Influence of System Characteristics and Scheduling Patterns on Commuter Rail Energy Efficiency

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Abstract
As concerns about the environmental impacts and sustainability of the transportation sector continue to grow, modal energy efficiency is increasingly considered as a factor in evaluating benefits and costs of transportation systems and justifying future investment. 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 paper seeks to move towards such a model by identifying, and further investigating, basic system characteristics with the greatest influence on commuter rail energy efficiency. To identify the factors with the influence on commuter rail energy efficiency, data on the energy consumption and transportation productivity of 26 commuter rail systems in the United States were collected from the National Transit Database. A series of preliminary single-variable statistical analyses were conducted to identify trends and correlations between specific system characteristics and energy efficiency. To illustrate the potential of implementing different stopping patterns to reduce the energy consumed in moving a given passenger demand, this research conducts a case study of a commuter rail line in the Midwestern United States. The case study examines alternative scheduling patterns, including local, zonal, skip-stop, and express patterns, under controlled demand, infrastructure and consist configuration. A train performance calculator is used to simulate train movements and calculate the fuel consumption of each schedule scenario.

Keywords
Rail, Energy, Schedule, Patterns

1 Introduction

As concerns about the environmental impacts and sustainability of the transportation sector continue to grow, modal energy efficiency is increasingly considered as a factor in evaluating benefits and costs of transportation systems and justifying future investment. Commuter rail systems are widely regarded as an effective transportation alternative to reduce energy consumption and emissions in large urban areas. Commuter rail systems in the United States 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 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 consumption 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, average speed, and consist make-up. Thus, individual commuter rail systems may experience energy efficiency values that differ substantially from the national average (DiDomenico et al. (2013)). 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 paper seeks to move towards such a model by identifying, and further investigating, the basic system characteristics with the greatest influence on commuter rail energy efficiency.

To identify the factors with the greatest influence on commuter rail energy efficiency, data on the energy consumption and transportation productivity of 26 commuter rail systems in the United States were analysed from the National Transit Database (NTD). This data was supplemented with data from operating agency annual reports, publications and timetables to fully characterize the equipment, infrastructure, operational, service schedule and demand-related 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 conducts a case study of a commuter rail line in the Midwestern United States. The case study examines 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 are set according to existing operations on the line. A train performance calculator is used to simulate train movements and calculate the fuel consumption of each schedule scenario. Since the number of passenger-miles is fixed, the effect of each scheduling pattern on energy efficiency can be determined along with other service characteristics, such as train-miles and equipment utilization. Scheduling patterns that effectively minimize deceleration and reacceleration events (stopping at every other or every two stations) are more effective at increasing the energy efficiency of a train run than other scheduling patterns. However, scheduling too many express segments can increase the overall number of train runs 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 make 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 may 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.

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). Differing from many systems around the world, it is also common for commuter rail operations in North America to use corridors and tracks shared by freight and traditional passenger rail services (Brock and Souleyrette (2013)). Systems with high commuter train volumes during peak periods often use the corridors exclusively during peak periods to avoid interference and delay from freight trains. 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 overall 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 express 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. optimized stopping patterns to minimize passenger travel time on the Taiwan High-Speed Rail system (Jong et al. (2012)). The model uses 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. 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 (Sogin et al. 2012)). Ulusoy et al. 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 (Ulusoy et al. (2011)). However, improved travel time is not the only benefit of removing station stops. Express and skip-stop services decrease the amount of braking and acceleration required along a route, decreasing fuel consumption. Recently, a few studies have attempted to optimize timetables based upon 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 move towards an optimization model which minimizes the energy consumption of a service while meeting heterogeneous passenger demand and travel time constraints, 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 lowering operating costs associated with energy consumption.

3 Effect of System Characteristics on Commuter Rail Energy Efficiency

3.1 Methodology

Data used in this preliminary analysis was obtained from the National Transit Database (NTD). In the United States, recipients or beneficiaries of Federal Transit Administration (FTA) grants are mandated by the federal government to report various statistics related to revenue, expenses, ridership, operations, and safety that are summarized in the NTD (Federal Transit Administration (2012)). Data from the 2012 reporting year are used for this analysis. Annually reported operating statistics such as fuel/power purchased for revenue service, passenger-miles, train-miles, vehicle-miles, train-hours, and ridership are used to calculate the energy efficiency of each individual commuter rail system. Other information, such as type and age of equipment are also available in this database.

The NTD dataset has advantages and limitations that must be acknowledged. First, the datasets used in this study represent annual system-wide characteristics. While this data fits the scope of investigating high-level system characteristics that affect commuter rail energy efficiency, it 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 and motive power. 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 urban 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. This act will compound any errors present in the reported statistics. 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. The specific methodology used to convert the various fuels and electricity into common units of energy for calculation of energy efficiency and intensity is shown in equations (1) through (4) (DiDomenico et al. (2015)). Using this methodology, the incremental energy used in electricity generation for electrified commuter rail systems was included in the calculation, as shown in equation (2). Table 1 provides the generation intensity factors applied to electrified commuter rail systems based upon their geographic location.

$$E_{Purchased} = [(F_{diesel} \times \varepsilon_{diesel}) + (F_{B20} \times \varepsilon_{B20})] \times 1000 + (E_{Electric} \times C) \qquad (1)$$

Where:

$E_{Purchased}$ = purchased energy consumption (kJ)
$E_{electric}$ = purchased electric energy at the catenary (kWh)
C = energy unit conversion 3,600 kJ per kWh
ε_{diesel} = energy density of diesel fuel (35,799 MJ/m^3) (Frey and Graver (2012)).
ε_{B20} = energy density of biodiesel (33,904 MJ/m^3) (Frey and Graver (2012)).
F_{diesel} = diesel fuel consumed (m^3)
F_{B20} = B20 blended biodiesel consumed (m^3)

$$E_{Generation} = E_{electric} \times e_{Generation}. \qquad (2)$$

Where:

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

The energy efficiency and intensity can be analysed as shown in Equations 3 and 4.

$$Efficiency = \frac{n \times d}{E_{Purchased} + E_{Generation}}. \tag{3}$$

$$Intensity = \frac{E_{Purchased} + E_{Generation}}{n \times d}. \tag{4}$$

Where:
n = number of seats per passenger coach
d = vehicle-miles traveled

Table 1: Generation and upstream production energy by region and fuel type (US Energy Information Agency (2014); Wang (2013))

US Electric Generation Region	$e_{Generation}$ ($\frac{kJ}{kWh}$)
South Atlantic	8,623
Middle Atlantic	7,302
New England	7,561
West South Central	8,834
East South Central	8,870
West North Central	9,215
East North Central	9,035
Pacific	5,714
Mountain	8,817

3.2 Results

Previous research using the NTD database has identified the number of coaches per train as having a large effect on energy efficiency (DiDomenico et al. (2013)). Research analysing the energy efficiency of intercity passenger trains indicated that station spacing, or the number of stops a train makes on a fixed-length route, 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. However, there are other systems that offer more extensive service schedules but, 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 sorts of effects cloud 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 coincidental covariance with other factors such as train length or station spacing.

The analysis does indicate, as shown in Figure 1, that systems offering local-only service that stops at every station are 8% more energy intense (and correspondingly less efficient)

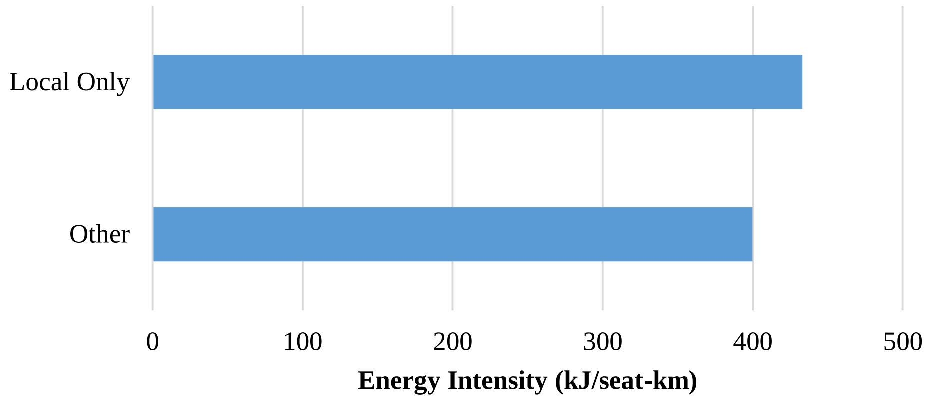


Figure 1: NTD analysis showing the effect of scheduling pattern on energy intensity

than those offering other service schedules, such as zonal, express, and skip-stop. Because the NTD dataset is comprised of high-level gross annual averages for each commuter rail system, it is impossible to analyse the relationship between stopping pattern and energy consumption in a more detailed way. Many 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 train runs and periods of service in more detail.

4 Effect of Scheduling Patterns on Commuter Rail Energy Efficiency

4.1 Methodology

In order to investigate the effects of commuter rail system scheduling patterns on energy efficiency in more detail, a case study of a commuter rail line in the Midwestern United States was conducted. The case study simulates 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.

The MMPASSIM tool simulates the energy consumption of rail movements using a simplified train performance calculator based upon traditional train energy methodology (modified Davis equation). Differing from more detailed train performance calculators, MMPASSIM aggregates gradient and curvature along a route into a distribution, rather than simulating the train movement over a detailed elevation profile and curvature alignment. The model has the ability to use detailed train consist information, including train length, mass, resistance coefficients, hotel power configuration, nominal traction power, and many other inputs in the calculation of energy consumption. Due to length constraints of this paper, the train performance methodology used in the MMPASSIM model cannot be shown explicitly, but can be found in the corresponding "Rail Simulation Module" document (TranSys Research (2015)).

Route Characteristics

To characterize the route, a distribution of the grade, curvature, station stops, and speed limits from railroad track charts are used. The case study 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 121 kilometres per hour. The existing commuter rail service operates with a mixture of express and local trains that serve varying numbers of station stops. The commuter service is operated 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 assumes that, with freight train path conflicts eliminated due to temporal separation, the triple-track mainline provides sufficient capacity for express trains to overtake local trains. Thus the schedules presented in subsequent sections are assumed to be operationally feasible with adequate headways and overtaking/turnaround time.

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. For this analysis, peak period is defined as the period from the first morning inbound train to 9:15 AM (Metra (2007)). The candidate skip-stop, zonal and express train schedule patterns for this period are shown in Tables 2 through 4 respectively. The local scenario, where each train stops at every station on the route, is not shown due to its simplicity. The current operating schedule pattern for the same period (Table 5) uses a mixture of train runs that are similar in stopping pattern to those in each of the alternative train schedule patterns.

Stopping patterns for local trains provide service to every station along the line with each train run. Therefore, in order to match existing train service frequencies at each station, fewer total local train runs are required than patterns that do not stop at every station. Skip-stop patterns skip stations in small increments, increasing the effective distance between acceleration and deceleration events and decreasing trip time. Zonal stopping patterns are comprised of trains stopping at zones of consecutive stations followed by a direct trip to the end terminal. Express scheduling patterns combine the patterns found in local and zonal scenarios by providing several local train runs and supplementing high-demand stations with zonal "express" trains. This philosophy reduces service at low-demand stations that are over-served by the local-only candidate train schedule pattern. Finally, the existing peak-hour timetable, implemented by the operator under real-world service and demand-related constraints, is analysed 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 (Table 5) has been referenced 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 are constructed such that the scheduled station service frequencies match the current frequency of service to the extent

Table 2: Skip-Stop scenario train schedule pattern on case study line

Station	**Trains**																									
Aurora	■		■		■		■		■		■		■		■		■		■		■		■		■	
Route 59		■		■		■		■		■		■		■		■		■		■		■		■		■
Naperville	■		■		■		■		■		■		■		■		■		■		■		■		■	
Lisle		■				■		■		■		■		■		■		■		■		■		■		
Belmont	■						■		■		■		■		■				■		■		■		■	
Downers Grove		■				■		■		■		■		■		■		■		■		■		■		
Fairview Ave	■		■		■				■			■	■		■		■		■		■		■			
Westmont		■		■		■				■				■		■		■		■		■		■		■
Clarendon Hills			■		■		■		■		■		■		■		■				■		■		■	
West Hinsdale				■		■		■				■		■								■				■
Hinsdale	■		■		■		■		■		■				■		■		■		■		■			
Highlands				■						■						■		■		■				■		
Western Springs			■		■		■				■		■				■				■		■		■	
Stone Ave						■		■				■		■								■				■
La Grange	■		■				■		■				■		■		■		■				■			
Congress Park		■		■						■								■		■				■		
Brookfield			■		■		■				■		■				■				■				■	
Hollywood				■		■		■				■		■								■				■
Riverside	■		■		■				■						■		■		■				■			
Harlem Ave		■		■						■						■		■		■				■		■
Berwyn			■		■		■				■		■				■				■				■	
La Vergne						■		■		■				■		■				■		■				
Cicero	■								■		■		■		■						■				■	
Western Ave		■				■												■								
Halsted Street	■						■						■						■						■	
Union Station	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

Table 3: Zonal scenario train schedule pattern on case study line

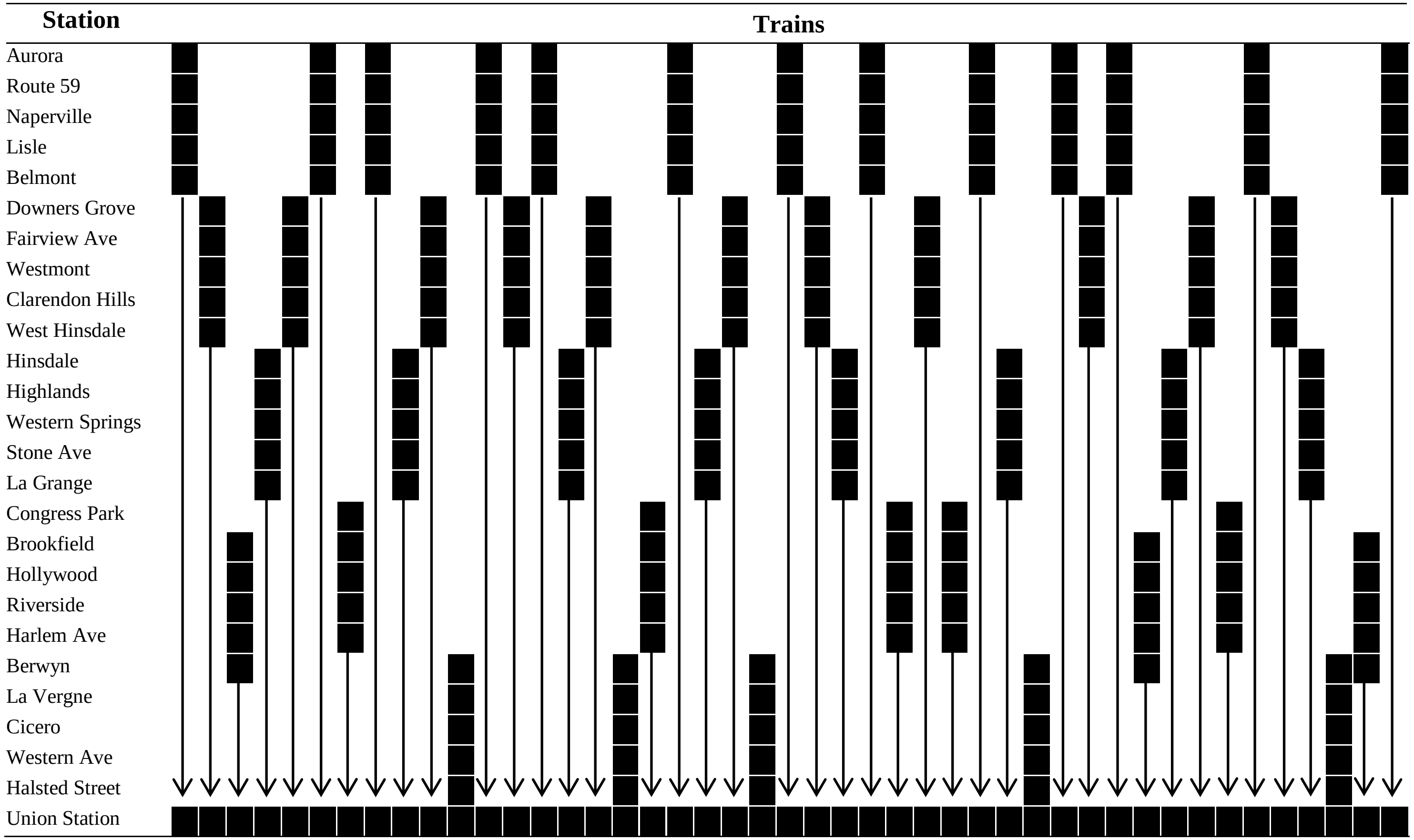
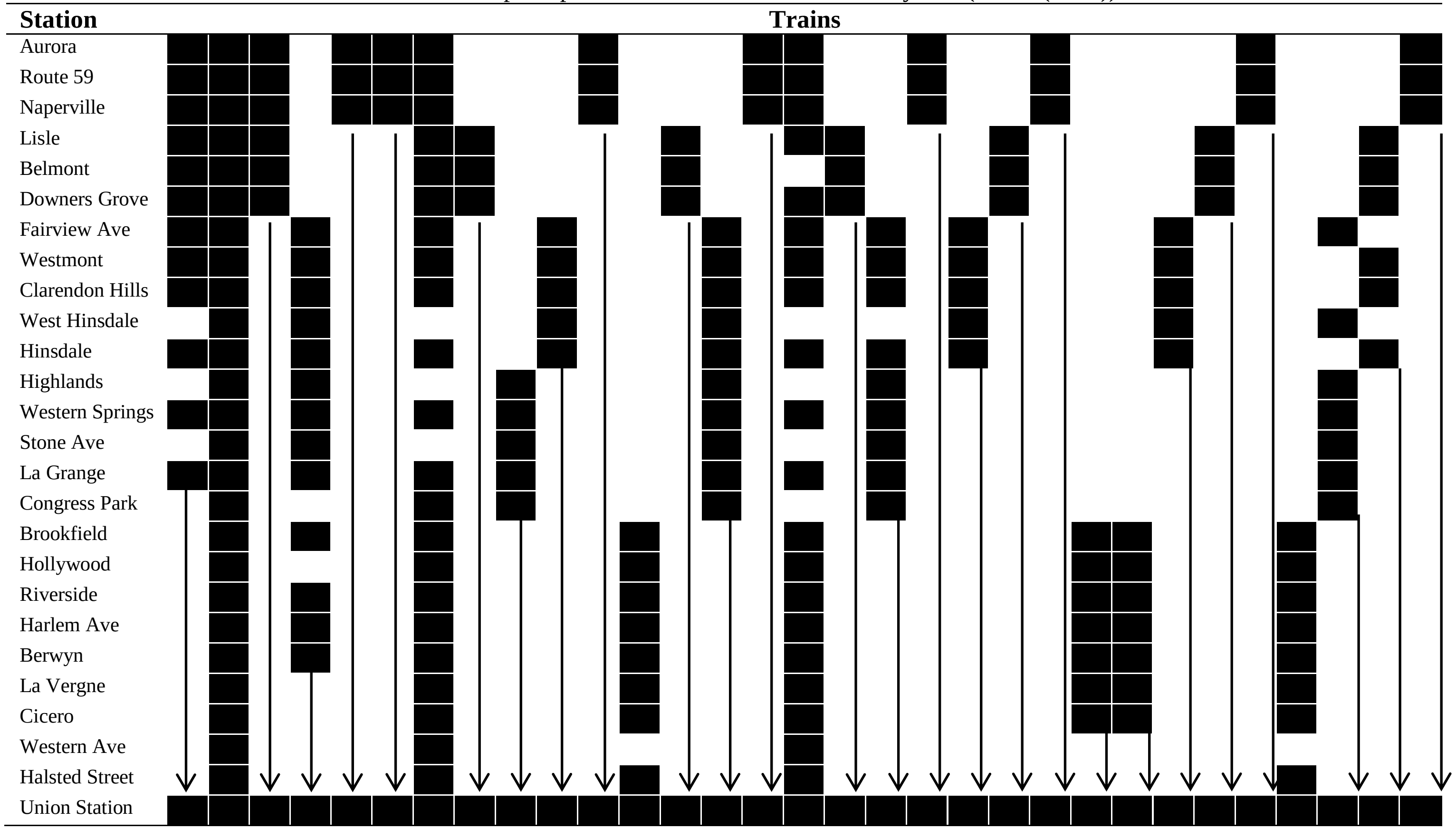


Table 4: Express scenario train schedule pattern on case study line

Station	Trains															
Aurora	■	■	■		■	■	■		■	■	■	■	■		■	■
Route 59	■	■	■		■	■	■		■	■	■	■	■		■	■
Naperville	■	■	■		■	■	■		■	■	■	■	■		■	■
Lisle	■	■	■		■	↓	■		■	■	■	↓	■		■	■
Belmont	■	↓	■	■	■	↓	■		■	↓	■	↓	■	■	■	↓
Downers Grove	■	↓	■	■	■	↓	■	■	■	↓	■	↓	■	■	■	↓
Fairview Ave	■	↓	■	■	■	↓	■	■	■	↓	■	↓	■	■	■	↓
Westmont	■	↓	■	■	■	↓	■	■	■	↓	■	↓	■	■	■	↓
Clarendon Hills	■	↓	■	■	■	↓	■	■	■	↓	■	↓	■	■	■	↓
West Hinsdale	■	↓	■		■	↓	■		■	↓	■	↓	■		■	↓
Hinsdale	■	↓	■	■	■	↓	■	■	■	↓	■	↓	■	■	■	↓
Highlands	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓
Western Springs	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓
Stone Ave	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓
La Grange	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓
Congress Park	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓
Brookfield	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓
Hollywood	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓
Riverside	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓
Harlem Ave	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓
Berwyn	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓
La Vergne	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓
Cicero	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓
Western Ave	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓
Halsted Street	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓	■	↓
Union Station	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

Table 5: Current peak-period train schedule on case study line (Metra (2012))



that the flexibility in each pattern allows. Constructing the alternative schedules with this approach assumes a fixed origin-destination passenger demand matrix that is not influenced by unique deviations from existing operations in each scheduling scenario.

Table 6 lists the service counts at each station under the different scheduling patterns and the required number of train runs. The skip-stop service exactly matches the current service frequency at all stations while reducing the number of train runs by five. The local service uses the fewest train runs. However, since all local trains stop at every station, some stations are over-served compared to current operations. While these extra stops could be skipped in practice, to provide the most extreme case for comparison purposes, these extra stops were retained in the analysis. The express pattern eliminates many extra stops but adds more train runs to provide individual train schedules with lengthy express segments. Since each zonal train only serves a small group of stations before running express to the end terminal, the zonal schedule pattern requires the greatest number of train runs. The zonal pattern requires 14 more train runs than current operations.

Table 6: Scheduling pattern service counts

Station	Distance (km)	Service Count				
		Current	**Local**	**Skip-Stop**	**Zonal**	**Express**
Aurora	61.8	13	13	13	13	13
Route 59	50.8	13	13	13	13	13
Naperville	45.7	13	13	13	13	13
Lisle	39.3	11	13	11	13	11
Belmont	36.8	10	13	10	13	10
Downers Grove	33.9	11	13	11	11	11
Fairview Ave	32.7	11	13	11	11	11
Westmont	31.2	11	13	11	11	11
Clarendon Hills	29.3	11	13	11	11	11
West Hinsdale	28.6	7	13	7	11	8
Hinsdale	27.0	11	13	11	8	11
Highlands	26.2	6	13	6	8	8
Western Springs	24.8	9	13	9	8	8
Stone Ave	22.7	6	13	6	8	8
La Grange	22.0	9	13	9	8	8
Congress Park	20.9	6	13	6	5	8
Brookfield	19.8	8	13	8	8	8
Hollywood	18.8	7	13	7	8	8
Riverside	17.7	8	13	8	8	8
Harlem Ave	16.1	8	13	8	8	8
Berwyn	15.4	8	13	8	8	8
La Vergne	14.5	7	13	7	5	8
Cicero	11.3	7	13	7	5	8
Western Ave	6.0	3	13	3	5	8
Halsted Street	2.9	5	13	5	5	8
Union Station	0.0	31	13	26	45	16
Total Train Runs		**31**	**13**	**26**	**45**	**16**

Table 7: 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

Train Characteristics

All trains simulated in this experiment use a single diesel-electric locomotive with a nominal traction power of 2,237 kilowatts and a varying number of bi-level gallery commuter rail coaches. Each coach has 146 seats, with a total passenger capacity of 246 (including standing room).

Passenger boarding and alighting counts from each station along the line have been analysed to determine the passenger demand at each station. This station-by-station demand allows 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 in Table 7 is used for all trains. The required number of coaches for Consist A was determined by analysing passenger boardings and alightings at each station to determine the maximum net passenger load on an inbound peak-period local train.

A second set of simulations were designed to examine the effect of scheduling pattern on peak-period energy consumption using train consists of different lengths sized to more accurately reflect the passenger demand of individual train runs. To simplify use of the MMPASSIM tool, only three discrete train consist options were used. Consists B and C represent medium and low passenger capacity respectively, while Consist A represents high passenger capacity. Train consists are assigned to individual train runs by matching the net passenger load for the stopping pattern of each train run to consist capacity.

4.2 Results

Efficiency of Average Train Runs for Candidate Scheduling Scenarios

Each scenario has a varying number of total required trains over the peak-period (Table 6). In addition to having different stopping patterns, individual trains travel various distances. For example, zonal trains originating in the middle of the route have shorter runs. This disparity in trip length and number and location of stops causes the relative energy consumption to vary between individual train runs within candidate schedule scenarios. Therefore, to draw comparisons between scheduling patterns, it is important to understand the performance of the average train run under each scenario.

For the case of a constant train consist (Consist A), the energy consumption and intensity of the average train in each candidate scheduling pattern is presented in Table 8 Since the local trains all traverse the entire route and make the most stops, the average local train has the highest energy consumption and energy intensity per train-kilometre. The average zonal train consumes the least energy per train, since it makes few stops and only travels a portion of the overall route length.

Similar results are obtained for the case using variable train consists (Table 9). The local train consumes the most energy per train, and is also the most energy intense per train-km.

Table 8: Energy of average trains for each scheduling pattern using Consist A

Train Type	**Stops**	**Trip Dist. (km)**	**Speed (km/ hr)**	**Energy (GJ/ train)**	**Intensity (GJ/ train-km)**	**Intensity (kJ/ pax-km)**	**Intensity (kJ/ seat-km)**
Local	26	61.8	27	32	0.51	448	351
Express	16	56.9	38	22	0.38	378	261
Skip-Stop	9	56.3	63	16	0.28	444	190
Existing	8	44.3	52	14	0.31	465	213
Zonal	6	36.3	59	11	0.30	542	209

Table 9: Energy of average trains for each scheduling pattern using variable consists

Train Type	**Energy (GJ/train)**	**Speed (km/hr)**	**Intensity (GJ/train-km)**	**Intensity (kJ/pax-km)**	**Intensity (kJ/seat-km)**
Local	32	27	0.51	448	351
Express	20	39	0.34	342	297
Skip-Stop	11	69	0.19	311	228
Existing	9	59	0.21	318	245
Zonal	6	70	0.18	315	243

This reinforces the preliminary results presented in Figure 1, suggesting that commuter rail systems in the US running local-only scheduling scenarios have a higher energy intensity (per seat-km) than systems using other patterns.

Comparison of the values in Table 8 and 9 reveals 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 decreases the energy intensity per passenger-km, resulting in a more efficient operation. However, the energy intensity (per seat-km) is higher in each scenario with the variable consist. Although the variable consist scenario has shorter trains (and correspondingly lower energy per train-km), each train has fewer seats over which to distribute the fixed resistance of the locomotive. This causes the energy per seat-km to increase and operation to appear less efficient from the perspective of seat-km. Since all local trains always use Consist A, there is no change in the local results between Tables 8 and 9.

The relationship between energy consumption of individual train runs within each scheduling scenario and the number of station stops made by a particular train shows a distinct relationship (Figure 2). Increasing the number of station stops made by a particular train run increases its energy consumption. This result is due to the increased number of acceleration and deceleration events, as shown previously by Fullerton et al. (Fullerton et al. (2014)). Finally, note that there is some variability in the energy consumption of skip-stop and zonal schedules with the same number of stops. This suggests there is potential to optimize the system energy consumption based on the exact combination of station stops built into each scheduled train run.

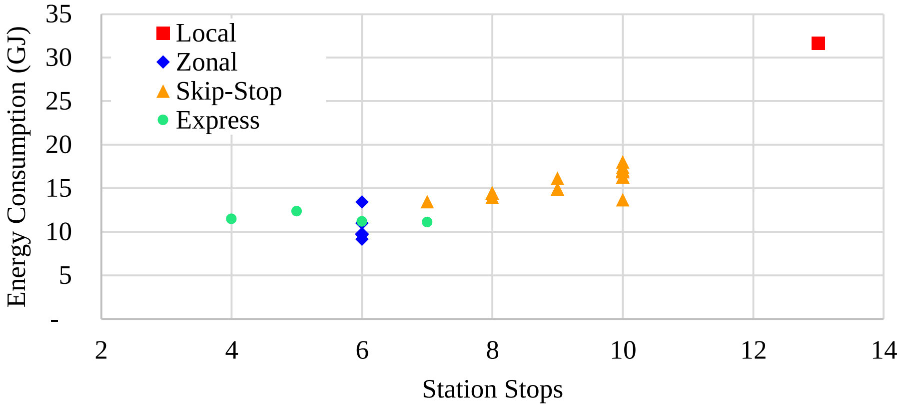


Figure 2: Total energy consumption of individual train runs versus number of station stops for each candidate scheduling pattern

Constant Train Consist

The overall energy consumption for the peak period of each candidate scheduling pattern shows the combined effect of the efficiency of each train run with a constant consist and the total number of train runs required to provide the service (Figure 3).

The relative difference between each scheduling scenario is amplified due to the consistent use of Consist A (10 coaches) even for individual train runs that have low passenger demand. Despite the average zonal train run using the least energy per train, due to the high number of trains required to meet service requirements, the zonal scenario requires the most energy. Specifically, in order to maintain current service frequency, this scenario requires 46 train runs, as opposed to 31, 26, 16, and 13 for the current, skip-stop, express, and local scenarios respectively. Since it uses far fewer trains, peak-period energy

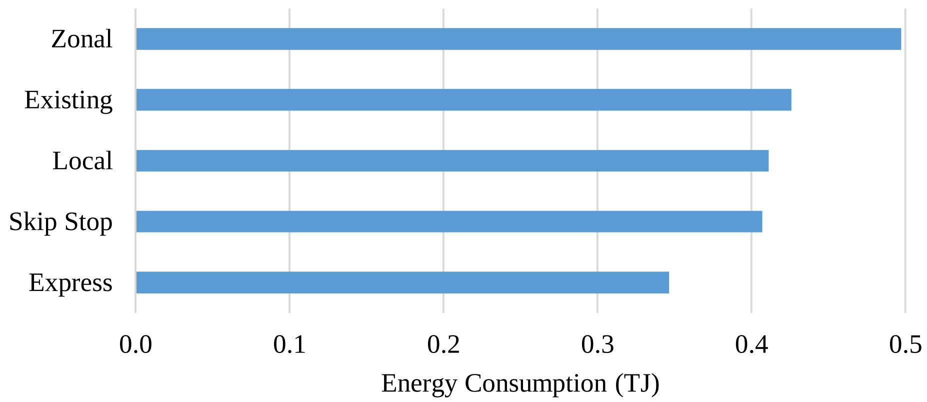


Figure 3: Energy consumption of peak-period operations using constant train consists for each scheduling scenario

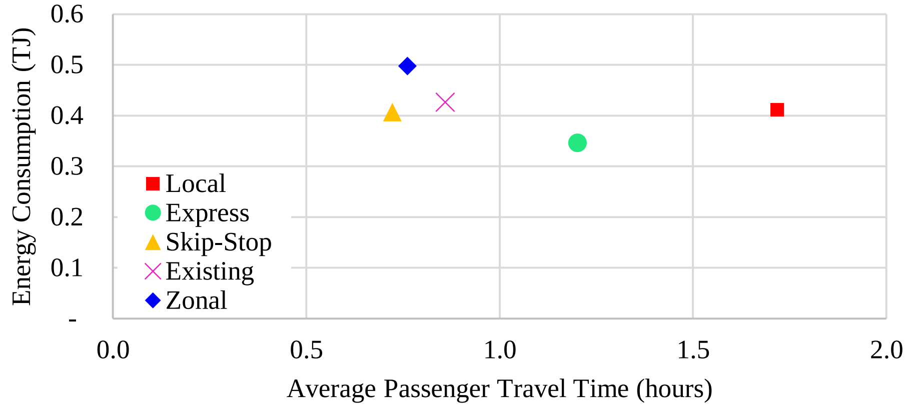


Figure 4: Pareto-optimal plot of energy consumption versus weighted average travel time of peak-period operations using constant train consists for each scheduling scenario

consumption for the local scenario requires 17% less energy than the zonal scenario. Note that efficiency of the zonal trains is reflected in the finding that despite requiring three-times the number of train runs, the zonal scenario only requires approximately 40 percent more energy than the express scenario.

Although the local and express scenarios require the least energy for the peak-period, they also require the most run time per trip. For the express scheduling pattern, the long trip time is due to the local trains required to complete the service schedule at stations not served by the express trains with low run times. Figure 4 plots the total peak-period energy consumption and the average passenger travel time for each candidate train scheduling pattern.

Travel times output from the model are somewhat exaggerated due to the acceleration effects of the longer train consist. The zonal scenario has the highest total energy consumption, but also offers a low average travel time.

In illustrating the trade-off between peak period energy consumption and average passenger travel time, Figure 4 takes the form of a pareto-optimal plot. The origin of the plot represents utopia, with 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 are valued equally, the feasible candidate train service schedule pattern that is 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 is pareto-optimal, followed very closely by the zonal and existing operating schedules. Operators that place different premiums on energy consumption or travel time can weight them accordingly to create a different direction of optimality emanating from the origin. 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 and 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. The different consists were assigned to each individual train run based upon the maximum net passenger demand between any two stations for each train run and the capacity of the consist type. This allocation of passenger coaches to train runs allows for shorter train consists on train runs that do not stop at enough high-demand stations to justify the 10 coaches used in the previous analysis.

Figure 5 shows the total energy consumption during the peak-period for each scheduling scenario using the variable train consists. The local scenario requires the most energy. The skip-stop and zonal scenarios require the least energy in this case, using 32% less energy than the local scenario. The change in relative ranking is due to the required use of Consist A on all of the local train runs, while the other scenarios can use shorter train consists on lower-demand runs. The express scenario runs half of the peak-period trains as local with Consist A, while the other half are express with Consists B or C, depending on passenger demand. Despite the addition of three train runs, and higher overall operating

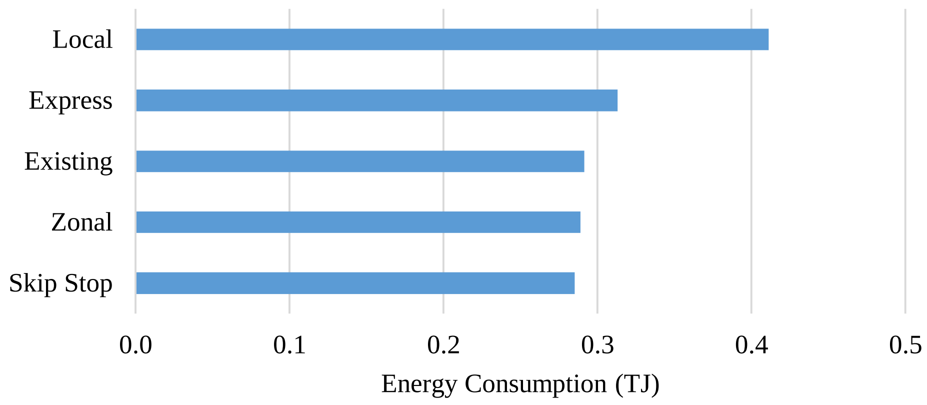


Figure 5: Energy consumption of peak-period operations using variable train consists for each scheduling scenario

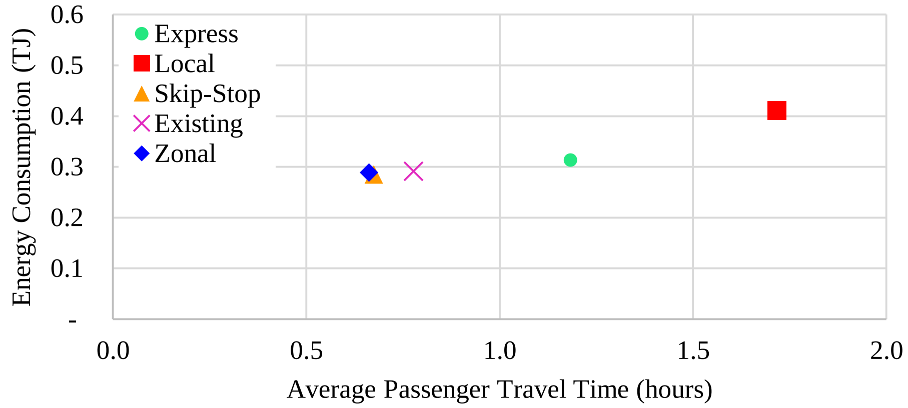


Figure 6: Pareto-optimal plot of energy consumption versus weighted average travel time of peak-period operations using variable train consists for each scheduling scenario

speed, the elimination of stops and reduction in trailing coaches on the eight express trains decreases the total energy consumption below that of the local scenario.

Figure 6 plots the total peak-period energy consumption and the average passenger travel time for each candidate train scheduling pattern with a variable train consist. The trade-off between improved service (lower average passenger travel time) and energy consumption is less obvious, skewed slightly by the longer trains in the local and express scenarios. From a pareto-optimaltiy perspective, the skip-stop and zonal scenarios are closest to the origin, and clearly improve upon the current operating schedule pattern (i.e. both scenarios have lower energy consumption and shorter travel time than the current operation). Similarly, the express service pattern clearly dominates the local service pattern.

5 Conclusions

Single-variable analysis indicates that stopping pattern may have an impact on the operating energy consumption of commuter rail systems in the United States. To investigate the effects further, a case study of a commuter rail line in the Midwestern United States 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 indicate that due to the high number of station stops, the local scheduling scenario uses the most total energy during the peak period and is the most energy intense (per train-km). The express scenario uses the least energy per peak-period when using a constant 10-coach consist. When the train consist is 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 show a trade-off between total peak-period energy consumption and average travel time. With a constant train consist, the scenarios consuming the most energy provided 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 train consists.

Operating energy consumption is a large expense for transit agencies, which are increasingly under budget constraints and financial scrutiny. However, transit agencies are also concerned with offering a high level of service to their riders, requiring them to minimize the average trip time for each passenger. 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 appears 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 blanket application of a single rigorous scheduling methodology.

This research introduces 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.

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