotive internal combustion. This analysis method adds the efficiency of onboard traction power systems and auxiliary losses to the operations, infrastructure, and rolling stock effects captured by the *traction analysis*. This method does not consider upstream energy consumption or energy used in the generation of electric power. Thus, it is not a good comparison point for overall system efficiency. However, since it deals directly with purchased energy, it can provide a good measure of the economic energy efficiency of the operation if the operator's purchase price of various forms of energy is included in the analysis. Therefore, the *purchased analysis* could be very important for commuter rail agencies and operators conducting an economic analysis of operational, infrastructure or equipment changes that may impact energy consumption for a single method of propulsion. It is less useful for making comparisons between propulsion systems.

Because the NTD data provides purchased fuel and electricity, this method is the simplest of those presented in this chapter. Purchased energy consumption, $E_{Purchased}$ (Equation 3.4), is the energy purchased for the movement of the train during normal service duty cycles (including idling). In this case, the equation is merely a unit conversion of the fuel and electricity purchased by each commuter rail agency as reported in the NTD dataset. Purchased energy consumption values could also be supplied by simulation or direct measurements.

$$E_{Purchased} = (F_{diesel} \times \varepsilon_{diesel}) + (F_{B20} \times \varepsilon_{B20}) + (E_{Electric} \times C) \tag{3.4}$$

Where:

$E_{Purchased}$ = purchased energy consumption (BTU)
ε_{diesel} = energy density of diesel fuel (128,450 BTU/gallon) (Frey & Graver 2012)
ε_{B20} = energy density of biodiesel (121,650 BTU/gallon) (Frey & Graver 2012)

Energy efficiency and intensity can be calculated (Equations 3.5 and 3.6).

$$Efficiency = \frac{n \times d}{E_{Purchased}} \tag{3.5}$$

$$Intensity = \frac{E_{Purchased}}{n \times d} \quad (3.6)$$

3.4.3 Energy Conversion Analysis

The energy conversion method analyzes efficiency from the point of energy conversion to the useful power output at the wheels (Figure 3.1). This analysis adds energy used in generating electricity for electric traction vehicles to the purchased electricity and diesel fuel in the *purchased analysis*. In this manner, the *energy conversion* method accounts for energy losses associated with generating electricity in either traction power system. Therefore, this method creates a fair comparison between systems using varying combinations of electric and diesel-electric traction. This method is not as useful as the *traction analysis* for analyzing the energy efficiency of the vehicles themselves because it accounts for the efficiency of outside systems (power generation, power supply system, etc.). This method is also not as useful for an economic analysis of energy efficiency for commuter rail operators using electric traction because it includes energy losses at electrical generating stations that are not owned by the agency (although these losses may contribute to the purchase price of electricity). A commuter rail agency might consider using this method to analyze energy efficiency if mandated to improve energy efficiency and emissions on a regional or statewide level.

For diesel-electric traction, energy input into the conversion process via diesel fuel is the same as the previous calculation of purchased energy. However, to determine the energy input into the conversion process for electric traction, purchased electrical energy must be increased to account for the losses of the generation of electricity (Equation 3.7). Electricity is generated using a variety of methods and fuels that vary by region. In this case, the particular electric generation mix serving each commuter rail system is accounted for using the US regional power generation mixes developed by the US Energy Information Administration (EIA) (USEIA 2014a) and the energy intensity of electricity generation in the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model (Wang 2013). These values include the losses associated with transmission and distribution of electric power from the generating station to the commuter rail system substation (Table 3.1). Since each region has different average generation efficiency, the geographically-appropriate intensity factor, $e_{Generation}$, must be used for each rail system (regions labeled as defined by Census Regions and Divisions map) (USEIA 2014b).

$$E_{Generation} = E_{electric} \times e_{Generation} \tag{3.7}$$

Where:

$E_{Generation}$ = the input energy consumed to generate $E_{electric}$ (BTU)
$E_{electric}$ = the purchased electrical energy (kWh)
$e_{Generation}$ = energy used to generate 1 kWh of purchased electricity (BTU/kWh from Table 3.1)

The energy efficiency and intensity can be analyzed (Equations 3.8 and 3.9).

$$Efficiency = \frac{n \times d}{E_{Purchased} + E_{Generation}} \tag{3.8}$$

$$Intensity = \frac{E_{Purchased} + E_{Generation}}{n \times d} \tag{3.9}$$

Table 3.1 Generation and upstream production energy by region and fuel type (Wang 2013, USEIA 2014a)

US Electric Generation Region	$e_{Generation}$ ($\frac{BTU}{kWh}$)	$e_{Upstream}$ ($\frac{BTU}{MBTU}$)
South Atlantic	8,173	111,038
Middle Atlantic	6,921	103,445
New England	7,167	149,910
West South Central	8,373	137,062
East South Central	8,408	97,845
West North Central	8,735	64,826
East North Central	8,564	77,397
Pacific	5,416	84,174
Mountain	8,357	88,131
Liquid Fuel		$e_{Upstream}$ ($\frac{BTU}{MBTU}$)
US Conventional Diesel	-	200,123
B20 Biodiesel blend	-	327,837

3.4.4 Upstream Analysis

The upstream analysis considers energy efficiency of the entire system from the upstream point to the useful power output at the wheels (Figure 3.1). This analysis incorporates energy used for exploration, recovery, transportation, and refinement of the raw materials fueling electric or diesel-electric traction. It also includes energy used for transporting the refined fuel to fueling stations or transmission to the pantograph. This type of analysis is most appropriate when conducting complete life-cycle assessments of competing modes to determine the overall environmental impact of each large-scale project alternative.

Since it includes all of the steps along the energy flow path, *upstream analysis* is the most complex of the methods discussed in this chapter. The first step in developing the *upstream analysis* is to calculate energy conversion inputs for both electric and diesel-electric traction as described in the previous section (Equations 3.4 and 3.7). The result of the *energy conversion analysis* is then multiplied by appropriate factors to calculate the upstream energy consumed by the exploration, recovery, transportation, and refinement of the raw materials used in electricity generation or the production of liquid fuel. In this case, upstream energy consumption for each fuel type and generation mix is calculated according to Equation 3.10 using the published values in the GREET model (Table 3.1). Note that $e_{Upstream}$ for B20 biodiesel is a weighted average of $e_{Upstream}$ for pure biodiesel (B100) and US conventional diesel (Wang 2013).

$$E_{Upstream} = (E_{generation} \times e_{Upstream}) + \left(E_{Electric} \times C \times e_{Upstream}\right) + (F_{diesel} \times \varepsilon_{diesel} \times e_{Upstream}) + (F_{B20} \times \varepsilon_{B20} \times e_{Upstream}) \tag{3.10}$$

Where:

$E_{Upstream}$ = additional energy consumed to supply the input energy (BTU)
$E_{generation}$ = input energy consumed in electrical generation (BTU)
$e_{Upstream}$ = energy used upstream to generate or produce 1 MBTU of energy (electric or fuel) shown in Table 3.1

Finally, the energy efficiency and intensity can be calculated (Equations 3.11 and 3.12). Since Equation 3.10 only calculates the additional energy consumed upstream, it must be added to the sum of energy from the previous methods to determine the total upstream energy consumption for the system from the *upstream* to *traction* points.

$$Efficiency = \frac{\sum E_{Purchased} + E_{Generation} + E_{Upstream}}{n \times d} \tag{3.11}$$

$$Intensity = \frac{n \times d}{\sum E_{Purchased} + E_{Generation} + E_{Upstream}} \qquad (3.12)$$

3.5 Case Studies of Commuter Rail Systems

The four methods described in this chapter were used to assess the energy efficiency of 25 commuter rail systems in the US (Table 3.2). Table 3.2 is sorted by ranking according to the *traction analysis* to show how the rankings change between the different analysis methods.

It is clear that systems with certain characteristics exhibit a wide variation in their efficiency ranking when analyzed at the four points along the energy path. Two of the systems, SEPTA and NICTD, operate exclusively with electric traction. The *traction analysis* ranked NICTD as the fourth and SEPTA as 17th most efficient system based on BTU per seat-mile. However, using the *purchased analysis*, which considers efficiency with respect to the energy purchased by the transit agency, these two entirely electric systems rose in the rankings to second and third behind only NJ Transit (a system that also uses a large proportion of electric traction). The other systems using a mix of electric traction (Metro-North, Long Island Railroad, Metra and MARC) all increased similarly in their ranking under the *purchased analysis*. This rise is caused by excluding losses associated with the generation of electricity for systems using electric traction and the inclusion on-board energy conversion losses for systems using diesel-electric traction. This penalized the systems using diesel-electric traction, causing them to fall in the rankings.

When the efficiency of electricity generation in each geographic region was accounted for using the *energy conversion analysis*, the same electric traction and mixed systems that rose in the rankings under the *purchased analysis* drop back in the rankings. Overall, the efficiency rankings for the *traction* and *energy conversion* analyses were similar. This suggests that, from the point of *energy conversion*, the efficiency of each commuter rail system was relatively equal, regardless of the use of electric or diesel-electric traction.

Table 3.2 Energy intensity (BTU/seat-mile) of US commuter rail systems in 2012 as calculated and ranked by four different analysis methods

		Traction Analysis		Purchased Analysis		Energy Conversion Analysis		Upstream Analysis		Overall Efficiency
System Name	**Motive Power**	**EI**	**Rank**	**EI**	**Rank**	**EI**	**Rank**	**EI**	**Rank**	
NJ Transit (Commuter)	M	132	1	181	1	354	1	374	1	0.354
Altamont Corridor Express	D	149	2	446	6	446	2	535	3	0.278
NJ Transit (River Line)	D	150	3	450	7	450	3	540	4	0.278
NICTD Chicago South Shore	E	154	4	202	2	508	6	524	2	0.294
NCTD San Diego (Coaster)	D	162	5	485	8	485	4	582	5	0.278
MBTA Boston	D	168	6	503	9	503	5	604	7	0.278
NCTD San Diego (Sprinter)	D	170	7	510	10	510	7	612	9	0.278
Metrolink Los Angeles	D	172	8	515	11	515	8	618	10	0.278
Caltrain San Francisco	D	197	9	591	14	591	11	709	12	0.278
Virginia Railway Express	D	198	10	592	15	592	12	710	13	0.278
Metro-North RR New York	M	204	11	333	4	557	9	603	6	0.339
Northstar Minneapolis	D	204	12	611	16	611	14	733	14	0.278
Long Island Railroad	M	205	13	334	5	558	10	604	8	0.339
Sound Transit Seattle	D	211	14	630	17	630	15	756	16	0.278
New Mexico Rail Runner	D	211	15	631	18	631	16	757	17	0.278
Metra Chicago	M	212	16	561	12	649	17	754	15	0.281
SEPTA Philadelphia	E	227	17	299	3	607	13	638	11	0.357
Front Runner Salt Lake City	D	237	18	709	19	709	18	850	19	0.278
MARC Maryland	M	242	19	587	13	738	19	846	18	0.286
Capital Metro Austin	D	249	20	744	20	744	20	893	20	0.278
TRI-Rail Miami	D	256	21	767	22	767	22	920	21	0.278
TRE Dallas-Ft. Worth	B20	278	22	745	21	745	21	990	22	0.281
DCTA A-Train	D	290	23	869	23	869	23	1,043	23	0.278
Music City Star Nashville	D	291	24	872	24	872	24	1,046	24	0.278
TriMet Portland	B20	434	25	1,165	25	1,165	25	1,547	25	0.281

Efficiency rank sorts systems from most efficient (1) to least efficient (25)
D indicates a system using diesel-electric locomotive power
E indicates a system using electric motive power
M indicates a system using a mix of diesel-electric locomotive and electric motive power
B20 indicates a system using diesel-electric motive power with B20 biodiesel fuel

Examining the *upstream analysis*, there were some small changes in the ranking compared to the *energy conversion analysis*. The systems using larger amounts of electric traction had a reduction in relative efficiency and they decline in ranking due to the upstream energy consumption of electrical generation in each respective geographic region. This effect was amplified because the electrified commuter operations tended to be in the northeast, where the upstream energy associated with electricity generation is higher compared to western regions, where more hydroelectricity and other renewable sources are available. The two systems using B20 biodiesel (TRE in Dallas-Ft. Worth and TriMet in Portland) also experienced more substantial relative reductions in efficiency than other systems when comparing upstream and purchased results. This was attributed to the higher upstream energy consumption required for biodiesel production compared to conventional diesel fuel.

The overall system efficiency, shown in the final column in Table 3.2, was calculated as the ratio of useful traction energy output per unit upstream energy input to measure the cumulative effect of all losses and conversions along the entire energy flow path. All of the diesel-electric rail systems had the same overall efficiency since the analysis was based on the efficiency of a single locomotive model. The rail systems using electric traction either exclusively or in a mix with diesel-electric had higher overall efficiencies than the diesel-electric systems. The exact value is dependent on the regional electricity generation mix of each commuter rail system.

3.6 Operational Characteristics and Energy Efficiency Analysis

Each of the four analyses characterizes a commuter rail operation with a single gross annual average efficiency metric. Beyond the difficulties in accurately analyzing and comparing the energy efficiency of passenger rail systems with different vehicles, traction types, and infrastructure, there are various operational characteristics of commuter rail systems that suggest a single metric may not adequately reflect their energy efficiency. If multiple metrics are developed, the question of which metric is most representative of a certain situation arises.

It is common to analyze transportation system efficiency through gross annual averages using metrics that account for ridership such as BTU per passenger-mile. Like highways, many passenger rail systems experience peak-demand periods each day, usually during the morning and evening commuting hours. Commuter rail systems often have all available seats occupied during peak periods, making those particular trains relatively efficient. However, during off-peak periods, it is common for these trains to have few passengers, making those trains relatively inefficient. For systems that experience large daily fluctuations in the percentage of occupied seats, gross annual averages do not highlight the significantly improved energy efficiency during peak periods or the reduced energy efficiency during off-peak hours. DiDomenico & Dick (2014) illustrated the potential efficiency differences when considering average load factor, as shown in Chapter 4. For three similar diesel-electric commuter rail systems in 2011, the annual average efficiency considering average load factor was 40 passenger-miles per gallon, compared to 198 seat-miles per gallon under peak loads. During peak periods, the efficiency of these systems is likely closer to the efficiency measured by seat-miles per gallon (or may even exceed this number if standing passengers are allowed). During off-peak operation with below-average load factors, certain trains will not even reach the average of 40 passenger-miles per gallon. This presents a large range of possible trip efficiencies from a per-passenger perspective.

To avoid inefficient trips, several commuter rail systems, particularly newly developed systems, only operate during peak weekday periods, resulting in improved annual energy efficiency at the expense of reduced equipment utilization. However, it has been noted by Kohn (2000) that decreasing service frequency correlates with decreasing urban transit ridership, potentially limiting the passenger demand side of the efficiency calculation. Conversely, systems experiencing growing ridership have increased seating capacity and off-peak service frequency using more complex scheduling patterns (zonal, skip-stop, etc.) (Allen & Levinson 2014). When analyzing energy efficiency, gross annual averages may best reflect the overall efficiency of a passenger rail system including peak and off-peak operations. Conversely, analyses during peak periods should account for the increased passenger railway efficiency under peak loads.

Another drawback of using gross annual averages to measure modal efficiency is that this method averages many trips on a single mode in isolation. Commuter trips often involve other modes of transportation to access the commuter rail station and reach the passenger's final destination. The gross annual average measures the efficiency of the rail portion of the trip, but in a society increasingly conscious of its environmental impact, passengers may evaluate their individual trip energy efficiency from a door-to-door perspective. Door-to-door energy efficiency for a single trip considers the efficiency of all trip segments including the access/egress modes at either end. For example, a commuter might travel downtown using a city bus to access the commuter rail station, then walk to their final destination from the downtown rail station. This trip would likely result in improved energy efficiency per passenger-mile compared to a trip made entirely by light-duty vehicle with the commuter as its sole occupant. Door-to-door energy efficiency analyses are useful in modal comparisons considering individual passenger behavior for specific trips, rather than analyzing entire transportation systems. In the future, to complement time, distance and congestion metrics, door-to-door energy analysis could be included in mapping software such as Google Maps to encourage passengers to consider efficient transportation alternatives.

The advantage of door-to-door analyses is that energy efficiency can be examined from a single-passenger perspective over a specific trip. However, for public transportation systems such as commuter rail, the per-passenger-mile energy efficiency of a trip by one passenger is influenced by the actions of other commuters as they board and disembark from the train. Thus, when considering an individual trip, the load factor and energy efficiency per passenger-mile will fluctuate at each passenger station on a given line. For example, an inbound train may pick up a small number of passengers at the first station but be full by the end of the trip (Figure 3.2). An end-to-end analysis for passengers boarding at the first station would show the first portion being relatively energy intense as the energy consumed by the train is divided between few passengers. By the end of the line, the efficiency would have improved dramatically as the train filled. The last passenger boarding the train may claim to have the most efficient trip. However, if it were not for the initial inefficient miles, the last passenger boarding the train would not have a train to board at all, and therefore should equally share the energy consumed during the entire trip. For individual trips, using average load factors along a route for specific trains or times of day eliminates complications due to these fluctuations.

For many purposes, energy efficiency calculations only consider the energy consumed by revenue commuter train movements. However, in order to operate a revenue train, energy must be consumed by non-revenue activities. Without direct measurement or simulation, it is difficult to separate energy consumed by non-revenue activities from gross totals of purchased energy. Von Rozycki et al. (2003) conducted a unique assessment of the energy consumed by the high-speed service between Hanover and Wuerzburg, Germany, and found the "overhead energy" consumed in making up and servicing the train to be 1.20 kWh per train-km (6,590 BTU per train-mile). Researchers must define the activities that are included in energy efficiency analyses.

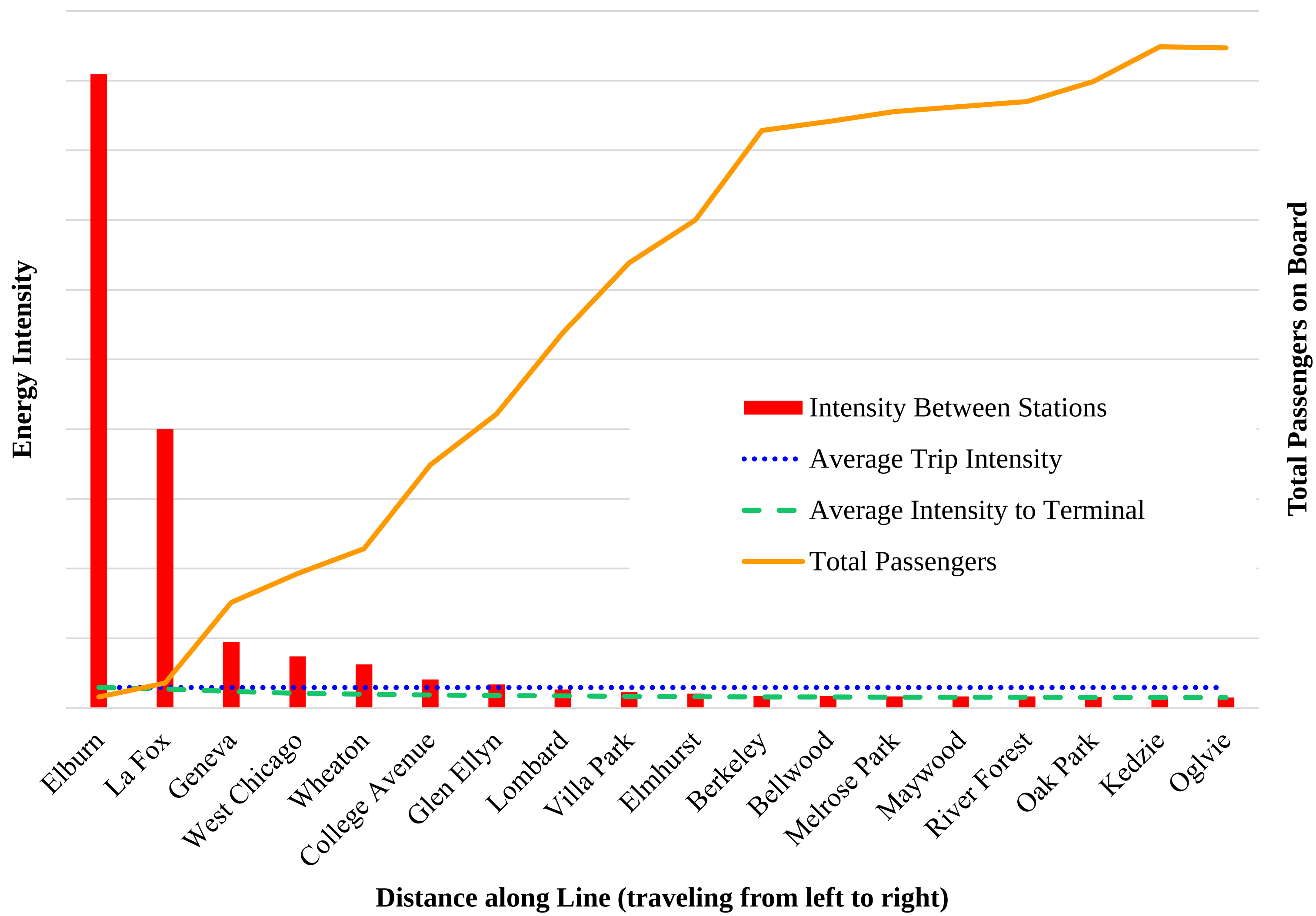


Figure 3.2 Variation in efficiency due to ridership on inbound peak-period train on Metra UP West line

3.7 Analogies for the Analysis of Other Modes

Energy efficiency analyses for other transportation modes are subject to complications similar to those discussed here in the context of commuter rail. Each mode and its corresponding fuel types have varying energy paths with different efficiencies and losses in the system. It is important to understand the energy flow of each mode being analyzed and choose system boundaries that make an accurate and fair comparison possible.

Modes that use on-board liquid fuel combustion have an energy path similar to the diesel-electric passenger rail system (Figure 3.1b). Upstream energy consumption, chemical fuel density, and efficiencies of the vehicles will vary depending on the combination of mode and fuel, but the energy path and processes are analogous for the purposes of energy efficiency analysis. Plug-in electric vehicles have an energy path similar to that of the electric passenger rail system in Figure 3.1a. Parallel and series hybrid highway vehicles, with or without plug-in capability, have a more complex energy flow, but through careful accounting of all energy flows and losses, equivalent points on the flow path can be defined to facilitate meaningful comparisons to other vehicles. Comparisons of the energy efficiency of commuter rail and competing passenger travel modes is investigated further in Chapter 9.

3.8 Conclusions

Energy flows through passenger rail systems differ with fuel type, traction power, equipment, and geographic location. Despite these differences, passenger rail energy efficiency can be analyzed and compared at four common points on the energy flow path. Corresponding to these four points, four methods to analyze passenger rail system energy efficiency have been described: *traction analysis*, *purchased analysis*, *energy conversion analysis* and *upstream analysis*. These methods were used to analyze 25 US commuter rail systems to illustrate the similarities and differences of intensity rankings produced by each method. For systems using a large proportion of electric traction, the results showed significant changes in relative energy efficiency between analysis methods. Variation in the relative energy efficiency between the four analysis methods highlighted the importance of conducting energy efficiency comparisons between traction types or modes at meaningful points along the energy path. Comparing the energy efficiency of one system to another at unequal points along the energy path can produce results that overstate the relative efficiency of a fuel, vehicle type, traction type, operation, or mode. Researchers must have a clear understanding of the energy path for each system being analyzed to ensure consistent comparisons. By better understanding the challenges of energy efficiency analyses and the methodology described here, practitioners can make more informed decisions regarding the appropriate method of analysis to draw accurate comparisons between passenger rail systems and competing modes.

CHAPTER 4: ANALYSIS OF TRENDS IN COMMUTER RAIL ENERGY EFFICIENCY

Earlier versions of this research appeared in:

DiDomenico, G.C. & C.T. Dick. 2014. Analysis of Trends in Commuter Rail Energy Efficiency. In: Proceedings of the 2014 Joint Rail Conference. American Society of Mechanical Engineers (ASME). Colorado Springs, CO, USA.

4.1 Introduction

Increasing highway transportation demand has led to greater traffic congestion and associated energy efficiency and emissions concerns, especially in metropolitan areas. Consequently, there is greater need to account for these in urban and regional planning. In 2011, the average energy intensity (proportional to emissions intensity for combustion-based systems) of the automobile in the United States (US) was 4,689 BTU per passenger-mile (USDOT 2013a), while commuter rail systems measured 2,348 BTU per passenger-mile. Furthermore, fluctuations in fuel prices have led more commuters to consider rail as an effective alternative to highway travel. Statistical analyses reveal that increases in commuter rail ridership can be correlated to fuel price increases, with as much as a 0.1% increase in ridership for every $0.01 increase in fuel price (Haire & Machemehl 2007).

Commuter rail operations can be categorized into “legacy systems” (those systems using long-established routes historically operated by private railroads) and “new-start systems” (those originally established by public agencies after 1980) (Brock & Souleyrette 2013). This research analyzes the energy efficiency trends of 23 commuter rail systems in the US. Of these, nine are classified as legacy systems and 14 as new-start systems, with eight of these new-start systems commencing operations in the past decade (Brock & Souleyrette 2013).

While ridership has increased for many reasons, both legacy and new-start commuter rail systems have developed marketing campaigns around their fuel efficiency and general perception as a “green” mode of transportation by potential riders. One of the key benefits cited to justify investment in the newest commuter rail systems is the resulting environmental benefit from reduced highway congestion and emissions. For example, considering a commute between Riverside and downtown Los Angeles, California, the total amount of emissions (CO, NO_x, HC, and PM) are less when commuting by the Metrolink commuter rail system than by automobile

(Barth et al. 1996). Although the gross average modal energy intensity statistics from the United States Department of Transportation (USDOT) support the results of this approach, there are many factors that can influence the energy efficiency of a particular commuter rail system relative to competing modes for specific trips. Thus, the commuter rail systems in the US vary greatly from one another in both structure and efficiency, as will be demonstrated. Commuter rail systems are uniquely adapted to the needs and characteristics of the metropolitan area they serve. For example, some systems operate from suburban areas to downtown, while others operate between two downtown areas or two suburban population centers. Some systems operate only during peak periods on weekdays while others provide comprehensive service seven days per week. The systems also employ different combinations of rolling stock, traction types, and energy supply with varying inherent efficiencies (Chapter 3).

By analyzing the trends in energy efficiency of these commuter rail systems in relation to system and operating characteristics, this research can provide policy makers with information to make more informed decisions regarding the environmental benefits of commuter rail systems in the future. Understanding the trends in energy efficiency of commuter rail in the US is important as these systems continue to attract new riders, and continue to become more prevalent in major metropolitan areas with strong public support for expansion.

4.2 National Transit Database

Data used in this analysis were obtained from the National Transit Database (NTD). Recipients or beneficiaries of Federal Transit Administration grants are mandated by Congress to report various statistics related to revenue, expenses, ridership, operations, and safety that are summarized in the NTD (2013). Annually reported operating statistics such as fuel/power purchased for revenue service, passenger-miles, train-miles, vehicle-miles, train-hours, and ridership are the foundation for this study.

The NTD dataset has advantages and limitations that must be acknowledged. First, the datasets used in this study represent annual system-wide characteristics, fitting the high-level scope of analyzing historic trends in commuter rail energy efficiency. As discussed in Chapter 3, data should not be interpreted as an accurate representation of the efficiency of individual train or passenger trips. Many commuter rail systems have multiple lines that operate very differently with trains of varying length. A commuter rail system may even operate both diesel-electric traction and electric-traction locomotives. In all cases, the operator will aggregate the reported statistics on a system-wide basis. However, the commuter rail statistics are reported separately from rapid transit operations that may be managed by the same agency.

While the NTD datasets are quite detailed, there are some statistics related to operations and efficiency that are not reported directly. In this research, these statistics were derived from combinations of other reported metrics. For example, the average number of passengers per car can be calculated by dividing the reported passenger-miles by revenue vehicle-miles. Derivations of all metrics used in this analysis are defined in the methodology section.

4.3 Comparing the Efficiency of Diesel-Electric and Electric Propulsion

Several commuter rail systems in the US use electric propulsion in some (or all) of their operations, while others only use diesel-electric propulsion. Some systems even employ dual-mode locomotives that use diesel-electric propulsion for part of their trip and electric propulsion for the remainder. Correspondingly, commuter rail systems report both fuel consumption in gallons and electricity consumption in kilowatt-hours (kWh) to the NTD where appropriate. The use of two energy sources complicates direct comparisons of efficiency metrics between systems, as well as compared to the highway mode on the "per-gallon" basis familiar to the general public.

The fact that electric locomotives are intrinsically more efficient than diesel-electric locomotives further obscures energy efficiency comparisons. Thermal efficiency of electric locomotives, when measured from the pantograph (or power meter) to the work performed by the wheels at the rails, is approximately 76-85% (Andersson 2012, Hoffrichter et al. 2012). Meanwhile, diesel-electric locomotive efficiency is between 28-30% (Hoffrichter et al. 2012). As described in Chapter 3, this intrinsic difference in the efficiency of electric and diesel-electric propulsion skews simple comparisons of energy efficiency as measured by purchased fuel or electricity reported in the NTD. A tank or meter to wheels comparison ignores significant losses associated with energy conversion prior to delivery of electricity to the pantograph. While the conversion of fuel to electricity for traction and associated losses takes place on board the diesel-electric locomotive, electricity is delivered to the electric locomotive after fuel was converted at a remote generating station. The losses due to transmission from that point to the train are generally not accounted for when considering the efficiency of an electric train.

Although a complete "well-to-wheels" *upstream* analysis on a per-BTU basis does account for these generation losses to provide a truer comparison with diesel, such comparisons are highly influenced by the varying efficiency of the different energy sources comprising the generation profile supplying electric power to the commuter rail operator. Thus, two systems with identical ridership and rail operations can have widely varying efficiency based solely on the generation of electricity from coal as opposed to renewable energy sources. A complete accounting such as this is important for understanding the environmental benefits of commuter rail; however, in this analysis, it is more interesting to compare the effects of system operating characteristics (ridership, number of cars per train, average train speed, etc.) that are under control of the operator on energy efficiency. To isolate these relationships, the intrinsic efficiency differences of electric propulsion must be normalized. In other words, it is necessary to analyze the efficiency of the electric trains as if they were obtaining their energy in the same manner and with the same thermal efficiency as a diesel-electric train.

To make this comparison, the electric energy used to power electric locomotives was converted to an equivalent volume of diesel fuel while accounting for the differences in efficiency between the locomotive tank, wheels and pantograph. This is a modified version of the *traction* analysis presented in Chapter 3, using gallons of diesel fuel as the energy unit to facilitate comparisons to common auto efficiency metrics. Based on the efficiency of electric locomotives, it was assumed that 85% of the energy (kWh) reported to the NTD was consumed by the electric traction motors to provide propulsion (Lukaszewicz 2001). This energy consumed for traction is what was of interest in this study. Tests on a calibrated, four-axle, diesel-electric locomotive with the same diesel prime mover found in the locomotives used on many commuter rail systems have shown that 0.0795 gallons of diesel fuel were consumed per kWh of electricity delivered to the traction motors (Rownd & Newman 1984). This factor was used to convert the electrical energy consumed in the traction motors of the electric locomotives into an equivalent amount of diesel fuel. Combining the 85% and 0.0795 gallons/kWh factors, each kWh of electricity reported to the NTD was equivalent to 0.068 gallons of diesel fuel in this analysis. Since this captures the efficiency of the operation regardless of propulsion type, these diesel fuel equivalent (DFE) gallons were used to calculate efficiency metrics that are easily compared to diesel-only systems and the highway mode (Equation 4.1).

$$DFE\ (gal) = 0.068\ \times\ E\ (kWh) \tag{4.1}$$

4.4 Methodology

NTD data detailing energy consumption, train operations, and service characteristics were obtained for the years 1997 through 2011 for all reporting commuter rail operators in the US (Table 4.1). This list also includes several systems defined as hybrid rail that use diesel multiple-units (DMU) and provide similar service to traditional commuter rail. Not all of the operators reported data every year during the study period. Also, the span of reported data from each system does not necessarily correspond to the beginning of operations. For various reasons, several of the newer systems did not begin reporting energy consumption data until 2009, despite operating prior to that year.

Table 4.1 List of commuter rail operators analyzed

State	System Name	[a]Mode	Years
CA	Coaster and Sprinter (NCTD)	CR, YR	2009-2011
CA	Caltrain (PCJPB)	CR	2009-2011
CA	Metrolink (Southern California Regional Rail Authority)	CR	1997-2001 2009-2011
CA	Altamont Commuter Express (ACE)	CR	2009-2011
FL	South Florida Regional Transportation Authority (Tri-Rail)	CR	2009-2011
IL	Metra (NIRCRC)	CR	1997-2011
IN	South Shore Line (NICTD)	CR	1997-2011
MA	Massachusetts Bay Transportation Authority (MBTA)	CR	1998-2001 2002-2007 2009-2011
MD	Maryland Transit Administration (MARC)	CR	2009-2011
MN	NorthStar (Metro Transit)	CR	2009-2011
NJ	New Jersey Transit Corporation (NJ TRANSIT)	CR, YR	[b]1997-2011
NM	Rail Runner Express (RMRTD)	CR	2009-2011
NY	Metro-North Commuter Railroad Company (MTA-MNCR)	CR	1997-2011
NY	MTA Long Island Rail Road (MTA LIRR)	CR	1997-2011
OR	Westside Express Service (Tri-Met)	YR	2009-2011
PA	Southeastern Pennsylvania Transportation Authority (SEPTA)	CR	1997-2011
TN	Music City Star (RTA)	CR	2009, 2011
TX	Capital MetroRail (CMTA)	YR	2010-2011
TX	Trinity Railway Express (TRE)	CR	2009-2011
TX	A-Train (DCTA)	YR	2011
UT	FrontRunner (UTA)	CR	2008-2011
VA	Virginia Railway Express (VRE)	CR	2009-2011
WA	Sounder (Sound Transit)	CR	2009-2011

[a]CR: Commuter Rail YR: Hybrid-rail (commuter rail service using diesel multiple-units)
[b]NJ Transit data from 2000 was excluded from the analysis due to data errors

Energy consumption reported in the NTD accounts for the volume of liquid fuels (diesel or biodiesel) and the electrical energy (kWh) purchased for use in revenue service. Reported service operations data include passenger-miles, unlinked passenger-trips, and vehicle-miles.

For commuter rail, vehicles are individual passenger coaches on a locomotive-hauled train or individual passenger-carrying units comprising a self-powered electric-multiple or diesel-multiple unit (EMU or DMU) train. Train operations data include train-hours and train-miles. These data were used to derive a number interesting statistics of interest in this study. Metrics used to describe energy efficiency of the system are passenger-miles per gallon, train-miles per gallon, vehicle-miles per gallon, and seat-miles per gallon. Passenger-miles per gallon describes the energy efficiency of the system considering the ridership and load factor (percentage of seats occupied by passengers) of the system (Equation 4.2). Train-miles per gallon describes the energy efficiency of the entire train and is influenced by the length of the train (Equation 4.3). Vehicle-miles per gallon describes the efficiency of each railcar on a train, and is probably the best measure of the inherent efficiency of the system rolling stock design and infrastructure (Equation 4.4). Seat-miles per gallon describes efficiency independent of ridership and is a measure of the potential per-trip efficiency of the system under fully loaded conditions (Equation 4.5). Estimations of the seating capacity of the average car for each system were gathered independently of the NTD data from operator websites.

$$\frac{Passenger-miles}{gallon}=\frac{Passenger-miles}{DFE\ (gal)} \tag{4.2}$$

$$\frac{Train-miles}{gallon}=\frac{Train-miles}{DFE\ (gal)} \tag{4.3}$$

$$\frac{Vehicle-miles}{gallon}=\frac{Vehicle-miles}{DFE\ (gal)} \tag{4.4}$$

$$\frac{Seat-miles}{gallon}=\frac{Seating\ Capacity\ \times\ Vehicle-miles}{DFE\ (gal)} \tag{4.5}$$

Other statistics related to the operating characteristics of each system were derived from the reported data (Equations 4.6 to 4.11).

$$Passengers\ per\ Train = \frac{Passenger - miles}{Train - miles} \tag{4.6}$$

$$Trip\ Length\ (miles) = \frac{Passenger - miles}{Unlinked\ Passenger\ Trips} \tag{4.7}$$

$$Average\ Train\ Speed = \frac{Train - miles}{Train - hours} \tag{4.8}$$

$$Passengers\ per\ Car = \frac{Passenger - miles}{Vehicle - miles} \tag{4.9}$$

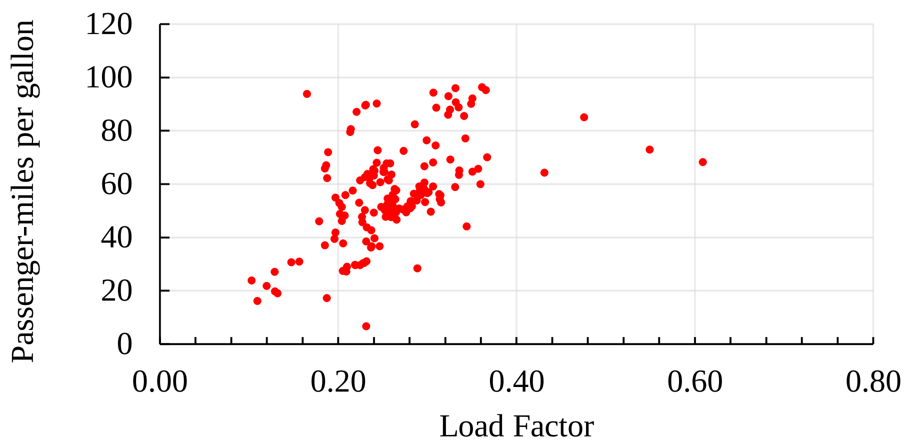
$$Cars\ per\ Train = \frac{Vehicle - miles}{Train - miles} \tag{4.10}$$

$$Average\ Load\ Factor = \frac{Passengers\ per\ Car}{Seating\ Capacity} \tag{4.11}$$

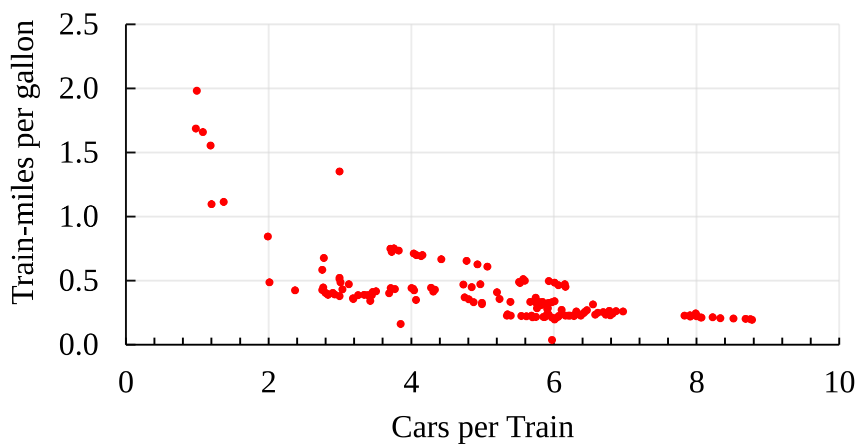
These statistics were calculated for each commuter rail system reporting data in the years 1997 to 2011. Then, national averages of all commuter rail systems in the US were calculated over the same time span, accounting for the size of each system by deriving each statistic using the sum of the respective factors, rather than taking arithmetic averages of each system's efficiency. The results for established individual systems reporting data over the majority of the study period were also analyzed as case studies. Case studies of SEPTA in Philadelphia, Pennsylvania and Metra in Chicago, Illinois are discussed in this chapter.

4.5 Fundamental Relationships

The efficiency of a commuter rail system is influenced by operating characteristics that vary with each system. Efficiency can change with the load factor, number of cars per train, the length of each trip, and several other characteristics derived in the methodology section. To determine if the NTD data exhibited the expected intuitive fundamental relationships between operating characteristics and various efficiency metrics, the efficiency of each individual system during a given year was plotted against different operating parameters to create point clouds (Figure 4.1). Although there was much variation given the wide range of conditions present on the various systems, the data illustrate the expected fundamental relationships. For example, passenger-miles per gallon increased as the load factor increases, indicating the importance of filling the train with passengers to increase energy efficiency (Figure 4.1a). Efficiency with respect to train-miles per gallon decreased as the number of cars per train increases (Figure 4.1b). This illustrated the effect of longer and heavier trains, increasing fuel consumption and reducing energy efficiency per train-mile. Although not shown in the figure, the data also suggested that as the length of the average passenger trip increased, the efficiency of the train with respect to passenger-miles per gallon did as well. Presumably this relationship arose from a combination of higher load factor on systems with longer trips and efficiencies gained from making less frequent starts and stops. Finally, efficiency with respect to vehicle-miles per gallon followed the expected trend of a slight improvement with increases in the number of cars per train due to aerodynamic effects and the distribution of the locomotive rolling resistance over more trailing vehicles.



(a)



(b)

Figure 4.1 Fundamental relationships of energy efficiency and operating characteristics

These fundamental relationships are helpful in analyzing the causes of changes in efficiency over time in the national system and the case studies of individual systems. Each chart also illustrates the wide variation in efficiency between each system. Each commuter rail system has unique operating characteristics influencing efficiency and causing large variations when comparing results between systems.

4.6 National Historic Averages

The efficiency of the average automobile (passenger-miles per gallon) declined slightly during the study period, most likely due to the reduction in average vehicle occupancy, rather than a reduction in vehicle efficiency (Figure 4.2). When compared to the results of the historic energy efficiency analysis of commuter rail systems in the US (Figure 4.3), the average efficiency of the commuter rail systems was at least 1.7 times more efficient than the average automobile in any year studied.

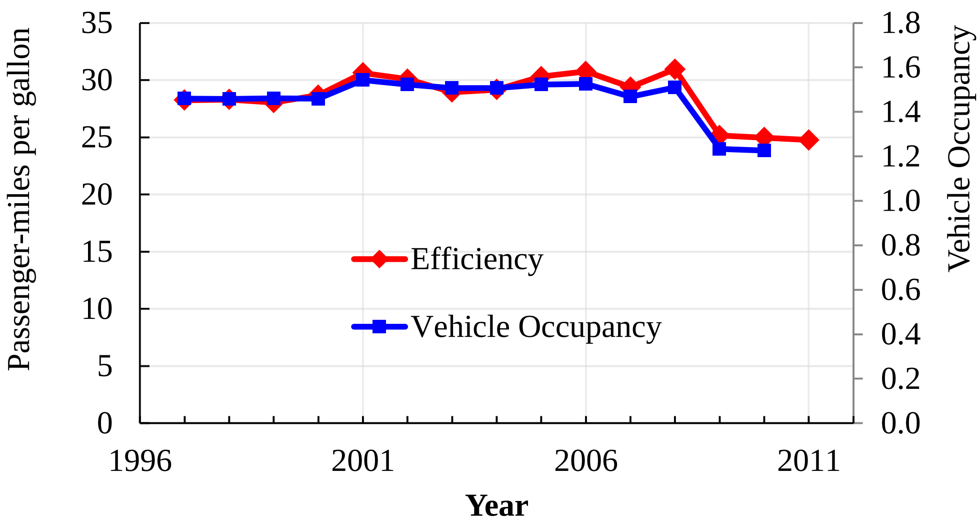
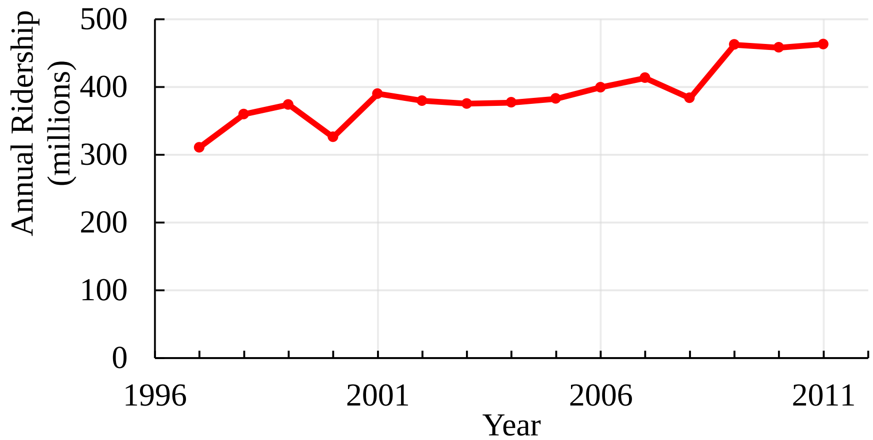


Figure 4.2 Trends in US Automobile Efficiency and Load Factor (USDOT 2013a)



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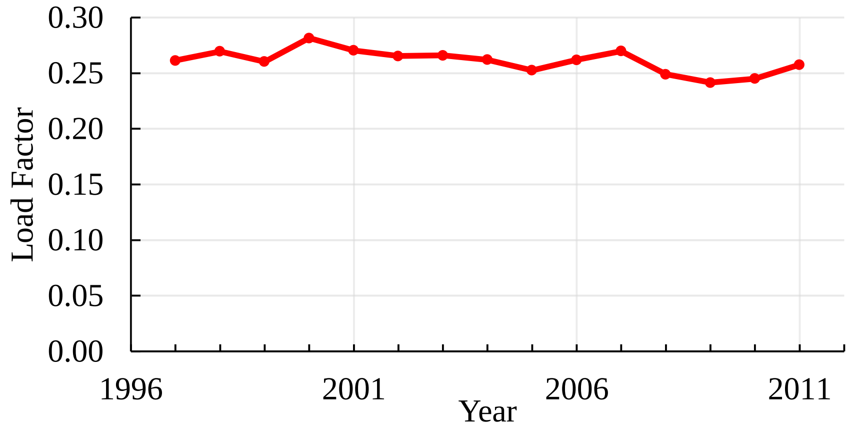

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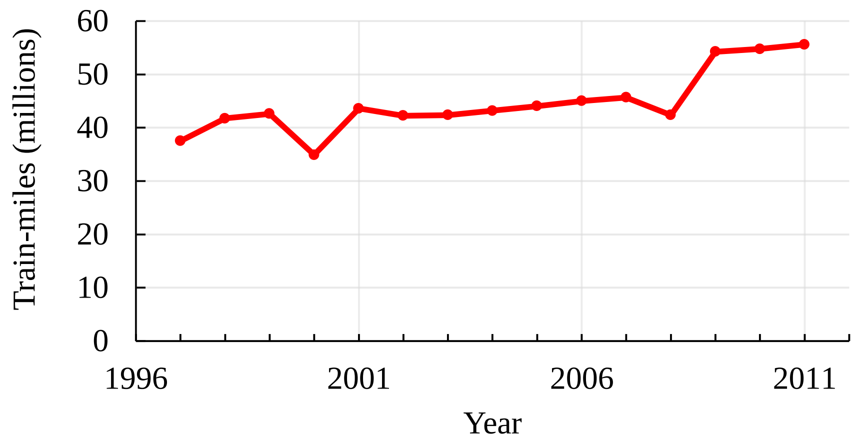
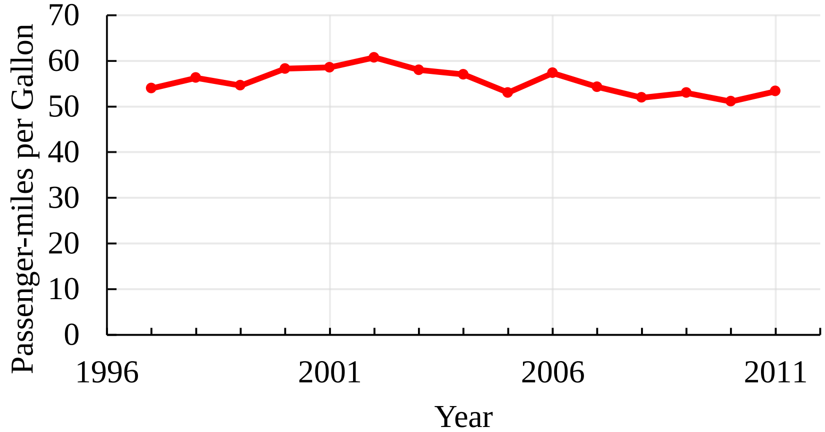
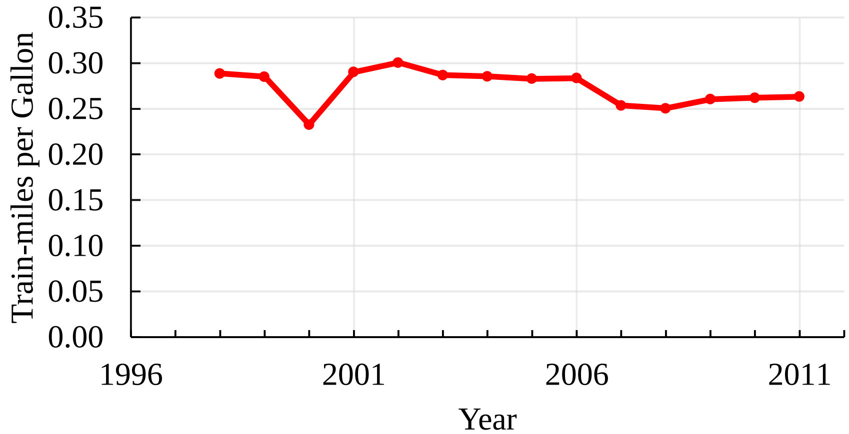


(c)

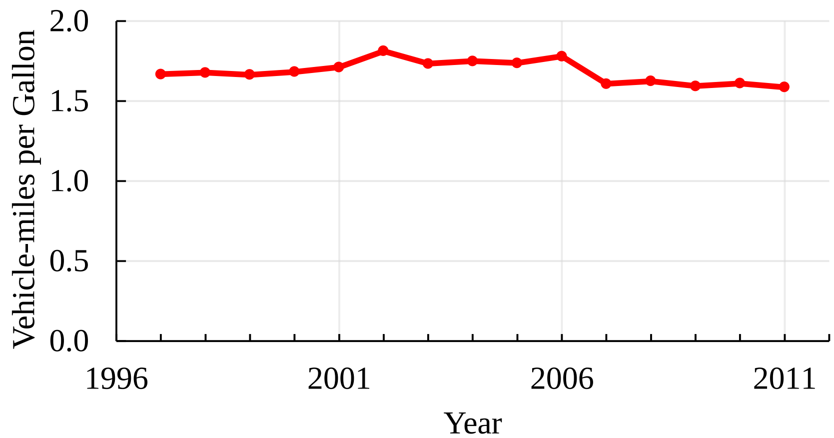
Figure 4.3 National average historic trends in ridership (a), load factor (b), and train-miles (c) of commuter rail systems in the US



(d)



(e)



(f)

Figure 4.3 (cont.) National average historic trends in passenger-miles per gallon (d), train-miles per gallon (e), and vehicle-miles per gallon (f) of commuter rail systems in the US

It is interesting that ridership has increased so rapidly, yet the passenger-miles per gallon efficiency remained steady over the same period (or even decreased slightly in recent years). This trend can be attributed to several factors. One cause could be that operators are responding to increases in ridership with greater increases in train frequency (Figure 4.3c) and cars per train than necessary. This scenario results in an increased number of empty seats per train, offsetting the efficiency gains from the higher ridership. This may help explain the trends in Figure 4.3, as adding additional cars to trains would reduce the train-miles per gallon metric, and an influx of larger, heavier bi-level railcars with additional seating capacity would reduce vehicle-miles per gallon. Both of these trends would also be consistent with aging locomotive fleets, nearing heavy engine maintenance and rebuilding, that become less efficient in terms of train and vehicle-miles with time (Frey & Graver 2012).

The efficiencies of individual systems in any year varied widely from the annual gross averages shown above. In 2009, the standard deviation of the passenger-miles per gallon metric was 19.6 passenger-miles per gallon. Variations in energy efficiency of individual systems in any given year can be attributed to a number of factors, most of them operating characteristics. Some potential factors are the load factor, number of passengers per car, the number of cars per train, the frequency of stops, and the average speed.

4.7 Comparing Legacy and New-Start Systems

Since the systems included in the national averages varied over time, it is possible that recent trends were driven more by the inclusion of newer systems in the dataset as opposed to any actual trends in efficiency. In an effort to control for this, the average efficiencies of the legacy systems from 2009-2011 were compared to the new-start systems (Table 4.2).

The ridership of the 14 new-start systems was only a fraction of the ridership of the nine legacy systems, with the load factor of both categories about the same. However, the efficiency

Table 4.2 Legacy and new-start system metrics (2009-2011 average)

Metric	Legacy Systems	New-start systems
Ridership	429,833,147	31,407,389
Load Factor	0.26	0.24
Train-miles per gallon	0.25	0.41
Passenger-miles per gallon	52	58
Vehicle-miles per gallon	1.60	1.53

measured by passenger-mile per gallon and train-miles per gallon of the new-start systems was noticeably higher than the legacy systems; however, the load factor did not increase. This suggests that the new-start systems had more efficient rolling stock and were operating shorter trains with greater capacity per car. In many cases, the new-start systems were employing two or three-car trains of bi-level coaches and a modern, efficient locomotive while the legacy systems operate longer trains (four to seven cars), often of single-level cars, with much older locomotives.

When carrying the same number of passengers at the same load factor, the former operation tended to be more efficient than the latter. The longer trains of the legacy systems allowed them to obtain economies of scale and produce more vehicle-miles per gallon than the new-start systems.

The greater efficiency of the new-start systems could also be due to the operating characteristics of new-start systems being more closely tailored to the specific peak ridership patterns and needs of the area (i.e. peak-only service), while the legacy systems were operating a more comprehensive schedule of service that may not be efficient for the modern commuting needs of the area. Although, as discussed in Chapter 3, Kohn (2000) found that decreasing service frequency correlates with decreasing urban transit ridership, potentially limiting the passenger demand side of the efficiency calculation.

4.8 Locomotive-Hauled and DMU systems

To investigate the effects of equipment characteristics on efficiency, two groups of operators using identical rolling stock were compared. One group used locomotive-hauled, diesel-electric propulsion and bi-level railcars while the second group used modern self-propelled, light-weight, single-level DMU railcars.

Three new-start systems used the same model of MotivePower MPXpress locomotives and similar numbers of identical Bombardier bi-level passenger railcars (Table 4.3). With any variation due to equipment and train make-up removed, the three systems achieved similar efficiencies (seat-mile per gallon). In 2011, the efficiencies (seat-miles per gallon) varied by less than 13% (Table 4.3), indicating the importance of infrastructure and operating practices on energy efficiency when ridership and equipment are held constant.

Five of the systems used self-propelled DMU railcars, with three of these using European

Table 4.3 Comparison of locomotive-hauled and self-propelled DMU systems

Locomotive-Hauled Diesel-Electric Systems (Similar Equipment)		
System	Passenger-miles per gallon	Seat-miles per gallon
Front Runner (UTA)	30	207
Rail Runner Express (RMRTD)	49	185
Northstar (Metro Transit)	48	209
Average	40	198
European DMU Systems		
Sprinter (NCTD)	64	230
River Line (NJ Transit)	62	200
Capital MetroRail (CMTA)	56	214
Average	62	210

DMUs (Table 4.3) under FRA waivers and temporal separation from conventional rail traffic. The seat-miles per gallon metric of the three systems using modern European DMUs varied less than eight percent. Again, this shows the magnitude of the variation that can be attributed to infrastructure and operating characteristics when the effects of ridership and equipment differences were normalized (by comparing the seat-miles per gallon metric systems between very similar DMUs).

Comparing the two types of equipment, the five systems that used DMUs achieved 198 seat-miles per gallon, and the subset of three European DMUs achieved an average of 210 seat-miles per gallon on average in 2011. For comparison, the average of all diesel-electric locomotive-hauled systems achieved an average of 226 seat-miles per gallon in 2011 and the three new-start systems using similar equipment averaged 198. These results differed from an analysis done by Messa (2006) that concluded DMUs or trains of double-deck DMUs pulling trailers always produced less emissions (and correspondingly consume less fuel) per seat-mile than locomotive-hauled trains. Messa's results were derived from train performance simulation and testing of FRA-compliant DMUs, rather than European DMUs. Since modern European DMUs have been in operation for several years in the US, the NTD data provide a more accurate indication of true average in-service energy efficiency. However, a comparison against all diesel-electric locomotive-hauled systems is somewhat biased since many of the established locomotive-hauled systems are designed to be high-capacity systems that can obtain economies of scale not possible with the smaller DMUs.

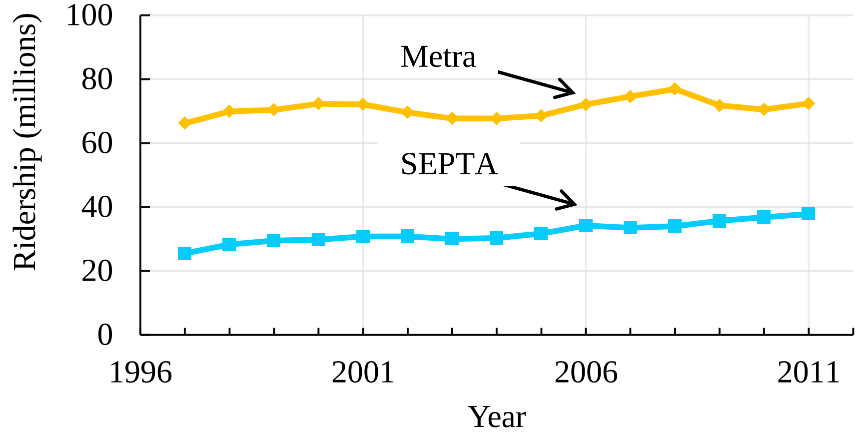
A more accurate comparison is to contrast the DMUs with the three new-start systems that use shorter two or three-car locomotive-hauled trains. The three systems with European DMUs were more efficient than the locomotive-hauled new-start systems (Table 4.3). The modern DMUs achieved higher passenger-miles per gallon in new-start service due to the operation of lighter, lower-capacity vehicles, often on more frequent headways, compared to heavier, high-capacity vehicles on traditional locomotive-hauled services. Thus, when starting up a new commuter rail service, it may be more efficient to use more frequent DMU service (where possible with FRA waivers) to build ridership before implementing longer, heavier locomotive-hauled trains with greater capacity.

4.9 Case Studies of Legacy Systems

Given the wide variation in efficiency metrics between individual systems, case studies to investigate the historic trends of specific commuter rail systems were conducted. The case studies illustrate the historical variation in energy efficiency among individual systems and can show how different operating strategies can influence trends in the efficiency of each system over time. Case studies of two legacy systems are discussed in this section: SEPTA and Metra.

The Southeastern Pennsylvania Transportation Authority (SEPTA) operates commuter rail services in the metropolitan area of Philadelphia, Pennsylvania. The system was established in its current publicly-owned form in 1983, after passenger services were abandoned by privately-owned railroads. It features 289 track-miles and 153 stations, with a daily ridership of 123,500 passengers. SEPTA is one of two entirely electric systems in the US (Brock & Souleyrette 2013).

Over the study period, the system experienced a 49% increase in ridership (Figure 4.4a), following trends in national ridership during the study period. The load factor of the system steadily increased and efficiency measured by passenger-miles per gallon has increased by 46% over the study period. This increase corresponded closely with the increased ridership on the system and contrasts with the national trend of slightly declining efficiency. This suggests that SEPTA responded to the increasing ridership with proportional increases in additional capacity by adding new cars or increasing trips in a manner that increased the load factor, thus improving the efficiency measured by passenger-miles per gallon. Indeed, SEPTA only increased the number of cars per train by 22% over the study period while ridership increased at roughly double this rate (Figure 4.4f).



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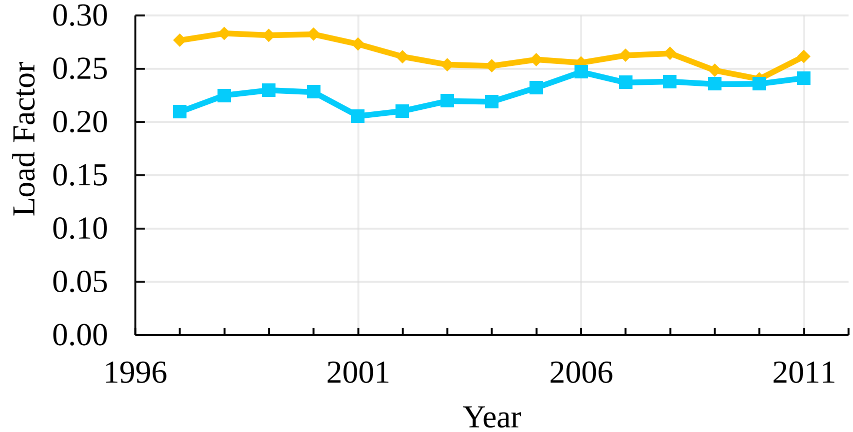

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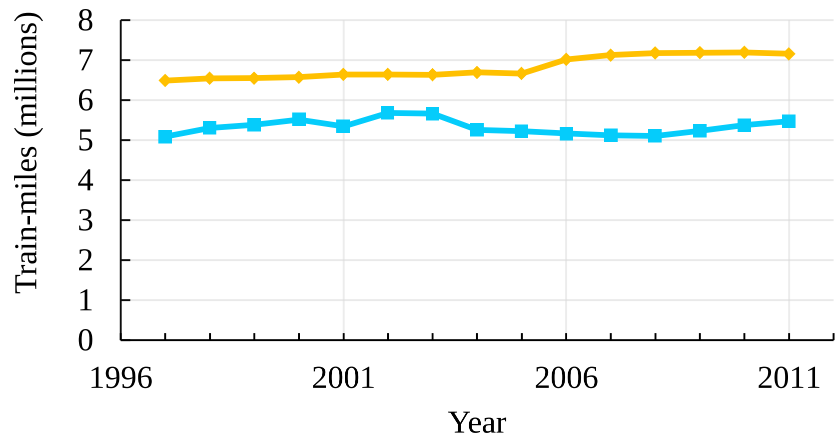
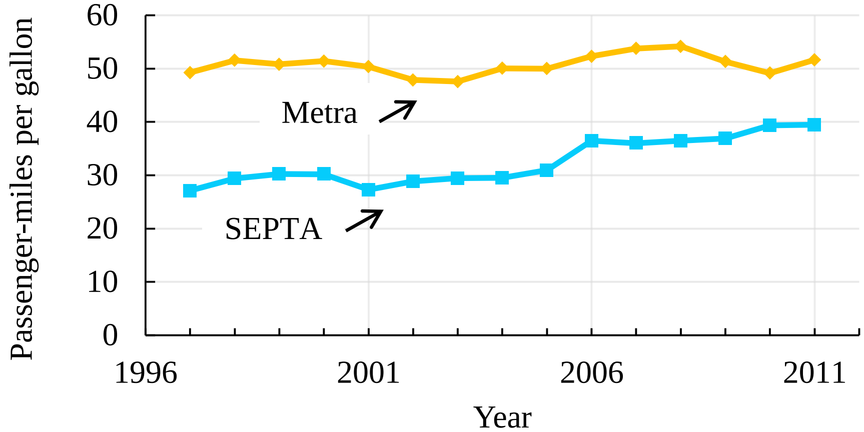
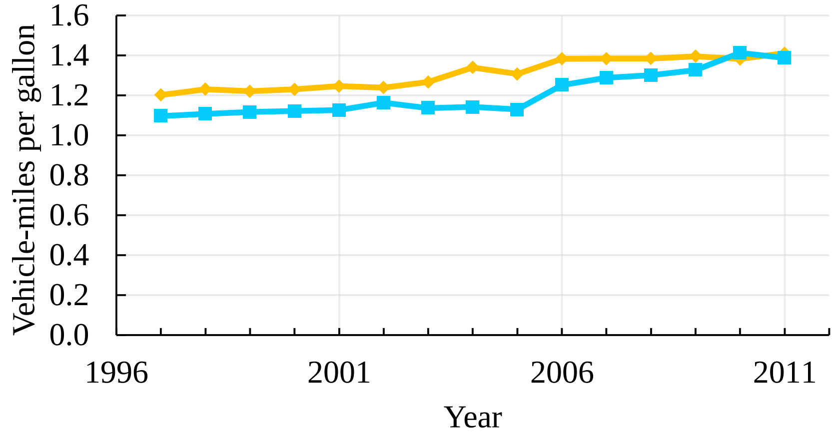


(c)

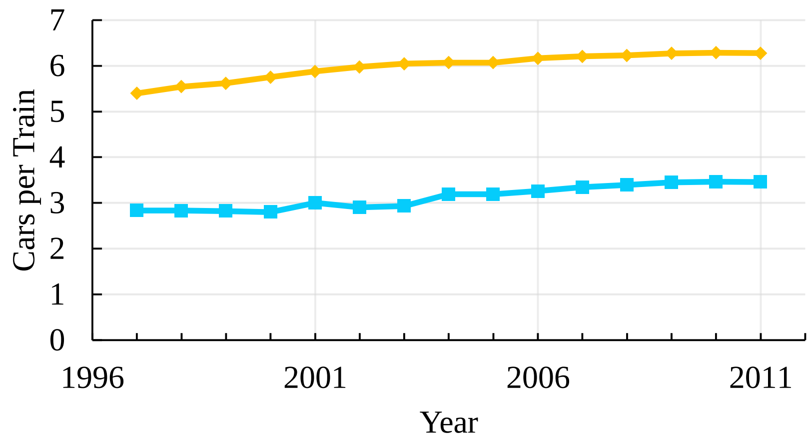
Figure 4.4 Trends of ridership (a), load factor (b), and train-miles (c) on Metra and SEPTA



(d)



(e)



(f)

Figure 4.4 (cont.) Trends of passenger-miles per gallon (d), vehicle-miles per gallon (e), and cars per train (f) on Metra and SEPTA

Vehicle-miles per gallon on SEPTA increased by 27% over the study period (Figure 4.4e). This improvement was due to a combination of the economies of the additional cars per train described above and equipment changes, namely the procurement of new, more efficient, Silverliner V electric multiple-units (EMU), built in 2010 by Hyundai Rotem (SEPTA 2010). SEPTA also installed wayside energy storage technology at a substation serving the Market-Frankford line (SEPTA 2012). This technology allowed the energy recovered from regenerative braking to be stored for opportune use or sold back to the grid. Although this technology's use is limited on the SEPTA system, it is estimated to reduce electricity costs at the substation by 10% (SEPTA 2012).

Metra is operated by the Northeast Illinois Regional Commuter Railroad Corporation and servers the metropolitan area of Chicago, Illinois. Metra was established as a publicly-owned railroad in 1984, after passenger services were abandoned by privately-owned railroads. It consists of 488 miles of track and 239 stations, carrying 304,300 passengers daily (Brock & Souleyrette 2013). Metra's ridership increased at a much slower rate than the national average (9%) over the study period, while the system's load factor decreased slightly (Figure 4.4a and Figure 4.4b). Metra marginally increased efficiency as measured by passenger-miles per gallon (Figure 4.4d) from 47.5 in 1997 to 49.7 in 2011.

Metra experienced a 17% increase in vehicle-miles per gallon. It is suspected that these gains were largely due to the delivery of new fuel-efficient MP36PH-3S locomotives manufactured by Motive Power, Inc. from 2003-2004 (Wabtec 2001). Over the past five years, Metra has been rebuilding older EMD F40PH models with new prime movers and improved electronics that increased efficiency. Metra also purchased EMUs with regenerative braking capabilities from Nippon Sharyo in 2005, for use on the Metra Electric District (Nippon Sharyo 2013). These EMUs, although limited to use on the Electric District, can recover braking energy and help reduce the overall consumption of each trainset. Aerodynamic efficiencies and economies of scale of longer train lengths may also have contributed to the increase in vehicle-miles per gallon. Metra added cars per train at a slower rate (16% increase), than SEPTA. However, this rate exceeded ridership growth, partly explaining the decline in load factor. It appears that on a passenger-mile basis, the efficiency gains from the new equipment were offset by reductions in load factor. Since the trends in the efficiency of Metra closely followed those of the national averages, this may be a widespread occurrence with commuter rail systems as they renew their fleets with more efficient modern equipment. At least in the short term, efficiency may decrease until ridership has enough time to grow and take advantage of the new system capacity. Investments in new equipment will only realize their full potential to increase efficiency when properly matched with ridership growth.

Despite not experiencing sustained improvement in passenger-miles per gallon, the efficiency of the Metra system was higher than SEPTA in all efficiency metrics, further illustrating the large variability in efficiency between individual systems. However, both systems had similar vehicle-miles per gallon efficiencies and load factors, suggesting that the average passenger coach seating capacity could explain the large difference in the passenger-miles per gallon metric. Metra generally uses bi-level gallery style cars, with an average passenger seating capacity of 140 seats. SEPTA uses mostly self-powered EMU coaches, with an average seating capacity of 118 seats. Therefore, although the systems had similar load factors, Metra is transporting more passengers per vehicle, resulting in an increased passenger-miles per gallon metric.

4.10 Conclusions

On a gross annual average, the energy efficiency of commuter rail remained largely constant over the past 15 years. Despite dramatic increases in ridership, the load factor of the commuter rail systems in the US has also remained nearly constant. New-start systems have a slightly higher efficiency measured in passenger-miles per gallon compared to legacy systems despite a very similar load factor, indicating more efficient rolling stock in new-start systems.

More frequent service using lighter, lower-capacity DMU vehicles may provide more efficient service for new-start systems building a ridership base compared to heavier, higher-capacity locomotive-hauled trains. A case study of the SEPTA system showed an increase in ridership and increases in energy efficiency measured by passenger-miles per gallon and vehicle-miles per gallon fostered by increases in system capacity proportional to ridership increases. The case study of the Metra system showed a slower rate of improvement in energy efficiency by passenger-miles per gallon, where potential gains in efficiency offered by new equipment are offset by the creation of excess capacity and reduced load factor. The case studies also illustrated the variability in energy efficiency between individual commuter rail systems.

US commuter rail services and ridership have grown over the past 15 years, with eight new systems being established in the past decade. Urban and regional planners considering the energy efficiency and air quality impact of transportation options will benefit from consistent and objective research of rail versus other modes of passenger transportation.

CHAPTER 5: EFFECTS OF CONGESTION ON PASSENGER RAIL ENERGY EFFICIENCY

Earlier versions of this research appeared in:

Fullerton, G., G.C. DiDomenico, M.C. Shih, & C.T. Dick. 2014. Congestion as a Source of Variation in Passenger and Freight Railway Fuel Efficiency. In: Proceedings of the 2014 Joint Rail Conference. American Society of Mechanical Engineers (ASME). Colorado Springs, CO, USA.

Fullerton, G., G.C. DiDomenico, & C.T. Dick. 2015. Sensitivity of Freight and Passenger Rail Fuel Efficiency to Infrastructure, Equipment and Operating Factors. Accepted: Transportation Research Record: Journal of the Transportation Research Board. Washington, DC, USA.

5.1 Introduction

Previous research has concluded that portions of the rail network are approaching congested conditions as traffic rebounds to pre-recession levels. Without significant investment in capacity, growth in current rail traffic sources (not including modal shift) will create severe network congestion (Cambridge Systematics 2007). Additional traffic resulting from modal shift induced by increased railway fuel efficiency will compound this congestion and create additional network delay. As this begins to hinder movement of rail traffic, increased traffic may reduce rail fuel efficiency because of more idling and acceleration events. Consequently, better understanding the relationship between rail traffic levels, congestion, and fuel efficiency will provide insight about how specific changes in traffic levels and operating parameters can affect the attractiveness of rail compared to competing modes.

Given its impact on operating costs, the railroad industry has ongoing interest in research on ways to reduce fuel cost. Railroads can reduce fuel costs by: consuming less energy by reducing train resistance or operating more efficiently; or switching to lower-cost alternative fuels and energy sources (Stodolsky 2002, Barton & McWha 2012, Brecher et al. 2014). While the former approach has been achieved through a combination of operational and infrastructure changes, maintenance practice (rail and wheel lubrication), and modifications to conventional diesel-electric locomotives, the latter approach requires the development of new forms of motive power and fuel/energy supply infrastructure. To capitalize on the low costs of natural gas, several railroads have been testing liquefied natural gas (LNG) locomotives for line-haul applications (Progressive Railroading 2013). Battery-hybrid locomotives that reuse regenerated braking energy for traction have been proposed conceptually to reduce energy consumption (Painter & Barkan 2006, Barton & McWha 2012). Plug-in battery tenders could make use of lower-cost electricity to supplant fossil fuels for portions of train runs. Wayside energy storage is also being explored for electrified passenger and commuter rail applications (Romo et al. 2005). Other technologies such as electromagnetically controlled pneumatic brakes and positive train control have been identified as potential railroad system upgrades that, while aimed to address other operational and maintenance issues, may also reduce railroad fuel expense under certain conditions (Stodolsky 2002).

The capital investment required to develop, test, pilot, commercialize, and implement any of these new technologies is sizeable. To justify this investment, it becomes very important to be able to analyze the feasibility of technologies in a comprehensive, yet cost-effective, manner. Previous evaluation of new motive power technology has shown that fuel efficiency benefits can vary greatly between routes and operating environments (Painter & Barkan 2006). It is infeasible, even using simulation, to determine the benefits of a technology on every route under all possible service operating conditions. Understanding how different factors affect fuel efficiency is a valuable asset to determine the proper number and range of case studies required to provide a representative assessment of the potential of a given technology. Likewise, understanding the interaction between these factors can be used to extrapolate the results of technology case studies to different operating conditions such as train speed and traffic volume.

Therefore, this chapter first considers the relationship of total traffic volume and station spacing on the energy efficiency of passenger trains using single-factor analyses. Building on these analyses, a second investigation of the factors affecting the energy efficiency of these passenger trains was conducted. This analysis used results from Rail Traffic Controller (RTC) simulations to develop a multivariate regression model. This model was then used to determine the sensitivity of passenger train energy efficiency to changes in each of the factors analyzed. These analyses identified the most significant operational parameters to consider when evaluating potential energy-saving technologies. Practitioners can use this knowledge to focus on a subset of route and operational characteristics when planning experiments to evaluate the technology's potential. This reduces the number of simulation trials or experiments required to evaluate the technology, and allows engineers to focus detailed data collection efforts on certain factors. Average values may be used for less-significant factors without affecting the results.

5.2 Methodology

5.2.1 Rail Traffic Controller

For an ideal non-stop run, or for a set schedule with all stops and dwell times known, a simple train performance calculator (TPC) can be used to calculate the efficiency metrics for a passenger train over a known route. On single-track railways in North America, such free-flow conditions are rarely encountered. Passenger trains are often operated in mixed traffic with freight trains on privately-owned tracks. The acceleration, deceleration, and time spent idling while waiting for the opposing train all reduce fuel efficiency and the frequency of these events will vary depending on the operating characteristics of a given line.

Given that North American freight mainlines do not adhere to a strict schedule of operations, and meeting points between trains are not predetermined but are set by train dispatchers during the course of operations, the amount and number of delay incidents encountered by a particular train can vary greatly between runs. This variation and uncertainty in train operating patterns grows in complexity as line operating characteristics change, particularly when both passenger and freight trains are operating on the same rail corridor, decreasing the utility of simple TPC runs. To capture the variability in operations experienced as traffic increases to congested conditions, more sophisticated simulation software that emulates train dispatching decisions must be used to generate the time and distance inputs for the train performance calculation. For this study, Rail Traffic Controller (RTC) software, developed by Berkeley Simulation Software, was employed (Wilson 2013). Each case was simulated using RTC software, with the resulting fuel efficiency recorded and statistically analyzed.

RTC is widely accepted by the railroads in North America as a standard simulation model for rail traffic analysis, and is particularly useful for simulation of single-track operation. RTC considers detailed inputs including maximum allowable track speed, curvature, grades, signal system, train departure time, and locomotive and railcar characteristics to simulate train movements. The train dispatching logic in RTC can generate a result by detecting conflicts between trains and modifying the train paths to avoid infeasible movements. In addition, RTC may delay or reroute one or more trains according to their given priority to reflect freight railroad business objectives. The emulation of dispatching decisions under given train priority makes RTC more realistic than analyzing energy consumption using other TPCs or analytical models.

For this study, RTC was used to simulate mixed-use freight and passenger train movements on a 242-mile subdivision of single-track mainline dispatched with centralized traffic control (CTC) signals. Single-track operation is representative of the North American railway network, where only 11% of the entire rail network and 30% of higher-density mainlines are double track (Richards & Cobb 2006). Grade was varied in each experiment from 0%, negative 2.22% and positive 2.22% (Table 5.1). This was achieved by assigning a discrete grade value in the simulations: the positive grade value to one direction of the 242-mile route, with the reverse direction representing the negative grade. Fuel consumption results were extracted with respect to consistent directions corresponding to upgrade and downgrade operation. Due to the shared-corridor setting, the freight trains were assigned characteristics (Table 5.1). To ensure that the results were not dominated by particular train schedule assumptions, and to better emulate the unscheduled North American operating environment, each particular scenario was simulated for five days of traffic with trains being randomly dispatched from each end terminal during a 24-hour time period. Thus, the final transportation and efficiency metrics for a particular combination of factor levels represented multiple days of randomly scheduled train operations (Sogin 2013). The TPC embedded within RTC generated data on the fuel consumption of every train running through the study corridor. RTC did this by calculating the speed profile and

Table 5.1 Route and train characteristics used in RTC simulations

Route Parameters	Value
Length (miles)	242
Type	Single Main Line
Siding Spacing (miles)	10
Siding Length (feet)	10,000
Signal System	3-aspect CTC
Freight Train Parameters	**Value**
Locomotive Type	SD70-4300
Locomotives	2
Gross Rail Load (tons)	143
Train Length (number of cars)	100
Freight Speed (mph)	40
Passenger Train Parameters	**Value**
Locomotive Type	GE P-42
Coach Type	Amfleet I
Coach Weight	55 tons
Coach Seating Capacity	84 seats

throttle/brake settings of each train based on the assigned locomotive type, train consist, and infrastructure characteristics (Table 5.1). Unlike a stand-alone TPC, service reliability metrics such as train delay are also calculated by RTC, so the effects of these metrics on efficiency can be evaluated as well.

5.2.2 Single-Variable Analysis

Previous research has considered the fundamental relationship between traffic volume and delay that describes railway congestion and level of service (Kreuger 1999). The delay-volume relationship takes the form of a curve with relatively little delay at low traffic volumes but exponentially increasing delay at higher volumes. This research seeks to understand how this relationship translates into a similar curve describing fuel efficiency as a function of traffic volume. Given that fuel efficiency is also influenced by many other factors such as vertical gradient and alignment, axle loads, train length, load factor, operating speed and the inherent efficiency of the locomotives assigned to the train, this research also considers the relative sensitivity of fuel efficiency to these other factors.

A single-variable study was performed in order to isolate the fuel efficiency effects of certain factors of interest specifically related to measures of railway congestion. Traffic volume (in total number of trains) and station spacing were investigated. The fuel efficiency response from changes to the above factors was determined via a series of simulation experiments in which train operations were systematically varied. Total traffic volume values were varied from eight to 40 trains per day in increments of eight trains, allowing for an even directional traffic mixture of 75% freight trains and 25% passenger trains in each direction. The station spacing was simulated at intervals of five, 30, 80, 120, and 240 miles, representing stop spacing of various types of passenger train operation. The five-mile spacing represents typical commuter rail operations, 30 represents a regional intercity service, 80 and 120-mile spacing represents varying levels of long-distance intercity service, and the 240-mile run represents an express intercity service such as the Amtrak "Auto Train".

The "seat-miles per gallon" efficiency metric was chosen to describe energy efficiency to normalize the effect of ridership on fuel efficiency (as opposed to the passenger-miles per gallon metric, which is influenced by the ridership). Seat-miles per gallon gives the efficiency of a passenger train as if all the seats were occupied by passengers, illustrating the potential per-trip efficiency of a system. However, this metric is heavily influenced by the number of seats per railcar. For example, commuter coaches have much higher capacity than long-distance coaches, and sleeping cars have even less. These differences in seating configuration can overshadow the base efficiency of a system.

5.2.3 Multi-Variable Regression and Sensitivity Analysis

Factor Selection

Several factors with demonstrated effects on fuel efficiency of passenger rail transportation were selected for this analysis. Each factor and representative range of values was selected to reflect real-world conditions on a mixed-use corridor (Table 5.2). Previous studies and train energy modeling consider grade one of the most significant factors in train fuel consumption (Hay 1953, Sierra Research 2004, Fullerton et al. 2014, Tolliver et al. 2014). Although existing mainline grades can exceed 3.0% for short distances, the maximum grade for freight railroad that most passenger trains operate on is about 1.0% (AREMA 2003).

Table 5.2 Factors investigated in freight and passenger fuel efficiency study

Passenger Experiment Factors	**Low**	**Medium**	**High**
Grade (%)	-2.22	0	2.22
Traffic Volume (trains per day)	8	16	24
Percentage Freight Trains	25	50	75
Passenger Speed (miles per hour)	50	79	110
Train Length (number of coaches)	6	9	12
Locomotives	-	1	2
Station Spacing (miles)	5	120	240

Traffic volume was included as a proxy for congestion, representing realistic train volumes for a single-track line with passing sidings. The percentage of freight trains represented the heterogeneity of traffic on the line. Lines with greater heterogeneity have been shown to experience more train delay for a given traffic volume (Dingler et al. 2013, Dingler et al. 2014). The extra delay could disproportionately affect freight train fuel consumption with increased passenger traffic (Sogin et al. 2012a).

Speed of freight and passenger trains was also considered due to the increased train resistance associated with higher speeds. Train resistance forces also increase with train length and weight, represented by number of cars and gross railcar load. Train length was also considered, but passenger coach weight was held constant across all simulations. These factors also determined the transportation productivity of each train, as they control the number of seat-miles to be used in the fuel efficiency calculation. The number of locomotives providing tractive effort was also a factor.

Design of Experiments (DOE) methodology was used to develop a partial-factorial experiment matrix that designates unique cases with varying combinations of factors in Table 5.2 to accurately describe the response surface. Using DOE reduced the required computing time and power by using a partial-factorial experiment, rather than full-factorial. The partial-factorial passenger experiment constructed using DOE required 80 cases, compared to 1,458 total cases for a full-factorial experiment.

Multivariate Regression Analysis

Fuel efficiency results from the simulations in RTC were used to construct a multivariate regression model, with the factors in Table 5.2 as input parameters and fuel efficiency as the response output. JMP was used to analyze the results from the RTC simulations and construct the regression model. The model recreated the response surface using the least squares regression technique with the results from the RTC simulations. Fuel consumption (gallons) was predicted by the passenger fuel efficiency regression model. Efficiency (seat-miles per gallon) was then evaluated separately based on the output of the model and the respective number of seats in the train consist. This was done to avoid over-fitting in the software due to the effects of seating capacity on the relationship between the response variable and inputs.

Sensitivity Analysis

After constructing the regression model, the sensitivity of the calculated fuel efficiency to changes in the inputs (Table 5.2) was quantified by the arc elasticity method as described by Allen and Lerner (1934). This approach has been used in similar research investigating the influence of different factors on train delay (Sogin et al. 2013). The arc elasticity method quantified how fuel efficiency responds to normalized unit changes in each factor with respect to a base case. Normalization of units is desirable due to the bias that could be introduced by varying the units and order-of-magnitude ranges of the analyzed factors.

The base case for the experiment used the combination of the medium factor values (Table 5.2), with a few exceptions. The factor ranges used to construct the regression model include the extreme values of each parameter in order to produce a larger response surface. Therefore, the high and low values for several factors did not present a reasonable range of uncertainty or variability in anticipated service conditions. Thus, some of the base, minimum, and maximum factor values were modified in the sensitivity analysis to reflect more realistic ranges. Each factor was varied between its low and high values, while the other factors were held constant at their respective medium value and recording the output fuel efficiency (Figure 5.3). The arc elasticity of the fuel efficiency response was then calculated (Equations 5.1 and 5.2). The output of each equation was the ratio of the percent change in fuel efficiency to the percent increase or reduction in the factor. Arc elasticity values represented the corresponding percent-change in fuel consumption to a one-percent change in each input factor. Larger magnitudes of arc elasticity indicate that a particular factor has a larger influence on fuel efficiency than factors with lower magnitudes of arc elasticity.

Table 5.3 Base, minimum, and maximum values used in passenger fuel efficiency sensitivity analysis

Passenger Experiment Factors	Minimum	Base	Maximum
Grade (%)	-2.22	0	2.22
Traffic Volume (trains per day)	8	16	24
Percentage Freight Trains	25	50	75
Passenger Speed (miles per hour)	50	79	110
Train Length (number of coaches)	6	9	12
Locomotives	-	1	2
Station Spacing (miles)	5	40	75

$$e_{high} = \left[\frac{Y_{i,high} - Y_0}{\frac{1}{2}(Y_{i,high} + Y_0)}\right]\left[\frac{\frac{1}{2}(X_{i,high} + X_{i_0})}{X_{i,high} - X_0}\right] \quad (5.1)$$

Where:

e_{high}	=	arc elasticity with respect to high input variable value
Y	=	output variable
X_i	=	input variable
(X_{i_0}, Y_{i_0})	=	base input and corresponding response

$$e_{low} = \left[\frac{Y_{i,low} - Y_0}{\frac{1}{2}(Y_{i,low} + Y_0)}\right]\left[\frac{\frac{1}{2}(X_{i,low} + X_{i_0})}{X_0 - X_{i,low}}\right] \quad (5.2)$$

Where:

e_{low}	=	arc elasticity with respect to low input variable value

5.3 Results and Discussion

5.3.1 Single-Variable Analysis

Trains were simulated over two routes: a zero-grade route and a route on a 2.22% grade in one direction (Figure 5.1). Trains moving west travel over the +2.22% grade and trains moving east travel over the -2.22% grade. The fuel efficiency results were averaged in the latter scenario to create the "averaged grade" results shown in this section. This represents an average gradient of zero percent, but the trains experienced positive and negative gradients during their runs, as opposed to a truly flat route. Due to the speed and priority of the passenger trains, they appeared to be largely insensitive to increases in traffic volume on this freight-dominated corridor. However, it was hypothesized that at some higher traffic volume (network saturation point), the capacity limit of the line will be reached and delay will increase rapidly (Fullerton et al. 2014). At this point, it is expected that traffic volume will have a larger effect on passenger train fuel efficiency. Furthermore, if this were a line with a greater proportion of passenger trains, such as a commuter line with little or no freight traffic, the passenger trains may become more sensitive to traffic volume, as the priority trains will eventually start to interfere with each other on single track.

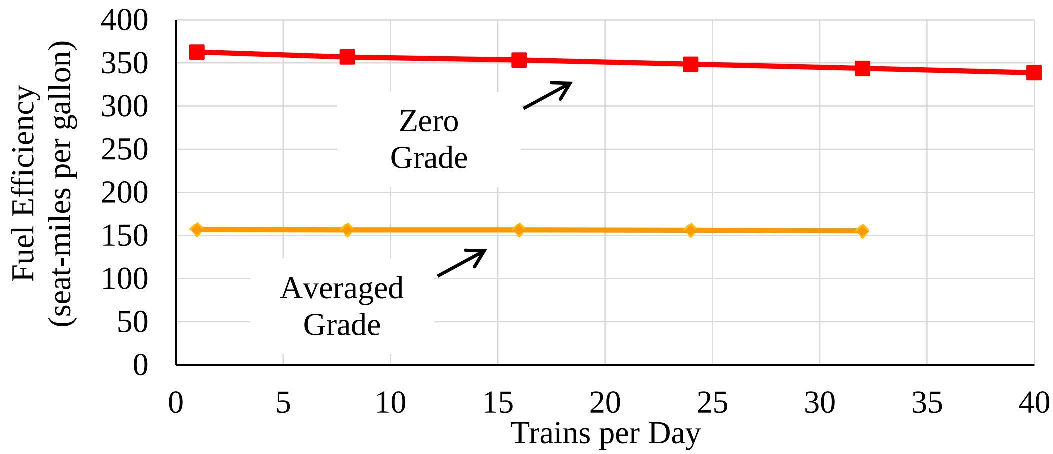


Figure 5.1 Traffic volume vs. passenger efficiency

Operating passenger trains with less frequent stops can greatly improve efficiency in terms of seat-miles per gallon (Figure 5.2). Under these conditions, since the short consists typically had more power available than required to overcome train resistance at maximum track speed, the train spent more time cruising as opposed to constantly consuming fuel at the maximum rate to accelerate from station stops. For the averaged grade condition, much more fuel was consumed overcoming train resistance so the impact of additional acceleration was reduced and there was little variation once stop spacing exceeded 30 miles. This is intuitive for conventional diesel-electric trains; however, a hybrid locomotive or a system using electric propulsion with regeneration or wayside storage may benefit more from those technologies with closer station spacing. Also, systems with regenerative braking or wayside storage may be less sensitive to closer station spacing because they are able to reuse braking energy during the increased number of acceleration events. These ideas are explored further in Chapter 8.

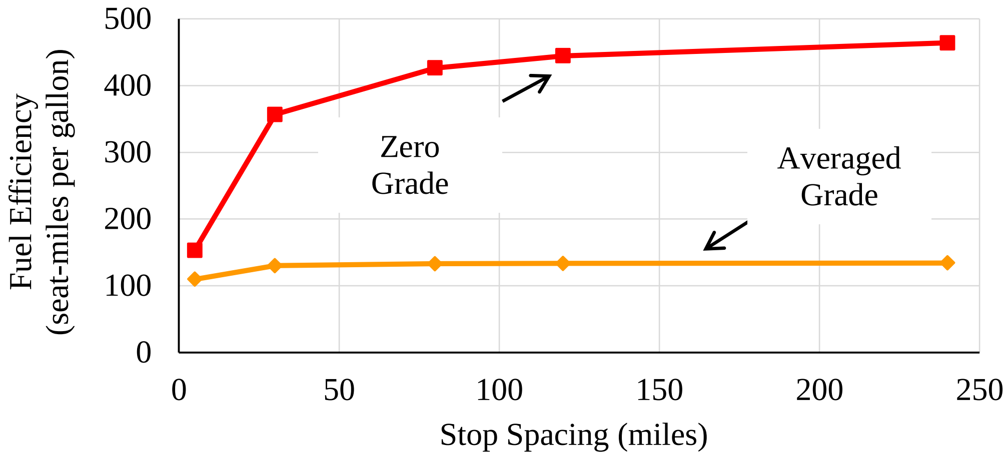


Figure 5.2 Stop spacing vs passenger efficiency

5.3.2 Multi-Variable Regression and Sensitivity Analysis

Overall, fuel efficiency outputs of the multivariate passenger regression model varied with the experiment factors from 134 to 1,357 seat-miles per gallon (Table 5.4). The ranges presented may seem high, but were within the range of fuel consumption for passenger train types. The passenger rail efficiencies were higher than average: Amtrak's 2013 national average was 157 seat-miles per gallon and an analysis of a corridor of similar length in North Carolina showed an efficiency of 75 seat-miles per gallon (Frey & Graver 2012, USDOT 2013b, Amtrak 2014). It is likely that the high priority given to passenger trains within the RTC algorithm combined with the favorable route characteristics were inflating the values. Ultimately, this research was focused on the relative magnitude of the values as the input factors were varied. The passenger model's correlation coefficient (R^2) value is 0.989.

Table 5.4 Fuel efficiency results from the passenger (seat-miles/gal) regression model

Passenger Experiment Factors	Minimum	Base	Maximum
Grade (%)	1,357	578	134
Traffic Volume (trains per day)	583	578	492
Percentage Freight Trains	575	578	772
Passenger Speed (miles per hour)	854	578	478
Train Length (number of coaches)	577	578	396
Locomotives	-	578	336
Station Spacing (miles)	449	578	716

A sensitivity analysis of the factors analyzed in the passenger model was conducted (Figure 5.3). Orange bars represent the elasticity (as defined before) of fuel efficiency in response to increases in each respective factor. Blue bars represent the elasticity of fuel efficiency in response to reductions in each respective factor. A positive elasticity indicates that the corresponding change in each factor causes an increase in fuel efficiency. A negative elasticity indicates that the corresponding change in each factor causes a reduction in fuel efficiency.

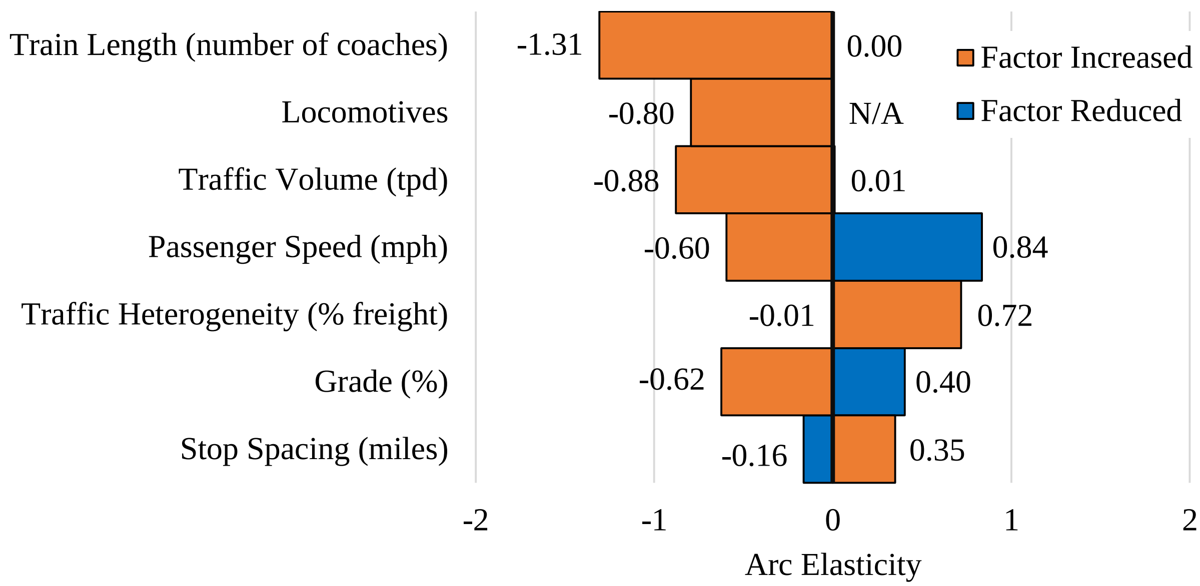


Figure 5.3 Sensitivity analysis results of the passenger regression model

Fuel efficiency results from this model were most sensitive to increases in the train length (number of trailing passenger coaches), corresponding to a reduction in fuel efficiency. Reducing the number of trailing coaches had a smaller effect on fuel efficiency. An increase in seat-miles per gallon was expected, despite the increased train weight, due to increased seating capacity. The extra coaches provided additional seats over which to distribute the locomotive resistance, analogous to increasing the weight and length of the freight trains. However, the severe grades used in this experiment amplified the effects of the added weight of additional passenger coaches. Furthermore, the freight trains sharing the line moved slowly on the severe grades while adhering to a fixed horsepower-to-trailing ton ratio. The passenger trains attempted to maintain maximum speed on grades, so the longer and heavier trains had substantially higher fuel consumption. This appears to offset the extra seating capacity of additional coaches.

Increases in traffic volume (a proxy for traffic congestion) yielded a reduction in fuel efficiency. Reductions in traffic volume had a much smaller, albeit positive, effect on fuel efficiency. Traffic volume did not severely affect the fuel efficiency of the passenger trains until the "network saturation point" (Section 5.3.1). Reductions in passenger speed led to increases in fuel efficiency, and vice-versa. As the percentage of freight trains increased, so did the fuel efficiency of passenger trains. This can be attributed to the priority of the passenger trains. As the number of conflicts between passenger and freight trains increased, the number of conflicts between passenger trains was reduced, and the passenger trains were dispatched more favorably. This scenario reduced the number of acceleration and idling cycles and improved fuel efficiency.

Steeper grades result in reduced fuel efficiency, while reductions in gradient result in higher fuel efficiency. Gradient had a smaller effect on the fuel efficiency of passenger trains relative to other factors in this study. Increased distance between station stops increased the fuel efficiency of the passenger trains, while shorter distances between stations reduced their efficiency. This relationship is also supported by previous single-variable analysis of stop-spacing (Fullerton et al. 2014).

5.4 Conclusions

In order to better understand the basic factors affecting passenger train energy efficiency, single variable analyses of traffic volume and station spacing were conducted to determine the effects on passenger train fuel efficiency. These analyses showed that traffic volume has a minimal effect on the passenger train efficiency indicating that under relatively high traffic volumes, the energy efficiency of the passenger train was not affected, and thus will not suffer a significant reduction in efficiency due to a modal shift of freight or passengers to rail. It was also shown that station spacing has a large effect on energy efficiency of passenger trains (neglecting any effects of grade). However, when high gradients were considered, the effect of station spacing on efficiency was overshadowed by the amount of energy consumed to overcome the gradients.

DOE software was used to create partial-factorial experiments to investigate the effects of several factors on freight and passenger train fuel efficiency. Rail simulation software was used to run trial cases designed using the DOE software, and calculate the energy consumption of each under single-track operating conditions with delays due to meets and passes. Results from the simulation software were used to create a multivariate regression model to predict passenger train fuel efficiency. A sensitivity analysis of this model identified the relative effects of these factors on passenger train fuel efficiency. The equipment, in particular the weight of the train, was the most influential factor for fuel efficiency. Gradient had a large and consistent effect on fuel consumption and efficiency. This effect may be underestimated in these experiments by the difficulty in calculating reasonable arc elasticity values for factor ranges that were very near or equal to zero where elasticity is undefined.

In order to continue to provide competitive, cost-effective transportation service, reducing fuel consumption is increasingly important to passenger railroads due to rising fuel costs and constrained budgets. In an effort to reduce operating costs, railroads are investigating fuel-saving technologies and options for transitioning to less expensive fuels and sources of energy. Overall, each factor studied had a substantial impact on fuel efficiency. Rather than focusing on a subset of the parameters analyzed in this chapter when planning experiments on fuel efficiency, no factors should be ignored in data collection for a system wide analysis. When evaluating technologies to improve fuel efficiency using TPCs or simulation models like RTC, efforts should be focused on collecting detailed input data describing the route profile and station spacing, equipment characteristics, and expected traffic volumes. This chapter identifies basic factors that must be evaluated in future research and a means to validate the resulting effects of these factors on rail system fuel efficiencies.

CHAPTER 6: INTRODUCTION TO MULTIMODAL PASSENGER SIMULATION TOOL (MMPASSIM) AND CREATING HIGHWAY GRADE DISTRIBUTIONS AND CONGESTION CHARACTERIZATIONS USING GIS TOOLS

6.1 Introduction

Traditionally, gross annual average energy consumption metrics have been used to quantify the energy efficiency of passenger rail operations in the US. However, as shown in Chapter 3, commuter rail energy efficiency varies significantly between off-peak and peak hours and different train consist configurations. Such averages are not useful in analyzing the energy efficiency of individual passenger train runs. As an effort to move away from simple averages, TranSys Research Limited of Glenburnie, Ontario, Canada, in conjunction with RailTEC at the University of Illinois at Urbana-Champaign, has developed the Multimodal Passenger Simulation Tool (MMPASSIM), a Microsoft Excel-based simulation model that quantifies energy consumption of passenger rail transportation and competing passenger modes. The development of this model was solicited and funded by the National Cooperative Rail Research Program (NCRRP) project 02-01 “Comparison of Passenger Rail Energy Consumption with Competing Modes”. This project aims to eliminate the shortcomings of traditional energy consumption comparisons of passenger rail and competing travel modes by providing a methodology for like-for-like comparisons for door-to-door passenger trips (TRB 2012).

MMPASSIM simulates the energy consumption of rail movements using a simplified train performance calculator based on traditional train energy methodology (modified Davis equation). 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. The model has the ability to use detailed train consist information, including train length, mass, resistance coefficients, head-end power (HEP) configuration, nominal traction power, and many other inputs in the calculation of energy consumption.

Chapters 7, 8, and 9 of this thesis use MMPASSIM to simulate the energy consumption of a Midwestern commuter rail service. Chapter 7 focuses on the effects of scheduling patterns on peak-period energy consumption, and uses the tool to quantify the total energy required during each scenario. Chapter 8 investigates the effects of energy-saving strategies and technologies that could be implemented on this service. Finally, Chapter 9 compares the energy intensity of the commuter rail service to equivalent trips using light-duty automobiles and intercity bus service.

6.2 Rail Module

The core of MMPASSIM is the rail simulation module that uses input data describing the train consist and route to quantify the energy consumption and GHG emissions from the rail portion of a passenger trip. The rail module uses a modified version of a detailed train performance calculator due to several characteristics of passenger trains that allow for simplifications (TranSys 2015). First, passenger trains are shorter and lighter than freight trains, lessening the impact of grade. Therefore, rather than using detailed elevation profiles of each route, the model only requires a simplified gradient distribution table, describing the frequency of various gradient severities over predefined route segments.

The rail module uses a common methodology for quantifying train resistance (Equation 6.1) (AREMA 2013, TranSys 2015).

$$R = \mathrm{R}_A + \mathrm{R}_B\mathrm{V} + \mathrm{R}_C V^2 \quad (6.1)$$

Where:

R = Inherent resistance force (N)

V = Speed (m/s)

R_A = Resistance coefficient associated with journal resistance, rolling friction, and track resistance

R_B = Resistance coefficient associated with rolling losses that vary with speed

R_C = Resistance coefficient associated with aerodynamic drag varying with the square of the speed

Resistance coefficients R_A, R_B, and R_C are typically gathered by conducting empirical tests on passenger equipment. Empirical formulas can be developed from the test results and applied to similar equipment.

The tractive effort curve is calculated using Equation 6.2. Acceleration tables without the effect of grade are calculated in one-mile-per-hour increments using Equation 6.3 (AREMA 2013, TranSys 2015).

$$TE = Min\left[T_q\left(1 - e^{\frac{-t}{T_c}}\right), \frac{P}{V}\right] \tag{6.2}$$

Where:
TE = Tractive Effort (N)
V = Speed (m/s)
T_q = Torque-limited tractive effort (N)
t = time since power was applied (s)
C = traction power rating of the locomotive minus HEP loads (Watts)

$$A = \frac{(TE - R)}{(M + N_a K_r)} \tag{6.3}$$

Where:
A = Acceleration ($^{m}/_{s^2}$)
M = Consist mass (kg)
N_a = Number of axles in consist
K_r = mass-equivalent rotational inertia of each axle (kg)

Basic train resistance is calculated for each segment. Kinetic energy from the acceleration of the train is calculated and used to find the braking energy (either regenerated or dissipated as heat in friction or dynamic brakes) (TranSys 2015). Additional energy components related to the gradients and curvature along the route, braking used to maintain speed limits on down grades, and 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 using an *energy conversion* analysis by adding the incremental energy consumed in the generation of the electricity used by the train (Table 3.1), as discussed in Chapter 3.

6.3 Modules for Competing Modes

MMPASSIM allows for the energy consumption and resulting efficiencies of passenger rail simulations to be compared to simulations of competing modes of passenger travel. The model has the capability to simulate the energy consumption of light-duty vehicle (LDV), intercity bus, and air trips. Although the method used to simulate the energy consumption of these modes is not directly relevant to this research, the main inputs required to simulate the modes explored in Chapter 9 are discussed in this section. Energy consumption modules for the competing passenger modes are explained in great detail in the resulting final report of the NCRRP 02-01 project (TranSys et al. 2015).

6.3.1 Light-Duty Automobile

Main travel segments using automobile light-duty vehicles are defined 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, fuel type). Vehicle types include averages of the purchased and driven fleets for recent years, or specific types of automobiles such as sedan, truck, sport-utility vehicle, etc.

On extended intercity trips, congestion effects vary along the route as the highway user moves through urban areas. This includes urban centers at the start and end of a trip along with any congested areas encountered along the route. 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.

6.3.2 Bus

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 are not modelled as non-stop express services but do 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 is included to account for driver breaks and station dwell time.

6.4 Access and Egress Modes

For each of the competing modes defined for main travel segments, various access and egress modes are available. Access and egress modes are selected based on the distance to each alternative terminal, mode choice (and respective average energy intensity), number of travelers, time of day, season, and dwell time at the transfer terminal or station. Multiple access and egress modes can be selected for each alternative (i.e. walking to the subway). Dwell time is defined as the idle wait time between modal leg trips or 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.

6.5 Creating MMPASSIM Input Consists and Routes

To create a new consist, open the MMPASSIM model and navigate to the 'Rail-Consist' sheet. Any new consists will follow the format of the existing default consists in this sheet, with cells colored in green containing user-defined data, yellow cells containing calculations, and pink cells being changed by macros using inputs from the 'Master-IO' sheet. When creating a new consist, the user should input data in the green colored cells only. To begin, copy a column containing a default consist and paste it seven columns to the right of the last consist on the sheet (six blank columns between consists). Each row represents an input, described by the entry in column A for each respective row.

Begin by assigning a unique Consist ID in row 2. Row 3 allows you to input a short description of the train consist that will be displayed in the 'Master-IO' sheet interface when selecting cases to simulate. Rows 5-20 are required inputs that describe the physical characteristics of the train consist, such as number of locomotives/power cars, number of coaches, total weight, passenger load factor (ratio of full seats to total seats), and consist length. Rows 26-28 contain the train resistance coefficients A (N), B (N/(km/hr)), and C (N/(km/hr)^2). The user can input known data from equipment specifications or tests, or empirical formulas that calculate each coefficient based on the inputs in rows 5-20. Transmission efficiency coefficients can be input in rows 38-39. The pink cells in rows 40-41 describing propulsion and fuel types can be adjusted manually using the 'Rail-Consist' sheet, or adjusted using the user interface found on the 'Master-IO' sheet. Row 42 (yellow) describes the traction power (kW) at the wheels of the power unit, after head-end power and other auxiliary losses are subtracted. The user can adapt the formula used to calculate this value by inputting the nominal traction power (prior to any losses), or directly input the traction power at the wheels if known. Rows 50-91 describe traction engine and dynamic braking characteristics. Row 63 is a binary flag for dynamic brake usage (1 if yes, 0 if no). The pink cells in rows 65-67 describing dual-fuel power units and HEP can be configured manually on this sheet or using the user interface on the 'Master-IO' sheet. Similarly, the pink cells in Row 81 and 85 can be configured manually for regenerative braking characteristics or set on the 'Master-IO' sheet.

6.5.1 Creating Input Routes

To create a new rail route, open the MMPASSIM model and navigate to the 'Rail-Route' sheet. Any new routes will follow the format of the existing default routes in this sheet. Only cells colored in green should be manually edited when creating a new route. To begin, copy an existing route entry (spanning a width of 13 columns, beginning from the first column containing a unique ID, such as RR.1) and paste it in the column immediately to the right of the last route entry.

Begin by describing the route in row 2. Rows 4-34 are used to describe the gradient and curvature of the route. Generally, the user will have this information in track chart form. In order to convert the gradient and curvature information from track-chart form to the required format on this sheet, the route preprocessing tool included with the model will be required. Gradient, curvature, and speed data by milepost are input into the preprocessor, with the output containing the total curvature and final grade table that can be input in the 'Rail-Route' sheet. Further instructions on the use of this preprocessing tool are included in the documentation describing the MMPASSIM model structure and usage (TranSys 2015). The total curvature can be input in the green cell in row 4 of the 'Rail-Route' sheet. The output gradient table can be copied and pasted from the preprocessing tool into the gradient table in rows 6-34.

Rows 41-85 are used to specify the locations along the route where the train will be stopping. The first column, labeled 'User Value Forward Direction', should be completed with the mileposts of the stops, with the trip origin and destination being the first and last entries, respectively. The third column, labeled 'Wayside Storage' can be used to indicate if wayside storage is available at each station location. The sixth column, labeled 'Default Computed Reverse Direction' calculates the mileposts of the stops in the reverse direction. These values can be copied and pasted in column 7, labeled ‘User Value Reverse Direction’ if the same stops are desired for the reverse trip. Otherwise, the mileposts for the stops of the reverse trip should be input here.

Rows 87-96 describe the average expected slow orders and/or interference speed reductions per one-way trip. Similarly, rows 98-100 describe the average expected unscheduled stops per one-way trip, along with the speed limits in sidings. Also, extra idle and non-revenue travel can be described in rows 102-105. Rows 106-126 describe the boundaries of fuel use along the route in the case that the fuel/traction type vary along the route (e.g. dual-fuel locomotives).

Rows 132-561 describe the speed limits along the route. Column 1 contains the mileposts that correspond to the conventional and tilt-body speed limits (in columns 3 and 4 respectively). In this table, the origin and destination speed limits must be duplicated in the first and last two rows respectively.

6.5.2 Using Newly Created Train Consists and Routes

To use a newly created consist and route, navigate to the ‘Master-IO’ sheet and select the type of simulation desired. Select “Define Baseline” to bring up a dialogue window. Select the ‘Add’ button towards the bottom of the window. This will create a new rail trip, and can be named using the ‘Description’ box at the top. Newly input consists and routes should appear in the drop down list near ‘Consist ID’ and ‘Route ID’. To edit details of the consist or route, double click inside the yellow box containing the ‘Consist ID’ or ‘Route ID’. Complete the remaining input fields, then select ‘Save’ in the bottom left corner of the window. Finally, select ‘Select & Return’ to select the trip characteristics and return to the ‘Master-IO’ sheet.

6.6 Creating Highway Grade Profile Inputs using GIS

Modal comparisons require not only detailed information regarding the specified rail trip, but also detailed information regarding corresponding trips using competing modes. Auto/LDV and intercity buses use highway and arterial roads along the specified route containing varying gradient profiles and traffic congestion distributions. Highway gradient and traffic congestion have a significant effect on the energy consumption of Auto/LDV and Bus trips. 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 a user-defined highway gradient profile for the case studies presented in Chapter 9.

6.6.1 Methodology

ESRI's Geographic Information Systems (GIS) software ArcMap was used to characterize the highway grades for the case study of competing passenger travel modes from Aurora to Chicago used in Chapter 9. The interstate highways used for this trip include Interstate 88 from Aurora to Hillside and Interstate 290 from Hillside to Chicago. Arterial roads used to access the interstate highway segment of the route were assumed to have the same gradient distribution as the interstate highway segment.

To begin, the ArcMap file must be configured using the appropriate projected coordinate system for each region. In this case, NAD 1983 UTM (Universal Transverse Mercator) projection with the zone specific to the highway route being analyzed. However, if possible, it would be preferable to preserve distance accuracy by using region specific, equidistant projections, rather than transverse Mercator projections. In this case, it was assumed that the NAD 1983 UTM Zone 16 projection was accurate in the small region being analyzed. However, for long distance routes, such as a highway trip from Chicago to Los Angeles, the North American Equidistant Conic projection or similar equidistant projection should be used, due to the long length of the route. In the horizontal plane, ESRI database shapefiles of the United States (US) Interstate Highway system centerlines were used to create the initial equivalent highway route for the case study. Vertically, Digital Elevation Models (DEM) for the highway route were obtained from the USGS National Elevation Dataset at a resolution of 1 arc-second (Gesch et al. 2002, Gesch 2007).

First, the DEMs were processed to combine them into a single layer covering the entire route using the "Mosaic to New Raster" tool in the "Data Management" toolbox. In this case, since the two individual DEM rasters were of the same resolution, the resulting new raster also has a resolution of 1 arc-second. However, some routes may not have DEM files of consistent resolutions available. In that case, the resulting new raster would have a new resolution. Next, the individual roadway line segments comprising small portions of Interstates 88 and 290 were combined to create a continuous line representing the entire highway route. This was done by creating a new line feature using the “Trace” tool to trace a new, continuous line segment along the highway centerline feature from the ESRI US Interstate Highway shapefile. Next, the continuous line feature just created must have the elevation data from the DEM interpolated to points along the highway route, creating a three-dimensional line. This is done using the “Interpolate Line” tool from the “3D Analyst” toolkit.

Finally, again using the “3D Analyst” toolkit, elevation information from the DEM along the route centerline is extracted with the “Profile Graph” tool, creating an elevation profile along the centerline of the highway route. 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. This raw grade dataset is then processed to create a simplified highway grade distribution table, used as a direct input required by the ‘LDV-Route’ sheet in the MMPASSIM model. After an entry for the desired highway route has been created on the ‘LDV-Route’ sheet, copy and paste the output highway grade distribution from the preprocessing tool into the Intercity Grade Distribution table in rows 75-104.

6.6.2 Results

The distribution of grades along Interstates 88 and 290 from Aurora to Chicago was calculated (Table 6.1) for use in the modal comparisons in Chapter 9. MMPASSIM requires this format as an input to simulate light-duty vehicle trips along interstate highways. The first column contains the gradient bins, the second column contains the fraction of the inbound trip (from Aurora to Chicago) on a descending gradient, and the third column contains the fraction on an ascending grade. Roughly 30% of the route was on effectively level terrain, 35% on a descending grade and 35% on an ascending grade.

Table 6.1 Intercity highway grade distribution along highway route from Aurora to Chicago (inbound)

Grade Class (%)	Descending grade (inbound)[1] (pu)	Ascending grade (inbound)[2] (pu)
-0.25 - 0.25 (~level)	0.153	0.153
0.25 - 0.50	0.090	0.068
0.50 - 0.75	0.037	0.046
0.75 - 1.00	0.037	0.037
1.00 - 1.25	0.032	0.026
1.25 - 1.50	0.023	0.025
1.50 - 1.75	0.016	0.023
1.75 - 2.00	0.018	0.016
2.00 - 2.25	0.015	0.016
2.25 - 2.50	0.008	0.013
2.50 - 2.75	0.009	0.008
2.75 - 3.00	0.008	0.012
3.00 - 3.25	0.004	0.006
3.25 - 3.50	0.006	0.006
3.50 - 3.75	0.003	0.005
3.75 - 4.00	0.003	0.003
4.00 - 4.25	0.004	0.005
4.25 - 4.50	0.004	0.003
4.50 - 4.75	0.002	0.005
4.75 - 5.00	0.003	0.004
5.00 - 5.25	0.003	0.002
5.25 - 5.50	0.003	0.002
5.50 - 5.75	0.000	0.001
5.75 - 6.00	0.001	0.001
6.00 - 6.25	0.002	0.003
6.25 - 6.00	0.000	0.002
6.50 - 6.75	0.002	0.001
6.75 - 7.00	0.000	0.000
>7.00	0.012	0.010
Total = 1.000	0.498	0.502

[1]Descending grade (inbound) becomes the ascending grade for the outbound direction
[2]Ascending grade (inbound) becomes the descending grade for the outbound direction

6.7 Characterizing Highway Traffic Congestion Using GIS

Highway congestion in urban areas can have an impact on the overall energy intensity of automobile and bus trips, depending on the severity and length of the congested highway segments. Therefore, the highway segments from Aurora to Chicago, Illinois were analyzed to characterize the traffic congestion along the case study route.

6.7.1 Methodology

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 (ATRI) has constructed a GIS tool called the National Corridors Analysis and Speed Tool (N-CAST) (American Transportation Research Institute 2012). This GIS database contains information about the performance of freight-by-truck movements on the US Interstate Highway system. Average speeds of truck movements along Interstate 88 from Aurora to Hillside and Interstate 290 from Hillside to Chicago were obtained from this database. These speeds were delineated by time of day (AM peak, mid-day, PM peak, and overnight). For this analysis, light-duty vehicle speeds were assumed to be equivalent to truck speeds during the congested AM peak, mid-day, and PM peak periods where the data exhibit average speeds that were less than free-flow speeds. For the overnight period, it was assumed that the trucks were able to travel at free-flow speeds, and the light-duty vehicle speeds were an average of ten percent higher than the truck speeds. After the data has been extracted from the N-CAST GIS database, it was preprocessed to correspond to the MMPASSIM user-defined ‘LDV-Drive-Schedules’ and ‘Bus-Drive-Schedules’ sheets input format. The congestion distribution created from the preprocessing tool can be stored on the ‘LDV-Drive-Schedules’ and/or ‘Bus-Drive-Schedules’ sheets.

6.7.2 Results

The highway congestion distribution for the case study route from Aurora to Chicago along Interstates 88 and 290 (Table 6.2) was calculated for use in the modal comparison in Chapter 9. The vertical columns represent various average traffic speeds, while the horizontal rows represent time of day. The value in each cell represents the percentage of the route in each range of average traffic speeds at a given time of day. In addition to the congestion along the highway portion of the route, the model also contains a default distribution of congestion on urban arterial roads. When a specific highway trip is input, the length of the route on both highways and urban arterial roads is specified, and the respective congestion distributions were applied accordingly during simulation.

Table 6.2 Highway congestion distribution for a trip from Aurora to Chicago along Interstates 88 and 290

	Percentage of Route Distance by Speed (%)							
Time of Day	**0-8 mi/hr**	**9-15 mi/hr**	**16-20 mi/hr**	**21-25 mi/hr**	**26-45 mi/hr**	**46-60 mi/hr**	**60-75 mi/hr**	**>75 mi/hr**
AM Peak	0	0	1	4	27	68	0	0
PM Peak	0	4	1	7	35	53	0	0
Mid-day	0	0	0	0	14	86	0	0
Overnight	0	0	0	0	1	44	54	0

6.8 Using Newly Created Highway Grade and Congestion Distributions

To use a newly created highway route with user-defined gradient and congestion distributions, navigate to the 'Master-IO' sheet and select 'Modal Comparison' in row 4. Select "Define Alternative" to bring up a dialogue window, select 'Auto/LDV' or 'Bus' from the drop-down menu, then choose 'Select & Edit'. Choose the desired highway route from the dialogues next to 'Route ID'. Route parameters can be edited by double clicking in the yellow box next to 'Route ID'. Complete the remaining input fields, then select 'Save' in the bottom left corner of the window. Finally, select 'Select & Return' to select the trip characteristics and return to the 'Master-IO' sheet.

In order to use specific highway congestion distributions, the user must load the corresponding congestion distribution before executing the simulation. Navigate to the 'LDV-Drive-Schedules' and/or 'Bus-Drive-Schedules' sheet and find the congestion distribution required for the desired simulation. Copy and paste the desired congestion distribution into the table beginning at column BC. This is the table that will be used by the simulation.

Finally, return to the 'Master-IO' sheet and complete the remaining alternatives desired for the modal comparison.

CHAPTER 7: INFLUENCE OF SYSTEM CHARACTERISTICS AND SCHEDULING PATTERNS ON COMMUTER RAIL ENERGY EFFICIENCY

Earlier versions of this research appeared in:

DiDomenico, G.C. & C.T. Dick. 2015. Influence of System Characteristics and Scheduling Patterns on Commuter Rail Energy Efficiency. In: Proceedings of the 6th International Conference on Railway Operations Modelling and Analysis. Tokyo, Japan.

7.1 Introduction

Commuter rail systems in the United States have developed marketing campaigns around their fuel efficiency and the general perception among potential riders that they are a “green” mode of transportation. One of the key benefits cited by municipalities to justify investment in the newest commuter rail systems is the environmental benefit from reduced highway congestion and emissions. On the cost side of the economic justification, operating energy is a vital consideration for a commuter rail project, as it can represent a large portion of the overall long-term system operating expenses. In the planning stages of a commuter rail project, these cost and benefits are often based on national averages for the commuter rail mode. However, operating energy efficiency varies with many factors such as vehicle type, traction power type, interference from other trains, service frequency, stopping patterns, infrastructure characteristics, average speed, and train consist make-up. Thus, individual commuter rail systems may experience energy efficiency values that differ substantially from the national average (Chapter 4). Since poor assumptions on the efficiency of the system can alter the economics of investment in commuter rail, there is a need for a planning-level model of commuter rail energy efficiency to aid planners, engineers, and policy makers in the development of new commuter rail lines. This chapter identifies and further investigates the basic system characteristics with the greatest influence on commuter rail energy efficiency that would be needed for such a model.

To identify the factors with the greatest influence on commuter rail energy efficiency, data on the energy consumption and transportation productivity of commuter rail systems in the United States (US) were analyzed using the National Transit Database (NTD). This database was supplemented with data from individual operating agency annual reports, publications, and timetables to fully characterize the relevant aspects of each commuter rail system.

To illustrate the potential of implementing different scheduled stopping patterns to reduce the energy consumed in moving a given passenger demand, this research conducted a case study of a commuter rail line in the Midwestern US. The case study examined alternative scheduling patterns, including local, skip-stop, zonal, and express patterns, under controlled demand, infrastructure, and consist configuration. To meet passenger demand, stopping frequencies at each station were set according to existing operations on the line. A train performance calculator was used to simulate train movements and calculate the fuel consumption of each schedule scenario. Since the number of passenger-miles was fixed, the effect of each scheduling pattern on energy efficiency was determined along with other service characteristics, such as train-miles and equipment utilization. Scheduling patterns that reduce deceleration and acceleration events (i.e. by skipping selected station stops) are more effective at increasing the energy efficiency of a train than other scheduling patterns. However, scheduling too many express segments can increase the overall number of trains required to meet passenger demand, offsetting the benefits of increased efficiency of a particular trip.

The results of this research can help planners, engineers, and policy makers prepare better estimates of commuter rail energy efficiency, and correspondingly improved estimates of system benefits and costs when justifying investment in the commuter rail mode. Operating agencies and service planners can consider the energy consumption implications of service schedule patterns when developing changes to timetables. In the future, this research can lead to a multi-objective optimization model to select schedule stopping patterns that meet demand-related constraints while simultaneously minimizing energy consumption and overall operating and equipment costs.

7.2 Literature Review

In the North American context, commuter rail transportation is characterized by passenger rail services operating from a major urban center to outlying communities. It differs from urban rapid transit by using more traditional passenger rail equipment and offering services tailored to the predominant passenger demand during the peak commuting hours (inbound in the morning and outbound in the evening). Unlike many systems elsewhere in the world, it is common for commuter rail operations in North America to share corridors and trackage with freight services (Brock & Souleyrette 2013). Busy systems with high commuter train volumes may be temporally segregated from freight traffic to avoid interference and delay during peak periods. Smaller systems operate commuter and freight traffic simultaneously at all times of the day. Several newer systems only operate on weekdays during the peak hours, while others operate during off-peak hours and on weekends at a lower frequency.

On average, commuter rail stations are spaced at four-mile intervals (Federal Transit Administration 2012). However, the spacing on specific lines is largely related to the distribution of demand relative to geographic constraints. This may result in closer station spacing and frequent stops that reduce average train speed and increase congestion on the line. To better serve passengers during peak periods, rather than each train stopping at every station, skip-stop trains commonly serve a smaller subset of stations, while zonal trains eliminate large numbers of stops. The design of these more complex timetables has focused largely on demand-related constraints, distributing schedule slack optimally, and optimization of driver behavior under a given timetable. Jong et al. (2012) optimized stopping patterns to minimize passenger travel time on the Taiwan High-Speed Rail system. The model used a genetic algorithm to find the optimal combination of stops that minimize total passenger travel time, while meeting the constraints of heterogeneous demand on a complex intercity high-speed rail system. Sogin et al. (2012b) extended this concept to a commuter rail line to minimize travel time while meeting a minimum service frequency at each station, allowing transit agencies to optimize the use of limited infrastructure. Ulusoy et al. (2011) optimized local and express scheduling patterns to minimize a total cost function that indirectly accounted for energy costs as part of vehicle operating costs per hour. However, improved travel time is not the only benefit of removing station stops. Zonal and skip-stop services reduce the amount of braking and acceleration required along a route, thereby conserving fuel. Recently, a few studies have attempted to optimize timetables based on total passenger travel time and energy consumption, but these focus on schedule patterns that stop at all stations (Ghoseiri et al. 2004, Dominguez et al. 2011).

In order to develop a multi-objective optimization model as mentioned above, the effect of various scheduling patterns must be better understood. This research establishes the relationship between total peak-period energy consumption and common scheduling patterns by an illustrative case study of a commuter rail line. In the future, this concept can be applied to an optimization model that can be used to help transit agencies provide optimal service while reducing operating costs associated with energy consumption.

7.3 Effect of System Characteristics on Commuter Rail Energy Efficiency

7.3.1 Methodology

Data used in this preliminary analysis were obtained from the 2012 National Transit Database (NTD). Annually reported operating statistics such as fuel or electricity purchased for revenue service, passenger-miles, train-miles, vehicle-miles, train-hours, and ridership were used to calculate the energy efficiency of the 25 US commuter rail systems discussed in Chapter 3.

While these NTD datasets are extremely detailed, there are some statistics related to operations and efficiency that are not reported directly. In this research, these statistics were derived from combinations of other reported metrics. This may compound errors present in the reported statistics. Furthermore, while the annual gross average statistics provided by the NTD are useful in high-level analyses, simulations are best to further investigate the results of the preliminary findings in this section on individual train runs. To supplement the NTD information, additional system operating and infrastructure characteristics such as the scheduling pattern were obtained from public timetables for each commuter rail system.

Energy efficiency (units of useful transportation per unit energy) and energy intensity (units of energy per unit of useful transportation) were calculated using the purchased volumes of diesel fuel and electricity, and the vehicle-miles of useful transportation output reported in the NTD by each operator, as shown in Table 3.2. The *energy conversion* analysis, detailed in section 3.4.3, was used to calculate the energy intensity values using the NTD. Using this methodology, the incremental energy used in electricity generation for electrified commuter rail systems was included in the calculation. Table 3.1 provides the generation intensity factors applied to electrified commuter rail systems based on their geographic location. The energy intensity values calculated in Table 3.2 were then compared with system characteristics obtained from individual commuter operator reports to gain a preliminary understanding of their effects on energy intensity. System characteristics considered include system route-miles, total number of stations, hours of service, days of service, use of alternative scheduling patterns, dispatch control, average equipment age, primary passenger car type, and primary locomotive type.

7.3.2 Results

As shown in Chapter 4, the number of cars per train had a large effect on energy efficiency (DiDomenico & Dick 2014). Also, the analysis in Chapter 5 indicated that station spacing, or the number of stops a train makes on a fixed-length route, also has a significant effect on energy efficiency (Fullerton et al. 2014).

Preliminary single variable statistical analyses were conducted to identify trends and correlations between specific system operating and scheduling characteristics and energy efficiency. No significant correlations were found between energy efficiency and total hours of service or days of service. There are some weekday peak-only services that are very efficient because concentrated ridership results in high load factors. There are other systems that offer more extensive service schedules and, due to higher overall ridership, can sustain longer peak-period trains that are more efficient and, on the whole, compensate for low off-peak ridership. These effects obscure any expected trends between service period and energy efficiency.

The analysis suggested that systems operating on lines dispatched by the commuter rail agency were slightly more energy efficient than commuter rail systems operating on lines where rail traffic is controlled by the host freight railroad train dispatcher. However, it is difficult to determine if this is an actual cause-and-effect relationship or if it is just a result of covariance with other factors such as train length or station spacing.

The analysis indicated that systems offering local-only service with stops at every station were more energy intense than those offering other service schedules, such as zonal, express, and skip-stop. Local-only systems had an average energy intensity of 661 BTU/seat-mile and systems using other patterns had an energy intensity of 610 BTU/seat-mile (an 8% reduction). Because the NTD dataset is comprised of high-level gross annual averages for each commuter rail system, it was not possible to analyze the relationship between stopping pattern and energy consumption in a more detailed way. Systems use complex stopping patterns during busy peak-periods and revert to local-only service during off-peak service hours. Furthermore, individual trains with different stopping patterns will likely have varying lengths according to the demand and number of stops the train makes. Therefore, a case study of a commuter rail line using complex stopping patterns was conducted to analyze the effects of various stopping patterns on energy consumption of individual trains and periods of service.

7.4 Effect of Scheduling Patterns on Commuter Rail Energy Efficiency

7.4.1 Methodology

A case study of a commuter rail line in the Midwestern US was conducted to investigate the effects of commuter rail system scheduling patterns on energy efficiency. The study simulated the energy consumption of trains during the morning peak period under various scheduling patterns using the Multimodal Passenger Simulation Tool (MMPASSIM). This excel-based train performance simulation model is under development by TranSys Research Limited in Ontario, Canada, and has been in use at the Rail Transportation and Engineering Center (RailTEC) at the University of Illinois at Urbana-Champaign as part of ongoing research on passenger rail energy efficiency.

MMPASSIM simulates the energy consumption of rail movements using a simplified train performance calculator based on traditional train energy methodology (modified Davis equation). 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. The model has the ability to use detailed train consist information, including train length, mass, resistance coefficients, head-end power (HEP) configuration, nominal traction power, and many other inputs in the calculation of energy consumption. The train performance methodology used in the MMPASSIM model is described in more detail in Chapter 6.

7.4.2 Route Characteristics

To characterize the route, a distribution of the grade, curvature, station stops, and speed limits from railroad track charts were used. The case study route was characterized by relatively low grades, with most of the route between -0.2 and +0.4% in the inbound direction of travel and maximum passenger train speeds of 79 mph. The existing commuter rail service operates with a mixture of express and local trains that serve varying numbers of station stops. The trains operate on a high-capacity triple-track mainline owned by a Class 1 freight railroad. This line operates under a “curfew” or temporal separation concept where most freight trains are run outside of peak commuter rail operating hours. The following analysis of scheduling scenarios assumed that, with freight train path conflicts eliminated due to temporal separation, the triple-track mainline provided sufficient capacity for express trains to overtake local trains. Thus the schedules presented in subsequent sections were assumed to be operationally feasible with adequate headways and overtaking/turnaround time. Finally, to account for the energy used in non-revenue train movements, a ratio of total distance to revenue distance of 1.023 was applied to the simulation results. Non-revenue train movements do not generate revenue seat-miles, however the energy consumption associated with these movements was included in the total energy intensity. This ratio was applied uniformly across each simulation. Any non-revenue movements to reposition trains were assumed to be included in the energy used for outbound trains and not included in this analysis.

7.4.3 Alternative Train Scheduling Patterns

To compare the effect of train schedule on commuter rail energy efficiency, five candidate scheduling patterns were simulated for the morning peak period, including: local, skip-stop, zonal, express, and the current peak-period operating schedule (Figure 7.1 through Figure 7.4). For this analysis, peak period was defined as the period from the first morning inbound train at 4:30 AM until 9:15 AM (Metra 2007). The candidate skip-stop, zonal and express train schedule patterns for this period are shown in Figure 7.1 through Figure 7.3, respectively. The local scenario, in which each train stopped at every station on the route, was not shown due to its simplicity. The current operating schedule pattern for the same period (Figure 7.4) used a mixture of trains that were similar in stopping pattern to those in each of the alternative train schedule patterns.

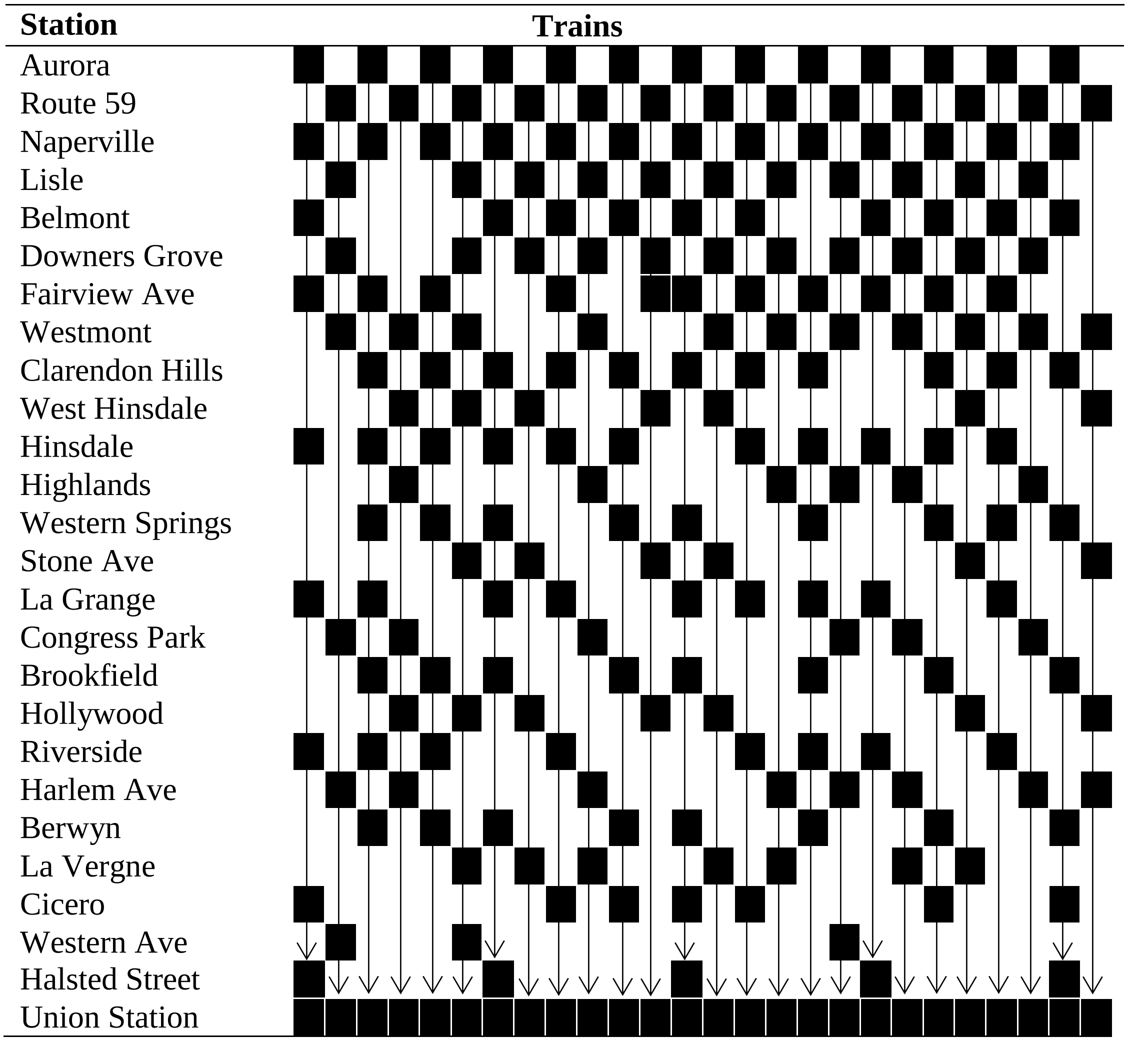


Figure 7.1 Skip-Stop scenario train schedule pattern on case study line

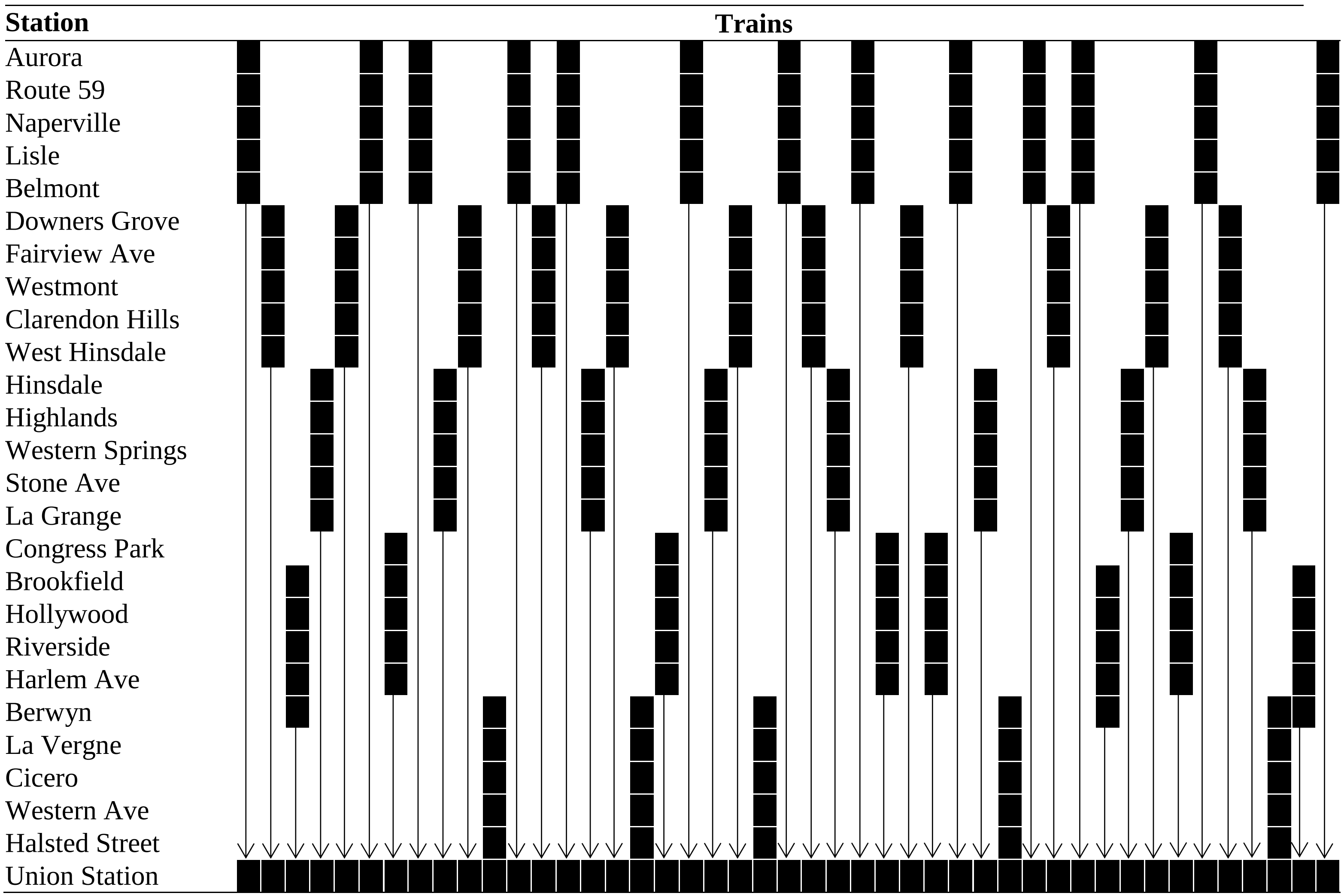


Figure 7.2 Zonal scenario train schedule pattern on case study line

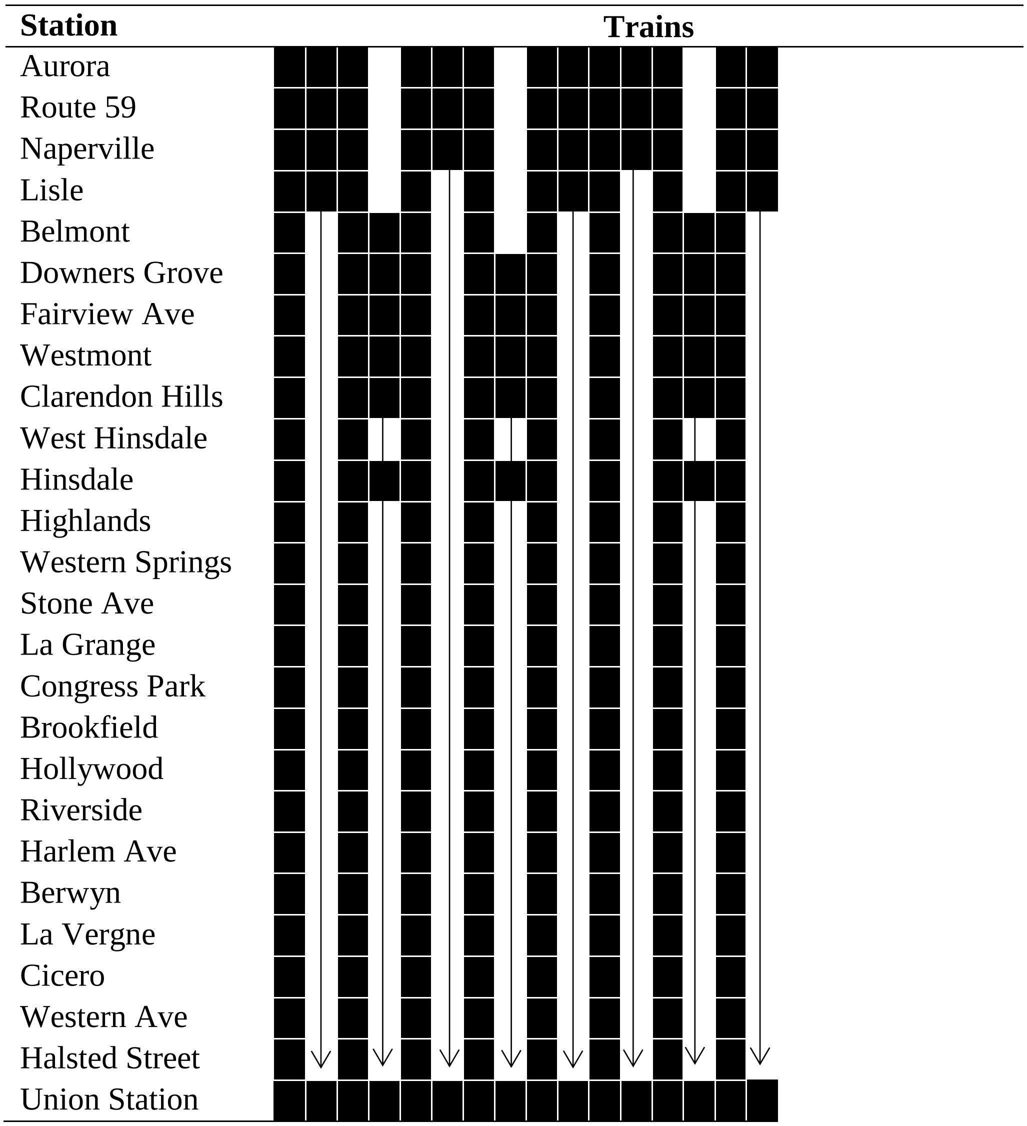


Figure 7.3 Express scenario train schedule pattern on case study line

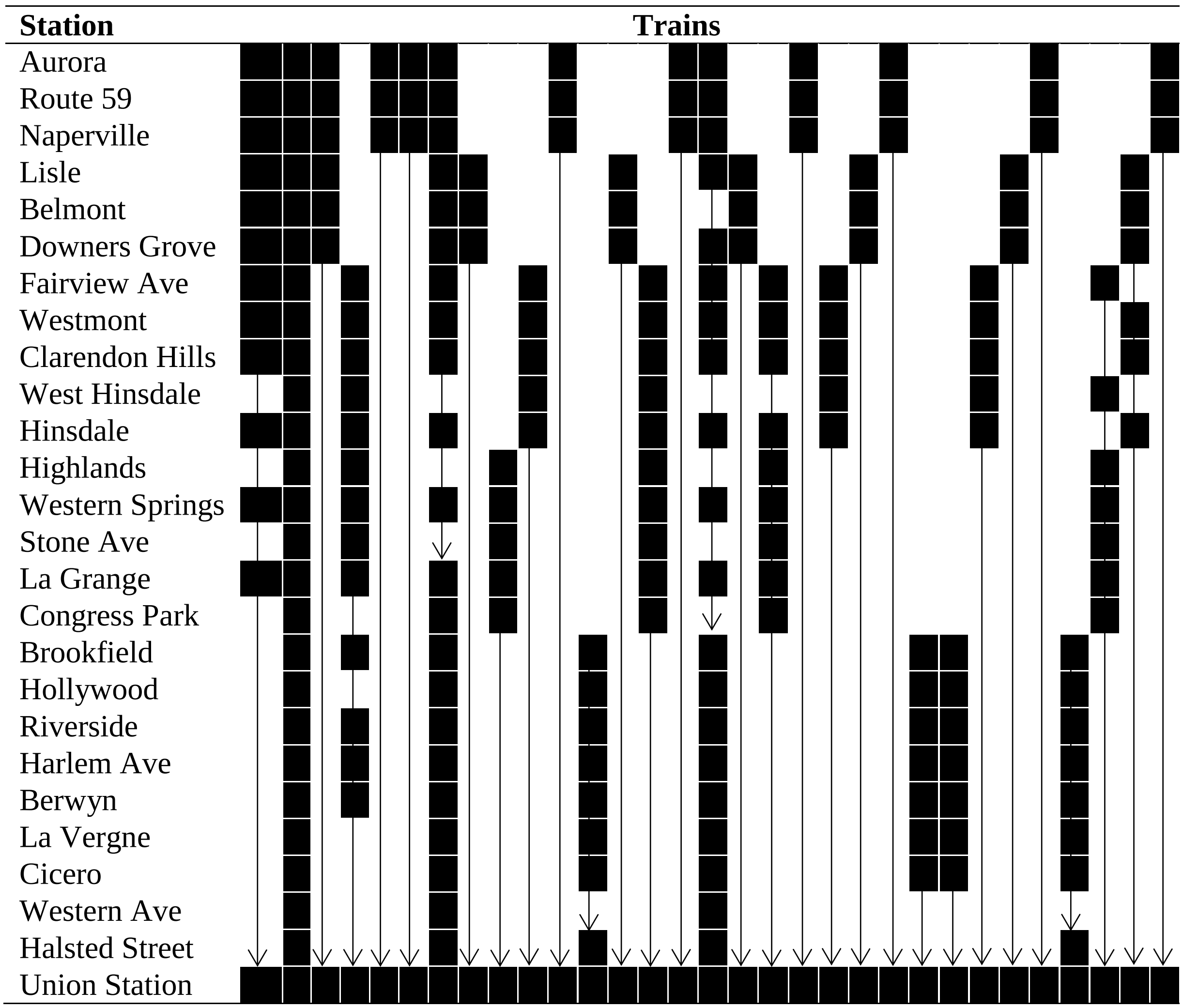


Figure 7.4 Current peak-period train schedule on case study line (Metra 2012)

Stopping patterns for local trains provided service to every station along the line with each train run. Therefore, in order to match existing train service frequencies at each station, fewer local trains were required than patterns that do not stop at every station. Skip-stop patterns skipped stations in small increments, increasing the effective distance between acceleration and deceleration events and reducing trip time. Zonal stopping patterns were comprised of trains stopping at zones of consecutive stations followed by a direct trip to the end terminal. Express scheduling patterns combined the patterns found in local and zonal scenarios by providing several local trains and supplemented high-demand stations with zonal “express” trains. This philosophy reduces service at low-demand stations that were over-served by the local-only train schedule pattern. Finally, the existing peak-period timetable, implemented by the operator under real-world service and demand-related constraints, was analyzed as a basis for comparing the energy consumption results of the other train schedule patterns.

The latest passenger schedule published by the commuter operator for this route (Figure 7.4) was analyzed to determine the baseline number of trains that serve each station during the peak period. To meet passenger demand and hold the level of service at each station constant, the alternative scheduling patterns were constructed such that the scheduled station service frequencies matched the current frequency of service to the extent that the flexibility in each pattern allowed (Table 7.1). Constructing the alternative schedules with this approach assumed a fixed origin-destination passenger demand matrix that is not influenced by unique deviations from existing operations in each scheduling scenario.

The skip-stop service exactly matched the current service frequency at all stations and reduced the number of trains by five. The local service required the fewest train runs. However, since all local trains stop at every station, some stations were over-served compared to current operations. While these extra stops could be skipped, in order to provide the most extreme case for comparison purposes, they were included in the analysis. The express pattern eliminated many extra stops but added more trains to provide individual train schedules with lengthy express segments. Since each zonal train served a smaller group of stations before running express to the terminal, the zonal schedule pattern required the greatest number of trains; 14 more than current operations.

Table 7.1 Scheduling pattern service counts

Station	Distance (mi)	Service Count Current	Local	Skip-Stop	Zonal	Express
Aurora	38.4	13	13	13	13	13
Route 59	31.6	13	13	13	13	13
Naperville	28.4	13	13	13	13	13
Lisle	24.4	11	13	11	13	11
Belmont	22.9	10	13	10	13	10
Downers Grove	21.1	11	13	11	11	11
Fairview Ave	20.3	11	13	11	11	11
Westmont	19.4	11	13	11	11	11
Clarendon Hills	18.2	11	13	11	11	11
West Hinsdale	17.8	7	13	7	11	8
Hinsdale	16.8	11	13	11	8	11
Highlands	16.3	6	13	6	8	8
Western Springs	15.4	9	13	9	8	8
Stone Ave	14.1	6	13	6	8	8
La Grange	13.7	9	13	9	8	8
Congress Park	13.0	6	13	6	5	8
Brookfield	12.3	8	13	8	8	8
Hollywood	11.7	7	13	7	8	8
Riverside	11.0	8	13	8	8	8
Harlem Ave	10.0	8	13	8	8	8
Berwyn	9.6	8	13	8	8	8
La Vergne	9.0	7	13	7	5	8
Cicero	7.0	7	13	7	5	8
Western Ave	3.7	3	13	3	5	8
Halsted Street	1.8	5	13	5	5	8
Union Station	0	31	13	26	45	16
Total Trains		**31**	**13**	**26**	**45**	**16**

7.4.4 Train Characteristics

All trains simulated in this experiment used one diesel-electric locomotive with a nominal traction power of 3,150 horsepower and varying numbers of bi-level, gallery commuter-rail coaches. Each coach had 146 seats, with a total passenger capacity of 246 (including standing room).

Passenger boarding and alighting counts from each station along the line were analyzed to determine the passenger demand at each station. This station-by-station demand allowed for reasonable estimates of required train consist length as a function of train stopping pattern (Metra 2007).

The analyses of inbound peak-period trains under the candidate scheduling patterns were conducted under two different train length assumptions. In one set of simulations, a constant train consist, shown as Consist A (Table 7.2), was used for all trains. The required number of coaches for Consist A was determined by analyzing passenger boardings and alightings at each station to determine the maximum net passenger load on an inbound peak-period local train.

Table 7.2 Consist configurations

Consist Name	Bi-level Coaches	Total Seats	Total Capacity (standing room)
Consist A	10	1,460	2,460
Consist B	6	876	1,476
Consist C	4	584	984

The second analysis examined the effects of each scheduling pattern on the peak-period energy consumption using variable train consists sized to more accurately reflect the passenger demand of individual train runs. To simplify use of the MMPASSIM tool, only three discrete commuter train consist options were used in these cases. Consist A represented high passenger capacity and Consists B and C represented medium and low passenger capacity respectively. Train consists were assigned to individual trains according to the net passenger load for the stopping pattern of each train and the total capacity of each consist type.

7.4.5 Results

Efficiency of Average Trains for Candidate Scheduling Scenarios

Each scenario had a varying number of total required trains over the peak-period (Table 7.1). In addition to having different stopping patterns, individual trains traveled various distances. For example, zonal trains originating in the middle of the route had shorter runs. This disparity in trip length and number and location of stops caused the relative energy consumption to vary between individual trains within schedule scenarios. Therefore, to draw comparisons between scheduling patterns, it is important to understand the performance of the average train under each scenario.

For the case of a constant train consist (Consist A), the energy consumption and intensity of the average train in each scheduling pattern is presented in Table 7.3. Since the local trains all traversed the entire route and make the most stops, the average local train had the highest energy consumption and energy intensity per train-mile. The average zonal train consumed the least energy per train, since it made fewer stops and only traveled a portion of the overall route length.

Similar results were obtained for the case using variable train consists (Table 7.4). The local train consumed the most energy per train, and was also the most energy intense per train-mile. This is consistent with the preliminary results presented in Section 7.3.2 suggesting that commuter rail systems running local-only scheduling scenarios had a higher energy intensity (per seat-mile) than systems using other patterns.

Comparison of the values in Table 7.3 and Table 7.4 revealed an interesting trade-off in the intensity metrics. In the case with variable train consists, reducing the size of each train to meet passenger demand also reduced the energy intensity per passenger-mile, resulting in a more efficient operation. However, the energy intensity (per seat-mile) was higher in each scenario with the variable consist. Although the variable consist scenario had shorter trains (and correspondingly lower energy per train-mile), each train had fewer seats to distribute the fixed resistance of the locomotive. This increased the energy per seat-mile to cause the operation to appear less efficient from the perspective of seat-miles. Since all local trains always used Consist A, there was no change in the local results between Table 7.3 and Table 7.4.

Table 7.3 Energy of average trains for each scheduling pattern using Consist A

Train Type	Stops	Trip Dist. (mi)	Speed (mph)	Energy (therms[1]/ train)	Intensity (therms[1]/ train-mi)	Intensity (BTU/ pax-mi)	Intensity (BTU/ seat-mi)
Local	26	38.4	17	303	7.78	683	535
Express	16	35.4	24	209	5.80	576	398
Skip-Stop	9	35.0	39	152	4.27	677	290
Existing	8	27.5	32	133	4.73	709	325
Zonal	6	22.6	37	104	4.58	827	319

Table 7.4 Energy of average trains for each scheduling pattern using variable consists

Train Type	Speed (mph)	Energy (therms[1]/ train)	Intensity (therms[1]/ train-mi)	Intensity (BTU/ pax-mi)	Intensity (BTU/ seat-mi)
Local	17	303	7.78	683	535
Express	24	190	5.19	522	453
Skip-Stop	43	104	2.90	474	348
Existing	37	85	3.20	485	374
Zonal	44	57	2.75	480	371

[1]Therm (EC) unit equals 100,000 BTU_{IT}

The relationship between energy consumption of individual trains within each scheduling scenario and the number of station stops made by a particular train showed a distinct relationship (Figure 7.5). Increasing the number of station stops made by a particular train increased its energy consumption. This result was due to the increased number of acceleration and deceleration events (Fullerton et al. 2014). Finally, there was some variability in the energy consumption of skip-stop and zonal schedules with the same number of stops. This suggested there was potential to optimize the system energy consumption based on the exact combination of station stops built into each scheduled train run.

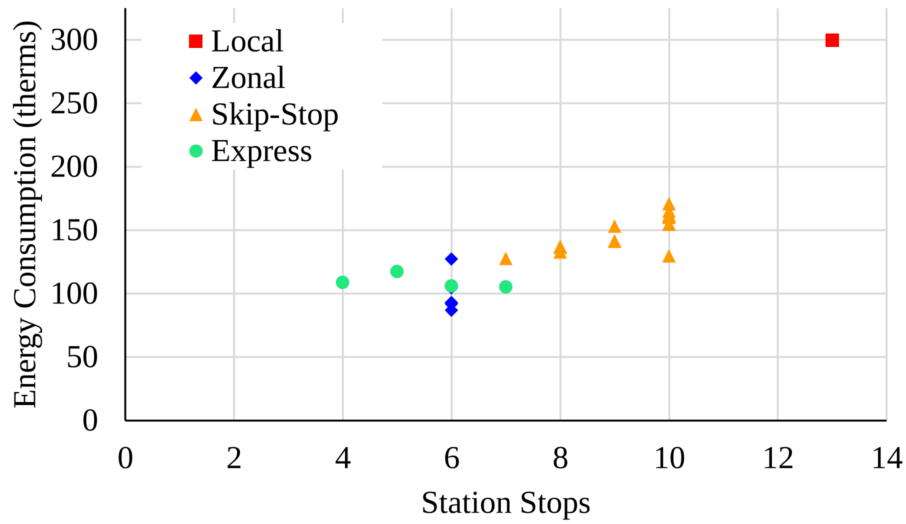


Figure 7.5 Total energy consumption of individual trains versus number of station stops for each candidate scheduling pattern

Constant Train Consist

The overall energy consumption for the peak period of each candidate scheduling pattern was calculated (Figure 7.6). This showed the combined effect of the efficiency of each train with a constant consist and the total number of trains required to provide the service.

The relative difference between each scheduling scenario was amplified due to the consistent use of Consist A (10 coaches), even for trains that have low passenger demand. Although the average zonal train used the least average energy per train (Table 7.3), due to the high number of trains required to meet service requirements, the zonal scenario required the most energy over the entire peak period. Specifically, in order to maintain current service frequency,

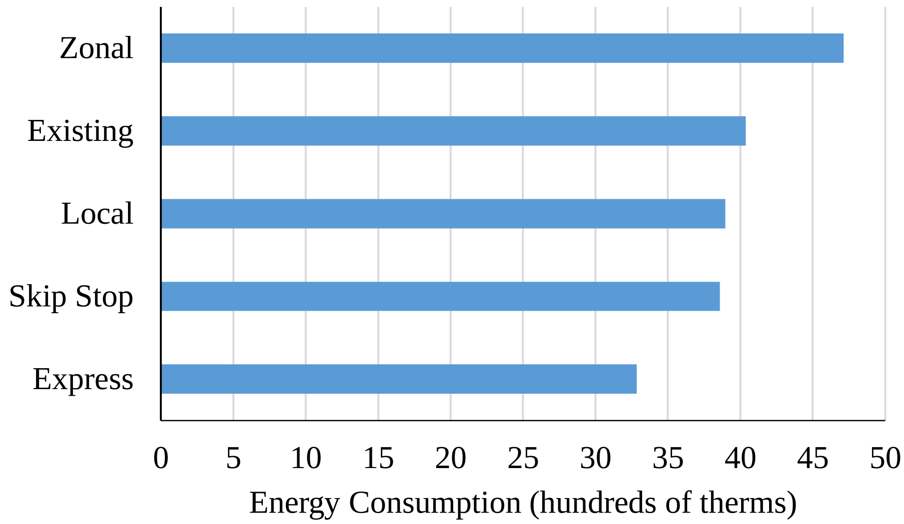


Figure 7.6 Energy consumption of peak-period operations using constant train consists for each scheduling scenario

this scenario required 46 trains, as opposed to 31, 26, 16, and 13 for the current, skip-stop, express, and local scenarios, respectively. Since it used fewer trains, peak-period energy consumption for the local scenario required 17% less energy than the zonal scenario. The efficiency of the zonal trains was reflected by the zonal scenario only required approximately 40% more energy than the express scenario, despite requiring three-times the number of trains.

Although the local and express scenarios required the least energy for the peak-period, they also required the longest run time per trip. For the express scheduling pattern, the long trip time was due to the local trains required to complete the service schedule at stations not served by the express trains with low run times. The total peak-period energy consumption was compared to the average passenger travel time for each candidate train scheduling pattern (Figure 7.7). Travel times output from the model were somewhat exaggerated due to the acceleration effects of the longer train consist. The zonal scenario had the highest total energy consumption, but also offered a low average travel time.

In illustrating the trade-off between peak period energy consumption and average passenger travel time, Figure 7.7 took the form of a pareto-optimal plot. The origin of the plot represents a train service schedule that consumes no energy and provides infinitely short travel times. Obviously this is an infeasible solution; however, if both energy efficiency and travel time

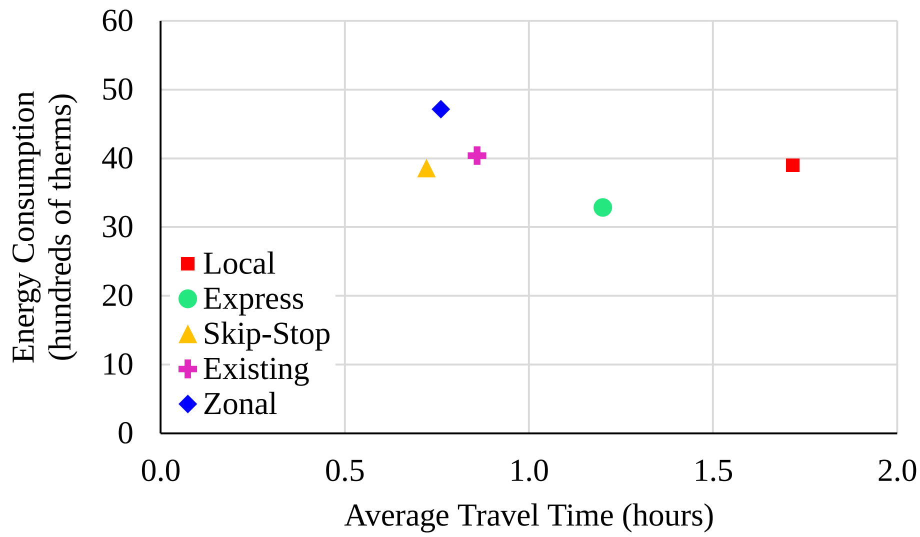


Figure 7.7 Pareto-optimal plot of energy consumption versus weighted average travel time of peak-period operations using constant train consists for each scheduling scenario

were valued equally, the feasible candidate train service schedule pattern that was the closest to approaching the origin will be optimal in terms of both energy consumption and travel time. For this case study, the skip-stop pattern was pareto-optimal, followed very closely by the zonal and existing operating schedules. Operators that place different priorities on energy consumption or travel time can weight them accordingly to find the optimality that reflects their goals. The intersection of this vector with the pareto-optimal frontier of feasible schedule solutions will indicate the optimal train schedule pattern. Operators may find this graphical technique to be a useful method for visualizing the trade-off between energy consumption and travel time when determining optimal train schedule patterns.

Variable Train Consist

To more accurately reflect actual operations, the analysis was repeated using the three different train consists shown in Table 7.2. The consists were assigned to each individual train based on the maximum net passenger demand between any two stations for each train and the capacity of the consist type. This allocation of passenger cars to trains allowed for shorter train consists on trains that do not stop at enough high-demand stations to justify the 10 coaches used in the previous analysis.

The total energy consumption during the peak-period for each scheduling scenario was calculated using the variable train consists (Figure 7.8). The local scenario required the most energy and the skip-stop and zonal scenarios required the least energy, using 32% less than the local scenario. The change in relative ranking was due to the required use of Consist A on all of the local train runs, while the other scenarios used shorter consists on lower-demand runs. Half of the peak-period trains in the express scenario used local Consist A, while the other half were express with Consists B or C, depending on passenger demand. Despite the addition of three trains, and higher overall operating speed, the elimination of stops and reduction in trailing coaches on the eight express trains reduced the total energy consumption below that of the local scenario.

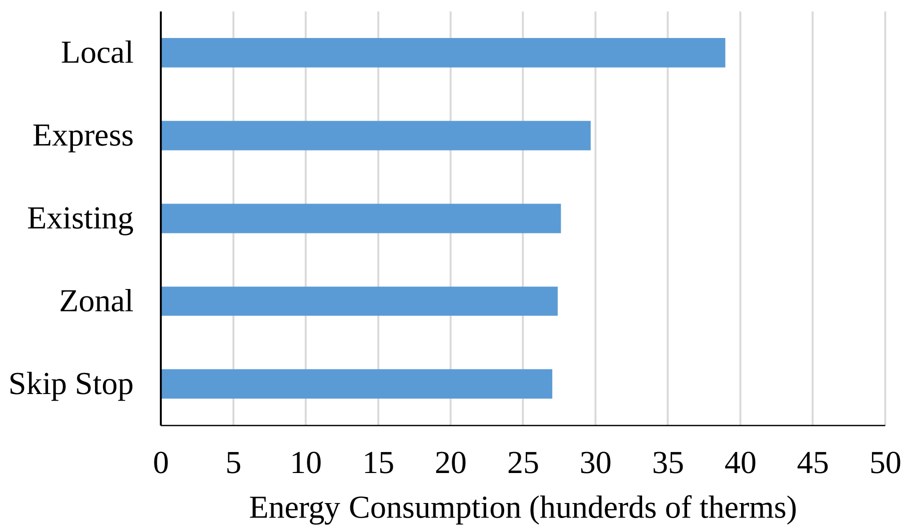


Figure 7.8 Energy consumption of peak-period operations using variable train consists for each scheduling scenario

The total peak-period energy consumption and the average passenger travel time for each candidate train scheduling pattern with a variable train consist was calculated (Figure 7.9). The trade-off between improved service (lower average passenger travel time) and energy consumption was less obvious, skewed slightly by the longer trains in the local and express scenarios. From a pareto-optimaltiy perspective, the skip-stop scenario was closest to the origin, and clearly improved the current operating schedule pattern (i.e. lower energy consumption and shorter travel time than the current operation). Similarly, the express service pattern clearly dominated the local service pattern.

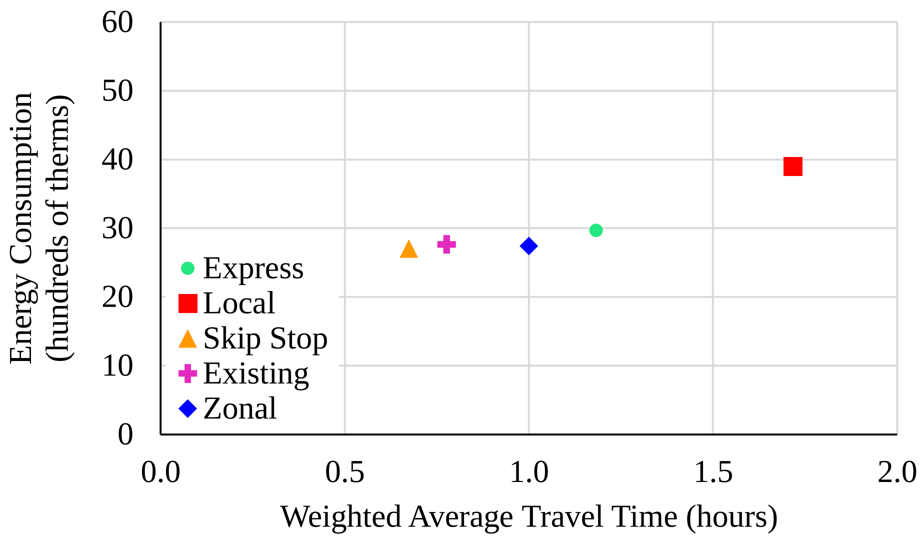


Figure 7.9 Pareto-optimal plot of energy consumption versus weighted average travel time of peak-period operations using variable train consists for each scheduling scenario

7.5 Conclusions

Single-variable analysis suggests that stopping pattern affects the operating energy consumption of commuter rail systems in the US. To investigate the effects further, a case study of a commuter rail line in the Midwestern US was conducted. The case study examined candidate peak-period scheduling scenarios, including local, zonal, skip-stop, and express patterns, under controlled demand and infrastructure conditions. Simulations of the individual train movements comprising each peak-period schedule were performed using a train performance simulation tool. Results using a constant 10-coach commuter train consist with a single locomotive indicated that due to the high number of station stops, the zonal scheduling scenario used the most energy during the peak period and was the most energy intense per train-mile. The express scenario used the least energy per peak-period when using a constant 10-coach consist. When the train consist was varied according to demand, the skip-stop scenario consumed the least total energy during the peak-period, benefitting from the reduction in consist length on trains with lower demand.

The results showed a trade-off between total peak-period energy consumption and average travel time. With a constant train consist, the scenarios consuming the most energy had the lowest average passenger travel times, while those consuming the least energy had higher average travel times. This trade-off was less apparent in the analysis with variable consists.

Operating energy consumption is a large expense for transportation agencies that are increasingly under budget constraints and financial scrutiny. However, transit agencies must be concerned with offering a high level of service to their riders and trying to minimize the average trip time for passengers. The ability of a train schedule pattern to optimize both energy consumption and average passenger trip time can be visualized by a pareto-optimal plot of possible schedule solutions. This graphical technique may be a useful approach for practitioners to evaluate their existing operations relative to new train operating plans. When applied to the case study data, it appeared that the optimal scheduling solution would include a mixture of skip-stop and express services with station stops that conform to passenger demand and not a general application of a single rigid scheduling methodology.

This research introduced basic relationships between total peak-period energy consumption and common commuter rail scheduling patterns. In the future, these concepts can be integrated into an optimization model to help transit agencies provide optimal service times while lowering operating costs and energy consumption.

CHAPTER 8: EFFECTS OF ENERGY-SAVING TECHNOLOGIES AND SERVICE IMPROVEMENTS ON ENERGY INTENSITY OF COMMUTER RAIL: CASE STUDY

8.1 Introduction

To accommodate growing ridership with constrained public-agency budgets, commuter railroads are working to reduce energy consumption while improving current service levels. Commuter railroads in North America use a diverse fleet of passenger equipment, traction power types, operating philosophies, and infrastructure configurations. Due to these differences, energy-saving strategies that have been implemented successfully on one railroad may not produce similar results on another property. Furthermore, development, testing, and implementation of some energy-saving technologies, strategies, or service improvements require significant capital investment. Modelling energy consumption of passenger rail services can be a cost-effective method of evaluating the possible benefits of implementing new energy-saving projects. This chapter used the Multimodal Passenger Simulation Tool (MMPASSIM) introduced in Chapter 6 to analyze the effects of implementing new operational strategies, equipment and track infrastructure modifications, and electrification on the energy intensity of a commuter rail route in the Midwestern US.

8.2 Methodology

8.2.1 Multimodal Passenger Simulation Tool (MMPASSIM)

The Multimodal Passenger Simulation Tool (MMPASSIM) is an excel-based passenger transportation energy model with train performance calculator developed by TranSys Research Limited of Glenburnie, Ontario, Canada, in conjunction with RailTEC at the University of Illinois at Urbana-Champaign, as part of the National Cooperative Rail Research Program (NCRRP) project 02-01 “Comparison of Passenger Rail Energy Consumption with Competing Modes”. An introduction to this model and a detailed description of the rail performance module can be found in Chapter 6. This model was used to simulate the baseline energy consumption of a Midwestern United States (US) commuter rail service. This baseline energy consumption was compared to simulated energy consumption and intensity results for the service using several energy-saving technologies and strategies.

As discussed in Chapter 7, commuter rail operators have implemented a variety of scheduling patterns to meet passenger demand more efficiently from both an operational and an energy perspective. Some energy-saving strategies may be more effective under one scheduling pattern than another. For example, an optimal coasting driver-advisory system may reduce energy intensity more under a local train schedule relative to a zonal service because the local has more stops, and therefore more opportunity to take advantage of coasting into stations. Therefore, each technology/strategy was analyzed on local, zonal, and skip-stop schedule patterns.

Commuter railroads are also trying to reduce passenger travel time while reducing operating expenses. In some cases, modifications that reduce travel time, such as equipment upgrades or speed increases, are analyzed to illustrate the compromise between travel time and energy intensity.

8.2.2 Rail Route Description

The route used in this analysis is the same one described in Chapter 7 (Table 8.1). It was characterized using railroad track charts to develop a distribution of the grade, curvature, station stops, and speed limits. The route begins in Aurora, Illinois and terminates in downtown Chicago, Illinois. The route is characterized by relatively low grades, with most of the route between -0.2 and +0.4% in the inbound direction of travel and maximum passenger train speeds of 79 miles per hour on a high-capacity, triple-track mainline owned by a Class 1 freight railroad.

Table 8.1 Key MMPASSIM route input parameters

Parameter	Value			
Scheduled Stops	Local: 26	Zonal: 6	Skip-Stop: 10	
Average Expected Speed Reductions per One-Way Trip	**Num.**	**Speed (mph)**	**Length (mi)**	
	0.05	25	0.2	
	0.1	40	0.1	
Average Expected Unscheduled Stops per One-Way Trip	**Num.**	**Speed (mph)**	**Length (mi)**	**Duration (min)**
	0.5	25	0.5	2
Ratio of Total Distance to Revenue Distance	1.023			

This line operates under a “curfew” or temporal separation concept, where most freight trains are operated outside of peak commuter rail operating hours. Finally, to account for the energy used in non-revenue train movements, a ratio of total distance to revenue distance was applied to the simulation results. Non-revenue train movements do not generate revenue seat-miles, however the energy consumption associated with these movements was included in the total energy intensity. This ratio was applied uniformly across each simulation.

8.2.3 Rail Consist Description

The train consist used as the baseline for comparison in this analysis corresponds to Consist B with six coaches (Table 7.2). The baseline train and most other cases used a single F40PH diesel-electric locomotive with a nominal traction power of 3,150 horsepower and a variable-speed head-end power (HEP) configuration (Table 8.2). Each coach had 146 seats.

Table 8.2 Key MMPASSIM consist input parameters

Parameter	Value
Consist Description	1 F40PH Loco., 6 Bi-level coaches
Total Weight (no passengers) (lbs)	956,149
Total Length (ft)	566
A (N)	5,133
B (N/km/h)	0
C ($N/(km/h)^2$)	0.838
Nominal Traction Power (hp)	3,150
Primary Fuel Type	US Conventional Diesel
HEP Provision Code	2 (PTO-inverter)
Energy Recovery Type	0 (none)

8.3 Energy-Saving Technology Evaluation

8.3.1 Operational Strategies

Optimal Coasting

Optimal coasting is a system affecting train driver behavior (acceleration, deceleration, and speed control) with respect to the available schedule slack time. With this simulation feature enabled, coasting advice was calculated and suggested to the driver at each scheduled stop based on the average usable schedule slack per one-way trip (1.5 minutes in this case). The train can be instructed to coast in order to reduce energy consumption while meeting schedule constraints. However, Lukaszeiwicz (2001) found that drivers may not always follow the optimal coasting advice. The parameter "O" (percentage of coasting advice obeyed) was used to account for the effectiveness of the optimal coasting advice at varying levels of implementation by drivers.

A sensitivity analysis of an optimal coasting driver advisory system on energy intensity was conducted (Table 8.3). When 10% of the coasting advice was obeyed by the driver, energy intensity was reduced by an average of 3%. Energy intensity was reduced by an average of 12% with a 35% obedience rate and by 23% with a 65% obedience rate. The number of coasting opportunities varied with the number of stops of each schedule pattern. Therefore, the local pattern had the greatest energy intensity reduction.

Table 8.3 Effects of optimal coasting driver advisory system on energy intensity

		Optimal Coasting (per seat-mi)					
Schedule Pattern	**Baseline (per seat-mile)**	**O=10%**		**O=35%**		**O=65%**	
	BTU	BTU	reduction	BTU	reduction	BTU	reduction
Local	421	404	4%	349	17%	283	33%
Zonal	309	302	2%	281	9%	256	17%
Skip-Stop	371	362	2%	333	10%	298	20%
Average	367	356	3%	321	12%	279	23%

Consist Length

Consist length can have a large impact on the energy consumption of commuter trains, as shown by the reduced energy consumption when using shorter consists in the Variable Consist analysis of Chapter 7. To investigate this further, the energy intensity of the baseline train consist was simulated with an increasing consist length, adding one additional coach with each train up to a maximum of 20 coaches. Then, when the round trip travel time exceeded a threshold of 3.5 hours, an additional locomotive was added to the consist to improve running time (Figure 8.1). Each locomotive has a fixed resistance that was distributed over the seats in the consist. Each additional coach increased the resistance of the consist, but also increased the number of seats that the fixed resistance of the locomotive was distributed over. In the case with only one locomotive, the energy intensity decreased according to a power function, with the horizontal asymptote approaching the fixed resistance of the single railcar (Figure 8.1). When the quality-of-service limit of 3.5 hours was reached with one locomotive and seven coaches, another locomotive was added to the consist with eight coaches. This increased the energy intensity, but reduced the round trip travel time. This occurred again at 15 coaches, where a third locomotive was added to meet the quality-of-service constraint. The addition of locomotives to meet schedule requirements effectively limited the economies of scale and set a lower bound to the energy intensity (per seat-mile) even as the train became very long. The problem of consist management is primarily driven by demand-related constraints and not energy consumption. However, optimizing the consist length to meet passenger demand and service-related constraints while minimizing energy can have a significant impact on the energy intensity.

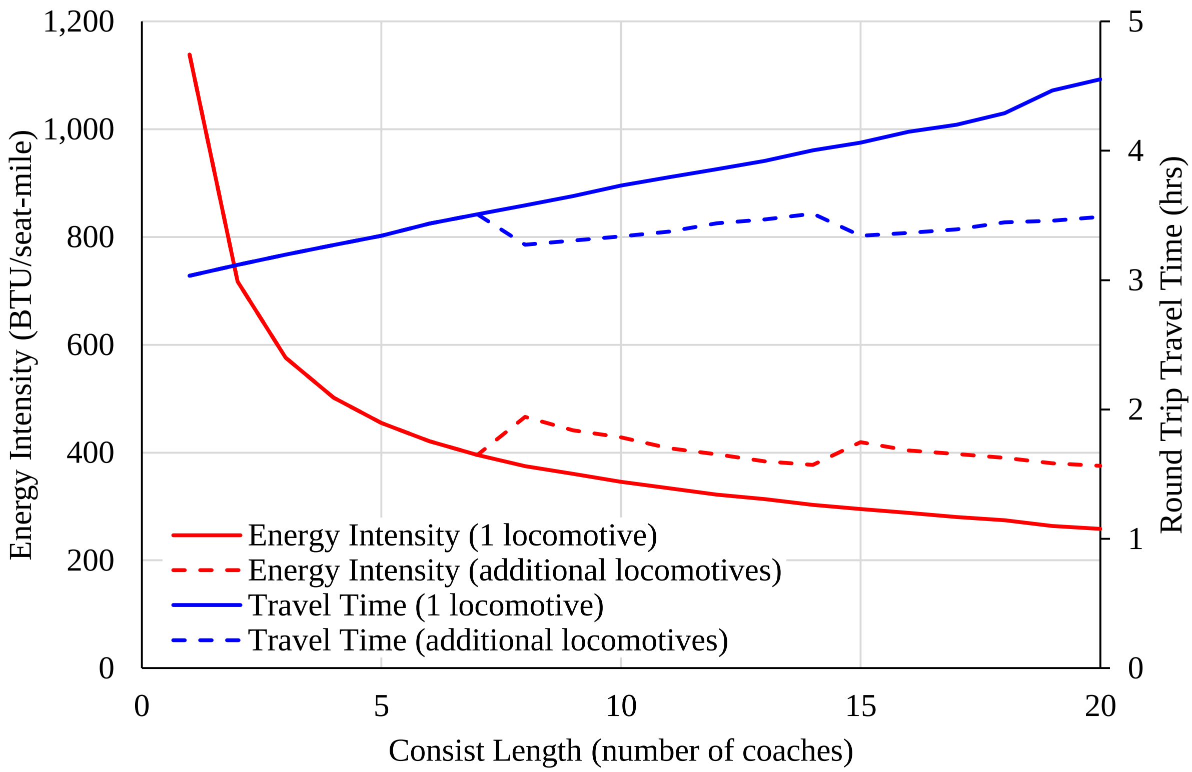


Figure 8.1 Effect of consist length on energy intensity and travel time

8.3.2 Equipment Modifications

Railroads may make equipment changes or upgrades to improve travel time or average speed. In the first case, an additional F40PH locomotive was added to the baseline consist (Table 8.4). The additional locomotive resulted in an increase in energy intensity per seat-mile for the local, zonal, and skip-stop patterns; however, the additional locomotive resulted in travel time reductions from 4%-7% (Table 8.5).

Table 8.4 Effect of equipment changes on energy intensity

		Equipment (per seat-mile)					
Schedule Pattern	**Baseline (per seat-mile)**	**2 Locomotives**		**MPI36-PH**		**Equivalent Single Level**	
	BTU	BTU	increase	BTU	increase	BTU	increase
Local	421	528	25%	506	20%	578	37%
Zonal	309	361	17%	404	31%	447	45%
Skip-Stop	371	449	21%	461	24%	521	40%
Average	367	446	21%	457	25%	515	41%

Table 8.5 Effect of equipment changes on service metrics

			Equipment					
Schedule Pattern	**Baseline Travel Time**	**Baseline Average Speed**	**2 Locomotives**		**MPI36-PH**		**Equivalent Single Level**	
	hrs	mph	hrs	mph	hrs	mph	hrs	mph
Local	3.44	22	3.20	24	3.65	21	3.45	22
Zonal	1.74	44	1.68	46	1.81	42	1.75	44
Skip-Stop	2.14	36	2.02	38	2.26	34	2.15	36
Average	2.44	34	2.30	36	2.57	32	2.45	34

Next, the effect of exchanging the baseline F40PH locomotive for an MPI36-PH model was analyzed (Table 8.4 and Table 8.5). This change might be made to take advantage of a higher-power unit (3,600 horsepower) or to comply with Tier 1 or 2 EPA emissions regulations (LTK Engineering Services 2009). The change did not reduce the travel time, but increased the energy intensity by 20%, 31%, and 24% for the local, zonal, and skip-stop trains respectively.

The baseline train consist used bi-level gallery cars with 146 seats per coach. Several commuter railroads use single-level coaches with a lower seating capacity. In some situations, this may be done because passenger demand does not warrant higher capacity coaches. However, if passenger demand does warrant the higher capacity of bi-level coaches, there is an energy intensity reduction that can be expected. To illustrate this, the baseline case was modified to use single-level coaches. To provide an equivalent seating capacity, 10 single-level coaches with 84 seats per coach were used (840 seats compared to 876 seats in the baseline consist with 6 bi-level coaches). This change increased energy intensity per seat-mile by 37%, 45%, and 40% for the local, zonal, and skip-stop patterns respectively (Table 8.4). Furthermore, round trip travel time increased by an average of 5%. High-capacity bi-level coaches have the potential to improve service and reduce energy intensity for commuter railroads with high ridership. These reductions in energy intensity used metrics of energy per seat-mile. As shown in Chapter 4, new-start systems with a smaller, but rapidly growing ridership tended to have higher energy efficiency (by passenger-miles) using vehicles with less seating capacity and more frequent service. However, systems with larger demand can achieve a higher load factor with high-capacity coaches and reduce energy intensity (per passenger-mile).

8.3.3 Infrastructure Modifications

Increase Speed Limit to 75 mph

Another method to improve service is to upgrade the infrastructure to allow for higher maximum speeds along the line. Typically, this would involve upgrading the signaling system and/or reducing grade and curvature, which requires capital investment. To investigate this, a hypothetical case of speed increases was developed (Table 8.6). The increased speed limit case increased the speed limit over 34 miles of the route. Speed limits near the downtown area were held at the current speed limits due to tight geometry constraints of dense urban areas.

The changes had the largest effect on the zonal schedule because it can benefit from the increased speed limits without stopping between its last stop and the terminal (Table 8.7). The energy intensity of the zonal schedule increased by 6%, while travel time was reduced by 4%. The skip-stop schedule had less reduction in travel time, but still had a 6% increase in energy intensity. The local schedule energy intensity increased by 3%, caused by the short distance between stops that prevent the local train from taking full advantage of increased speed limits.

Table 8.6 Changes in passenger speed limit

Milepost	Current Speed Limit (mph)	Increased Speed Limit (mph)
0	25	25
1.7	60	75
3.7	70	75
35.3	55	75
38.4	75	75

Table 8.7 Effects of increased speed limit on energy intensity and service metrics

				Increase Speed Limit to 75 mph					
Schedule Pattern	**Baseline (per seat-mile)**	**Travel Time**	**Avg. Speed**	**Energy**		**Travel Time**		**Avg. Speed**	
	BTU	hrs	mph	BTU	inc.	hrs	red.	mph	inc.
Local	421	3.4	22	520	3%	3.3	0%	22	0%
Zonal	309	1.7	44	327	6%	1.6	4%	46	4%
Skip-Stop	371	2.1	37	393	6%	2.0	2%	37	2%
Average	367	2.4	34	413	5%	2.3	2%	35	2%

Unplanned Stops and Speed Reductions

Another way to improve service is to reduce the frequency of unplanned stops and speed reductions. On a commuter railroad shared with freight operations, unplanned stops and speed reductions occur as a result of conflicts with freight movements: meets, passes, trains entering yards, etc. Other causes of unplanned stops or speed reductions include slow orders due to track maintenance or safety violations. Investment in the infrastructure through increased capacity or maintenance can reduce these occurrences by providing additional track capacity and well-maintained track to avoid slow orders.

MMPASSIM accounts for unplanned stops and speed reductions using a user-input Expected Speed Reduction and Unexpected Stop frequencies (Table 8.1). To analyze the effect of the unplanned stops and speed reductions on energy intensity, the baseline frequencies were reduced to zero unplanned stops and speed reductions and increased by factors of two and three. Eliminating unplanned stops and speed reductions reduced energy intensity and travel time by an average of 3% (Table 8.8 and Table 8.9). Doubling the frequency of such events increased energy intensity and travel time by an average of 3%. Tripling the frequency of these events increased energy intensity by an average of 7% and increased travel time by an average of 6%.

Table 8.8 Effect of changes in unplanned stops and speed reductions on energy intensity

		Unplanned Stops and Speed Reductions (per seat-mile)					
Schedule Pattern	**Baseline (per seat-mile)**	**Eliminate**		**Double**		**Triple**	
	BTU	BTU	reduction	BTU	increase	BTU	increase
Local	421	409	3%	433	3%	445	6%
Zonal	309	296	4%	321	4%	333	8%
Skip-Stop	371	359	3%	383	3%	395	6%
Average	367	355	3%	379	3%	391	7%

Table 8.9 Effect of changes in unplanned stops and speed reductions in service metrics

			Unplanned Stops and Speed Reductions					
Schedule Pattern	**Baseline Travel Time**	**Baseline Average Speed**	**Eliminate**		**Double**		**Triple**	
	hrs	mph	hrs	mph	hrs	mph	hrs	mph
Local	3.44	22	3.36	23	3.51	22	3.58	21
Zonal	1.74	44	1.67	46	1.82	42	1.89	41
Skip-Stop	2.14	36	2.07	37	2.21	35	2.28	34
Average	2.44	34	2.37	35	2.51	33	2.58	32

8.3.4 Electrification

As shown in Chapter 3, an analysis of operating energy efficiency between the *upstream* and *traction* points of Figure 3.1 showed that electric traction and diesel-electric traction achieve similar efficiencies if the electricity is generated using the average electricity generation source profile of the US. However, this varies greatly by geographic region and electricity generation source profile. Changing from diesel-electric to electric traction may lead to reduced energy intensity if the electricity generation sources in the region are more efficient than average, and relatively efficient vehicles are used. However, electrification of a system requires significant capital investment and upstream energy costs associated with construction. Therefore, a cost-benefit analysis would be necessary to determine the savings (if any) to the commuter railroad and other stakeholders.

To analyze the energy benefits of electrification, the baseline case was modified to use an AEM7 model electric locomotive and bi-level gallery coaches. Another case used “Highliner” electric-multiple unit (EMU) bi-level gallery coaches (Lukaszewicz 2007, Nippon Sharyo 2013). Each configuration was simulated with and without regenerative braking energy recovery. Regenerative braking is a type of energy recovery that uses the electric motors as generators during braking phases. In some cases, regenerative braking energy must either be used by nearby accelerating trains or dissipated in on-board resistors, limiting the ability to use it. However, in this case, energy was assumed to be regenerated to the existing power grid at an acceptance ratio of 65%. In other words, 65% of the energy recovered was returned to the power grid. This requires substations that are capable of receiving power from the catenary, as well as transmitting to it. This is not the case in many systems, but was examined here to show the potential energy intensity reductions.

Using an *Energy Conversion* analysis, the model used the “East North Central” generation intensity from Table 3.1 to account for the incremental energy consumption used in electricity generation. When switching to electric locomotives, energy intensity was reduced by 6%, 12% and 8% for the local, zonal, and skip-stop patterns respectively. When using EMUs, a greater energy intensity reduction occurred, reducing energy intensity by 10%, 17% and 14% for the local, zonal, and skip-stop patterns respectively (Table 8.10 and Table 8.11). The EMUs were heavier than the baseline bi-level coaches due to the addition of traction motors and other electric equipment on each coach; however, the incremental weight was less than the additional weight of the electric locomotive, so the EMUs achieve a greater reduction in energy intensity. The zonal schedule had the largest energy intensity reduction because it was able to operate without stopping for most of the route, whereas the other patterns require more braking and accelerating. In the regenerative braking cases, the energy intensity was reduced most in the local schedule and least in the zonal schedule due to the increased number of braking regeneration events in the local schedule. Overall, using an electric locomotive with regenerative braking reduces the energy intensity by 28% and using EMUs reduced the energy intensity by 29% on average.

Table 8.10 Effect of electric locomotives on energy intensity

Schedule Pattern	Baseline (per seat-mile)	Electric Locomotive (per seat-mile)			
		No Regeneration		Regeneration (65% acc.)	
	BTU	BTU	reduction	BTU	reduction
Local	421	396	6%	293	30%
Zonal	309	272	12%	227	26%
Skip-Stop	371	344	7%	267	28%
Average	367	337	8%	263	28%

Table 8.11 Effect of EMUs on energy intensity

Schedule Pattern	Baseline (per seat-mile)	EMUs (per seat-mile)			
		No Regeneration		Regeneration (65% acc.)	
	BTU	BTU	reduction	BTU	reduction
Local	421	380	10%	293	30%
Zonal	309	256	17%	223	28%
Skip-Stop	371	321	14%	265	29%
Average	367	319	14%	260	29%

8.4 Conclusions

Simulations using MMPASSIM on a commuter railroad service in the Midwestern US indicated that converting to electric traction by electrifying the existing infrastructure and using electric motive power had the greatest average reduction in energy intensity of the cases evaluated (an average reduction of 29%). However, energy intensity reduction due to such a change would depend heavily on the regional electricity generation source intensity. Furthermore, this energy-saving strategy requires significant capital investment and faces a number challenges, such as use of privately-owned freight corridors and container clearance requirements. Alternatively, optimal coasting driver advisory systems showed the potential to reduce energy intensity by an average of 23%, depending on the acceptance and implementation of the advice by drivers. This strategy requires a smaller capital investment and can produce similar reductions in energy intensity.

In order to improve service by reducing travel time, the effectiveness of three modifications to the train consist or motive power were analyzed. Adding horsepower with an additional locomotive led to a 5% average reduction in travel time and a 21% average increase in energy consumption. Exchanging the baseline F40PH locomotive for a higher-power unit resulted in no travel time reduction and a 25% average energy intensity increase. The effectiveness of using coaches with higher seating capacity, such as bi-level gallery type, was demonstrated by simulating a consist with an equivalent number of single-level coaches, resulting in an average 41% increase in energy intensity. This suggested that commuter railroads with sufficient passenger demand can benefit from high-capacity coaches.

Reducing unplanned stops and speed reductions reduced energy intensity and travel time by an average of 3% on this service. Reducing the frequency of these events would require investment in infrastructure to increase the capacity and maintain the track quality to prevent slow orders. Investment in infrastructure to reduce gradient and curvature and improve the signal system can lead to increases in the timetable speed limit. When the timetable speed limit was increased to 75 mph along the case study route, energy intensity increased by 5% while travel time was reduced by 2%.

Commuter railroads endeavor to efficiently provide the best passenger service while reducing operating costs. Railroads around the US are employing a variety of strategies to reduce energy consumption, which is a large portion of each railroad's total operating budget. MMPASSIM allows railroads to cost-effectively evaluate the effects of changes in operations, equipment, or infrastructure on energy consumption. This case study of a Midwestern US commuter railroad can serve as a guide for the evaluation of energy-saving technologies and strategies and service improvements and their effects on energy intensity.

CHAPTER 9: ENERGY INTENSITY OF COMMUTER RAIL COMPARED WITH COMPETING PASSENGER TRAVEL MODES: CASE STUDY

9.1 Introduction

Commuter rail is often seen as a "green" mode for passenger transportation, perceived by the public as an energy-efficient alternative to competing modes. In recent years, researchers have been comparing the energy intensity of rail to automobile, bus, air, and other modes using several different approaches. As discussed in Chapter 3, gross annual averages of modal energy intensity are useful in system-wide comparisons, but do not accurately reflect the comparison of competing passenger modes at various times of day or on specific services. The Multimodal Passenger Simulation tool (MMPASSIM) is a Microsoft Excel-based simulation model developed by TranSys Research Ltd. used to quantify energy consumption of passenger rail transportation and competing passenger modes (see Chapter 6 for more detail). This chapter used MMPASSIM to compare the energy intensity of a Midwestern United States (US) commuter rail service to equivalent automobile and bus trips at varying times of day. The analysis examined the impact of passenger load factor (percentage of occupied seating capacity) and highway traffic congestion on the modal comparison. The case studies serve as a framework for future applications of the MMPASSIM model as a planning tool for commuter rail operators and public planners. Commuter rail operators can use this model to compare the energy consumption of specific rail services to competing travel modes using detailed consist, route, and service data. Planners can use this tool to understand the comparisons between competing modes in a region, providing environmental information for decisions on future investment in public transportation projects.

9.2 Methodology

9.2.1 General Case Description

The energy intensity of trips via rail, light-duty automobile, and bus from Aurora to Chicago were simulated using the Multimodal Passenger Simulation Tool (MMPASSIM) described in Chapter 6. This tool has modules dedicated to simulating the energy intensity of each mode based on several key inputs that are discussed in the following sections. This analysis examined the energy consumption associated with the direct activity of each mode for a round trip (not including access/egress from the main travel segment), using an *energy conversion* analysis (discussed in Chapter 3). The one-way rail trip was 38.4 miles, and used Consist B from Table 7.2, with 870 total passenger seats. The automobile case used the EPA "2013 driven fleet" average vehicle with four passenger seats (TranSys et al. 2015) and traveled a one-way trip distance of 35.0 miles (Table 9.1). The automobile route began and ended at the train stations, but was more direct than the rail route. The bus case used a 45-foot conventional diesel commuter bus with 56 passenger seats. The bus followed the same urban freeway route as the automobile case, but had additional distance associated with each wayside stop. Therefore, the one-way bus trip was 47.4 miles.

Table 9.1 General case study description

Mode	Service/Vehicle	One-way trip dist. (mi)	Total Seats
Rail	Aurora, IL-Chicago, IL	38.4	870
Auto	2013 Driven Fleet	35.0	4
Bus	45-foot Conventional US Diesel	47.4	56

9.2.2 Rail Route and Consist Description

The rail case used an F40PH locomotive with 6 bi-level coaches (Consist B from Table 7.2), (Table 9.2). The head-end power (HEP) load was supplied by the main engine, requiring the engine to maintain a fixed speed to provide the required power output. The total consist mass and weight-dependent resistance factors were based on a passenger load factor of 0.28. These values varied with load factor to account for changes in the total weight of the passengers on board.

Table 9.2 Key MMPASSIM inputs for Consist B (at load factor of 0.28)

Parameter	Value
Consist Description	1 F40PH Loco., 6 Bi-level coaches
Total Loaded Weight (lbs)	1,202,420
Total Length (ft)	566
A (N)	5,133
B (N/km/h)	0
C $(N/(km/h)^2)$	0.838
Nominal Traction Power (hp)	3,150
Primary Fuel Type	US Conventional Diesel
HEP Provision Code	2 (PTO-fixed speed main engine)
Energy Recovery Type	0 (none)

Several key inputs were required to characterize the rail route in MMPASSIM (Table 9.3). The local, zonal, and skip-stop routes had a varying number of scheduled stops to illustrate the effects of various stopping patterns on the modal comparison. To characterize unexpected speed reductions and stops due to freight interference, slow orders, etc., the assumed frequencies in Table 9.3 were used as inputs in the model. Finally, to account for energy used in non-revenue train movements, a ratio of total distance to revenue distance was applied. Non-revenue train movements do not generate revenue seat-miles; however, the energy consumption associated with these movements was included in the total energy intensity. This ratio was applied uniformly across each simulation.

Table 9.3 Key MMPASSIM inputs for rail route (Aurora to Chicago)

Parameter	**Value**			
Scheduled Stops	Local: 26	Zonal: 6	Skip-Stop: 10	
	Num.	**Speed (mph)**	**Length (mi)**	
Average Expected Speed Reductions per One-Way Trip	0.05	25	0.2	
	0.1	40	0.1	
Average Expected Unscheduled Stops per One-Way Trip	**Num.**	**Speed (mph)**	**Length (mi)**	**Duration (min)**
	0.5	25	0.5	2
Ratio of Total Distance to Revenue Distance	1.023			

9.2.3 Automobile Case Description

The automobile route began and ended at the commuter rail origin and destination (a total of 35.0 miles) (Table 9.4). The route required two miles of arterial road distance in Aurora and one mile in Chicago. Urban freeway distance along Interstates 88 and 290 totaled 32.0 miles. No wayside stops were made during the trip.

Table 9.4 Key MMPASSIM inputs for the automobile case

Parameter	**Value**
Description	I-88/I-290
Urban Freeway Distance (miles)	32.0
Urban Arterial Distance (miles)	3.0

The same highway gradient and traffic congestion distributions described in Chapter 6 (Table 6.1 and Table 6.2, respectively) were used in this case study. Energy intensities of each mode were analyzed during a low-congestion period (mid-day) and a higher-congestion period (AM/PM peak) to determine the impact of highway congestion on the modal comparison. At the mid-day congestion level, it was assumed that forward and reverse legs of the round trip both occur at that congestion level. Under the AM/PM peak scenario, it was assumed that the forward leg traffic congestion distribution was the AM period and the reverse leg was the PM period.

9.2.4 Bus Case Description

The bus followed the same urban interstate route along Interstates 88 and 290 as the automobile case (Table 9.5). Similarly, it traversed two miles of arterial roads in Aurora and one mile in Chicago. However, the bus made four wayside stops (two-minute duration) between Aurora and Chicago. Each stop added additional trip time and fuel was consumed as the engine idles. Furthermore, each stop required an additional 3.1 miles on arterial roads to access the stop location and return to the freeway. Due to the additional distance associated with the wayside stops, the bus moved a total of 47.4 miles per one-way trip. As in the automobile case, the highway gradient distribution and traffic congestion distribution developed in Chapter 6 were applied to the highway route for the bus case.

Table 9.5 Key MMPASSIM inputs for the bus case

Parameter	**Value**	
Description	I-88/I-290	
Urban Freeway Distance (miles)	32	
Urban Arterial Distance (miles)	3.0	
Intermediate Urban Arterial and Bypass (miles)	12.4	
Wayside Stops (including terminals)	Number 4	Duration (min) 2

9.3 Modal Comparison Results

The energy intensity results of each mode (Table 9.6) show the direct activity of each mode, and do not include upstream energy consumption or additional energy used to access/egress the main modal leg of the round trip. The rail mode was simulated under the alternative schedules.

Table 9.6 Round trip energy intensity of rail, automobile, and bus round trips from Aurora to Chicago

	Energy Intensity (BTU/seat-mile)			
Mode	**mid-day**	**Index to Rail**	**AM/PM Peak**	**Index to Rail**
Rail (Local)	421	-	438	-
Auto	1,377	3.27	1,486	3.39
Bus	483	1.15	509	1.16
Rail (Zonal)	309	-	321	-
Auto	1,377	4.46	1,486	4.63
Bus	483	1.56	509	1.59
Rail (Skip-Stop)	371	-	392	-
Auto	1,377	3.71	1,486	3.79
Bus	483	1.30	509	1.30

The local train had an energy intensity of 421 BTU/seat-mile under the mid-day congestion level. This increased to 438 BTU/seat-mile during the peak periods due to the additional weight of passengers under peak loads. To determine the additional weight, the mid-day train was assumed to operate at a load factor of 0.28 and the peak period was assumed to operate at a load factor of 1.0. This equated to an additional 627 passengers, with an assumed weight of 85 kilograms per person. However, the change in load factor did not affect the energy intensity in any other way, as the results are shown in energy per seat-mile. The automobile trip had an energy intensity of 1,377 BTU/seat-mile under the mid-day congestion. This increased to 1,486 BTU/seat-mile under the peak congestion distribution. Compared to the local train, the automobile was more than three times more energy intense under both congestion distributions. The bus used 483 BTU/seat-mile under the lower congestion levels and 509 during the increased congestion levels. Relative to the local rail trip, the bus was 1.15 times as energy intense under low traffic congestion and 1.16 times more energy intense under peak-period traffic congestion.

The difference between the energy intensity of the rail trip and the competing modes increased (relative to the local scenario) when analyzing the other schedule patterns, due to the reduced energy intensity of the rail trip under the zonal and skip-stop patterns. As discussed in Chapter 7, these schedule patterns used less energy per train due to reduced station stops, reducing the number of braking and acceleration events.

Although each one-way trip begins and ends at the same origin and destination (the train stations in Aurora and Chicago), they have differing total distances (Table 9.1) due to the circuity in the route used by each mode. Analyzing the energy intensity normalized by distance (Table 9.6) shows the performance of each mode. However, this can be misleading because it ignores the effect of route circuity. From the perspective of a passenger, the transportation productivity of each mode is the same (regardless of route circuity) because each mode transports the passenger to and from the same locations. Therefore, it is interesting to also calculate the energy consumption per seat-trip to analyze the effect of the route circuity on the trip (Table 9.7). This type of analysis is sometimes referred to as a "door-to-door" analysis and often also includes the energy used to access and egress the main modal leg of the trip; however, the following analysis only includes the energy used in the direct activity of the main modal leg of the round trip.

The relative ranking of each mode's energy intensity was the same as the previous analysis: rail was the least intense, followed by bus and auto. When indexed to rail, the auto intensity was reduced compared to the previous analysis because its route is 3.4 miles shorter than that of the rail. Conversely, when indexed to rail, the bus intensity increased compared to the previous analysis because its route is 9 miles longer than that of the rail. The comparison of the results from the modal performance perspective (Table 9.6) and the passenger's "door-to-door" perspective (Table 9.7) shows that slightly different conclusions can be made from each. They both provide useful results in different situations, but can be misleading if used incorrectly.

Table 9.7 Total round trip energy consumption (BTU/seat) of rail, automobile, and bus from Aurora to Chicago

	Energy Intensity (BTU/seat)			
Mode	**mid-day**	**Index to Rail**	**AM/PM Peak**	**Index to Rail**
Rail (Local)	32,352	-	33,647	-
Auto	96,420	2.98	103,998	3.09
Bus	45,761	1.41	48,278	1.43
Rail (Zonal)	23,701	-	24,665	-
Auto	96,420	4.07	103,998	4.22
Bus	45,761	1.93	48,278	1.96
Rail (Skip-Stop)	28,515	-	30,105	-
Auto	96,420	3.38	103,998	3.45
Bus	45,761	1.60	48,278	1.60

9.3.1 Load Factor Sensitivity

The BTU/seat-mile metric (Table 9.6) is a useful measure of the potential energy efficiency of each mode if it is operating at a load factor of 1.0 (full seating capacity); however, each mode often operates over a range of load factors between 0 and 1.0, depending on the demand at different times of the day. Thus, BTU/passenger-mile is a more useful metric if one wishes to account for the ridership and load factor in the comparison. Average mode-specific load factors are often used, as presented in the analysis of US commuter railroads in Chapter 4. This method is sufficient for high-level analyses of average system performance; however, with simulation tools such as MMPASSIM, it is possible to conduct analyses of competing modes with different load factors and to account for daily variation in ridership.

Load factor sensitivity charts can be used to compare modes at different load factors (Figure 9.1). A line of equal energy intensity along varying rail (vertical axis) and competing mode (horizontal axis) load factors is shown. To read this chart, choose the rail load factor that is

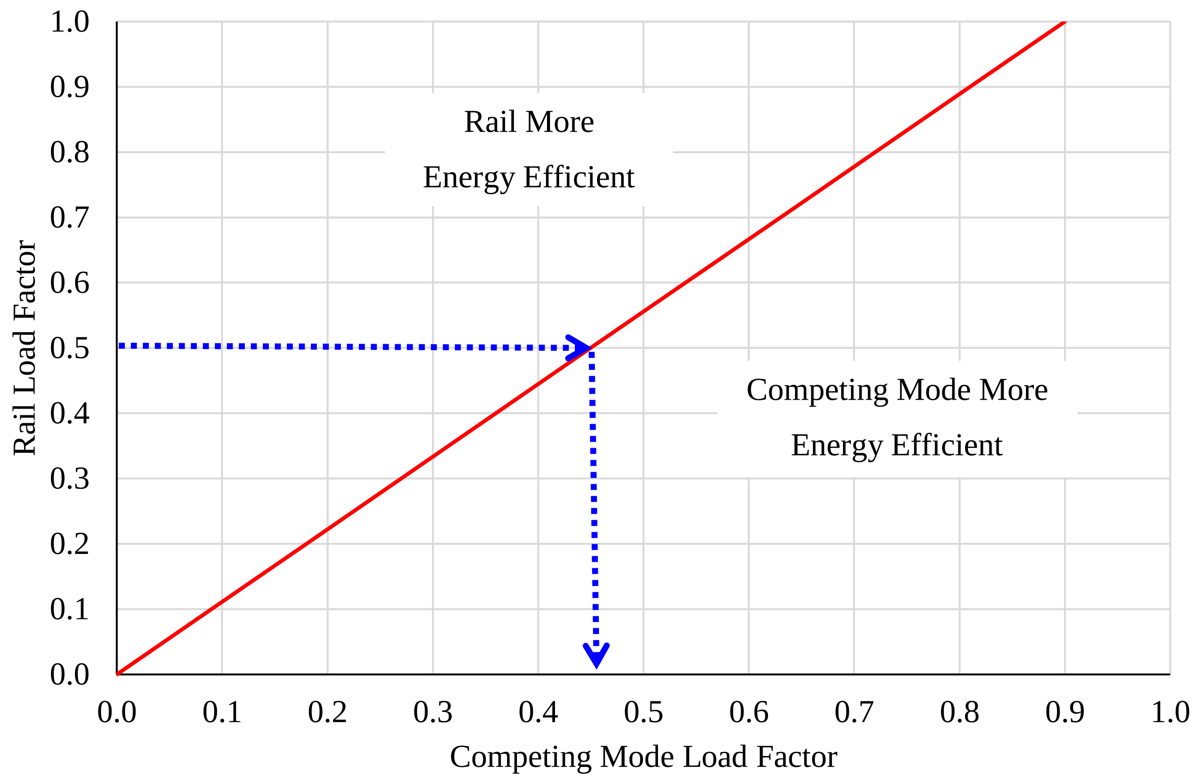


Figure 9.1 Example load factor sensitivity chart

desired for comparison. In this example, 0.5 is selected. Follow a horizontal line from the desired rail load factor on the vertical axis until it intersects the line of equal energy intensity. Then draw a vertical line until it intersects the horizontal axis. This value on the horizontal axis (0.45 in this example) represents the load factor the competing mode must achieve to have an energy intensity equal to the rail at a load factor of 0.5. The area above the line of equal energy intensity represents load-factor pairs where rail is the less energy intense mode. Conversely, the area below the line represents load-factor pairs where the competing mode is the less energy intense mode. For specific pairs of load factors, points above the line indicate that the rail is more energy efficient and points below the line indicate that the competing mode is more efficient.

Load factor sensitivity charts for the case study comparisons between commuter rail, bus, and automobile were developed for the mid-day and peak periods (Figure 9.2 and Figure 9.3). These charts display lines of equal energy intensity (BTU/passenger-mile) at varying rail and competing mode load factors for the trip from Aurora to Chicago.

Mid-day (low traffic congestion)

Load factor sensitivity lines for rail (under local, zonal, and skip-stop schedule patterns), automobile, and bus modes under low traffic congestion for a trip from Aurora to Chicago were developed (Figure 9.2). At the average rail load factor (0.28), the automobile would require a load factor of 0.91 and the bus would require a load factor of 0.32 to operate at equal energy intensity levels. For rail load factors greater than 0.3, the automobile trip is unable to perform at energy intensities less than or equal to the rail mode. The bus trip is unable to perform at energy intensities less than or equal to the rail mode operating at a load factor of 0.9 or above. When alternative schedule patterns such as zonal and skip-stop are used by the rail mode, the required load factors for automobile and bus are greater than under the local schedule, meaning the competing modes must operate at higher load factors to obtain energy intensities less than or equal to the rail mode.

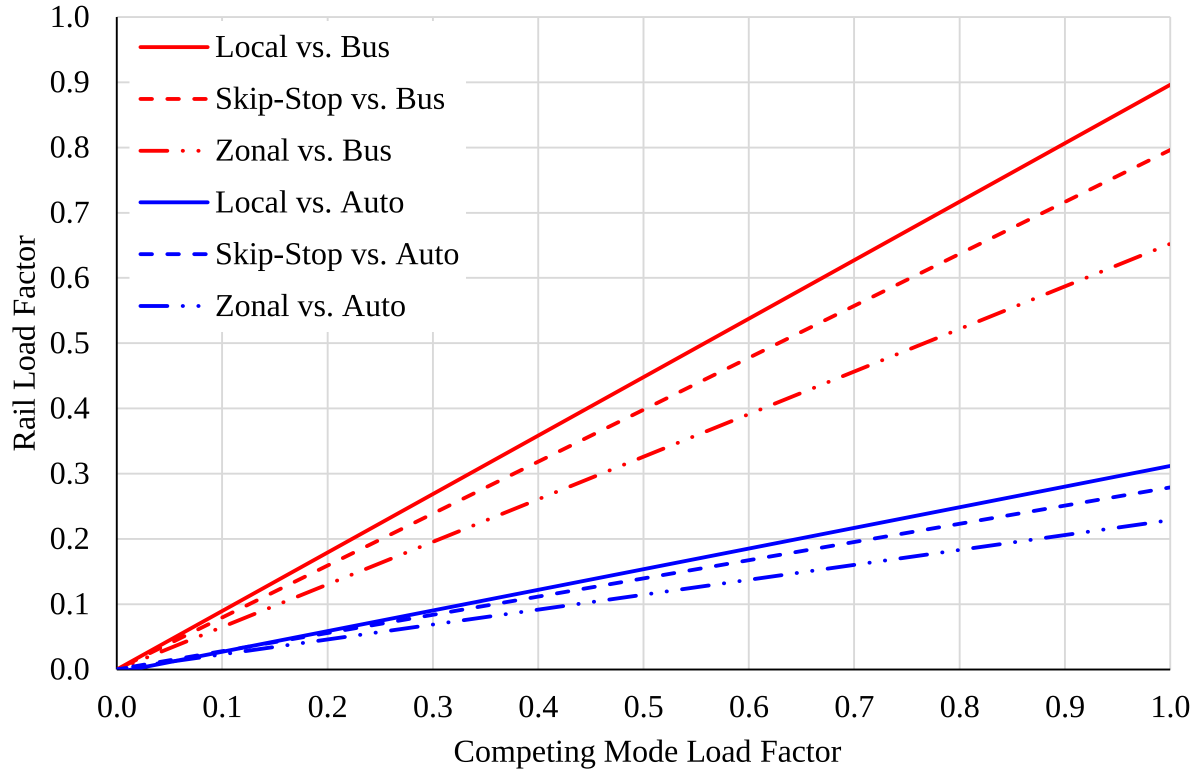


Figure 9.2 Load Factor Sensitivity chart for competing modes under low traffic congestion

Morning/Evening Peak (higher traffic congestion)

Load factor sensitivity lines for rail (under local, zonal, and skip-stop schedule patterns), automobile, and bus modes under peak traffic congestion were developed (Figure 9.3). Compared to Figure 9.2, the required competing mode load factors values are slightly higher due to the increased traffic congestion on the highway. For rail load factors greater than 0.28, the automobile trip is unable to perform at energy intensities less than or equal to the rail mode. The bus trip is unable to perform at energy intensities less than or equal to the rail mode operating at a load factor of 0.85 or above. The comparison with the alternative scheduling patterns is similar to the results in Figure 9.2, with the competing mode load factors increasing relative to the local pattern comparison due to the lower energy intensity of the alternative schedule patterns.

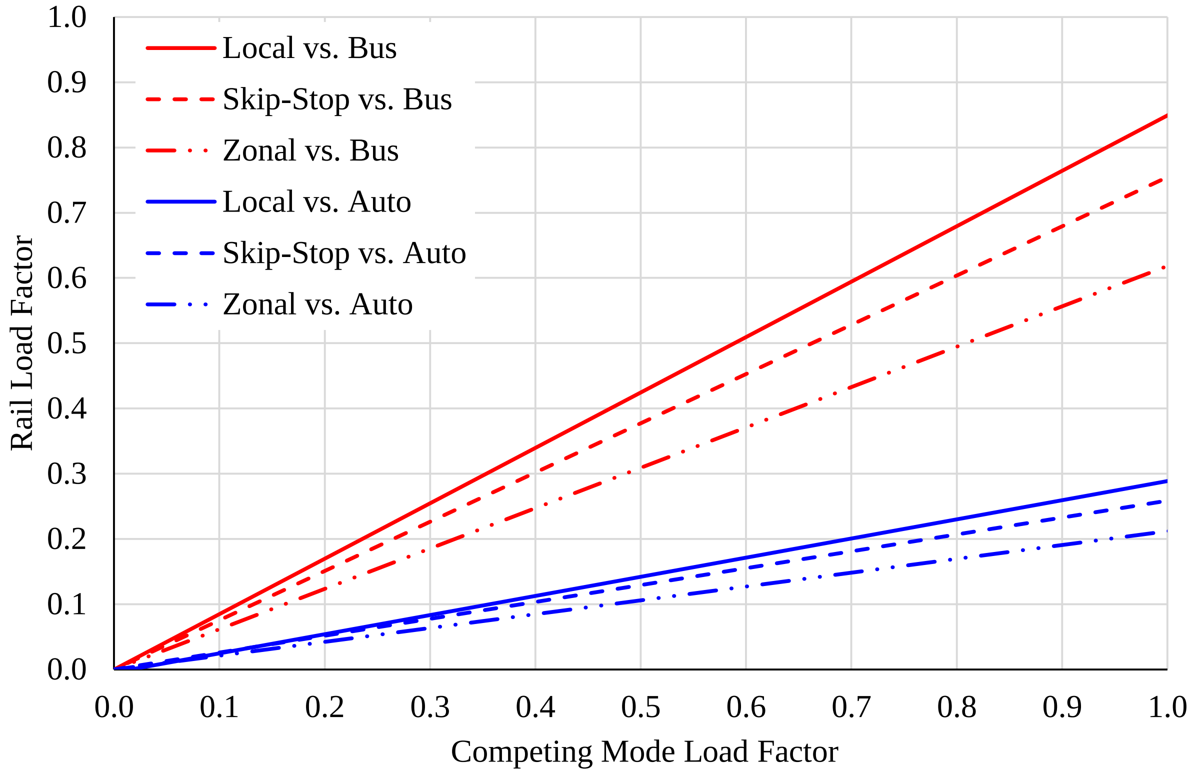


Figure 9.3 Load Factor Sensitivity chart for competing modes under peak traffic congestion

9.4 Conclusions

Modal comparisons of energy intensity of commuter rail, personal automobile, and bus trips from Aurora to Chicago, Illinois using simulation results from the MMPASSIM tool indicate that the commuter rail service is the least energy intense mode during both off-peak and peak periods. However, when the commuter rail service operates a local schedule at a mid-day passenger load (0.28), the bus trip has nearly equal energy intensity. Highway traffic congestion during peak periods increased the energy intensity of the automobile and bus modes, thereby increasing the difference between the commuter rail and competing trips. Alternative schedule patterns (zonal and skip-stop) lowered the energy intensity of the rail, thereby increasing the difference between the commuter rail and competing modes. When the trip is analyzed from the “door-to-door” perspective of the passenger by including the effect of route circuity, the energy intensity index of the auto relative to rail was reduced because the automobile route is shorter than the rail route. Conversely, the energy intensity index of the bus relative to rail was increased because its route is longer than the rail route.

To compare the modes under varying passenger load factors, load factor sensitivity charts were developed. These charts show lines of equivalent energy intensity as the load factor of the rail and competing modes changes. The results show that under low highway traffic congestion, the automobile trip is unable to perform at an energy intensity less than or equal to rail if the rail load factor is greater than or equal to 0.3. The bus mode is unable to perform at an energy intensity less than or equal to the rail mode if the rail load factor is greater than 0.9. Under peak highway traffic congestion, the automobile and bus trips are unable to perform at energy intensities less than or equal to the rail mode if the rail load factor is greater than or equal to 0.28 and 0.85 respectively. Furthermore, if the automobile load factor is 0.25 (i.e. individual drivers traveling alone), the rail mode only needs to achieve a 7-8% load factor, depending on the traffic congestion, to be more efficient. Load factor sensitivity charts can be developed for other services and used to quickly make modal comparisons under hypothetical load factors.

The case studies investigated in this chapter serve as a framework for commuter rail operators and public policy decision makers to evaluate the energy intensity of competing passenger transit options. MMPASSIM allows users to simulate specific rail, automobile, bus and air trips using detailed vehicle, route, and service characteristics. Modal comparisons can help operators and policy makers to effectively evaluate the environmental benefits of public transit modes and use the results to influence decisions on future investment and development strategies.

CHAPTER 10: GENERAL FINDINGS, CONCLUSIONS AND FUTURE WORK

10.1 General Findings and Conclusions

As concerns about the environmental impacts and sustainability of the transportation sector continue to grow, modal energy efficiency is increasingly important when evaluating the benefits and costs of future transportation system investment. The energy efficiency of passenger rail systems compared to other modes is often cited as a justification for new investment in commuter rail. Previous research has used statistical, empirical, and analytical methods to evaluate the environmental impacts of transportation projects. Research on the energy efficiency of commuter rail systems must be tailored to the purpose of the study to most accurately analyze and fairly compare the energy intensity of competing traction types, vehicle types, and competing modes. Gross annual average analyses use aggregate energy consumption and transportation productivity values to describe the efficiency of systems as a whole. However, these studies are unable to illustrate the energy efficiency differences between individual trains or peak/off-peak periods with varying passenger loads. Empirical analyses where energy consumption is measured from in-service train movements can be extremely accurate and detailed, but lack applicability to general conclusions across systems with multiple equipment and service types. Simulation models offer a compromise between annual averages and empirical analyses. They offer a low-cost methodology for evaluating varying equipment, route, and service alternatives, but require more detailed input data characterizing the route and vehicles.

Past studies approach the problem using each of these methods. However, these studies often draw comparisons between traction types or competing modes at unequal points along the energy flow path of each system. This tends to neglect energy losses along the energy flow path, and may overstate the benefits or costs of using a specific traction type, vehicle, or transit mode. Four methods to analyze the energy efficiency of electric and diesel-electric traction rail systems were identified in this research, each corresponding to points along the energy flow path: *traction analysis*, *purchased analysis*, *energy conversion analysis* and *upstream analysis.* Each can be useful depending on the particular question or application under consideration. Traction analyses provide the most basic measure of the efficiency of passenger rail coaches, analyzing the energy efficiency from the traction motors to the wheels. Purchased analyses are useful proxies for the economic efficiency of commuter rail systems because energy consumption directly purchased by operators is used, while energy consumption used upstream or by electricity generation is ignored. Energy conversion analyses are useful in comparisons between rail systems or competing modes because the energy used in electricity generation is included. Upstream analyses can be useful in assessing the environmental impacts of rail systems outside of the operator's boundaries, such as in a city or region. The application of the four methods to the United States (US) commuter rail systems serves as a framework for use with annual average statistics, but can also be applied to empirical or simulated energy consumption data.

Using a variation of the traction analysis method, an analysis of the US commuter rail systems was conducted using annual energy consumption data from the National Transit Database. Results show that despite large ridership growth, energy efficiency of the national commuter rail systems has remained nearly constant over the past 15 years. New-start systems tend to have a higher energy efficiency than legacy systems, indicating the use of newer, more energy efficient rolling stock.

To understand the factors affecting passenger rail energy efficiency, Rail Traffic Controller (RTC) was used to conduct single-variable and multi-variable analyses of passenger rail on a single-track corridor shared with freight trains. Single-variable analyses indicated that station spacing and gradient had a large impact on passenger train fuel efficiency. Multi-variable analyses indicated that all of the variables analyzed (train length, number of locomotives, traffic volume, speed, traffic heterogeneity, gradient, and station spacing) had impacts on passenger train fuel efficiency, and that all factors should be considered in efforts to improve energy efficiency through modeling.

Simulations using the Multimodal Passenger Simulation Tool (MMPASSIM) indicated that alternative timetable patterns can reduce total peak-period energy consumption compared to local trains that stop at every station along a line. Using a constant train consist for each run, express patterns (a combination of local and zonal trains) consumed the least energy during the peak period. When the consist size varied according to passenger demand along the line, the skip-stop scenario consumed the least energy during the peak period. Pareto-optimal curves of energy consumption versus passenger travel time illustrated a trade-off between the two metrics. Optimization models could be developed using this framework to meet minimum service constraints while also minimizing passenger travel time and energy consumption.

MMPASSIM was used to evaluate the effectiveness of strategies and technologies to reduce energy consumption or improve levels of service on a Midwestern US commuter rail service. Results indicated electrification of the existing infrastructure and a switch to electric motive power had the greatest potential to reduce operating energy consumption, reducing energy intensity by 29%. However, this strategy requires large investments in the infrastructure. Driver advisory systems to aid the driver in optimally coasting into stations, depending on schedule slack, reduced energy consumption by an average of 23% and require lower investment. Service improvements, such as decreasing travel time by increasing speeds or available horsepower, led to reductions in travel time but increases in energy intensity, further indicating a compromise between travel time and energy consumption.

Comparisons between the same Midwestern US commuter rail service and equivalent automobile and bus trips using MMPASSIM indicated that commuter rail is the least energy intense mode under off-peak and peak congestion levels. Implementation of alternative timetable patterns (such as zonal and skip-stop) reduced the energy intensity of the rail trip, increasing the difference between the energy intensity of rail and competing modes. Load factor equivalency charts showed lines of equal energy intensity over all possible combinations of rail and competing mode load factors. MMPASSIM and the simulation framework shown can help commuter rail operators and public policy makers analyze the environmental benefits of investments in passenger transit modes.

10.2 Future Work

10.2.1 Quality of Available Data

The quality of energy efficiency analyses can be improved by improving the quality of input data available to researchers. For several chapters in this thesis, the National Transit Database was used to analyze the energy efficiency of US commuter rail systems. The database provides a wealth of data that can be useful in continued research on the topic. Even so, the quality of the database can be improved to increase its applicability to academic research. One issue identified during the analyses was inconsistencies in reported data. Several fields had reported data that differed from what is requested by the NTD. For example, system mileage was reported by some agencies as track-miles (distance of individual track) versus route-miles (distance along routes, regardless of the number of tracks). Inconsistencies in reporting between operators can skew energy efficiency analyses attempting to find relationships between reported values and energy consumption.

MMPASSIM is a useful simulation tool for operators interested in evaluating the energy consumption of their rail movements because operators will have access to a wealth of input data regarding their track geometry, equipment resistance characteristics, and operations. This type of data may often be challenging for academic researchers to obtain because commuter rail operators often use private freight railroad property. This can be problematic when gathering track geometry data. Train resistance-related data and locomotive fuel consumption data are generally proprietary and difficult to find in published literature. Increasing the availability of such data will be helpful to researchers by providing robustness to simulation models such as MMPASSIM.

As shown by the analyses of the effects of peak-period schedule patterns and service-improvement strategies on energy intensity, a trade-off between improved service (reduced passenger travel time) and energy consumption exists. Commuter railroad operators strive to provide the best service to passengers, but are increasingly budget-constrained and aiming to reduce operating costs by improving energy efficiency. This research identifies a number of factors affecting energy efficiency and can serve as a starting point for the development of models to find the optimal balance between reduced travel time and energy consumption.

Finally, modal comparisons are useful for evaluating the environmental impact of passenger transportation options for future investment; however, passenger transportation is a multimodal system. Passengers use several modes to complete each trip from origin to destination (door-to-door). Although this feature was not used in this thesis, MMPASSIM has the capability to evaluate the energy efficiency of door-to-door trips, including the modes used to access and egress the main segment of a passenger trip. With the environmental movement growing, passengers may be interested in understanding more about the environmental impact of daily trips. It is possible to apply the capabilities of models like MMPASSIM to navigation software, such as Google Maps, to offer users the energy consumption for equivalent trips on competing modes alongside standard metrics like distance and travel time.

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