

MEASUREMENT AND ANALYSIS OF ACELA EXPRESS REGENERATIVE POWER RECOVERY

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ABSTRACT

Amtrak launched the first high-speed Acela Express passenger train service in the USA in 2000 on the Northeast Corridor (NEC) between Washington, D.C, New York, and Boston ^[1]. The NEC infrastructure is used by several other railroad/transit agencies that operate commuter train services under operating access agreements with Amtrak. With such an arrangement, all NEC passenger railroad/transit agencies contribute to the electrical demands of the traction power system on the southern division and in particular, between New York, and Washington, D.C.

Amtrak and the other railroad/transit agencies conduct periodic reviews of the cost-sharing arrangements for the electricity bills. As part of a recent review, accurate data on the power usage by the Acela Express fleet was needed. The Acela Express power cars are equipped with modern traction drives with controls that are capable of recovering some or all of the regenerative braking power they produce. The use of regenerative braking is automatically controlled by the onboard Braking Control Computer via the internal propulsion and braking network. This feature makes the Acela Express trains efficient in energy consumption and affects the cost allocation to Amtrak. The extent of the energy recovery is

dependent on how receptive the traction power system is when power is being regenerated from braking.

In order to obtain realistic data, two separate Acela Express power cars were instrumented. A large amount of data was collected in normal service conditions from the onboard instrumentation. This paper describes the instrumentation and the data collection procedure, and presents the analysis results of the collected data. The analyses were focused on two parameters: the “energy recovery ratio” and the “system receptivity” of the traction power supply system. The study contributed to the successful conclusion of a new electrical cost-sharing arrangement among the NEC passenger railroad/transit agencies, which was made public in October 2006 ^[2].

1 INTRODUCTION

In 2004, Amtrak commissioned SYSTRA Consulting, Inc. to carry out a study of the power consumptions by its fleet of Acela Express vehicles in the North East Corridor from Washington, D.C., to New York. The North East Corridor runs from Washington D.C., to Boston, Massachusetts, as illustrated in the following figure.



FIGURE 1. NORTH EAST CORRIDOR AND ITS TRACTION POWER SUPPLY SYSTEM

With a through train running between Washington D.C. and Boston, such as the Acela Express service, the train experiences three different power supply voltages from multiple systems, as illustrated in the above figure:

- 11kV, 25Hz – Between Washington D.C. and New York
- 13kV, 60Hz – Between New York and New Haven
- 25kV, 60Hz – Between New Haven and Boston

The North East Corridor is a shared corridor, with several other agencies running commuter trains in addition to Amtrak’s inter-city services. With such an arrangement in place, all agencies contribute to the electric bills of the traction power system; furthermore, the billing points are at the wayside substations, not on the trains that operate within the system. Each agency needs to be satisfied with the cost-sharing arrangements.

Any significant changes in the train service operations would cause changes in the energy consumption and its share by each agency. Introducing new rolling stocks into operation is one such change that warrants a review of the arrangements.

Each Acela Express trainset has a fixed consist, with two power cars (one at each end), five passenger coaches and one café car in the middle. The two power cars of the trainset are equipped with modern traction drives that are capable of regenerative braking through a propulsion and braking control system. The traction drives operate at or near unity power factor. (Due to this fact, which was verified in the measurement data, annotation for power in this paper is limited to real power only.) These features make the trainset very energy efficient. As part of the study, Amtrak required accurate data on the energy usage by the Acela Express fleet within the 11kV, 25Hz system.

When a power car is in motoring mode, the power flow diagram is shown in the following figure.

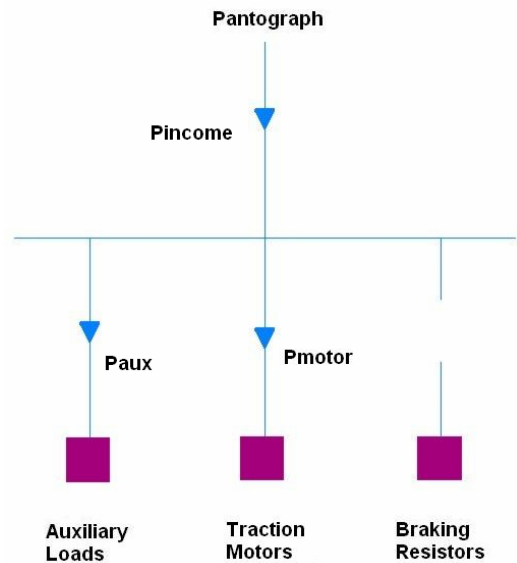


FIGURE 2. POWER FLOW DIAGRAM WHEN A TRAIN IS IN MOTORING MODE

When a power car is in regenerative braking mode, the power flow diagram is shown in the following figure.

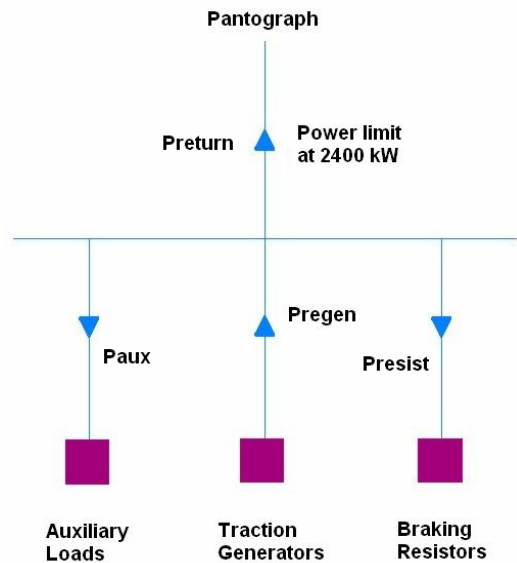


FIGURE 3. POWER FLOW DIAGRAM WHEN A TRAIN IS IN REGENERATIVE BRAKING MODE

When the available power for recovery is greater than 2400kW after auxiliary loads have been fed by the regenerated power, or, when the traction power system is

considered non-receptive by the power control electronics, the surplus power is dissipated as heat through a resistor grid system onboard the power car. The resistor grids are cooled by axial vane fans.

2 INSTRUMENTATION

After consultation with Amtrak operations and maintenance personnel, two train sets were identified for the instrumentation and data recording: Trainset #4 and Trainset #17.

- Data from Trainset #17 was recorded between December 5th, 2004 and January 8th, 2005.
- Data from Trainset #4 was recorded between January 8th, 2005 and February 5th, 2005.

The parameters that were measured are listed in the following table.

TABLE 1. ACELA EXPRESS INSTRUMENTATION ON TRAINSETS #4 AND #17 (DECEMBER 2004 TO FEBRUARY 2005)

CH #	Parameters	Sensor Type & Model	Manufacturer
1	Acceleration- mph/sec (LCF)	Jewell LCF-200-0.5G	Jewell Instruments ^[4]
2	HV Pantograph Voltage- Vrms (PT)	Acela PT-25kV/100V	Direct connection to onboard PT
3	HV Primary Current- Arms (CTL-CTA)	Flexcore CTL- 202/1000S (split core); Signal conditioner CTA213 (RMS), 0- 1000Hz Calib to 25Hz.	Flex-Core ^[3]
4	Supply Frequency (AFT)	Flexcore AFT 065D (0- 65Hz).	Flex-Core ^[3]
5	HV Reactive Power (GV5)	Flexcore GV5-001DY; 150V, 5A. Calib to 25Hz.	Flex-Core ^[3]
6	Speed- mph (MCR)	Phoenix MCR-f-UI-DC	Phoenix Contacts ^[5]
7	HV Real Power (GW5)	Flexcore GW5-001DY; 150V, 5A. Calib to 25Hz.	Flex-Core ^[3]

The output parameters from the above listed transducers were connected to a multi-channel data recorder (Astro-Med Dash 18^[6]). The digital data recorder was set to a sampling rate of 1 Hz (1 sample per second).

Three instruments are frequency-sensitive. These are current, real power and reactive power transducers. These instruments were calibrated by the manufacturer to 25 Hz.

The data was recorded all the time when the instrument was onboard the trainsets, including revenue operation between Sunnyside Yard, New York and Washington. In some cases, these trains operated to and from Boston. However, data collected for territory outside of the 11kV, 25 Hz supply was not used.

Only one power car of each Acela Express trainset was instrumented. Of the two power cars on the fixed trainset, both perform identically during normal operations. Under normal operations, the trailer power car is used to provide auxiliary power to the trailer power car and the passenger coaches, while the leading power car provides auxiliary power for the leading power car only.

During the course of the train operations, the instrumented car was put in position as a leading engine in some time periods and as a trailing engine at other time periods, depending on the direction of travel. Over the full course of the measurement time period, each Acela Express power car served as both a leading engine and a trailer engine for approximately equal amount of time. Therefore, both power cars in the fixed trainset consume approximately equal amounts of energy and recovered approximately equal amounts of energy in braking mode. Because the two power cars' pantographs contact the catenary at nearly the same point relative to the large distances between 25 Hz supply points, the receptivity experienced by the two power cars can be considered identical.

Note that due to the limitations imposed by the existing infrastructures in some track sections, the regenerative power that can be fed back to the catenary system from each Acela power car had been capped at 2400 kW. The recorded data reflected this limit.

The power cars and the instrumentation arrangements inside the power cars are shown in the following photographs.



FIGURE 4. ACELA POWER CAR 2001 (TRAINSET 4)



FIGURE 5. ACELA POWER CAR 2022 (TRAINSET 17)



FIGURE 8. INSTRUMENT BOARD FIXED IN THE OPEN SLOT



FIGURE 6. OPEN SLOT INSIDE THE CAR IDENTIFIED FOR HOUSING DATA RECORDER AND UPS UNIT



FIGURE 7. OPEN SLOT INSIDE THE CAR IDENTIFIED FOR HOUSING THE INSTRUMENT BOARD



FIGURE 9. ASTRO-MED DASH-18 DIGITAL CHART RECORDER IN FOREGROUND AND UPS IN THE BACKGROUND.

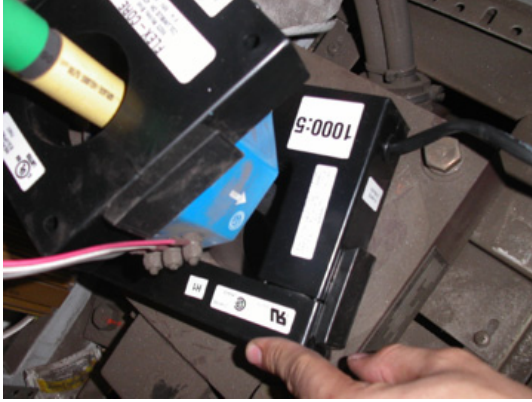


FIGURE 10. CURRENT SENSORS INSTALLED



FIGURE 11. WIRE RUNS BETWEEN THE INSTRUMENT BOARD AND THE RECORDER

3 DATA ANALYSIS

The recorded data was electronically stored and transferred into personal computers for processing.

3.1 Definition of Parameters

In the motoring mode, the “income energy” is calculated. This is the energy flowing from the catenary to the power car. In the regenerative braking mode, the “recovered energy” is calculated. This is the energy flowing from the power car to the catenary. The ratio of these two numbers produces the “energy recovery ratio” due to regenerative braking, as expressed by the following equation:

$$\alpha = \frac{\int Pr_{return} \bullet dt}{\int Pincome \bullet dt} \quad (1)$$

Where “ α ” is defined as the energy recovery ratio. “Preturn” and “Pincome” stands for power and are as shown in figures 2 and 3. “t” is for time.

“System receptivity” describes how receptive the traction power system is in absorbing the regenerated energy by the trains. It is defined as the ratio of two energy figures: “actually recorded recovered energy” over “potentially fully recovered energy”, as expressed by the following equation:

$$\beta = \frac{\int Pr_{eturn} \bullet dt}{\int Pr_{eturn_full} \bullet dt} \quad (2)$$

Where “ β ” is defined as the system receptivity. “Preturn_{full}” stands for power that could have been returned to the catenary if the traction power system were fully receptive. It is a function of four parameters: “Preturn”, recorded train voltage and two voltage settings on the power cars. These two voltage settings on the power cars govern how much regenerated power can be fed back to the catenary system.

Below 12.5kV, all regenerated power can be fed back to the catenary system (subject to the 2400 kW limit for each power car as mentioned above). Above 13.4kV, no regenerated power can be fed back to the catenary system. Between these two voltage levels, the regenerated power may be either fully recovered or partially recovered, depending on the power-voltage relationship at the given instant of time. This is illustrated by a sample plot of the recorded recovered power versus train voltage level in the following figure.

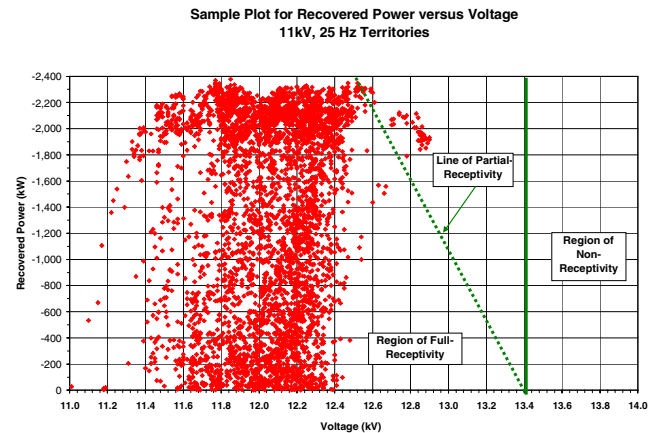


FIGURE 12. POWER VESUS VOLTAGE PLOT ILLUSTRATING SYSTEM RECEPTIVITY

As can be seen from the above, the parameter of “system receptivity” is sensitive to the system voltage levels and the voltage settings on the power cars. For a

given train journey, if its recorded voltage is below 12.5kV during all the time periods when it is in regenerative braking mode, the system receptivity for this train journey is at 100%. If there are instances when the train voltage is above 12.5kV in braking mode, some non-receptivity may have been encountered. Calculations determine what the “potentially fully recovered energy“ is, based on the power-voltage relationship from the recorded data, as illustrated in the above figure.

3.2 List of Results

Train speed and power demand for a typical train journey are shown in the following figure.

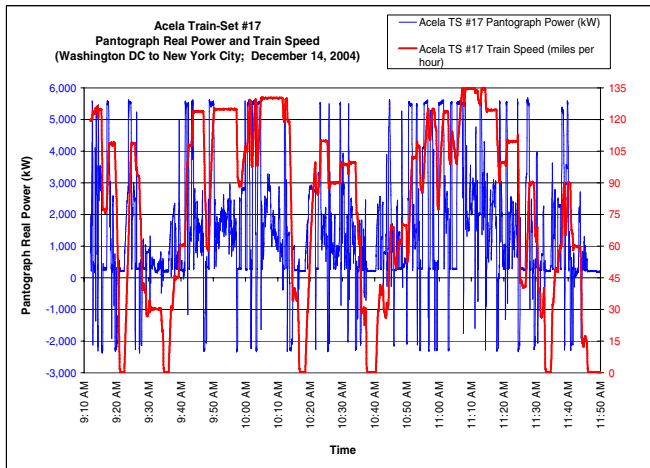


FIGURE 13. POWER AND SPEED PLOT FOR A SAMPLE TRAIN JOURNEY (WASHINGTON D.C. TO NEW YORK CITY)

A close-up view for a shorter time period is shown in the following figure.

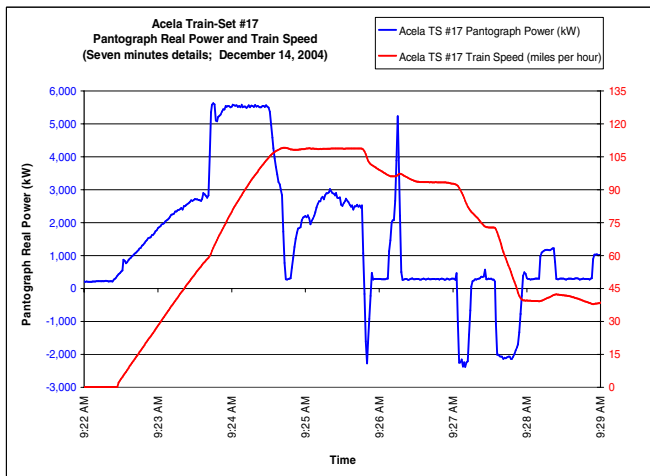


FIGURE 14. POWER AND SPEED PLOT FOR A SAMPLE TRAIN JOURNEY (SEVEN MINUTE DETAILS)

A full journal of the daily train movement was kept for the instrumented trainsets. For post-recording analysis, data was limited to “over the road” revenue operation in 25 Hz territory.

The results are shown in the following tables for the individual train journeys.

TABLE 2. SUMMARY OF TRAIN SET #17 RESULTS

Date	Start Time (hh:mm)	End Time (hh:mm)	Maximum Voltage (kV)	Energy Recovery Ratio (%)	System Receptivity (%)
12/13/2004	6:01	9:11	12.46	8.55%	100.00%
12/13/2004	18:35	22:00	12.75	7.26%	98.37%
12/14/2004	8:13/9:00	8:25/9:11	12.09	1.83%	100.00%
12/14/2004	9:11	12:13	12.64	8.45%	99.81%
12/14/2004	20:57	0:09	12.9	6.99%	98.65%
12/15/2004	9:58	15:43	12.5	5.16%	100.00%
12/15/2004	15:43/18:02	16:52/21:52	12.59	9.22%	99.71%
12/15/2004	4:39	7:43	12.46	6.68%	100.00%
12/16/2004	7:43/9:45	9:02/10:03	12.78	6.26%	99.16%
12/16/2004	18:31	20:49	12.59	6.37%	99.64%
12/16/2004	3:52/20:49	4:49/21:55	12.28	5.15%	100.00%
12/17/2004	6:01/11:01	8:52/12:49	12.52	10.16%	100.00%
12/17/2004	12:49/15:21/20:05	14:21/18:52/20:49	12.49	9.07%	100.00%
12/17/2004	3:27/20:49	3:54/22:58	12.53	7.54%	99.93%
12/20/2004	7:15/12:01	11:02/12:49	12.49	6.42%	100.00%
12/20/2004	12:50	15:12	12.54	9.01%	99.96%
12/21/2004	10:03	12:49	12.49	6.89%	100.00%
12/22/2004	14:38/19:01	17:46/20:50	12.55	7.08%	99.97%
12/22/2004	20:50	23:17	12.39	8.14%	100.00%
12/22/2004	6:03	7:41	12.16	7.19%	100.00%
12/23/2004	7:41/12:00	9:46/15:16	12.56	8.11%	99.97%
12/24/2004	8:33/13:01	11:44/15:41	12.61	8.43%	99.94%
12/25/2004	14:31/15:02	14:39/15:43	12.23	6.22%	100.00%
12/25/2004	15:43	17:53	12.42	6.21%	100.00%
12/26/2004	15:01	16:21	12.52	14.60%	100.00%
12/26/2004	16:21	18:14	12.47	10.00%	100.00%
12/27/2004	16:21	18:21	12.43	7.44%	100.00%
12/29/2004	9:03	12:14	12.64	7.84%	99.48%
12/30/2004	10:45	14:11	12.52	8.98%	100.00%
12/30/2004	17:01	20:18	12.49	8.29%	100.00%
12/31/2004	16:40/22:39	19:48/22:50	12.55	3.68%	99.92%
1/2/2005	15:02	16:24	12.55	13.25%	99.91%
1/2/2005	16:24	18:11	12.51	12.05%	99.96%
1/3/2005	14:31/19:02	18:02/20:23	12.49	9.03%	100.00%
1/4/2005	5:42	9:48	12.58	11.41%	99.96%
1/4/2005	12:01	15:12	12.55	6.46%	99.89%
1/5/2005	8:34	11:48	12.46	6.82%	100.00%
1/6/2005	10:35/16:01	13:48/17:11	12.6	7.23%	99.67%
1/6/2005	17:11	19:12	12.39	6.90%	100.00%
1/7/2005	14:36/15:02	14:44/15:19	12.07	9.78%	100.00%
1/7/2005	15:19/20:02	18:03/23:19	12.48	9.85%	100.00%
Overall Energy Recovery Ratio				7.86%	
Overall System Receptivity					99.85%

TABLE 3. SUMMARY OF TRAIN SET #4 RESULTS

Date	Start Time (hh:mm)	End Time (hh:mm)	Maximum Voltage (kV)	Energy Recovery Ratio (%)	System Receptivity (%)
1/11/2005	7:02	10:13	12.45	9.88%	100.00%
1/11/2005	19:49	21:43	12.51	5.51%	100.00%
1/11/2005	21:43	23:17	12.49	7.91%	100.00%
1/12/2005	5:00	6:08	12.55	5.33%	98.72%
1/13/2005	6:08	8:16	12.53	8.57%	99.97%
1/13/2005	16:32	19:54	12.36	6.59%	100.00%
1/14/2005	8:01	8:26	12.23	7.58%	100.00%
1/14/2005	8:26/14:04	10:59/16:26	12.56	9.62%	99.95%
1/14/2005	19:01	21:31	12.6	6.98%	99.72%
1/18/2005	14:00	17:17	12.4	5.57%	100.00%
1/19/2005	17:01	20:38	12.41	6.56%	100.00%
1/20/2005	11:38	15:07	12.42	11.77%	100.00%
1/20/2005	17:10	20:26	12.39	7.65%	100.00%
1/21/2005	9:29/12:59	9:34/15:20	12.56	8.33%	99.87%
1/21/2005	17:03	20:16	12.44	7.75%	100.00%
Overall Energy Recovery Ratio				7.65%	
Overall System Receptivity					99.92%

The data in tables above represents the logged data for all “over the road” revenue operation in 25 Hz territory. It reflects 79 hours of revenue train operation in by Trainset #4 and 178 hours by Trainset #17. The significant gaps in the time periods represent time periods when the trainsets were either in 60 Hz territory, or when in the yards, or when undergoing maintenance in workshops.

3.3 Summary

The overall results are summarized in the following table.

TABLE 4. SUMMARY OF AMTRAK REGENERATIVE BRAKING AND RECEPTIVITY MEASUREMENT

Parameters	Trainset #4	Trainset #17
25 Hz Territory Receptivity to Regenerative Braking Energy	99.92%	99.85%
Recorded Energy Recovery Ratio	7.65%	7.86%

The measurement data for Trainsets #4 and #17 shows remarkably similar results, both in terms of energy recovery ratio and system receptivity. It can therefore be concluded that there is little variation in regenerative braking performances amongst the Acela Express trainsets. An average of the very similar Trainset #4 and #17 results is representative of the Acela Express fleet.

All measurement took place without any engineer’s intervention. The Acela Express engineer’s control stand features a single handle for braking, without the

traditional separate locomotive brake handles for dynamic/regenerative braking and for air braking. On the Acela Express, “blended” braking of dynamic/regenerative and air braking is automatically implemented by a Brake Control Computer. As such, the Acela Express engineers cannot influence the degrees to which the Acela Express produces regenerative braking energy.

The energy recovery ratios listed above are measured at the pantograph and represent only the energy that was returned to the 25 Hz traction power system. The additional savings of supplying the auxiliary loads (lighting, heating, control, air conditioning and other onboard loads) while Acela Express trainsets are braking are not reflected in the above statistics, as this was not part of the study requirements. If auxiliary loads were taken into account in the calculations, the overall energy recovery ratio would be significantly higher. (Because other types of train equipment use braking power for auxiliary loads as well, no additional credit could be provided for Acela Express trains. Similarly, no credit was provided for Acela Express due to its unity power factor feature, since some other types of train equipment have this feature as well.)

At first sight, the receptivity figures from the calculations seem rather high (over 99%). Further analyses indicate that these are quite realistic figures. The reasons behind these high receptivity figures are listed below:

- The system voltage level in the 11kV, 25Hz territory is fairly low in comparison with the regenerative control voltage levels on the power cars, as illustrated in Figure 12 and the tables above. Many individual train journeys saw 100% of the regenerated power received by the traction power system (subject to 2400 kW limit).
- The maximum power that can be fed back to the catenary from each power car is capped at 2400 kW. This reduces the opportunity of pushing up the train voltage levels into the partially-receptive and non-receptive regions.
- The AC traction substations (with 138kV/11kV transformers) are able to back-feed power to the 138kV grid when there is excessive power in the 11kV traction power system.
- There is a high volume of train traffic in the North East Corridor that is supplied by the 11kV, 25Hz system. As a result, there is a good opportunity that some or all of the regenerated power from the Acela Express was absorbed by other trains that were nearby.

3.4 System Simulation Based on Measurement Data

Some follow-on work was carried out after the measurement and analysis of the Acela Express power data.

The “energy recovery ratio” and “system receptivity” figures derived from the measurement and described above were used as basic input data for the Acela Express trains in a computer simulation model for an “Energy Management-Usage/Capacity Study” project. This model utilized the RAILSIM[®] software to simulate all individual train journeys that were or will be operated within the 11kV, 25Hz territory by all railroad/transit agencies. From the model, power demand and energy consumption figures were derived for typical weekday and weekend operations; winter and non-winter operations; current and future operations. These individual figures were used in turn to make up the annualized figures. A detailed description of this modeling process is beyond the scope of this paper. The results from this model were analyzed and recommendations were made as to the share of the power demand and energy usage amongst all the concerned railroad/transit agencies.

Since the Acela Express parameters were obtained directly from measurement, a high level of confidence was placed on these parameters and the simulation model by the concerned railroad/transit agencies. With the aid of these tools, the agencies were able to conclude a new cost sharing regime in their negotiations.

4 CONCLUSIONS

The measurements revealed some significant energy savings by the Acela Express fleet. The resultant cost saving is substantial. When calculated over the Amtrak Mid-Atlantic system, an estimated \$1.6 million dollar average annual saving is due from the Acela Express fleet alone. With the capturing of this information and estimates from the other types of equipment in operation in this automatically controlled mode, an additional savings is being perused to be realized by Amtrak. The estimations show another \$1 million to \$1.2 million in additional annualized savings from the remainder of the fleet operation.

As noted in the above section, the regenerative power that can be fed back to the catenary system from each Acela Express power car had been capped at 2400 kW, due to the limitations imposed by the existing infrastructures in some track sections. These infrastructures are outside of Amtrak’s control. The energy saving data presented in this paper reflected this limit. The Acela Express power cars are capable of

producing much higher regenerative power than 2400 kW. With the limits imposed on the power cars, a significant amount of energy had been diverted to the braking resistor grids on board the train and wasted. If the limits are relaxed or removed in the future, more energy saving can be expected. This obviously depends on the future status of the concerned infrastructures.

This study has also revealed a great deal about automated braking management and furthered Amtrak’s internal interest in the implementation of an active power consumption and regeneration metering system. Through the implementation of this system, Amtrak will be able to measure the use of regenerative braking on Amtrak’s other equipment and change the approach of operation of the equipment to maximize energy savings in the future. The instrument for power metering on every electric locomotive throughout Amtrak’s fleet is now being designed by SYSTRA and Amtrak. The interest is not only for capturing and quantifying energy used and energy regenerated throughout each trip of all electric equipment, but also for providing a training tool for the operations of the vehicles to maximize energy savings. The metering system will be a standalone unit that may be commercially available to other operators of electric equipment in the near future.

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The viewpoints expressed in this paper are entirely the authors and are not those of Amtrak, SYSTRA Consulting, Inc. or the individuals mention above.

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