Methods of Analyzing and Comparing Energy Efficiency of Passenger Rail Systems

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Because of growing concerns about the future environmental impact of passenger travel, modal energy efficiency is becoming increasingly important when benefits and costs of transportation system investment are evaluated. Because passenger rail systems are often cited as being relatively more energy efficient than other modes, reduced environmental impact is one justification for investment in new commuter rail projects. It is important that studies of purported environmental benefits analyze the energy efficiency of passenger rail systems and competing modes accurately and fairly by clearly defining the flow of energy through each transportation system. Furthermore, operational practices and constraints of the railway environment can complicate the analysis of energy efficiency; this complication makes it important to choose metrics that accurately describe the situation. This research identifies and describes four methods for analyzing the energy efficiency of passenger rail systems. Each method applies to a different system within the energy flow path. The combined methods are used to analyze the energy efficiency of 25 commuter rail systems in the United States. The results of each energy efficiency calculation method are then compared to illustrate how the relative attractiveness of each system can change on the basis of the selected analysis approach. By better understanding the challenges of conducting energy efficiency analyses involving different energy sources and fair comparison methods, researchers and policy makers can make informed decisions concerning the most appropriate method of analysis for drawing accurate comparisons between rail technologies and competing modes.

As concerns about the environmental impacts and sustainability of the transportation sector continue to grow, modal energy efficiency is increasingly important when the benefits and costs of future transportation system investment are evaluated. Increased energy efficiency of passenger rail systems compared with other modes is often cited as a justification for new investment. Recent studies and published reference values on this topic have taken various approaches to quantifying the energy efficiency of passenger rail systems. Perhaps most prominent is the *National Transportation Statistics,* released annually by the Bureau of Transportation Statistics of the U.S. Department of Transportation (*1*). This publication collects energy consumption data from 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, whereas the average energy intensity of the U.S. automobile was 4,689 Btu per passenger mile (*1*).

Because of their influence on policy decisions, studies of the environmental benefits of transportation investments should 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 because of the use of different fuel types, traction power systems, operating equipment types, and geographic locations. As a result of such 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, 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), and 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 express 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 with 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.

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The reciprocal of each yields the energy intensity. For the purpose of this research, energy efficiency and intensity will be analyzed by using seat miles to ignore the effects of system ridership. However, the methods presented in this research can be applied when any of the energy consumption metrics described earlier are developed.

ELECTRIC AND DIESEL–ELECTRIC TRACTION ENERGY FLOW

U.S. intercity and commuter passenger rail systems rely predominantly on diesel–electric traction. However, two commuter services use electric traction exclusively, and Amtrak and several commuter services use a mixture of diesel–electric, electric, or dual-mode traction. These traction power delivery 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.

Figure 1 shows the flow of energy through electric (Path A) and diesel–electric (Path B) traction systems. Four critical points of the energy path identified in Figure 1 are upstream energy consumption, energy consumed by the energy conversion process, purchased energy, and energy consumed for traction. For an electric traction system, (Path A), the "upstream" point includes energy required for exploration, recovery, transportation, and refinement of the raw materials required for electricity generation, energy used in transporting the refined fuel to fueling stations or transmission to the pantograph, as well as the energy content of the raw materials themselves (*2*). 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, U.S. electricity generation 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 (*3*). Each method of electricity generation has an associated thermal efficiency; renewables such as hydroelectricity, solar, and wind are the most efficient. Given the average efficiency of the U.S. 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 generation to the electric train has been estimated to be 85% (*4*). 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% (*5*). This average value includes the efficiency of the traction motors, internal electronics, transmission, and traction auxiliaries. Electric rail vehicle efficiency can vary by specific vehicle model. For example, newer electric high-speed train sets claim vehicle efficiencies of up to 84% (*6*). Overall, after the losses at each critical point are combined, the total average efficiency from the upstream energy consumption to

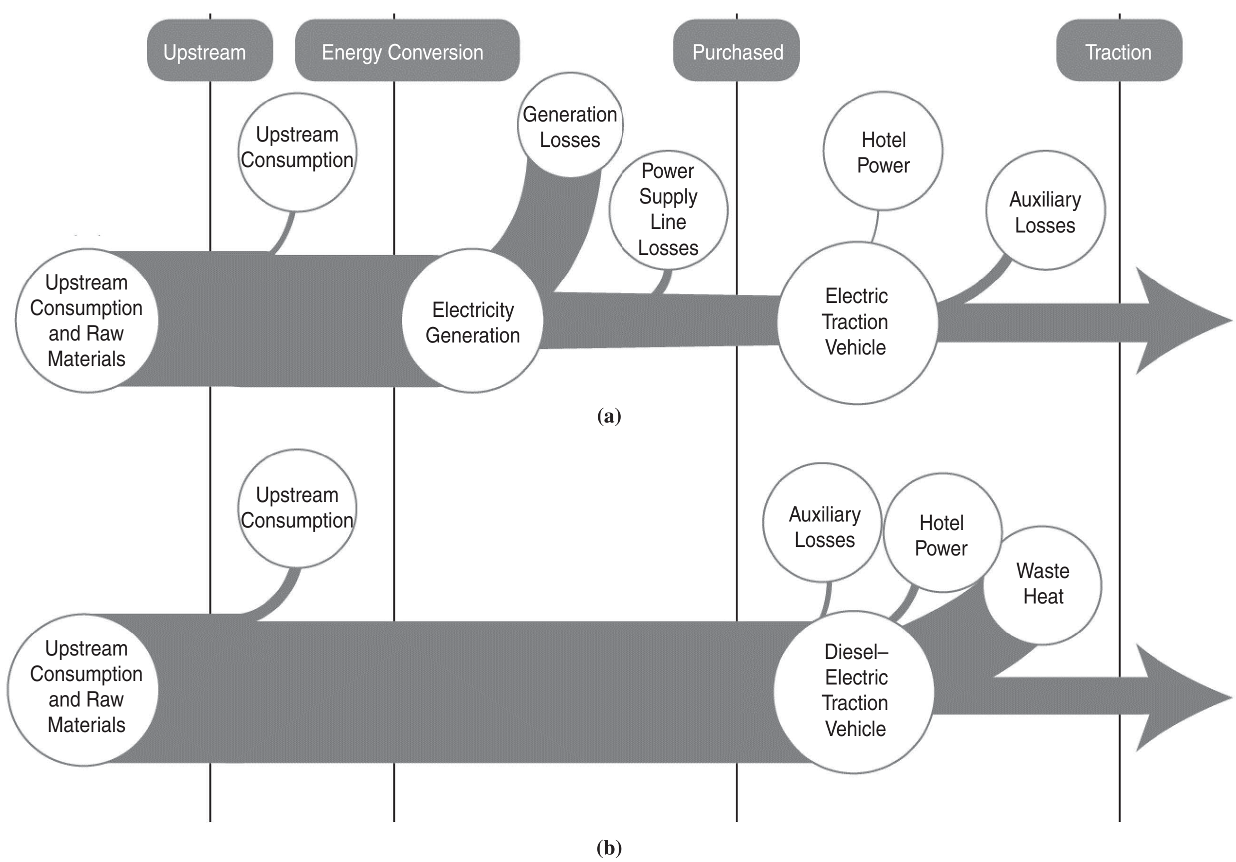

FIGURE 1 Energy path through electric and diesel–electric passenger rail systems: (*a*) Path A, electric traction system, and (*b*) Path B, diesel–electric system.

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 1 (Path B) includes energy required for exploration, recovery, transportation, and refinement of U.S. diesel fuel. Generation of usable electrical energy occurs onboard the diesel–electric vehicle rather than at an electricity 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 generator 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 efficiency can vary between specific locomotive models (*5*). Overall, after the losses at each critical point are combined, 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 is 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.

APPROACHES OF PREVIOUS STUDIES

Energy efficiency of passenger transportation modes, and passenger rail in particular, has been investigated thoroughly in the literature since the energy crisis of the 1970s. Studies of the subject have used varying methodologies, each analyzing the energy efficiency of the system from different points along the energy paths described earlier. In 1975, Hopkins 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 (*7*). In 1977, Mittal determined the energy intensity of passenger rail using statistical (reported annual averages) and analytical (route modeling) methods (*8*). 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 and then compared the results with those of competing modes.

In 1996, Barth et al. estimated emissions for a morning peak commuter rail trip and compared them with an equivalent automobile commute from Riverside, California, to downtown Los Angeles, California (*9*). Emissions for the line-haul portion of the commuter rail trip were determined by combining recorded locomotive throttle settings for an actual train run with locomotive-specific throttle-notch emission 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 investigated in-service fuel consumption and emission rates for the Amtrak regional intercity route between Raleigh and Charlotte, North Carolina (*10*). The study measured direct energy consumption values of in-service trains and calculated the energy efficiency between the purchased and traction points.

Andersson and Lukaszewicz led a study to compare energy consumption and emissions for modern train sets with those for older locomotive-hauled trains and averages for other modes of passenger transportation in Sweden (*4*). In an analysis between the purchased and traction points, the study ignored energy consumed in the generation of electricity; this omission caused comparisons with modes with onboard internal combustion energy conversion to be misleading. Garcia compared the efficiency of conventional rail and high-speed rail with that of competing modes of transportation on 10 different routes in Spain by using train simulations to determine the purchased energy consumption (*11*). The report acknowledged the difficulty in comparing the electrified modes of transportation with other modes and with each other because of regional and temporal variations of generation. M.J. Bradley and Associates compared passenger transportation modal energy efficiency, ignoring energy used to generate electricity for electric rail modes and electric trolley buses (*12*). The authors noted that this method leads to misleading comparisons with modes that use gasoline or diesel onboard energy conversion.

Messa conducted an emission analysis of electric and diesel–multiple unit railway vehicles between the energy conversion and traction points; the emissions from the electricity generation are included in the comparison (*13*). Gbologah et al. modeled the energy consumption of electric rail transit between the purchased and traction points but calculated emissions by using regional emission rates at the energy conversion point (*14*).

Wacker and Schmid developed a complete upstream energy consumption and emission model for passenger transportation, including the energy used on a main travel segment, the access and egress of the main segment mode, the energy used in upstream fuel production and supply, and the energy used producing, maintaining, and disposing of various transportation vehicles and infrastructure (*15*). The study also considered time of day and trip purpose in evaluating passenger trips. Sonnenberg also employed a full life-cycle assessment, including the upstream and downstream emissions (and implicitly energy consumption) of passenger transportation modes, including U.S. rail operations (*16*).

Finally, DiDomenico and Dick analyzed trends in U.S. commuter rail energy efficiency by using purchased diesel volumes and converting purchased electrical energy values, reported in the National Transit Database (NTD), to equivalent volumes of diesel fuel (*17*). The conversion process effectively analyzes the efficiency from the traction point by accounting for differences in efficiencies and losses between the locomotive tank, traction motors, and pantograph (*17*). Efficiency is analyzed on a per gallon basis to facilitate direct comparisons with the highway mode using metrics familiar to the public.

Clearly there has been no consistency in the methodology used to analyze energy efficiency. Commonly, investigations draw comparisons between passenger rail systems or other modes based on analyses conducted at different locations along the energy path. To standardize the comparison, this research describes four methods of analyzing the energy efficiency of passenger rail systems to help researchers and policy makers conduct analyses in an appropriate manner and make fair comparisons.

METHODS OF ANALYZING PASSENGER RAIL ENERGY EFFICIENCY

As mentioned earlier, energy efficiency of passenger rail systems can be analyzed at four main points along the energy flow path (Figure 1). Analysis at each point produces different results, each useful in specific applications. Because of 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 analysis may be accomplished for passenger rail, four methods of analyzing energy efficiency are described, one at each of the four main points along the energy flow path. Each method was applied to a case study of U.S. commuter rail systems by using information on purchased diesel fuel, biodiesel fuel, and electricity from the NTD (*18*). 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.

Traction Analysis

The traction analysis method considers the energy efficiency of the system at the traction point in Figure 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, which 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 cars. It also gives insight into the effect on energy efficiency of various infrastructure and operational characteristics, such as grade, curvature, speed profile, and stopping pattern.

To compare electric and diesel–electric traction systems fairly, electrical energy used by the traction motors must be calculated on the basis of the amount of purchased fuel and electricity, as shown in Equation 1. In the case of electric traction, energy used by the traction motors is the purchased electrical energy at the pantograph less the losses and auxiliary loads within the vehicle before 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% (*5*). 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 gal of diesel fuel is consumed per kW-h of electricity delivered to the traction motors (*19*). This factor has been adjusted for systems that use biodiesel according to the relative chemical energy content of diesel and B20 biodiesel to yield 0.0753 gal of B20/kW-h. For systems with dual-mode operation, both calculations are made as appropriate for the amounts of fuel and electricity purchased for the trip.

$$E_{\text{traction}} = \left(E_{\text{electric}} \times C \times e_{\text{elec.traction}}\right) + \left[\left(\frac{F_{\text{diesel}}}{A_{\text{diesel}}} + \frac{F_{\text{B20}}}{A_{\text{B20}}}\right) \times C\right] \quad (1)$$

where

E_{traction} = energy consumed by traction motors;
E_{electric} = purchased electric energy at catenary (kW-h);
$e_{\text{elec.traction}}$ = efficiency of electric locomotive, assumed to be 0.76;
F_{diesel} = diesel fuel consumed (gal);
F_{B20} = B20 blended biodiesel consumed (gal);
A_{diesel} = gallons of diesel fuel required to deliver 1 kW-h to traction motors of diesel–electric vehicle, assumed to be 0.0795 gal/kW-h;
A_{B20} = gallons of B20 biodiesel fuel required to deliver 1 kW-h to traction motors of diesel–electric vehicle, assumed to be 0.0753 gal/kW-h; and
C = energy unit conversion, 3,412 Btu/kW-h.

Once the traction energy is calculated, energy efficiency and intensity can be calculated as shown in Equations 2 and 3:

$$\text{efficiency} = \frac{n \times d}{E_{\text{traction}}} \quad (2)$$

$$\text{intensity} = \frac{E_{\text{traction}}}{n \times d} \quad (3)$$

where n is the average number of seats per passenger car and d is the vehicle miles traveled.

Purchased Analysis

The purchased analysis method analyzes energy efficiency between the "purchased" point in Figure 1 and the power at the wheels. 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 the method 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 method could be very important for commuter rail agencies and operators conducting an economic analysis of operational, infrastructure, or equipment changes that may affect energy consumption for a single method of propulsion. The method is less useful for making comparisons between propulsion systems.

Because the NTD data provide purchased fuel and electricity, this method is the simplest of those presented. Purchased energy consumption, $E_{\text{purchased}}$, is calculated as shown in Equation 4. This 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 data set. Purchased energy consumption values could also be supplied by simulation or direct measurements.

$$E_{\text{purchased}} = \left(F_{\text{diesel}} \times \varepsilon_{\text{diesel}}\right) + \left(F_{\text{B20}} \times \varepsilon_{\text{B20}}\right) + \left(E_{\text{electric}} \times C\right) \quad (4)$$

where

$E_{\text{purchased}}$ = purchased energy consumption (Btu),
$\varepsilon_{\text{diesel}}$ = energy density of diesel fuel (128,450 Btu/gal) (*10*), and
ε_{B20} = energy density of biodiesel (121,650 Btu/gal) (*10*).

Energy efficiency and intensity can be calculated as shown in Equations 5 and 6:

$$\text{efficiency} = \frac{n \times d}{E_{\text{purchased}}} \quad (5)$$

$$\text{intensity} = \frac{E_{\text{purchased}}}{n \times d} \qquad (6)$$

Energy Conversion Analysis

The energy conversion method analyzes energy efficiency from the "energy conversion" point in Figure 1 to the useful power output at the wheels. 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 by 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 the agency is 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 in 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 as calculated in Equation 7. Electricity is generated by using a mixture of methods and fuels that vary by region. In this case, the particular electric generation mix serving each commuter rail system is accounted for by using the U.S. regional power generation mixes developed by the U.S. Energy Information Administration (*20*) and the energy intensity of electricity generation in the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model (*21*). These values, found in Table 1, include the losses associated with transmission and distribution of electric power from the generating station to the commuter rail system substation. Since each geographic region has a different average generation efficiency, the geographically appropriate intensity factor, $e_{\text{generation}}$ must be used for each rail system (regions are labeled as defined by a *U.S. Census Regions and Divisions* map) (*22*).

TABLE 1 Generation and Upstream Production Energy by Region and Fuel Type (*20, 21*)

	$e_{\text{generation}}\left(\frac{\text{BTU}}{\text{kW-h}}\right)$	$e_{\text{upstream}}\left(\frac{\text{BTU}}{\text{MBTU}}\right)$
U.S. Electric Generation Region		
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		
U.S. conventional diesel	na	200,123
B20 biodiesel blend	na	327,837

NOTE: na = not applicable.

$$E_{\text{generation}} = E_{\text{electric}} \times e_{\text{generation}} \qquad (7)$$

where

$E_{\text{generation}}$ = input energy consumed to generate E_{electric} (Btu),
E_{electric} = purchased electrical energy (kW-h), and
$e_{\text{generation}}$ = energy used to generate 1 kW-h of purchased electricity (Btu/kW-h from Table 1).

The energy efficiency and intensity can be analyzed as shown in Equations 8 and 9:

$$\text{efficiency} = \frac{n \times d}{E_{\text{purchased}} + E_{\text{generation}}} \qquad (8)$$

$$\text{intensity} = \frac{E_{\text{purchased}} + E_{\text{generation}}}{n \times d} \qquad (9)$$

Upstream Analysis

The upstream analysis considers energy efficiency of the entire system from the "upstream" point in Figure 1 to the useful power output at the wheels. 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 complete life-cycle assessments are conducted of competing modes to determine the overall environmental impact of each large-scale project alternative.

Since it includes all the steps along the energy flow path, upstream analysis is the most complex of the methods discussed here. 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 sections (Equations 4 and 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 10 by using the published values in the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model shown in Table 1. It should be noted that e_{upstream} for B20 biodiesel is a weighted average of e_{upstream} for pure biodiesel (B100) and U.S. conventional diesel (*21*).

$$E_{\text{upstream}} = \left(E_{\text{generation}} \times e_{\text{upstream}}\right) + \left(E_{\text{electric}} \times C \times e_{\text{upstream}}\right) + \left(F_{\text{diesel}} \times \varepsilon_{\text{diesel}} \times e_{\text{upstream}}\right) + \left(F_{\text{B20}} \times \varepsilon_{\text{B20}} \times e_{\text{upstream}}\right) \qquad (10)$$

where

E_{upstream} = additional energy consumed to supply input energy (Btu),
$E_{\text{generation}}$ = input energy consumed in electrical generation (Btu), and
e_{upstream} = energy used upstream to generate or produce 1 MBtu of energy (electric or fuel) shown in Table 1.

Finally, the energy efficiency and intensity can be calculated as shown in Equations 11 and 12. Since Equation 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 the traction points.

$$\text{efficiency} = \frac{E_{\text{purchased}} + E_{\text{generation}} + E_{\text{upstream}}}{n \times d} \quad (11)$$

$$\text{intensity} = \frac{n \times d}{E_{\text{purchased}} + E_{\text{generation}} + E_{\text{upstream}}} \quad (12)$$

RESULTS AND DISCUSSION OF CASE STUDY

The four methods described were used to assess the energy efficiency of 25 U.S. commuter rail systems. Table 2 shows the energy intensity calculated according to each method and the corresponding rankings of the systems. Table 2 is sorted by ranking according to the traction analysis to show how the rankings change between the different analysis methods.

It is clear from Table 2 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, Southeastern Pennsylvania Transportation Authority and Northern Indiana Commuter Transportation District, operate exclusively with electric traction. The traction analysis ranks the latter as the fourth and the former as the 17th most efficient system based on Btu per seat mile. However, in the purchased analysis, which considers efficiency with respect to the energy purchased by the transit agency, these two entirely electric systems rise in the rankings to second and third behind only New Jersey Transit (a system that also uses a large proportion of electric traction). The other systems using a mix of electric traction (Metro-North Rail Road, Long Island Rail Road, Metra in Chicago, and MARC Train in Maryland) all experience similar increases in their ranking under the purchased analysis. This rise is a result of the purchased analysis's lack of accounting for losses in the generation of electricity for systems using electric traction, including onboard energy conversion losses for systems using diesel–electric traction. This increase penalizes the systems using diesel–electric traction and causes them to fall in the rankings. When the efficiency of electricity generation in each geographic region is accounted for by using the energy conversion analysis, the same electric traction

TABLE 2 Energy Intensity of U.S. Commuter Rail Systems in 2012 as Calculated and Ranked by Four Analysis Methods

System Name	Motive Power	Traction Analysis		Purchased Analysis		Energy Conversion Analysis		Upstream Analysis		Overall Efficiency
		EI	Rank	EI	Rank	EI	Rank	EI	Rank	
New Jersey Transit (commuter)	M	132	1	181	1	354	1	374	1	0.35
Altamont Corridor Express, California	D	149	2	446	6	446	2	535	3	0.28
New Jersey Transit (River Line)	D	150	3	450	7	450	3	540	4	0.28
NICTD, Chicago South Shore, Illinois	E	154	4	202	2	508	6	524	2	0.29
NCTD, San Diego (Coaster), California	D	162	5	485	8	485	4	582	5	0.28
MBTA, Boston, Massachusetts	D	168	6	503	9	503	5	604	7	0.28
NCTD San Diego (Sprinter)	D	170	7	510	10	510	7	612	9	0.28
Metrolink, Los Angeles, California	D	172	8	515	11	515	8	618	10	0.28
Caltrain, San Francisco, California	D	197	9	591	14	591	11	709	12	0.28
Virginia Railway Express	D	198	10	592	15	592	12	710	13	0.28
Metro–North RR, New York	M	204	11	333	4	557	9	603	6	0.34
Northstar, Minneapolis, Minnesota	D	204	12	611	16	611	14	733	14	0.28
Long Island Railroad, New York	M	205	13	334	5	558	10	604	8	0.34
Sound Transit, Seattle, Washington	D	211	14	630	17	630	15	756	16	0.28
New Mexico Rail Runner	D	211	15	631	18	631	16	757	17	0.28
Metra, Chicago	M	212	16	561	12	649	17	754	15	0.28
SEPTA, Philadelphia, Pennsylvania	E	227	17	299	3	607	13	638	11	0.36
Front Runner, Salt Lake City, Utah	D	237	18	709	19	709	18	850	19	0.28
MARC Train, Maryland	M	242	19	587	13	738	19	846	18	0.29
Capital Metro, Austin, Texas	D	249	20	744	20	744	20	893	20	0.28
Tri–Rail, Miami, Florida	D	256	21	767	22	767	22	920	21	0.28
TRE, Dallas–Fort Worth, Texas	B20	278	22	745	21	745	21	990	22	0.28
DCTA A-Train, Denton County, Texas	D	290	23	869	23	869	23	1,043	23	0.28
Music City Star, Nashville, Tennessee	D	291	24	872	24	872	24	1,046	24	0.28
TriMet, Portland, Oregon	B20	434	25	1,165	25	1,165	25	1,547	25	0.28

NOTE: Efficiency rank sorts systems from most efficient (1) to least efficient (25). EI = energy intensity, in Btu per seat mi; M = system using mix of diesel–electric locomotive and electric motived power; D = system using diesel–electric locomotive power; NICTD = Northern Indiana Commuter Transportation District; E = system using electric motive power; NCTD = North County Transit District; MBTA = Massachusetts Bay Transportation Authority; RR = railroad; SEPTA = Southeastern Pennsylvania Transportation Authority; MARC = Maryland Area Regional Commuter; B20 = system using diesel–electric motive power with B20 biodiesel fuel; TRE = Trinity Railway Express; DCTA = Denton County Transportation Authority.

and mixed systems that rose in the rankings under the purchased analysis drop down in the rankings. Overall, the efficiency rankings for the traction and energy conversion analyses are very similar. This finding suggests that from the point of energy conversion, the efficiencies of each commuter rail system are relatively equal, regardless of the use of electric or diesel–electric traction.

When the upstream analysis is examined, there are some small changes in the ranking compared with the energy conversion analysis. The systems using larger amounts of electric traction experience a decrease in relative efficiency and drop in ranking because of the upstream energy consumption of electrical generation in each respective geographic region. This effect is amplified because the electrified commuter operations tend to be in the Northeast, where the upstream energy associated with electricity generation is higher, compared with western regions, where more hydroelectricity and other renewable sources are available. The two systems using B20 biodiesel (TRE in Dallas–Fort Worth, Texas, and TriMet in Portland, Oregon) also experience more substantial relative decreases in efficiency than other systems when upstream and purchased results are compared. This finding can be attributed to the higher upstream energy consumption required for production of biodiesel compared with conventional diesel fuel.

The overall system efficiency is 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 have the same overall efficiency since the analysis is based on the efficiency of a single locomotive model. The rail systems using electric traction either exclusively or in a mix with diesel–electric have a higher overall efficiency than the diesel–electric systems. The exact value is dependent on the regional electricity generation mix of each commuter rail system.

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 that 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; this usage makes those particular trains relatively efficient. However, during off-peak periods, it is common for these trains to have few passengers; this usage makes those train runs 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 decreased energy efficiency during off-peak hours.

DiDomenico and Dick illustrated the potential efficiency differences when average load factors are considered (*17*). For three similar diesel–electric commuter rail systems in 2011, the annual average efficiency considering average load factor was 40 passenger mi/gal compared with 198 seat mi/gal. 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 train runs will not even reach the average of 40 passenger mi/gal. This situation 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; the result is improved annual energy efficiency at the expense of decreased equipment utilization. However, it has been noted by Kohn that decreasing service frequency correlates with decreasing urban transit ridership, potentially limiting the passenger demand side of the efficiency calculation (*23*). Conversely, systems experiencing growing ridership have increased seating capacity and off-peak service frequency by using more complex scheduling patterns (zonal, skip–stop, etc.) (*24*). When energy efficiency is analyzed and modal comparisons are drawn, 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 and egress modes at either end. For example, a commuter might travel downtown by using a city bus to access the commuter rail station and then walk to his or her final destination from the downtown rail station. This trip would likely result in improved energy efficiency per passenger mile compared with a trip made entirely by a light-duty vehicle with the commuter as its sole occupant. Door-to-door energy efficiency analyses are useful in modal comparisons that consider individual passenger behavior for specific trips rather than an analysis of the entire transportation system. 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 alight from the train. Thus, when an individual trip is considered, 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, as shown in Figure 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 among a 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, one could argue that if it were not

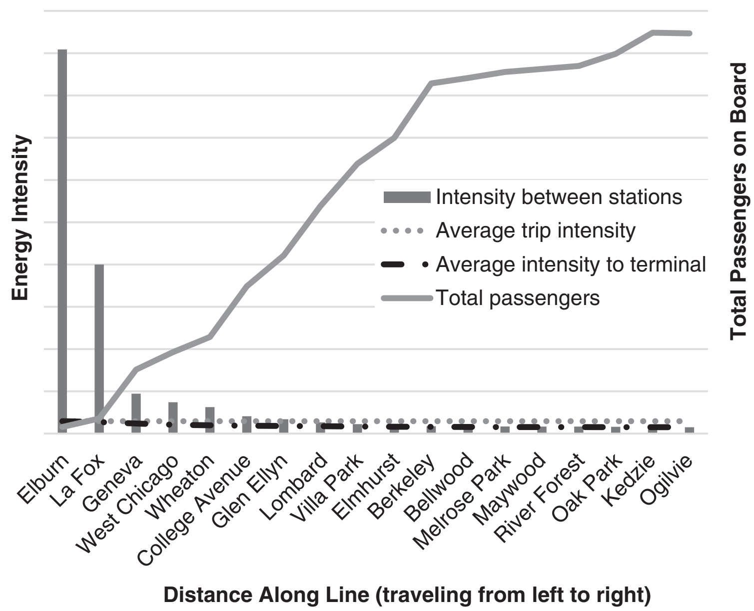

FIGURE 2 Variation of efficiency due to ridership on inbound peak-period train on Metra Union Pacific–West line.

for the initial inefficient miles, the last passenger boarding the train would not have a train to board at all and therefore should share the energy consumed during the entire trip equally. 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 from origin to destination. However, in order to operate a revenue train, energy is consumed by activities such as train consist makeup, idling, servicing, and other nonrevenue movements required to prepare equipment. Without direct measurement or simulation, it is often difficult to separate energy consumed by nonrevenue activities from gross annual measures of purchased energy as reported in the NTD or other databases. Von Rozycki et al. conducted a unique assessment of the energy consumed by the high-speed Intercity Express service between Hanover and Wuerzburg in Germany (*25*). The authors determined the amount of "overhead energy" consumed in making up and servicing the train to be 1.20 kW-h/train km. Researchers must define the revenue and nonrevenue activities that are included in energy efficiency analyses to allow accurate comparisons to be made.

ANALOGUES FOR 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 type 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 to choose system boundaries that make an accurate and fair comparison possible.

Modes that use onboard liquid fuel combustion have an energy path similar to the diesel–electric passenger rail system (Figure 1*b*). 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 1*a*. 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 with other vehicles.

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 were described: traction analysis, purchased analysis, energy conversion analysis, and upstream analysis. These methods were used to analyze 25 U.S. 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 show significant changes in relative energy efficiency between analysis methods. Variation in the relative energy efficiency among the four analysis methods highlights 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 with 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 fair 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.

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