F Vehicle Types

This appendix details the commuter rail vehicle technological assessment for Rail Vision. This technological assessment presents estimated unit capital costs and recommended spare margins for use in the Rail Vision analyses, and includes predicted energy usage, travel times, and emissions for candidate train technologies.

Predicted energy usage, travel times, and emissions for candidate train technologies are based on single train simulations. These simulations were completed for the North Side's Lowell Line and the South Side's Providence Line, reflecting a diversity of operating speeds and station stopping patterns. These results are averaged together to form overall comparative statistics representative of MBTA Commuter Rail operation. The specific train types evaluated on each of the two lines are shown in Table F-1.

The propulsion types represented in Table F-1 include existing MBTA diesel locomotives, new EPA Tier 4 emissions-compliant diesel locomotives, electric locomotives, self-propelled electric multiple units (EMUs) and self-propelled diesel multiple units (DMUs).

Table F-1 Train Types Evaluated for Rail Vision Analyses

Train Propulsion Type	Lowell Line Consists	Providence Line Consists
Existing HSP46 Tier 3 diesel locomotive (baseline)	5-, 6-, 7-, & 8-car	5-, 6-, 7-, & 8-car
MP54AC Tier 4 diesel locomotive	5-, 6-, 7-, & 8-car	5-, 6-, 7-, & 8-car
ACS-64 electric locomotive	6-car	6-car
Bi-Level EMU	8-car (Can be scaled)	8-car (Can be scaled)
Tier 4 DMU	9-car (Can be scaled)	9-car (Can be scaled)

Alignment

For the purpose of predicting emissions rates and energy usage per train-mile operated, varying stopping patterns and consists were simulated on the Lowell Line and Providence Line. Averages of the two lines serve as approximations of trips with different stopping patterns and consists across the full MBTA Commuter Rail network. Table F-2 provides trip starting locations and distances while Figure F-1 displays a map of the simulated segments.

The trips in Table F-2 are designed to represent four service types included in some or all of the Rail Vision alternatives – express, zonal express, local and Urban Rail. Express services operate from the outer zone of commuter rail lines, bypassing most stations closer to Boston. Zonal express services operate from the outer zone of commuter rail lines, serving blocks of stations in zones but skipping other intermediate blocks of stations. Local services originate at the end of commuter rail lines or intermediate terminal/turnback stations, serving all stations. Urban rail services operate within the inner portion of commuter rail lines, making high-frequency stops that include existing commuter rail stations plus possible new infill stations.

Figure F-1 Commuter Rail Lines Included in Simulation Analysis

Table F-2 Simulated Lines, Stopping Patterns and Distances

Line	Stopping Pattern(s)	First Station	Distance (Miles)
Lowell	Express, Zonal Express, Local	Lowell	24.30
Lowell	Urban Rail	Anderson/Woburn	11.74
Providence	Zonal Express, Local	Wickford Jct.	63.04
Providence	Express	Providence	43.57
Providence	Urban Rail	Route 128	10.74

Vehicle Characteristics

This section provides technical and performance documentation of the locomotive, passenger coach and EMU vehicle types comprising the train technology alternatives considered.

HSP46 Locomotive

Figure F-2 HSP46 Locomotive

The current HSP46 Tier 3 locomotive, pictured in Figure F-2, serves as the baseline for evaluating the performance of future vehicles. Figure F-3 shows the HSP46 tractive effort curve used in simulation, showing pounds of force at the wheels of the locomotive as a function of velocity at maximum locomotive power. The MBTA also uses F40PH locomotives, but these locomotives are assumed to be retired in the near future and are not included in the future baseline case.

Figure F-3 HSP46 Simulation Tractive Effort Curve

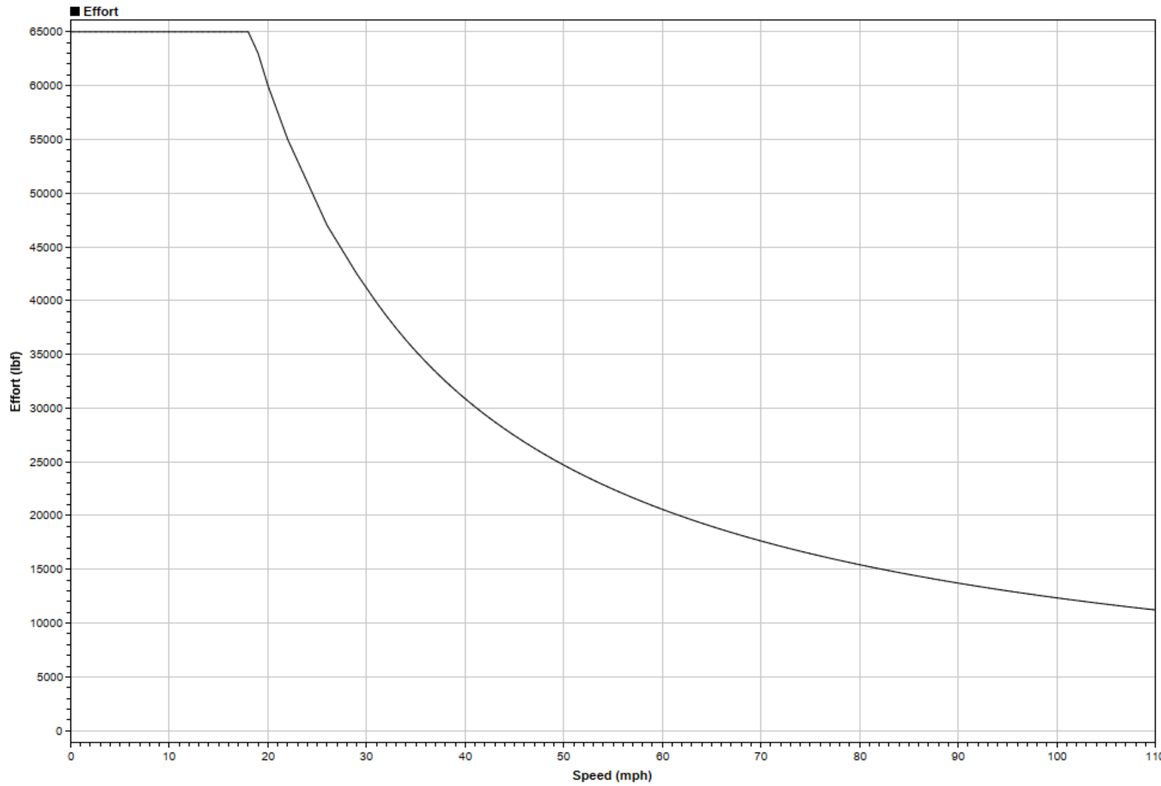


Table F-3 provides additional important train performance parameters for the HSP46. Deceleration was adjusted to a 1.2 mph/s practical service brake rate based on calibration to typical “real-world” brake rates.

As a diesel locomotive, the acceleration of the HSP46 locomotive is controlled by selecting one of eight throttle notches. In each notch, the engine outputs a constant power and consumes fuel at a constant rate. The total fuel consumed for a trip may be calculated by associating the fuel consumption rate with the duration of each locomotive notch level used in the simulation. Table F-4 provides the horsepower (known as brake horsepower, or BHP) and fuel consumption rate in each notch for the HSP46.

Table F-3 HSP46 Locomotive Parameters (Baseline Condition)

Parameter	Value	Units	Notes
Length	71	Feet	
Frontal Area	153.75	Square feet	Based on width and height
Weight	287,500	Pounds	
Axles	4		
Rotating weight	28,750	Pounds	
Power	4300	HP	
Resistance	Standard Davis Equation		
Acceleration Adhesion	28	%	
Deceleration	1.2	mph/s	Typical Locomotive Engineer comfort braking
Auxiliary Power	60	kW	Locomotive only, typical operation

Table F-4 HSP46 Energy Usage by Notch

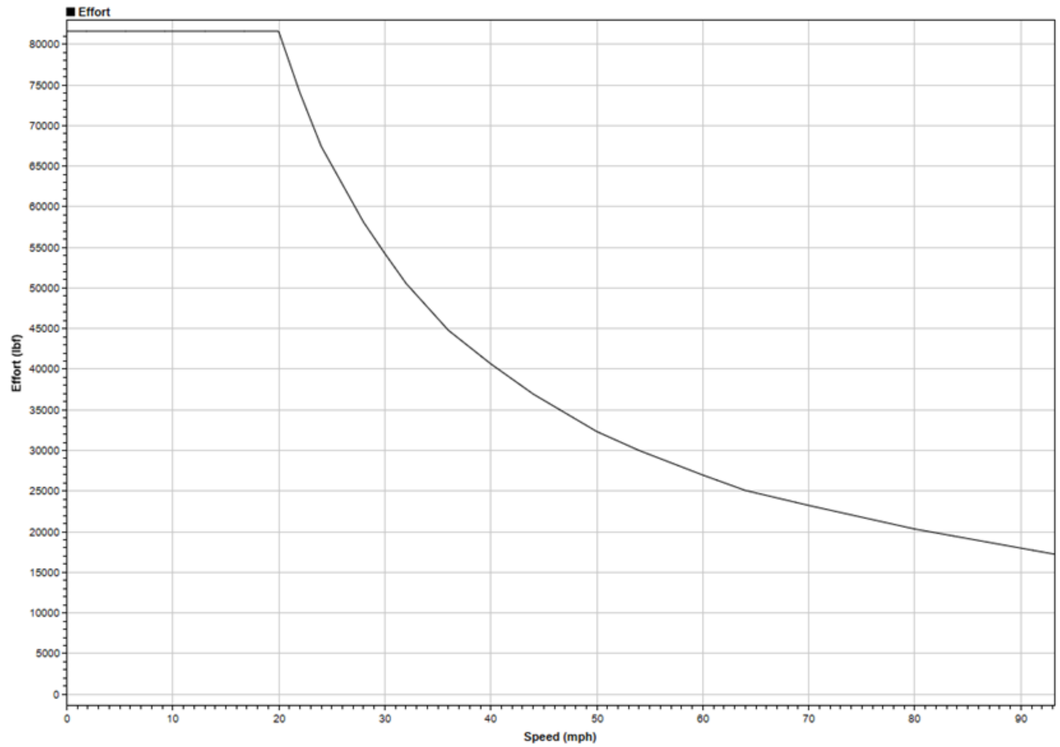
Notch	Brake-Horsepower (BHP)	Fuel Use (L/Hr)	Fuel Use (Gal/Hr)
1	251	45.42	12.00
2	566	102.21	27.00
3	1,131	204.41	54.01
4	1,655	299.05	79.01
5	2,200	397.47	105.01
6	2,933	529.96	140.02
7	3,583	647.31	171.02
8	4,400	794.94	210.02
Idle	62.8	11.36	3.00

MP54AC Locomotive

Figure F-4 MP54AC Locomotive
(Photo Credit: GO Transit)

The MP54AC, pictured in Figure F-4, is a state-of-the-art Tier 4 compliant locomotive operated by GO Transit in Toronto. An engineer can manually switch off one of the two diesel engines to lower fuel consumption when operating shorter trainsets. In addition, although the new MP54AC does not have a separate head-end power generator, it is able to use regenerative braking to recover energy during braking and supply it as electrical power to the trailing coaches. These features make the locomotive more efficient than other older diesel locomotives, especially when operating on lower ridership lines with shorter train lengths and on lines with frequent stops.

Figure F-5 MP54AC Simulation Tractive Effort Curve (Both Prime Movers Combined)



Tier 4 is the latest emission requirement established by the US Environmental Protection Agency (EPA), and new and rebuilt diesel locomotives were required to meet it by January 1, 2015. Tier 4 compliant locomotives reduce particulate matter (PM) and nitrogen oxides NOx) by approximately 86% from Tier 0 locomoties (those produced prior to 2002).

The tractive effort curve for the MP54AC locomotive, with the output of its two engines combined, is shown in Figure F-5. Initial tractive effort is maintained until a speed of 20 MPH. The maximum power output of the twin Cummins QK60 engines in the MP54AC is 5,400 horsepower. Approximately 4,000 true horsepower are produced at the wheel when operating in a typical consist, due to the need to supply power to the trailing cars for lighting, heating and air conditioning and other on-board systems.

Table F-5 provides additional important train performance parameters for the MP54AC. As it was for the HSP46, deceleration was adjusted to a 1.2 mph/s practical service brake rate.

As a diesel locomotive, the acceleration of the MP54AC and corresponding power output and fuel consumption is controlled by selecting one of eight throttle notches. **Table F-6** and **Table F-7** provide the horsepower and fuel consumption rate in each notch. Although it is possible to temporarily shut down one of the two engines on the locomotive to improve fuel economy, this is left to the discretion of the engineer.

This analysis simulated the train with both engines in operation for maximum performance.

Table F-5 MP54AC Locomotive Parameters

Parameter	Value	Units	Notes
Length	68	Feet	Coupler to coupler
Frontal Area	145	Square feet	Based on width and height
Weight	288,000	Pounds	
Axles	4		
Rotating weight	23,040	Pounds	
Power	5,400	HP	
Resistance	Standard Davis Equation		
Acceleration Adhesion	28	%	
Deceleration	1.2	mph/s	
Auxiliary Power	90	kW	Locomotive only, typical operation

Table F-6 MP54AC Energy Use by Notch (Single Engine Operating on Locomotive)

Notch	Brake-Horsepower (BHP)	Fuel Use (L/Hr)	Fuel Use (Gal/Hr)
1	115	51	13.47
2	300	127	33.55
3	700	239	63.14
4	1,100	369	97.49
5	1,500	488	128.93
6	1,900	616	162.75
7	2,300	748	197.62
8	2,700	905	239.10
Dynamic Brake	50	25	6.61
Idle	25	22	5.81

Table F-7 MP54AC Energy Use by Notch (Both Engines Operating on Locomotive)

Notch	Brake-Horsepower (BHP)	Fuel Use (L/Hr)	Fuel Use (Gal/Hr)
1	230	101	26.80
2	600	254	67.21
3	1,400	479	126.50
4	2,200	737	194.72
5	3,000	975	257.60
6	3,800	1,231	325.28
7	4,600	1,495	394.98
8	5,400	1,809	477.94
Dynamic Brake	100	50	13.21
Idle	50	43	11.36

Siemens ACS-64 (City Sprinter)

Figure F-6 Siemens ACS-64

Locomotive

The ACS-64, shown in Figure F-6, is the newest electric locomotive in Amtrak's fleet and is capable of speeds up to 136 mph (125 mph in service). Philadelphia commuter rail operator SEPTA also operates a fleet of ACS-64 locomotives. For the purposes of benchmarking electric locomotives, the ACS-64 is the state-of-the-art electric locomotive in North America. The ACS-64 tractive effort curve shown in Figure F-7 illustrates the design effort, the effort available in simulation, and the efficiency. A 28% adhesion value limits the initial starting effort to 60,800 pounds of force (lbf) as indicated by the top flat portion of the tractive effort curve. As an electric locomotive, the ACS-64 is significantly lighter than both the HSP46 and MP54AC. Table F-8 lists the vehicle parameters for the ACS-64.

Figure F-7 ACS-64 Simulation Tractive Effort and Efficiency Curve

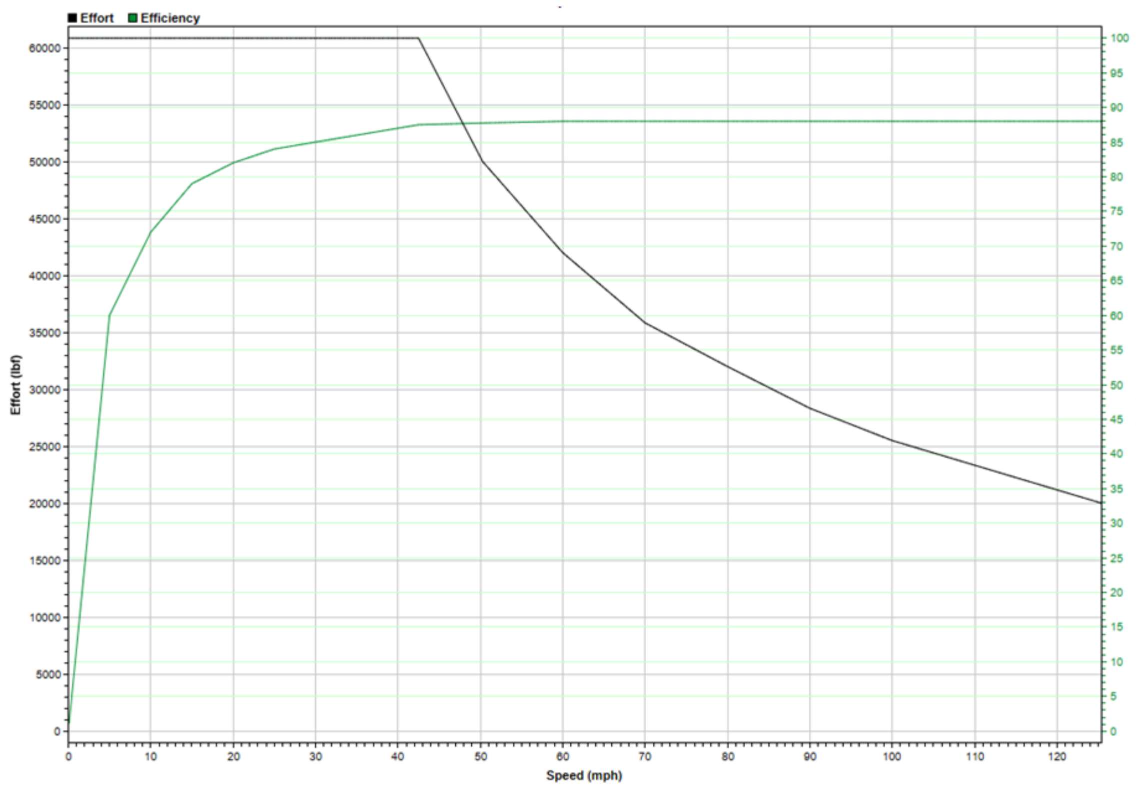


Table F-8 ACS-64 Locomotive Parameters

Parameter	Value	Units	Notes
Length	67.92	Feet	
Frontal Area	122.5	Square feet	Based on width and height
Weight	216,000	Pounds	
Axles	4		
Rotating weight	10,800	Pounds	Estimated at 5%
Power	6,700	HP	
Resistance	Standard Davis Equation		
Acceleration Adhesion	28	%	
Deceleration	1.2	mph/s	Typical Locomotive Operator
Auxiliary Power	71	kW	Locomotive only, typical operation

Kawasaki Bi-Level Trailer

Figure F-8 Kawasaki Bi-Level Trailer

The MBTA's current bi-level trailer coach, pictured in Figure F-8, is used in all simulated locomotive-hauled consists. Its simulation parameters are shown in Table F-9. The trailer coach solely provides passenger accommodations and cannot be used as the lead unit on a train as it does not include a control cab.

Table F-9 Bi-Level Trailer Parameters

Parameter	Value	Units	Notes
Length	85	Feet	
Frontal Area	N.A.	Square feet	Middle of Consist
Weight	120,600	Pounds	
Axles	4		
Rotating weight	10,251	Pounds	
Resistance	Standard Davis Equation		
Seats	180		
Auxiliary Power	50	kW	Typical operation

Kawasaki Bi-Level Cab Car

Figure F-9 Kawasaki Bi-Level Cab Car

Like the bi-level trailer, the bi-level cab car, pictured in Table F-9, is used by all simulated locomotive-hauled consists. The parameters for the simulated bi-level cab car appear in Table F-10.

Table F-10 Bi-Level Cab Car Parameters

Parameter	Value	Units	Notes
Length	85	Feet	
Frontal Area	N.A.	Square feet	End of Consist
Weight	127,200	Pounds	
Axles	4		
Rotating weight	10,812	Pounds	
Resistance	Standard Davis Equation		
Seats	180		
Auxiliary Power	50	kW	Typical operation

Stadler EMU 8 Car-4MT (AW0)

Figure F-10 Caltrain Stadler EMU

A bi-level EMU, the Stadler EMU, pictured in Figure F-10, has a higher seating capacity than most EMU vehicles but is still about 33% lower per car than the MBTA bi-level coaches currently in operation. The simulated car is an average of the parameters of four motor and four trailer cars making up an eight car trainset. Multiple-unit operation improves the train handling in braking; therefore, the brake rate has been increased from the value used for locomotive-hauled trains (1.2 mph/s) to a practical EMU service brake rate of 1.6 mph/s. The simulated vehicle is an eight-car multiple unit consist. Figure F-11 shows the simulated car's design effort and Table F-11 lists its input parameters.

Figure F-11 Stadler EMU 8 Car-4MT (AW0) Tractive Effort and Efficiency Curves

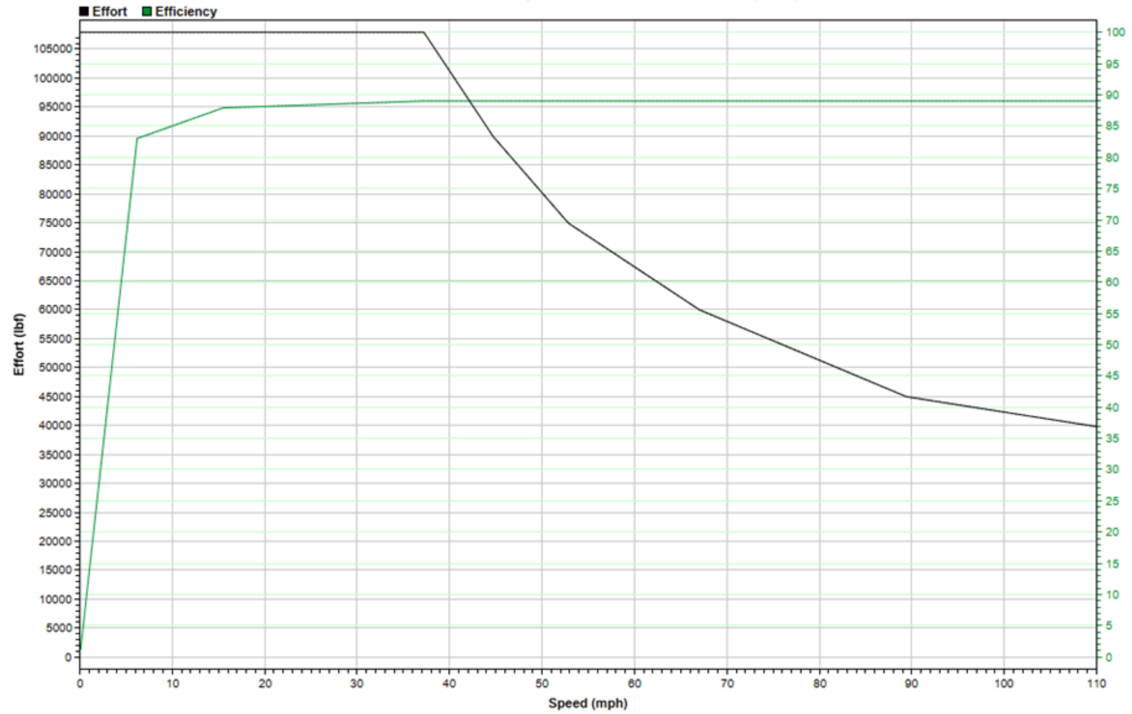


Table F-11 Stadler EMU Parameters (Per Car Averages)

Parameter	Value	Units	Notes
Length	85	Feet	
Frontal Area	140	Square feet	Based on width and height
Weight	175,157.5	Pounds	
Axles	4		
Rotating weight	104,078.2	Pounds	Estimated at 7.427%
Power	1,005.75	Hp	
Resistance	Standard Davis Equation		
Acceleration Adhesion	11.63	%	
Deceleration	1.6	Mph/s	Typical EMU operation
Seats	120	Per Car	
Auxiliary Power	60	kW	Typical operation

Nippon Sharyo DMU

Figure F-12 Nippon Sharyo DMU

As a single-level car, the Nippon Sharyo DMU pictured in Figure F-12 has the lowest seating capacity in the study, seating 90 passengers per car. This is due to equipment space allocation for propulsion control, vehicle HVAC and other systems, as well as all passenger seating being on a single level. No bi-level DMUs are presently available for the North American market. Like the EMU, the brake rate has been increased from the value used for locomotive-hauled trains (1.2 mph/s) to a practical service brake rate of 1.6 mph/s. The simulated train is a nine-car multiple unit consist in order to provide comparable passenger capacity to other simulated train consists.

Figure F-13 shows the simulated DMU's tractive effort curve and Table F-12 lists its input parameters. The DMU tractive effort curve has been derived from field data collected on the SMART system in California. Unlike the other trains considered, the DMU uses a five-speed hydrodynamic transmission instead of relying on electric motors for propulsion. This explains the somewhat unusual shape of the traction effort curve shown in Figure F-13. The concept of propulsion notches does not apply to the DMU given its hydrodynamic transmission.

Figure F-13 Nippon Sharyo DMU Tractive Effort Curve

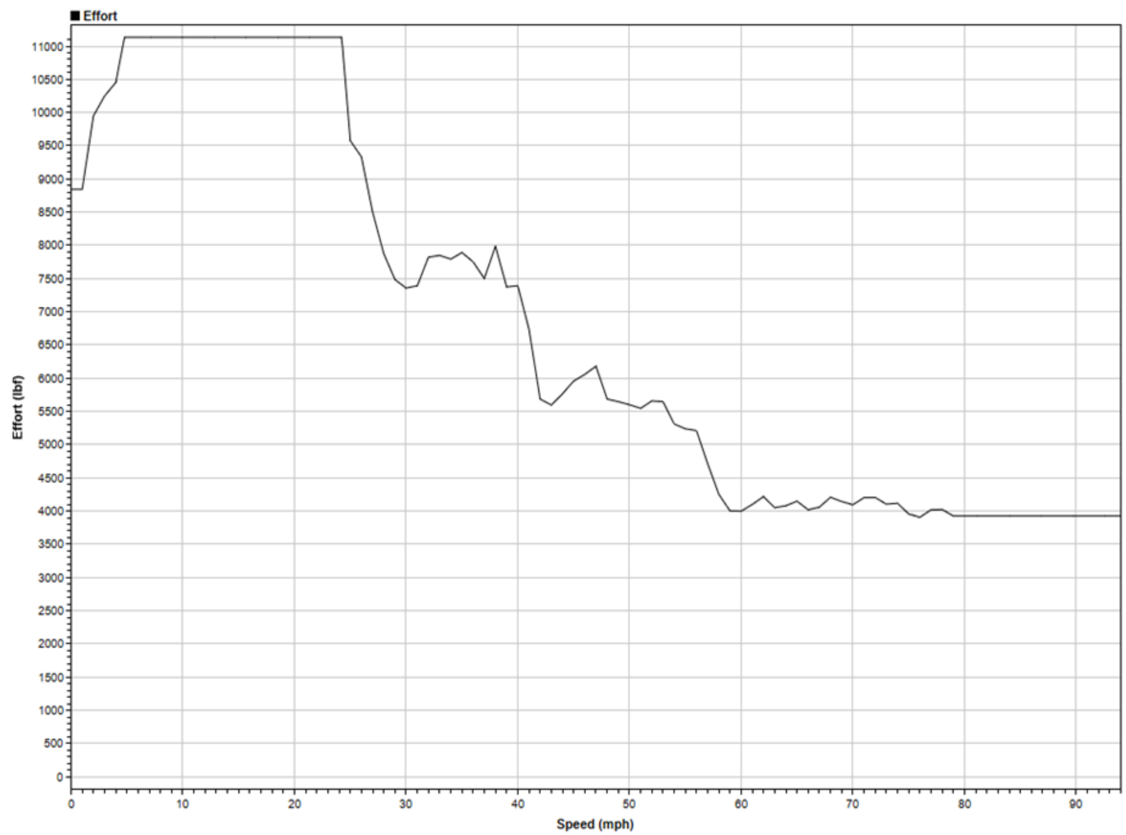


Table F-12 Nippon Sharyo DMU Parameters

Parameter	Value	Units	Notes
Length	85	Feet per car	
Frontal Area	130	Square feet	Based on width and height
Weight	148,000	Pounds	
Axles	4		
Rotating weight	14,800	Pounds	Estimated at 10%
Power	838	Hp	
Resistance	Standard Davis Equation		
Acceleration Adhesion	28	%	
Deceleration	1.6	Mph/s	Typical DMU operation
Seats	90	Per car	
Auxiliary Power	76	kW	Typical operation

Simulated Train Consists

Table F-13 provides details for each of the consists simulated. All consists were simulated with a full seated load. The longest consist simulated is a 9-car DMU.

For locomotive push-pull consists, simulated trips were run with one bi-level cab car each and four, five, six, and seven bi-level coaches. EMU and DMU performance is proportional to train length and can be factored up and down based on the number of cars in the consist. Therefore, only an 8-car EMU consist and a nine-car DMU consist were simulated.

For locomotive-hauled consists, a brake rate of 1.2 mph/s applies. EMU and DMU equipment uses a brake rate of 1.6 mph/s. The use of higher brake rates results in shorter travel times but can also increase energy usage. With higher brake rates, the train will brake later when approaching a speed restriction or station stop; this typically increases the time spent accelerating or maintaining speed which commensurately increases energy usage (but reduces trip time).

Table F-13 also provides a comparative metric for seating density by vehicle technology. The diesel and electric push-pull consists provide high seating densities due to the very efficient space utilization in the Kawasaki bi-level coaches and cab cars. The EMU seating density is lower due to the alternative vehicle crashworthiness compliance of the Stadler vehicle, which uses "crumple zones" at the ends of the train in order to comply with FRA standards. This structural design approach provides very generous engineer operating compartments with some loss of seating efficiency. Space is also lost to equipment lockers within the train. The DMU has the lowest seating efficiencies of the candidate vehicle technologies due to significant loss of interior space to equipment lockers.

Table F-13 Simulated Train Consists

Train Consist	Type	Seats	Total Length (ft)	Pass. / Foot
HSP46 loco + 4 coaches + 1 cab car	HSP46	900	496	1.81
HSP46 loco + 5 coaches +1 cab car	HSP46	1,080	581	1.86
HSP46 loco + 6 coaches + 1 cab car	HSP46	1,260	666	1.89
HSP46 loco + 7 coaches + 1 cab car	HSP46	1,440	751	1.92
MP54AC loco + 4 coaches +1 cab car	MP54AC	900	493	1.83
MP54AC loco + 5 coaches + 1 cab car	MP54AC	1,080	578	1.87
MP54AC loco + 6 coaches + 1 cab car	MP54AC	1,260	663	1.90
MP54AC loco + 7 coaches + 1 cab car	MP54AC	1,440	748	1.93
ACS64 loco + 5 coaches + 1 cab car	ACS-64	900	492.92	1.83
EMU 8-car	Stadler	960	680	1.41
DMU 9-car	Sumitomo MTU	810	765	1.06

Simulated Train Stopping Patterns

Each consist was simulated operating on the MBTA Providence and Lowell Lines with the stopping patterns shown in Table F-14.

These patterns are representative of the service types described in Table F-2. Only inbound trips were simulated as overall train technology metrics will be virtually identical in each of the two directions.

Stops at stations served by express trains were assigned 45-second dwells. Stations served by only local trains were assigned 30-second dwells.

Table F-14 Lowell and Providence Line Simulated Stopping Patterns

Lowell Stopping Patterns	Diesel Loco (Express)	Diesel Loco (Zonal Express)	Diesel Loco (Local)	Electric Loco (Express)	DMU (Urban Rail)	EMU (Express)	EMU (Zonal Express)	EMU (Local)	EMU (Urban Rail)
Lowell	x	x	x	x		x	x	x	
North Billerica		x	x				x	x	
Wilmington		x	x				x	x	
Anderson/Woburn	x	x	x	x	x	x	x	x	x
Mishawum					x				x
Winchester			x		x			x	x
Wedgemere			x		x			x	x
West Medford			x		x			x	x
North Station	x	x	x	x	x	x	x	x	x

Table F-14 Lowell and Providence Line Simulated Stopping Patterns (Cont.)

Providence Stopping Patterns	Diesel Loco (Express)	Diesel Loco (Zonal Express)	Diesel Loco (Local)	Electric Loco (Express)	DMU (Urban Rail)	EMU (Express)	EMU (Zonal Express)	EMU (Local)	EMU (Urban Rail)
Wickford Jct.		x	x				x	x	
T. F. Green		x	x				x	x	
Providence	x	x	x	x		x	x	x	
Pawtucket			x					x	
South Attleboro			x					x	
Attleboro			x					x	
Mansfield	x		x	x				x	
Sharon			x					x	
Route 128	x	x	x	x	x	x	x	x	x
Ruggles Street	x	x	x	x	x	x	x	x	x
Back Bay	x	x	x	x	x	x	x	x	x
Boston	x	x	x	x	x	x	x	x	x

Vehicle Technology Recommended Spare Margins

Suggested spare margins for vehicles and fleet types (large and small) are shown in Table F-15. These recommendations are based on peer commuter rail operations in North America.

Some of these spare margins, especially for small fleets, exceed FTA guidance and may need to be reduced where FTA funding applies. For the purposes of the fleet sizing, the Rail Vision analysis assumed spare ratios of 20% for all vehicle fleets, with the exception of DMUs (22%) due to the more complex equipment

Comparative Performance and Emissions Results

Travel Times

Table F-15 provides simulated travel times on the Lowell and Providence Lines, inbound towards Boston. Express stopping patterns are the fastest simulated trips for each respective consist. Shorter consists are faster for locomotive push-pull consists, though the EMU is the fastest of all consists. The more powerful MP54AC performs faster across all consist sizes than do the equivalent HSP46 diesel push-pull consists.

Table F-15 Elapsed Run Times

Train Consist	Type	Tier	Line	Simulated Trip Time (Hours)	Trip Length (Miles)	Average Speed (MPH)
Diesel Loco Express_HSP46_4+1	HSP46	Tier 3	Lowell	0.65	24.30	37.28
Diesel Loco Express_HSP46_5+1	HSP46	Tier 3	Lowell	0.66	24.30	36.87
Diesel Loco Express_HSP46_6+1	HSP46	Tier 3	Lowell	0.67	24.30	36.49
Diesel Loco Express_HSP46_7+1	HSP46	Tier 3	Lowell	0.67	24.30	36.08
Diesel Loco Express_MP54AC_4+1	MP54AC	Tier 4	Lowell	0.64	24.30	37.81
Diesel Loco Express_MP54AC_5+1	MP54AC	Tier 4	Lowell	0.65	24.30	37.47
Diesel Loco Express_MP54AC_6+1	MP54AC	Tier 4	Lowell	0.65	24.30	37.15
Diesel Loco Express_MP54AC_7+1	MP54AC	Tier 4	Lowell	0.66	24.30	36.84
Diesel Loco Local_HSP46_4+1	HSP46	Tier 3	Lowell	0.78	24.30	31.36
Diesel Loco Local_HSP46_5+1	HSP46	Tier 3	Lowell	0.79	24.30	30.81
Diesel Loco Local_HSP46_6+1	HSP46	Tier 3	Lowell	0.81	24.30	30.08
Diesel Loco Local_HSP46_7+1	HSP46	Tier 3	Lowell	0.82	24.30	29.56
Diesel Loco Local_MP54AC_4+1	MP54AC	Tier 4	Lowell	0.75	24.30	32.30
Diesel Loco Local_MP54AC_5+1	MP54AC	Tier 4	Lowell	0.76	24.30	31.83
Diesel Loco Local_MP54AC_6+1	MP54AC	Tier 4	Lowell	0.77	24.30	31.38
Diesel Loco Local_MP54AC_7+1	MP54AC	Tier 4	Lowell	0.79	24.30	30.96

Table F-15 Elapsed Run Times (Cont.)

Train Consist	Type	Tier	Line	Simulated Trip Time (Hours)	Trip Length (Miles)	Average Speed (MPH)
Diesel Loco Zonal Express_HSP46_4+1	HSP46	Tier 3	Lowell	0.70	24.30	34.62
Diesel Loco Zonal Express_HSP46_5+1	HSP46	Tier 3	Lowell	0.71	24.30	34.11
Diesel Loco Zonal Express_HSP46_6+1	HSP46	Tier 3	Lowell	0.73	24.30	33.37
Diesel Loco Zonal Express_HSP46_7+1	HSP46	Tier 3	Lowell	0.74	24.30	32.88
Diesel Loco Zonal Express_MP54AC_4+1	MP54AC	Tier 4	Lowell	0.69	24.30	35.39
Diesel Loco Zonal Express_MP54AC_5+1	MP54AC	Tier 4	Lowell	0.70	24.30	34.97
Diesel Loco Zonal Express_MP54AC_6+1	MP54AC	Tier 4	Lowell	0.70	24.30	34.57
Diesel Loco Zonal Express_MP54AC_7+1	MP54AC	Tier 4	Lowell	0.71	24.30	34.20
DMU Urban Rail	DMU	Tier 4	Lowell	0.46	11.74	25.39
Electric Loco Express	ACS-64		Lowell	0.64	24.30	38.19
EMU Express	EMU		Lowell	0.63	24.30	38.65
EMU Local	EMU		Lowell	0.72	24.30	33.90
EMU Urban	EMU		Lowell	0.44	11.74	26.70
EMU Zonal Express	EMU		Lowell	0.66	24.30	36.62
Diesel Loco Express_HSP46_4+1	HSP46	Tier 3	Providence	0.76	43.57	57.25
Diesel Loco Express_HSP46_5+1	HSP46	Tier 3	Providence	0.77	43.57	56.37
Diesel Loco Express_HSP46_6+1	HSP46	Tier 3	Providence	0.79	43.57	55.22
Diesel Loco Express_HSP46_7+1	HSP46	Tier 3	Providence	0.81	43.57	53.94
Diesel Loco Express_MP54AC_4+1	MP54AC	Tier 4	Providence	0.75	43.57	58.45
Diesel Loco Express_MP54AC_5+1	MP54AC	Tier 4	Providence	0.75	43.57	57.93
Diesel Loco Express_MP54AC_6+1	MP54AC	Tier 4	Providence	0.76	43.57	57.33
Diesel Loco Express_MP54AC_7+1	MP54AC	Tier 4	Providence	0.77	43.57	56.67

Table F-15 Elapsed Run Times (Cont.)

Train Consist	Type	Tier	Line	Simulated Trip Time (Hours)	Trip Length (Miles)	Average Speed (MPH)
Diesel Loco Local_HSP46_4+1	HSP46	Tier 3	Providence	1.39	63.04	45.46
Diesel Loco Local_HSP46_5+1	HSP46	Tier 3	Providence	1.39	63.04	45.46
Diesel Loco Local_HSP46_6+1	HSP46	Tier 3	Providence	1.39	63.04	45.46
Diesel Loco Local_HSP46_7+1	HSP46	Tier 3	Providence	1.39	63.04	45.46
Diesel Loco Local_MP54AC_4+1	MP54AC	Tier 4	Providence	1.35	63.04	46.81
Diesel Loco Local_MP54AC_5+1	MP54AC	Tier 4	Providence	1.37	63.04	46.11
Diesel Loco Local_MP54AC_6+1	MP54AC	Tier 4	Providence	1.39	63.04	45.33
Diesel Loco Local_MP54AC_7+1	MP54AC	Tier 4	Providence	1.39	63.04	45.27
Diesel Loco Zonal Express_HSP46_4+1	HSP46	Tier 3	Providence	1.22	63.04	51.89
Diesel Loco Zonal Express_HSP46_5+1	HSP46	Tier 3	Providence	1.23	63.04	51.20
Diesel Loco Zonal Express_HSP46_6+1	HSP46	Tier 3	Providence	1.25	63.04	50.35
Diesel Loco Zonal Express_HSP46_7+1	HSP46	Tier 3	Providence	1.28	63.04	49.42
Diesel Loco Zonal Express_MP54AC_4+1	MP54AC	Tier 4	Providence	1.19	63.04	52.85
Diesel Loco Zonal Express_MP54AC_5+1	MP54AC	Tier 4	Providence	1.20	63.04	52.43
Diesel Loco Zonal Express_MP54AC_6+1	MP54AC	Tier 4	Providence	1.21	63.04	51.94
Diesel Loco Zonal Express_MP54AC_7+1	MP54AC	Tier 4	Providence	1.23	63.04	51.42
DMU Urban Rail	DMU	Tier 4	Providence	0.26	10.74	40.79
Electric Loco Express	ACS-64		Providence	0.77	43.57	56.49
EMU Express	EMU		Providence	0.63	43.57	68.77
EMU Local	EMU		Providence	1.18	63.04	53.41
EMU Urban	EMU		Providence	0.24	10.74	44.96
EMU Zonal Express	EMU		Providence	1.06	63.04	59.71

Energy Usage

Revenue Trips

Comparing the energy consumption of diesel trains to electric trains requires developing comparative metrics regardless of the energy source to power trains of varying lengths and deployed in different types of service. For electric trains, it is necessary to know the efficiency of the generation of the power plant from its fuel or energy source, the transmission losses, and the efficiency of the traction power substation. For diesel trains, fuel usage must be calculated by summing the fuel used in each time step based on the notch. Electric powered trains in AC systems can return power to the overhead catenary while braking, supplying other trains in the network, or even returning power to the utility, for which an energy usage credit must be computed.

Table F-16 provides a universal set of inputs for the calculation of energy usage. The net energy usage of each trip pattern was calculated in horsepower-seconds (HP-S) where 1 HP equals .7457 kW. There is a small energy loss during transmission of power from the site of generation to the traction power substations, with the network efficiency being estimated at 97%. Finally, the conversion of the supply AC power to match the traction power system, and the transmission through the overhead catenary will result in some losses. For high density high voltage AC systems, this number can be as low as 2%. For the MBTA system, system losses of 3% are estimated.

Table F-16 Energy Usage Calculation Inputs

Item	Value	Units	Source
Network Efficiency	97	%	Estimated
Diesel Propulsion Efficiency	85	%	Estimated
Diesel Auxiliary Efficiency	90	%	Estimated

The regenerative braking efficiency of the electric trains depends on the usage of air brakes in addition to dynamic braking. On average, locomotive-hauled trains regenerate less power than EMU trains because air brakes are often used to brake the trailing coaches in the consist; it is generally not possible to maintain schedule if only the locomotive dynamic brake is used. The assumed regenerative rates for each simulated consist are shown in Table F-17. No regenerative braking credits were applied to diesel trains because the associated emissions benefits are small. It is not possible to know the state of the traction power network from the single train simulation results, so an estimated energy recovery percentage has been used for electric vehicles based on typical values from the Amtrak Northeast Corridor.

Table F-18 shows the energy used by each consist under each simulated stopping pattern. The values in the Per Mile column are color-coded from green to red, with green indicating the most favorable (lowest) energy usage and red the least favorable (highest).

Table F-17 Energy Recovery Percentage

Consist	Recovery
HSP46_4+1	0%
HSP46_5+1	0%
HSP46_6+1	0%
HSP46_7+1	0%
MP54AC_4+1	0%
MP54AC_5+1	0%
MP54AC_6+1	0%
MP54AC_7+1	0%
ACS64_5+1	10%
EMU 8-Car	20%
DMU 9-Car	0%

* Energy recovery limited to supplying auxiliary loads in locomotive and trailing cars during breaking

Table F-18 Simulated Energy Usage by Trip

Train Consist and Service Patern	Type	Tier	Line	Trip Length (Miles)	Gallons of Diesel	kWh	Per Mile
Diesel Loco_HSP46+4+1_Express	HSP46	Tier 3	Lowell	24.30	40.49		1.67
Diesel Loco _HSP46+5+1_Express	HSP46	Tier 3	Lowell	24.30	43.55		1.79
Diesel Loco _HSP46+6+1_Express	HSP46	Tier 3	Lowell	24.30	47.08		1.94
Diesel Loco_HSP46+7+1_Express	HSP46	Tier 3	Lowell	24.30	55.77		2.29
Diesel Loco_MP54AC+4+1_Express	MP54AC	Tier 4	Lowell	24.30	85.19		3.51
Diesel Loco_MP54AC_5+1_Express	MP54AC	Tier 4	Lowell	24.30	92.41		3.80
Diesel Loco _MP54AC+6+1_Express	MP54AC	Tier 4	Lowell	24.30	98.77		4.06
Diesel Loco_MP54AC+7+1_Express	MP54AC	Tier 4	Lowell	24.30	116.32		4.79
Diesel Loco_HSP46+4+1_Local	HSP46	Tier 3	Lowell	24.30	53.41		2.20
Diesel Loco_HSP46+5+1_Local	HSP46	Tier 3	Lowell	24.30	57.62		2.37
Diesel Loco_HSP46+6+1_Local	HSP46	Tier 3	Lowell	24.30	62.61		2.58
Diesel Loco_HSP46+7+1_Local	HSP46	Tier 3	Lowell	24.30	72.20		2.97
Diesel Loco_MP54AC+4+1_Local	MP54AC	Tier 4	Lowell	24.30	109.89		4.52
Diesel Loco_MP54AC+5+1_Local	MP54AC	Tier 4	Lowell	24.30	119.30		4.91
Diesel Loco_MP54AC+6+1_Local	MP54AC	Tier 4	Lowell	24.30	127.80		5.26
Diesel Loco_MP54AC+7+1_Local	MP54AC	Tier 4	Lowell	24.30	148.04		6.09
Diesel Loco_HSP46+4+1_Zonal Express	HSP46	Tier 3	Lowell	24.30	46.49		1.91
Diesel Loco_HSP46+5+1_Zonal Express	HSP46	Tier 3	Lowell	24.30	50.27		2.07
Diesel Loco_HSP46+6+1_Zonal Express	HSP46	Tier 3	Lowell	24.30	54.70		2.25
Diesel Loco_HSP46+7+1_Zonal Express	HSP46	Tier 3	Lowell	24.30	63.67		2.62
Diesel Loco_MP54AC+4+1_Zonal Express	MP54AC	Tier 4	Lowell	24.30	96.07		3.95
Diesel Loco_MP54AC+5+1_Zonal Express	MP54AC	Tier 4	Lowell	24.30	104.35		4.29
Diesel Loco_MP54AC+6+1_Zonal Express	MP54AC	Tier 4	Lowell	24.30	112.20		4.62
Diesel Loco_MP54AC+7+1_Zonal Express	MP54AC	Tier 4	Lowell	24.30	131.35		5.40

Table F-18 Simulated Energy Usage by Trip (Cont.)

Train Consist	Type	Tier	Line	Trip Length (Miles)	Gallons of Diesel	kWh	Per Mile
Diesel Loco_HSP46+4+1_Express	HSP46	Tier 3	Providence	43.57	68.36		1.57
Diesel Loco _HSP46+5+1_Express	HSP46	Tier 3	Providence	43.57	73.92		1.70
Diesel Loco _HSP46+6+1_Express	HSP46	Tier 3	Providence	43.57	80.28		1.84
Diesel Loco_HSP46+7+1_Express	HSP46	Tier 3	Providence	43.57	86.43		1.98
Diesel Loco_MP54AC+4+1_Express	MP54AC	Tier 4	Providence	43.57	132.81		3.05
Diesel Loco_MP54AC_5+1_Express	MP54AC	Tier 4	Providence	43.57	144.82		3.32
Diesel Loco _MP54AC+6+1_Express	MP54AC	Tier 4	Providence	43.57	158.22		3.63
Diesel Loco_MP54AC+7+1_Express	MP54AC	Tier 4	Providence	43.57	168.55		3.87
Diesel Loco_HSP46+4+1_Local	HSP46	Tier 3	Providence	63.04	118.40		1.88
Diesel Loco_HSP46+5+1_Local	HSP46	Tier 3	Providence	63.04	128.53		2.04
Diesel Loco_HSP46+6+1_Local	HSP46	Tier 3	Providence	63.04	136.07		2.16
Diesel Loco_HSP46+7+1_Local	HSP46	Tier 3	Providence	63.04	144.66		2.29
Diesel Loco_MP54AC+4+1_Local	MP54AC	Tier 4	Providence	63.04	233.63		3.71
Diesel Loco_MP54AC+5+1_Local	MP54AC	Tier 4	Providence	63.04	255.75		4.06
Diesel Loco_MP54AC+6+1_Local	MP54AC	Tier 4	Providence	63.04	276.33		4.38
Diesel Loco_MP54AC+7+1_Local	MP54AC	Tier 4	Providence	63.04	294.41		4.67
Diesel Loco_HSP46+4+1_Zonal Express	HSP46	Tier 3	Providence	63.04	98.81		1.57
Diesel Loco_HSP46+5+1_Zonal Express	HSP46	Tier 3	Providence	63.04	107.60		1.71
Diesel Loco_HSP46+6+1_Zonal Express	HSP46	Tier 3	Providence	63.04	116.70		1.85
Diesel Loco_HSP46+7+1_Zonal Express	HSP46	Tier 3	Providence	63.04	125.91		2.00
Diesel Loco_MP54AC+4+1_Zonal Express	MP54AC	Tier 4	Providence	63.04	195.33		3.10
Diesel Loco_MP54AC+5+1_Zonal Express	MP54AC	Tier 4	Providence	63.04	212.83		3.38
Diesel Loco_MP54AC+6+1_Zonal Express	MP54AC	Tier 4	Providence	63.04	230.89		3.66
Diesel Loco_MP54AC+7+1_Zonal Express	MP54AC	Tier 4	Providence	63.04	246.57		3.91

Table F-18 Simulated Energy Usage by Trip (Cont.)

Train Consist	Type	Tier	Line	Trip Length (Miles)	Gallons of Diesel	kWh	Per Mile
DMU Urban Rail	DMU	Tier 4	Lowell	11.74	66.02		5.62
DMU Urban Rail	DMU	Tier 4	Providence	10.74	37.06		3.45
Electric Loco Express	ACS-64		Lowell	24.30		655.53	26.97
EMU Express	EMU		Lowell	24.30		757.14	31.15
EMU Local	EMU		Lowell	24.30		978.24	40.25
EMU Urban	EMU		Lowell	11.74		608.84	51.85
EMU Zonal Express	EMU		Lowell	24.30		858.49	35.32
Electric Loco Express	ACS-64		Providence	43.57		1,100.43	25.25
EMU Express	EMU		Providence	43.57		1,338.72	30.72
EMU Local	EMU		Providence	63.04		2,553.69	40.51
EMU Urban	EMU		Providence	10.74		448.91	41.79
EMU Zonal Express	EMU		Providence	63.04		1,996.15	31.66

Stopping pattern, horsepower, and consist weight play large roles in energy usage. Urban and Local stopping patterns require more energy than do Express and Zonal Express stopping patterns. Longer and heavier consists require more energy than do shorter consists. Though the MP54AC trips perform faster than HSP46 trips, the MP54AC's larger engine consumes more energy.

Idling

Each consist's energy usage was also computed while idling, as shown in Table F-19. Each of the diesel locomotives, regardless of consist size, was assumed to idle in their respective second notch (out of eight notches). Auxiliary (lights, heat, air conditioning) demands prevent locomotives from idling in their notch defined as "Idle"; this applies only if there is no trailing consist auxiliary load.

Table F-19 Power Required for Idling

Consist	Loco	Tier	Fuel Burn Rate (gal./hr.)	HP while Idling
HSP46_4+1	HSP46	Tier 3	27.00	566.00
HSP46_5+1	HSP46	Tier 3	27.00	566.00
HSP46_6+1	HSP46	Tier 3	27.00	566.00
HSP46_7+1	HSP46	Tier 3	27.00	566.00
MP54AC_4+1	MP54AC	Tier 4	67.21	600.00
MP54AC_5+1	MP54AC	Tier 4	67.21	600.00
MP54AC_6+1	MP54AC	Tier 4	67.21	600.00
MP54AC_7+1	MP54AC	Tier 4	67.21	600.00
DMU 9-car	Sumitomo MTU	Tier 4	30.06	782.62

Pollutant Data Sources

Vehicle and power generation emission rates were applied to determine each consist's overall emissions. To match CTPS reports, overall emission rates were calculated for Hydrocarbons (THC), Nitrous Oxides (NO_x), Carbon Monoxide (CO), Carbon Dioxide (CO_2), Particulate Matter (PM), and Sulfur Dioxide (SO_2) on a per car-mile basis.

As part of the engine certification process, the EPA records emissions for diesel locomotive engines in each notch. These test results provided emission rates for the MP54AC and HSP46 for THC, PM, NO_x, and CO, shown in Table F-20. CTPS reports PM as $PM_{2.5}$ and PM_{10} but here the values are combined by the EPA into one generalized PM value. Combustion processes produce primarily $PM_{2.5}$. By totaling time spent in notches during simulated trips and by using each locomotive's horsepower per notch, pollutant emissions per notch were calculated and summed to find a total amount of pollution for each pollutant. SO_2 and CO_2 emissions were calculated based on their concentrations within ultra-low sulfur diesel fuel, 0.030 g/L for SO_2 and 2,680 g/L for CO_2. Using fuel usage rates per notch, total fuel usage was calculated and used to determine total SO_2 and CO_2 emissions for each simulated trip.

The DMU engine does not use notches, but the EPA certification for this engine involves a similar test process of measuring pollutant rates at

Table F-20 Diesel Locomotive Pollutant Rates, in grams per brake horsepower-hour (g/bhp-hr)

Locomotive	Notch	THC	PM	NOx	CO
HSP461	Notch 8	0.05	0.02	4.79	0.14
	Notch 7	0.04	0.02	4.48	0.17
	Notch 6	0.05	0.02	3.51	0.23
	Notch 5	0.05	0.03	4.23	0.36
	Notch 4	0.06	0.06	3.91	0.50
	Notch 3	0.08	0.06	4.56	0.66
	Notch 2	0.10	0.04	8.33	0.18
	Notch 1	0.09	0.06	8.74	0.24
	Normal Idle	1.92	0.29	30.59	1.95
	Dynamic Brake	0.96	0.26	32.83	2.12
MP54AC	Notch 8	0.01	0.01	0.15	0.05
	Notch 7	0.00	0.01	0.19	0.04
	Notch 6	0.00	0.01	0.21	0.04
	Notch 5	0.00	0.01	0.25	0.04
	Notch 4	0.00	0.01	0.20	0.03
	Notch 3	0.01	0.01	2.55	0.13
	Notch 2	0.01	0.01	1.65	0.07
	Notch 1	0.02	0.01	9.40	0.11
	Normal Idle	0.04	0.01	13.63	0.09
	Dynamic Brake	0.08	0.01	18.32	0.49

1 2014 EPA GE EGETG0958PGR (HSP46) Per Notch Pollutant Rate test results
2 2019 EPA Cummins Inc. KCEXG60.0AAC (MP54AC) Per Notch Pollutant Rate test results 2014

different horsepower levels. These horsepower output levels were then used similarly to how notches were used in calculations for the diesel locomotives. Simulated power outputs were mapped up to the next greatest horsepower level tested by the EPA. SO_2 was not included in the test results and instead had to be calculated based upon the known ratio of SO_2 to CO_2 within ultra-low sulfur diesel. DMU pollutant rates are shown in Table F-21.

Emissions for electric trains were calculated from pollutant rates for electric power generation in Massachusetts and New England, shown in Table F-22. Rates for CO_2, NOx, and SO_2 were taken from annual reports of ISO New England, the regional electric utility generation and transmission organization. The electric generation pollutant rate of CH4, assumed to be equivalent to THC, was taken from the EPA's eGRID data for Massachusetts. CO emissions for electric power generation were assumed to be negligible. Particulate matter was calculated through data from various published studies. Only PM2.5 data was reported for electric power plants, though PM10 can be approximated with the same values.

Table F-21 DMU Pollutant Rates, in grams per brake horsepower-hour (g/bhp-hr)[1]

Mode	NOx	THC	CO	CO_2	PM
8	1.86	0.01	0.06	396.30	0.01
7	1.57	0.01	0.04	381.86	0.04
6	1.65	0.02	0.05	398.16	0.01
5	1.03	0.01	0.03	380.30	0.00
4	1.90	0.03	0.08	417.98	0.01
3	1.11	0.01	0.03	389.94	0.01
2	7.17	0.11	0.84	757.25	0.06
1	12.41	0.13	0.11	1,021.66	0.15

1 2014 EPA QSK-19R Tier 4 Certification Results

Table F-22 Electric Generation Emissions Rates, in pounds per megawatt-hour (lb/MWh)

CO_2[1]	THC[2]	NOx[1]	SO_2[1]	PM[3]	CO_2[1]
654.00	0.10	0.15	0.08	0.11	654.00

1 2017 ISO New England Electric Generator Air Emissions Report, Location Marginal Unit (LMU) Values
2 2016 EPA eGRID Total Output Emission Rate for Massachusetts
3 Calculated based upon MA power generation blend and powerplant PM emissions by type

Pollutant Emissions

Revenue Trips

Table F-23 displays the emission rates for each consist and stopping pattern combination in grams per passenger-car-mile. A car is defined here as any non-locomotive vehicle. The results show that Urban and Local stopping patterns always pollute more than the same consist with an Express or Zonal Express schedule. The Tier 4 MP54AC emits less than the Tier 3 HSP46 in all categories except for CO_2 and SO_2. The DMU, despite being simulated only on the energy-intensive Urban Rail stopping pattern, is in the middle of the range in each pollutant. Electric trains emit the least NO_x, CO, and CO_2, but the electric grid's use of coal and biomass burden them with high PM and SO_2 emissions. Finally, longer train consists may require a higher notch compared to shorter consists to get to and maintain the same speeds or to satisfy the train's auxiliary load while dwelling at a station or moving, and that higher notch setting in turn results in higher emissions that are more than proportional to the increase in cars.

Table F-23 Pollutant Emission Rates of Trips for Combinations of Consists and Stopping Patterns

Train Consist and Stopping Pattern	Type	Tier	THC	NOx	CO	CO_2	PM	SO_2
Diesel Loco Express_HSP46_4+1	HSP46	Tier 3	0.42	31.00	1.03	3,281.61	0.21	0.04
Diesel Loco Express_HSP46_5+1	HSP46	Tier 3	0.37	27.03	0.95	2,948.78	0.18	0.03
Diesel Loco Express_HSP46_6+1	HSP46	Tier 3	0.33	24.46	0.95	2,738.94	0.17	0.03
Diesel Loco Express_HSP46_7+1	HSP46	Tier 3	0.33	22.69	0.93	2,712.56	0.17	0.03
Diesel Loco Express_MP54AC_4+1	MP54AC	Tier 4	0.03	6.23	0.16	6,647.97	0.07	0.07
Diesel Loco Express_MP54AC_5+1	MP54AC	Tier 4	0.02	4.94	0.16	6,024.15	0.07	0.07
Diesel Loco Express_MP54AC_6+1	MP54AC	Tier 4	0.02	4.31	0.15	5,576.15	0.06	0.06
Diesel Loco Express_MP54AC_7+1	MP54AC	Tier 4	0.02	5.19	0.15	5,487.12	0.06	0.06
Diesel Loco Local_HSP46_4+1	HSP46	Tier 3	0.52	39.59	1.31	4,134.85	0.24	0.05
Diesel Loco Local_HSP46_5+1	HSP46	Tier 3	0.46	34.76	1.26	3,,727.94	0.21	0.04
Diesel Loco Local_HSP46_6+1	HSP46	Tier 3	0.41	31.27	1.22	3430.86	0.19	0.04
Diesel Loco Local_HSP46_7+1	HSP46	Tier 3	0.40	28.72	1.16	3,338.48	0.19	0.04
Diesel Loco Local_MP54AC_4+1	MP54AC	Tier 4	0.04	6.82	0.23	8,346.24	0.09	0.09
Diesel Loco Local_MP54AC_5+1	MP54AC	Tier 4	0.03	5.40	0.23	7,579.19	0.08	0.08
Diesel Loco Local_MP54AC_6+1	MP54AC	Tier 4	0.03	4.70	0.22	6,986.40	0.08	0.08

Table F-23 Pollutant Emission Rates of Trips for Combinations of Consists and Stopping Patterns (Cont.)

Train Consist and Stopping Pattern	Type	Tier	THC	NOx	CO	CO_2	PM	SO_2
Diesel Loco Local_MP54AC_7+1	MP54AC	Tier 4	0.03	5.44	0.22	6,823.01	0.08	0.08
Diesel Loco Zonal Express_HSP46_4+1	HSP46	Tier 3	0.45	33.82	1.08	3,530.68	0.23	0.04
Diesel Loco Zonal Express_HSP46_5+1	HSP46	Tier 3	0.40	29.72	1.04	3,191.57	0.20	0.04
Diesel Loco Zonal Express_HSP46_6+1	HSP46	Tier 3	0.36	26.98	1.04	2,972.11	0.18	0.03
Diesel Loco Zonal Express_HSP46_7+1	HSP46	Tier 3	0.35	24.95	1.00	2,927.43	0.18	0.03
Diesel Loco Zonal Express_MP54AC_4+1	MP54AC	Tier 4	0.03	6.65	0.18	7,153.36	0.08	0.08
Diesel Loco Zonal Express_MP54AC_5+1	MP54AC	Tier 4	0.03	5.19	0.17	6,483.80	0.07	0.07
Diesel Loco Zonal Express_MP54AC_6+1	MP54AC	Tier 4	0.02	4.50	0.17	5,999.26	0.07	0.07
Diesel Loco Zonal Express_MP54AC_7+1	MP54AC	Tier 4	0.02	5.31	0.17	5,906.56	0.07	0.07
DMU Urban Rail	DMU	Tier 4	0.12	18.06	0.53	5,116.65	0.10	0.06
Electric Loco Express	ACS-64		0.20	0.30	0.00	1,291.08	0.21	0.16
EMU Express	EMU		0.18	0.26	0.00	1,147.21	0.18	0.14
EMU Local	EMU		0.23	0.34	0.00	1,497.27	0.24	0.18
EMU Urban	EMU		0.27	0.40	0.00	1,736.26	0.28	0.21
EMU Zonal Express	EMU		0.19	0.28	0.00	1,241.95	0.20	0.15

Figure F-14 displays results with passenger capacity and trip mileage factored in. Many of the same trends are visible, though the single-level DMU's relatively low seating density and energy-intensive Urban Rail stopping schedule causes it to perform poorly on a per-passenger basis.

Idling

Pollution rates for each idling consist were calculated and are shown in Table F-24. The same general patterns discussed previously are shown in the idling results. For the electric trains, some energy is needed to power the auxiliary loads (heating, cooling, lighting) while the train is laying over.

Figure F-14 Locomotive and MU Pollution per Passenger- Mile, Normalized by Pollutant

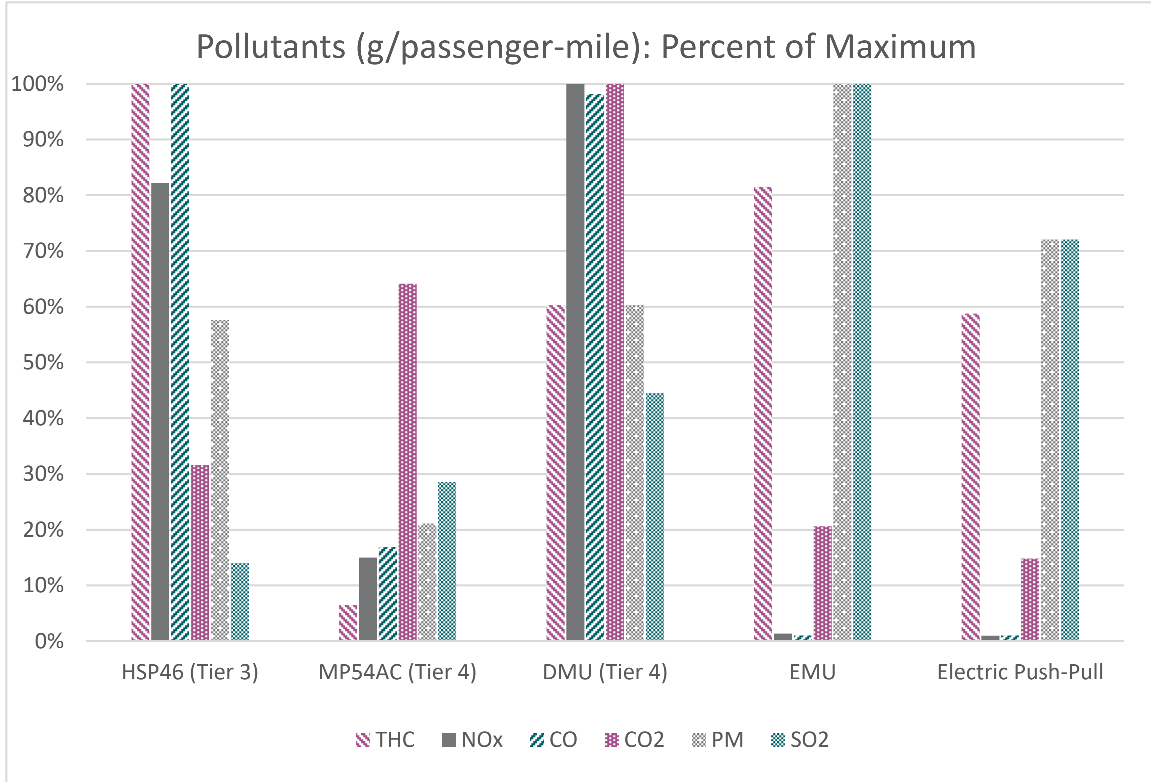


Table F-24 Emissions for Simulated Consists in Grams per Idling Hour

Train Consist and Stopping Pattern	Type	Tier	THC	NOx	CO	CO_2	PM	SO_2
HSP46_4+1	HSP46	Tier 3	56.60	4,714.78	101.88	273,922.80	22.64	3.07
HSP46_5+1	HSP46	Tier 3	56.60	4,714.78	101.88	273,922.80	22.64	3.07
HSP46_6+1	HSP46	Tier 3	56.60	4,714.78	101.88	273,922.80	22.64	3.07
HSP46_7+1	HSP46	Tier 3	56.60	4,714.78	101.88	273,922.80	22.64	3.07
MP54AC_4+1	MP54AC	Tier 4	6.00	990.00	42.00	681,792.00	6.00	7.63
MP54AC_5+1	MP54AC	Tier 4	6.00	990.00	42.00	681,792.00	6.00	7.63
MP54AC_6+1	MP54AC	Tier 4	6.00	990.00	42.00	681,792.00	6.00	7.63
MP54AC_7+1	MP54AC	Tier 4	6.00	990.00	42.00	681,792.00	6.00	7.63
ACS64_5+1	ACS64		12.16	52.55	0.00	75,404.42	14.24	17.02
EMU 8-Car	Stadler		16.16	69.85	0.00	100,226.02	18.93	22.63
DMU 9-car	Sumitomo MTU	Tier 4	5.96	871.99	25.04	305,175.68	5.78	3.42

Conclusions

On a per-seat, per trainset, and overall basis, consists of a diesel locomotive, bi-level cars, and bi-level cabs are estimated to have the lowest capital costs when compared to other vehicle technologies with comparable passenger capacity.

Clear patterns exist in energy efficiency. Trips with fewer stops require the least energy across all respective consists. Higher weight and larger engines require more fuel, though often have shorter travel times. Slight decreases in travel time do not make up for the additional weight and fuel needed. When viewed on a per-passenger-mile basis, consist seating density hurts the multiple-unit (MU) consists compared to locomotive consists with bi-level cars.

From an emissions perspective, there is no clear optimal consist. If all pollutants are weighed equally, consists with latest generation Tier 4-compliant diesels perform comparably overall to EMU and ACS-64 electric consists. If CO_2 is weighted more than the other pollutants, the electric consists show the lowest overall emissions. As Massachusetts power generation becomes cleaner, the comparative superiority of electrically-powered trains in overall emissions – especially CO_2 emissions – will become more pronounced.