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ANALYSIS OF TRENDS IN COMMUTER RAIL ENERGY EFFICIENCY

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ABSTRACT

Commuter rail systems are widely regarded as an effective transportation alternative to reduce energy consumption and emissions in large urban areas. Use of commuter rail systems in the United States is on the rise, with annual ridership increasing by 28 percent between 1997 and 2007 [1]. With growing concerns about the sustainability and environmental impacts of transportation, modal energy efficiency is increasingly considered amongst the metrics to evaluate the benefits and costs of transportation systems and justify future investment. To gauge the relative long-term efficiency trends for rail as an urban transportation mode, this study analyzes historic trends in energy efficiency metrics for US commuter rail systems. Commuter rail systems receiving, or benefiting from, Federal Transit Administration (FTA) grants are required to report operations and energy consumption data on an annual basis to the National Transit Database (NTD). NTD data on energy consumption, operations, and services supplied from 1997 to 2011 are analyzed to determine historic trends in various energy efficiency metrics for the commuter rail mode as a whole. The data analysis and comparison of the results with the highway mode is complicated by the use of electric traction by some commuter rail operators. These operators report energy consumption in purchased electricity (kWh) instead of gallons of liquid fuel. The different approaches that can be employed to compare these two forms of propulsion and their intrinsic efficiencies and energy sources are discussed. Energy efficiency of each commuter rail system and its relationship to individual system characteristics during the study period are also analyzed. Finally, case studies of historic energy efficiency of individual commuter rail systems with longer operating histories and reporting data over the majority of the study period are contrasted against more recent start-up systems. While many systems outperform the energy efficiency of a typical light-duty vehicle, there are others that, due to a variety of system parameters and characteristics, fail to achieve a load factor great enough to make them more attractive than the highway mode on a gross average level. It is hoped that highlighting trends and variation in commuter rail energy efficiency will allow policymakers to make more informed decisions regarding the environmental benefits of rail as an urban transportation mode.

INTRODUCTION

Commuter rail is defined as a passenger rail service operating between a downtown area of a major city and the outlying suburban areas on conventional track infrastructure that is often shared with freight rail operations. The purpose of commuter rail is to move riders within the greater metropolitan area of a city or region, as opposed to rapid transit (light rail, heavy rail or subway) focused on moving passengers within the city or intercity passenger rail (Amtrak) that covers longer distances between cities and metropolitan regions [2]. As highways and roads become increasingly congested, environmental concerns of energy efficiency and emissions reductions become integral in regional planning. Also, as fuel prices increase, commuter rail can be an effective alternative to the highway mode. In 2011, the average energy intensity of the automobile in the US was 4,689 BTU per passenger-mile [3], while commuter rail systems measured 2,348 BTU per passenger-mile. 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 [4].

Commuter rail is experiencing 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 [1] and by nearly 13% between 2008 and 2012, combining for a total increase of 49%. Commuter rail operations can be categorized into “legacy systems” (those systems on commuter service routes historically operated by private railroads) and “new-start systems” (those originally established by public agencies after 1980) [2]. This research analyzes the energy efficiency trends of 23 commuter rail systems in the US. Of these 23 systems, 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 [2].

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, CA and downtown Los Angeles, the total amount of emissions (CO, NO_x, HC, and PM) are less when commuting by the Metrolink commuter rail system than by automobile [5]. Although the gross average modal energy intensity statistics presented earlier justify 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, as will be demonstrated, efficiency. Each commuter rail system is uniquely tailored to the needs and characteristics of the metropolitan area it serves. 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 rush periods on weekdays while others provide comprehensive service seven days per week. The systems also employ different combinations of rolling stock, tractive power source and energy supply with their own inherent efficiencies.

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 increasingly important as these systems continue to attract new riders and, with strong public support for expansion, continue to become more prevalent in major metropolitan areas.

NATIONAL TRANSIT DATABASE

Data used in this analysis was obtained from the National Transit Database (NTD). Recipients or beneficiaries of Federal Transit Administration (FTA) grants are mandated by Congress to report various statistics related to revenue, expenses, ridership, operations, and safety that are summarized in the NTD [6]. Currently, NTD data covering years 1997 to 2011 are publically available online. 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, which fit the high-level research scope of analyzing historic trends in commuter rail energy efficiency. This 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. It should be noted, however, that the commuter rail statistics are reported separately from any light rail, heavy rail or other transit operations that may be managed by the same agency.

While the 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. 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.

COMPARING THE EFFICIENCY OF DIESEL-ELECTRIC AND ELECTRIC PROPULSION

Several commuter rail systems in the US utilize 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 kWh to the NTD where appropriate. 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.

The fact that electric locomotives are intrinsically more efficient than diesel-electric locomotives further clouds 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%. Meanwhile, diesel-electric locomotive efficiency is between 28-30% [7,8]. 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. As illustrated by the differences in the flow of energy through diesel-electric and electric locomotives in Figure 1, 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 is converted at a remote generating station with associated losses that are not accounted for when considering the efficiency of an electric train on this basis.

Although a complete "well-to-wheels" analysis on a per-BTU basis does account for these generation losses to provide a true comparison with diesel, such comparisons are

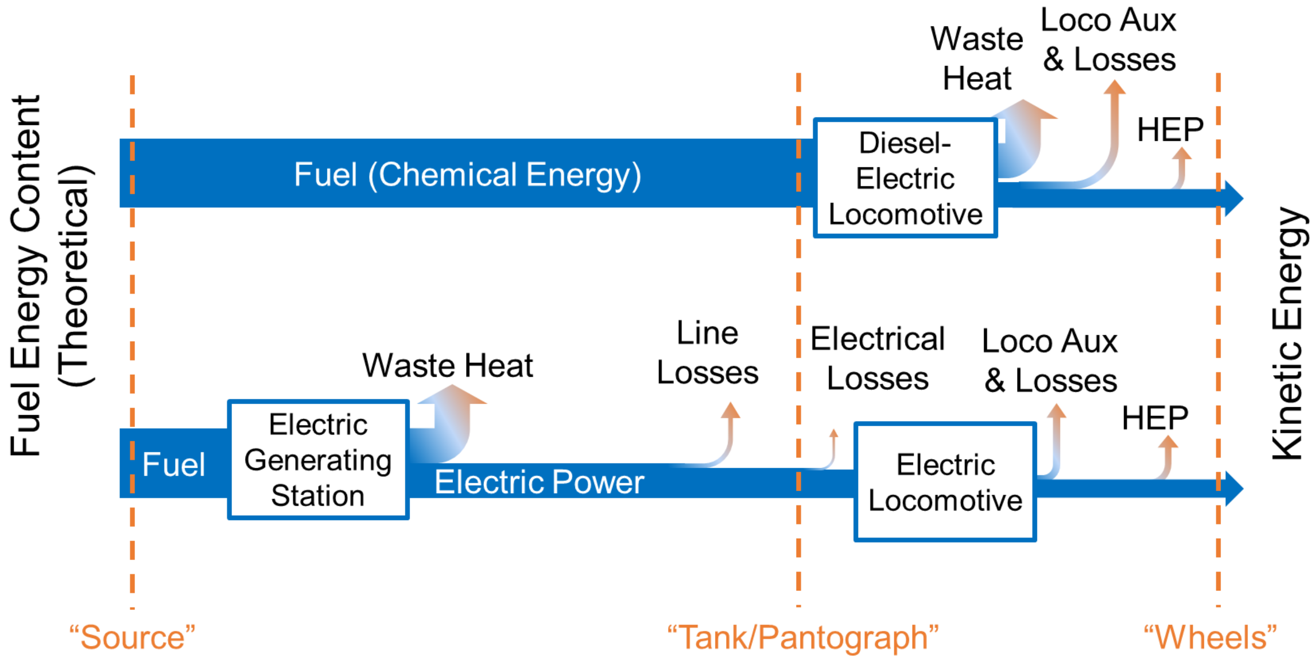

FIGURE 1. FLOW OF ENERGY THROUGH DIESEL-ELECTRIC AND ELECTRIC LOCOMOTIVES

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. Although this complete accounting is important for justifying the true environmental benefits of commuter rail, for this research, 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, this research takes the approach of converting the electric energy used to power electric locomotives to an equivalent volume of diesel fuel while accounting for the differences in efficiencies and losses between the locomotive tank, wheels and pantograph. Based on the efficiency of electric locomotives, it is assumed that 85% of the energy (kWh) reported to the NTD is actually consumed by the electric traction motors to provide propulsion [8]. It is this energy consumed for traction that is of interest to 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 is consumed per kWh of electricity delivered to the traction motors [9]. This factor is 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, for the purposes of the comparisons presented here, each kWh of electricity reported to the NTD is equivalent to 0.068 gallons of diesel fuel. Since this equivalence captures the true efficiency of the operation regardless of propulsion type, these diesel fuel equivalent (DFE) gallons are used to calculate efficiency metrics in a per-gallon form that are easily compared to diesel-only systems and the highway mode.

METHODOLOGY

NTD data detailing energy consumption, train operations, and service operations was obtained for the years 1997 through 2011 for all reporting commuter rail operators in the US. This list also includes several systems defined as hybrid rail which use diesel multiple-units (DMU) and provide similar service to traditional commuter rail. A comprehensive list of systems analyzed in this research can be found in Annex A. Note that not all of the operators reported data every year during the study period. It is also important to note that 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 this year.

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

For commuter rail, vehicles are individual passenger coaches on a train or individual passenger-carrying units comprising a self-powered EMU/DMU. Train operations data includes train-hours and train-miles. These data were used to derive many interesting statistics. 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 with passengers) of the system. Train-miles per gallon describes the energy efficiency of the entire train and is influenced by the length of the train. Vehicle-miles per gallon describes the efficiency of each car on a train, and is probably the best measure of the inherent efficiency of the system rolling stock design and infrastructure. 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. Estimations of the seating capacity of the average car for each system were gathered independently of the NTD data from operator websites.

$$\frac{Passenger-miles}{gallon}=\frac{Passenger-miles}{DFE\ (gal)} \tag{1}$$

$$\frac{Train-miles}{gallon}=\frac{Train-miles}{DFE\ (gal)} \tag{2}$$

$$\frac{Vehicle-miles}{gallon}=\frac{Vehicle-miles}{DFE\ (gal)} \tag{3}$$

$$\frac{Seat-miles}{gallon}=\frac{Seating\ Capacity\times Vehicle-miles}{DFE\ (gal)} \tag{4}$$

Other statistics related to the operating characteristics of each system were also derived from the reported data. The calculation for these other statistics is described below.

$$DFE\ (gal)=0.068\ \times\ E\ (kWh) \tag{5}$$

$$Passengers\ per\ Train=\frac{Passenger-miles}{Train-miles} \tag{6}$$

$$Trip\ Length\ (miles)=\frac{Passenger-miles}{Unlinked\ Passenger\ Trips} \tag{7}$$

$$Average\ Train\ Speed=\frac{Train-miles}{Train-hours} \tag{8}$$

$$Passengers\ per\ Car=\frac{Passenger-miles}{Vehicle-miles} \tag{9}$$

$$Cars\ per\ Train=\frac{Vehicle-miles}{Train-miles} \tag{10}$$

$$Average\ Load\ Factor=\frac{Passengers\ per\ Car}{Seating\ Capacity} \tag{11}$$

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. Discussed in this report are the case studies of SEPTA in Philadelphia, Pennsylvania and Metra in Chicago, Illinois.

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 the point clouds in Figure 2. Although there is 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 increases as the load factor increases, indicating the importance of filling the train with passengers to increase energy efficiency, as shown in Figure 2a. Efficiency with respect to train-miles per gallon decreases as the number of cars per train increases, shown in Figure 2b. This is the effect of longer and heavier trains increasing fuel consumption and decreasing energy efficiency per train-mile. Although not shown in the figure, the data also suggest that as the length of the average passenger trip increases, the efficiency of the train with respect to passenger-miles per gallon increases. Presumably this relationship arises 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 follows 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.

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 many unique operating characteristics influencing efficiency and causing large variations when comparing results between systems.

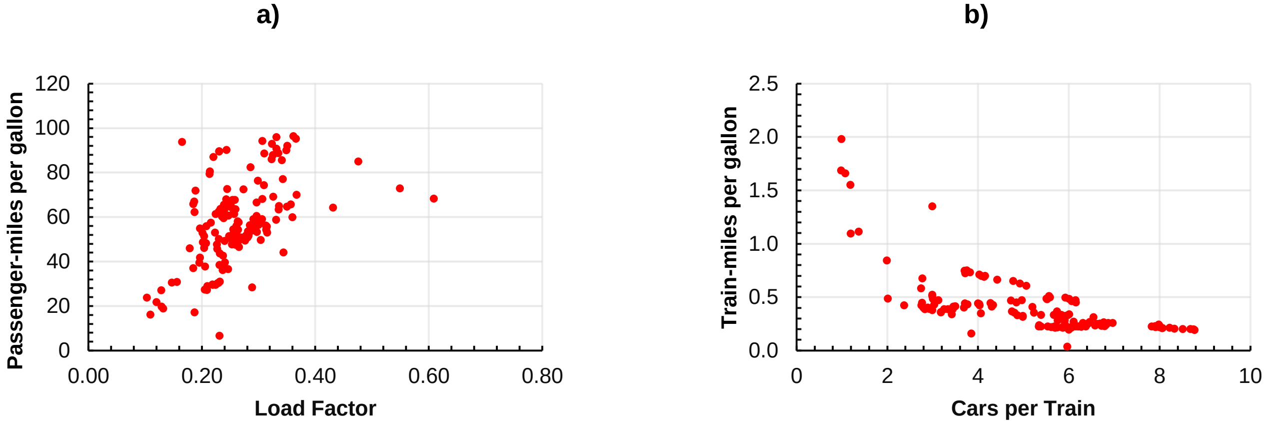

FIGURE 2. FUNDAMENTAL RELATIONSHIPS OF ENERGY EFFICIENCY AND OPERATING CHARACTERISTICS

NATIONAL HISTORIC AVERAGES

Figure 4 shows the results of the historic energy efficiency analysis of commuter rail systems in the US. According to the NTD, from 1997 to 2011, ridership has increased by 49%, while load factor has remained nearly constant, as shown by Figure 4a and Figure 4b. During this time, the efficiency as measured by passenger-miles per gallon (Figure 4d) has fluctuated minimally over the 15 year span, but with a slight downward trend over the past ten years. For comparison, Figure 3 shows the efficiency, measured by passenger-miles per gallon, of the average US automobile during the study period. The efficiency of the average automobile declines slightly during the study period, most likely due to the decrease in average vehicle occupancy, rather than a decrease in vehicle efficiency. Note that the efficiency of the commuter rail system is at least 1.7 times more efficient than the average automobile in any year during the study period.

Train-miles per gallon (Figure 4e) has fallen by nearly 9% during this time, with a dip in 2000. Vehicle-miles per gallon (Figure 4f) has been lower for the past five years compared to the first ten years of the study period.

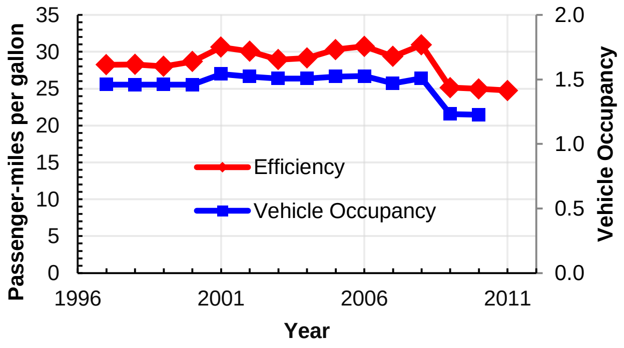

FIGURE 3. TRENDS IN U.S. AUTOMOBILE EFFICIENCY AND LOAD FACTOR [3]

It is interesting that ridership has increased so rapidly, yet the passenger-miles per gallon efficiency has 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 runs (Figure 4c) and cars per train than necessary. This scenario leaves an increasing number of seats empty on the train, offsetting any efficiency gains from the increase in ridership. Another scenario is the operator maintaining train and vehicle-miles but purchasing new cars with increased seating capacity, thus negating the potential efficiency gains of running full trains. Both of these possibilities can help explain the trends in Figure 4, as adding additional cars to trains would decrease the train-miles per gallon metric and an influx of larger, heavier bi-level railcars with additional seating capacity would decrease vehicle-miles per gallon. Both of these trends would also be consistent with aging locomotive fleets that become less efficient in terms of train and vehicle-miles with time.

The efficiencies of individual systems in any year vary widely about 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 many factors, most of them being 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.

COMPARING LEGACY AND NEW-START SYSTEMS

Since the systems included in the national averages vary over time, it is possible that any recent trends may be 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 possible effect, the average efficiencies of the legacy systems from 2009-2011 are compared to the new-start systems. The results of this analysis are shown in Table 1.

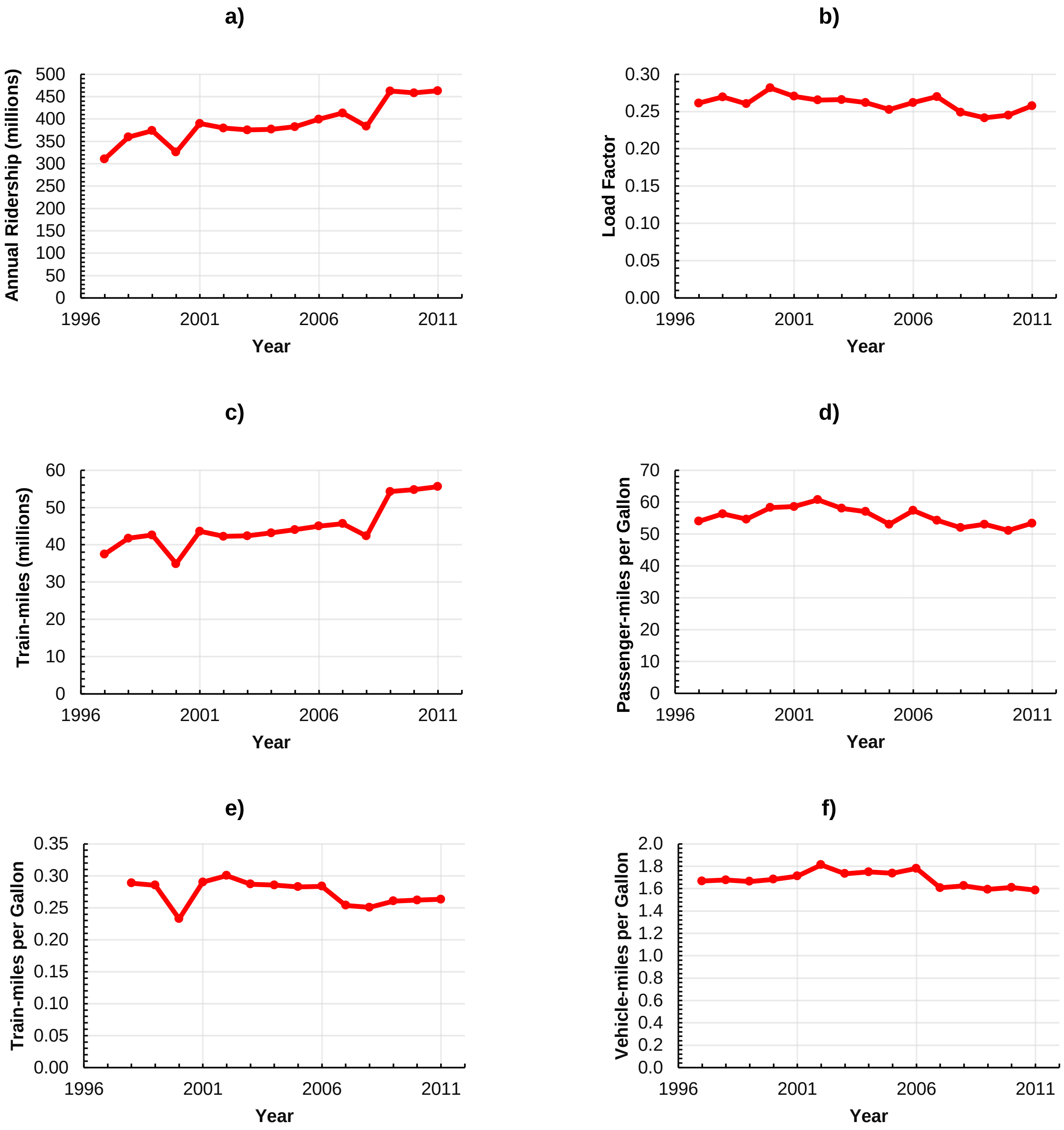

FIGURE 4. NATIONAL AVERAGE HISTORIC TRENDS IN ENERGY EFFICIENCY (D, E, F) AND OPERATING CHARACTERISTICS (A, B, C) OF COMMUTER RAIL SYSTEMS IN THE US.

The ridership of the 14 new-start systems is only a fraction of the ridership of the nine legacy systems, with the load factor of both categories about the same. However, the efficiency measured by passenger-mile per gallon and train-mile per gallon of the new-start systems are noticeably improved over the legacy systems. Because the train-miles per gallon and passenger-miles per gallon of new-start systems are both relatively high, while the load factor has no noticeable improvement, this suggests that the new-start systems have more efficient rolling stock and are operating shorter trains with greater capacity per car resulting in increased efficiency. In many cases, the new-start systems are 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 would tend to be more efficient than the latter. The longer trains of the legacy systems do allow them to obtain economies of scale and produce more vehicle-miles per gallon than the new-start systems.

TABLE 1. 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

The greater efficiency of the new-start systems could also be due to the route and operating characteristics of new-start systems being more closely tailored to the specific peak ridership patterns and needs of the area, while the legacy systems are operating a more comprehensive schedule of service over historic passenger routes that may not be efficient for the modern commuting needs of the area.

LOCOMOTIVE-HAULED AND DMU SYSTEMS

To investigate the effects of equipment characteristics on efficiency, two groups of operators using identical rolling stock were identified. One group utilizes locomotive-hauled diesel-electric propulsion and bi-level railcars while the second group utilizes modern self-propelled single-level diesel multiple-unit (DMU) railcars. Comparisons can be drawn within and between these two groups of operators.

Three new-start systems, listed below in Table 2, exclusively utilize the same model of MotivePower MPXpress locomotives and identical Bombardier bi-level passenger railcars. The three systems also operate similarly sized trains. With any potential variation due to equipment and train make-up removed, the three systems have achieved similar efficiencies in the seat-mile per gallon metric (normalizing ridership). As shown in Table 2, in 2011, the reported values of seat-miles per gallon varied by less than 13 percent. This variation in efficiency indicates the magnitude by which differences in infrastructure and operating practices can influence the potential efficiency of a commuter rail system when equipment and ridership is held constant.

Five of the systems utilize self-propelled DMU railcars, with three of these using modern European DMUs (listed in Table 2) under FRA waivers and temporal separation from conventional rail traffic. The seat-miles per gallon metric of the three systems using modern European DMUs vary less than 8 percent. Again, this shows the potential magnitude of the variation that can be attributed to infrastructure and operating characteristics when the effects of ridership and equipment differences are normalized (by comparing the seat-miles per gallon metric systems between very similar DMUs).

Comparing the two types of equipment, in 2011, on average, the five systems utilizing DMUs achieved 196 seat-miles per gallon, and the subset of three modern European DMUs achieved an average of 210 seat-miles per gallon. 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 differ from an analysis done by Messa in 2006 [10], which concluded that DMUs or trains of double-deck DMUs pulling trailers would always produce less emissions (and correspondingly consume less fuel) per seat-mile than locomotive-hauled trains. Messa's results are 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 against the three new-start systems that utilize shorter two or three-car locomotive-hauled trains. As shown in Table 2, the three systems with European DMUs are more efficient than the locomotive-hauled new-start systems. The modern DMUs can achieve higher passenger-miles per gallon in new-start service due to the operation of lower-capacity vehicles, often on more frequent headways, compared to high-capacity vehicles on traditional locomotive-hauled services. Thus, where possible under FRA waivers, when starting up a new commuter rail

TABLE 2. COMPARISON OF LOCOMOTIVE-HAULED AND SELF-PROPELLED DMU SYSTEMS

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

service, it may be more efficient to use more frequent DMU service to build ridership before implementing longer locomotive-hauled trains with greater capacity.

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 report: SEPTA and Metra.

The Southeastern Pennsylvania Transportation Authority (SEPTA) operates commuter rail serving the metropolitan area of Philadelphia, Pennsylvania. The system was established in 1983 and features 289 track miles and 153 stations, with a daily ridership of 123,500 passengers. SEPTA is one of two entirely electric commuter rail systems in the US [2]. Results from the analysis of the SEPTA system are shown in Figure 5. Over the study period, the system experienced a 49% increase in ridership (Figure 5a), which is very similar to the increase in national ridership during the study period. The load factor of the system has steadily increased and efficiency measured by passenger-miles per gallon has increased by 46% over the study period. This increase corresponds closely with the increased ridership on the system and contrasts 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, as shown by the plot of cars per train in Figure 5, SEPTA only increased the number of cars per train by 22% over the study period where ridership increased by roughly double this rate.

Vehicle-miles per gallon on SEPTA increased by 27% over the study period. This improvement is 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 [11]. SEPTA has also installed wayside energy storage technology at a substation serving the Market-Frankford line [12]. This technology allows 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% [12].

Metra is operated by the Northeast Illinois Regional Commuter Railroad Corporation and servers the metropolitan area of Chicago, Illinois. Metra was established in 1984 and consists of 488 miles of track and 239 stations, carrying 304,300 passengers daily [2]. Results from the analysis of the Metra system are also shown in Figure 5. Metra's ridership increased at a much slower rate than the national average, increasing by 9% over the study period, while the system's load factor decreased slightly (Figure 5a and 5b). Metra had marginal increases in efficiency measured by passenger-miles per gallon (Figure 5d), increasing from 47.5 in 1997 to 49.7 in 2011, which is similar to the national average.

Efficiency gains were made in terms of vehicle-miles per gallon, of which Metra experienced a 17% increase. It is suspected that these gains are largely due to the delivery of new fuel-efficient MP36PH-3S locomotives manufactured by Motive Power, Inc. from 2003-2004 [13]. Over the past five years, Metra has been rebuilding older EMD F40PH models with new prime movers and improved electronics that increase efficiency. Metra also purchased EMUs with regenerative braking capabilities from Nippon Sharyo in 2005, for use on the Metra Electric District [14]. These coaches, although limited to use on the Electric District, can recover braking energy and help reduce the overall consumption of each self-powered coach. Also, aerodynamic efficiencies and economies of scale of longer train lengths could contribute to the increase in vehicle-miles per gallon. Metra added cars per train at a slower rate (16% increase), than SEPTA but this rate did exceed ridership growth, partly explaining the steady decline in load factor. It appears that on a passenger-mile basis, any efficiency gains from the new equipment were offset by decreases in load factor. Since the trends in the efficiency of Metra closely follow 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 utilize the new system capacity. Only when properly matched with ridership growth will investments in new equipment realize its full potential to increase efficiency.

Despite not experiencing any sustained improvement in passenger-miles per gallon, the efficiency of the Metra system is higher than SEPTA in all efficiency metrics, further illustrating the large variability in efficiency between individual systems. However, both systems have 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 utilizes mostly self-powered EMU coaches, with an average seating capacity of 118 seats. Therefore, although the systems have a similar load factor, Metra is transporting more passengers per vehicle, resulting in an increased passenger-miles per gallon metric.

CONCLUSIONS

On an annual gross average basis, the energy efficiency of commuter rail has 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

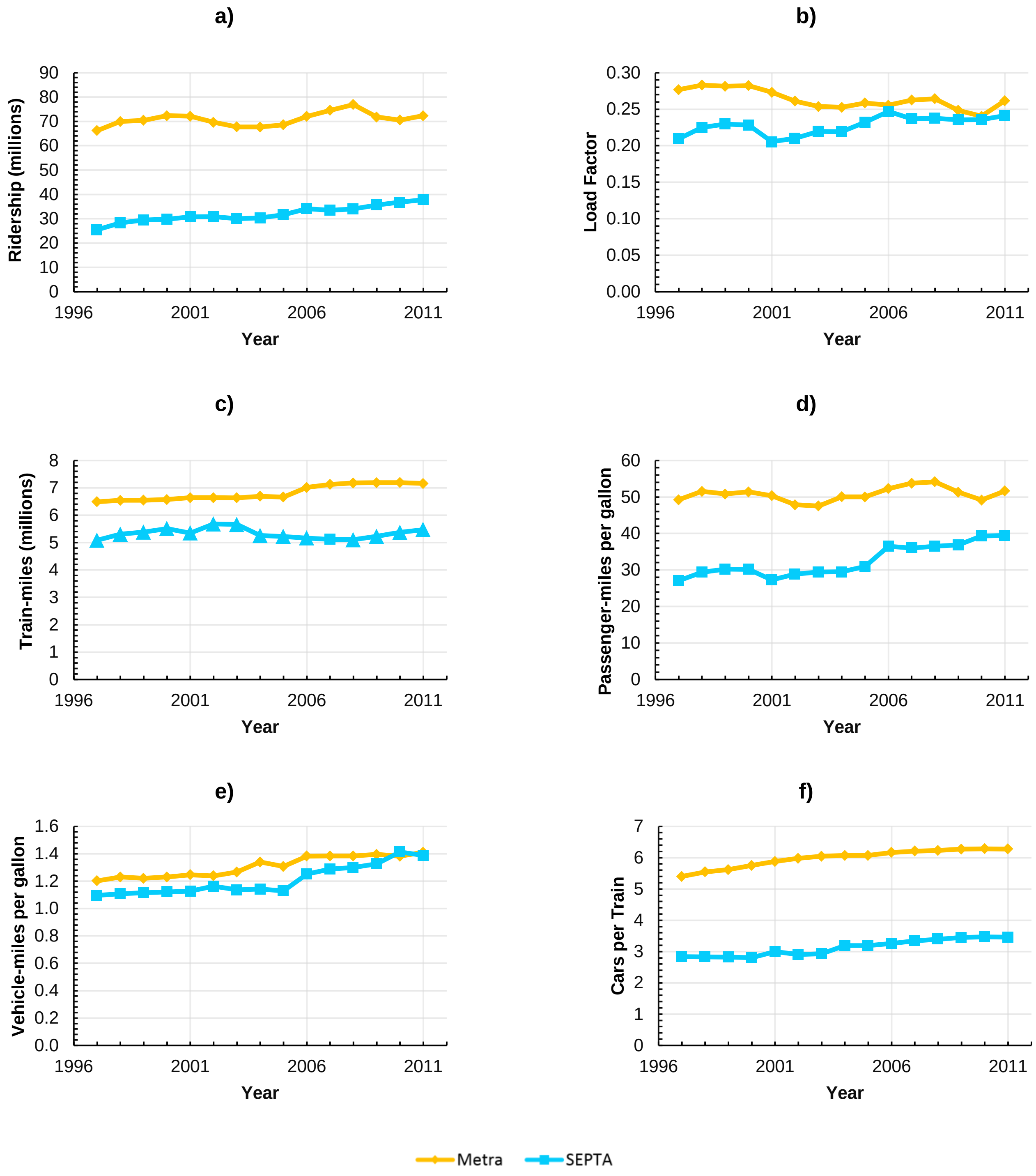

FIGURE 5. TRENDS OF OPERATING CHARACTERISTICS (A,B,C,F) AND EFFICIENCY (D,E) OF METRA AND SEPTA

compared to legacy systems despite a very similar load factor, indicating more efficient rolling stock in new-start systems.

DMUs have the potential to provide more efficient service for new-start systems as they build ridership compared to locomotive-hauled trains. A case study of the SEPTA system shows 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 shows 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 decreased load factor. The case studies also illustrate the variability in energy efficiency between individual commuter rail systems.

Commuter rail has become increasingly prevalent in the US over the past 15 years, with eight new systems being established in the past decade. As energy efficiency becomes an increasingly important factor in decision making in the transportation sector, analyses of energy efficiency can help to inform policy makers about the potential environmental benefits of commuter rail systems when compared to other modes of passenger transportation.

FUTURE WORK

To expand upon this research, future work will evaluate the energy efficiency of commuter rail systems using more detailed techniques that can analyze specific operating, system, or track characteristics. Simulations could be completed using a train simulator such as Rail Traffic Controller (RTC), to analyze the energy consumption of trains under service conditions by simulating realistic dispatching scenarios with specific route and rolling stock characteristics. Similar simulation analysis can also be completed for other rail modes such as intercity or high-speed rail and compared to other modes of passenger travel. Door-to-door simulation, including the energy efficiency of various modes of access/egress to and from passenger rail stations will be included to give a full accounting of the energy efficiency of passenger travel. These analyses will further assist decision makers in evaluating the potential environmental benefits of implementing passenger rail transportation.

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ANNEX A

List of Commuter Rail Operators Analyzed

State	System Name	[a]Mode	Reporting 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 (Northeast Illinois Regional Commuter Railroad Corporation)	CR	1997-2011
IN	Northern Indiana Commuter Transportation District 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