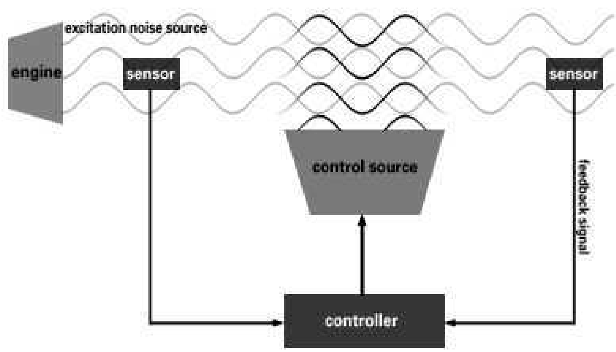
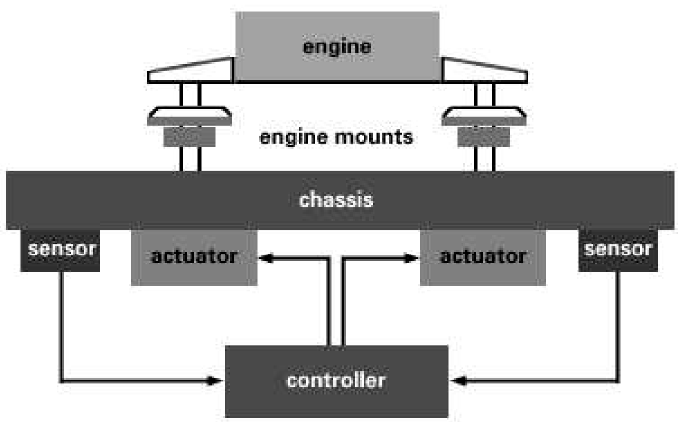
U.S. Department of
Transportation

**Federal Railroad
Administration**

Installation of Active Noise Control and Active Vibration Control on a GP40-2 Locomotive

Office of Research,
Development,
and Technology
Washington, DC 20590





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13. ABSTRACT (Maximum 200 words)
This project evaluated the performance of active noise control (ANC) and active vibration control (AVC) technologies using a GP40-2 locomotive located at the Transportation Technology Center (TTC) near Pueblo, CO, to determine the applicability of ANC and AVC technologies in the rail industry. Transportation Technology Center, Inc., provided support to Techno First SA engineers during the stereo recording of the engineer and conductor ear sound positions and tachometer signal during on-track operation of the locomotive pulling a freight train at TTC. It included curved track and ascending and descending a grade on the High Tonnage Loop at the Facility for Accelerated Service Testing.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

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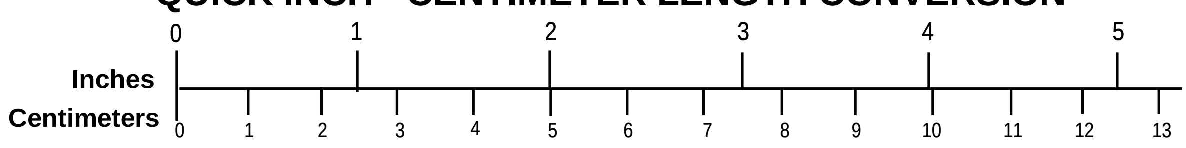
QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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Contents

Illustrations

Executive Summary

Transportation Technology Center, Inc. (TTCI) was tasked by the Federal Railroad Administration (FRA) to evaluate the performance of active noise control (ANC) and active vibration control (AVC) hardware in the cab of an older GP40-2 locomotive during static and on-track operations at the Transportation Technology Center (TTC). Two locations in the cab were used in the evaluation: the engineer's station and the conductor's station.

TTCI subcontracted with TechnoFirst SA (TechnoFirst) to perform the sound and vibration measurements. TechnoFirst was responsible for measuring the baseline noise and vibration in the GP40-2 locomotive at the two locations of interest. The baseline data included the noise and vibration signals observed with the locomotive stationary operating under self-load conditions and also operating under normal on-track conditions pulling a freight train. In self-load conditions, the locomotive can be operated in each throttle position while functioning at full power. The only difference is that the current is routed through the dynamic brake grids as opposed to through the traction motors. The freight train operation made it possible to measure the noise and vibration levels at the higher locomotive throttle positions, which produced higher sound and vibration levels than the self-load tests. The self-load data provided information related to the normal background noise and vibration produced by the locomotive engine. This data was necessary to ensure that the proper "Feed Forward" and "Feed Back" control algorithms could be developed by TechnoFirst.

During the baseline test, the proposed locations for installation of the ANC and AVC hardware were identified. TechnoFirst was also tasked with designing and fabricating the necessary speaker housings and actuator mounts as well as developing the ANC and AVC algorithms.

The final versions of the ANC and AVC hardware components were installed in the GP40-2 locomotive tested for proper operation using the locomotive's self-loading feature. Once the equipment settings were fine-tuned, the locomotive was added to the heavy axle load (HAL) train for on-track operation on the High Tonnage Loop (HTL) at TTC and tested for two weeks.

Week 1 entailed collecting data with the ANC and AVC hardware turned off. During week 2, the ANC and AVC hardware was turned on for the first half of each shift and turned off for the second half of each shift. This sequence allowed for a direct comparison of the noise levels in the two conditions: system on and system off.

During the on-track testing at TTC, vibration data was also collected to compare the effects of vibration cancellation at the engineer's and conductor's seats. Four 35-pound sandbags were placed on each seat to simulate the weight of the occupants. The vibration measurements were obtained by installing accelerometers on the bases of the two seats. This information was then used by the controller so an out-of-phase signal could be generated and applied to the actuators that had been mounted to the seats. The vibration data results showed little change when the AVC hardware in the on condition was compared with the hardware in the off condition. TechnoFirst engineers were unclear as to why no noticeable difference was observed.

The results from the ANC hardware showed promising results. The data indicated that the noise level on average was reduced by approximately 4 A-weighted decibels (dBA) and 7 to 9 C-weighted decibels (dBC).

1. Introduction

1.1 Background

TTCI was tasked by FRA to evaluate the performance of AVC and ANC technologies to assess their applicability in the rail industry. The evaluation was carried out in two phases.

In November 2009, Phase I of the project conducted a cursory evaluation of the ANC and AVC technologies. In Phase II, conducted in March 2011, a full-scale evaluation was completed. Figure 1 shows the GP40-2 locomotive (2001 locomotive) used in both phases of the project.

Figure 1. 2001 Locomotive

1.2 Project Objectives

The project evaluated the performance of ANC and AVC hardware using a locomotive at TTC. FRA will use the data obtained to evaluate the applicability of ANC and AVC technologies in the rail industry. TTCI subcontracted the tasks of data collection and analysis to TechnoFirst (replacing NVH Technologies, Inc., to complete the project).

1.3 Project Scope

This project evaluated the performance of ANC and AVC technologies using a GP40-2 locomotive located at TTC to determine applicability of ANC and AVC technologies in the rail industry. TTCI provided support to TechnoFirst engineers during the stereo recording of the engineer and conductor ear sound positions and tachometer signal during an on-track operation of the locomotive pulling a freight train at TTC. Operations included ascending and descending a grade on curved and straight track on the HTL at the Facility for Accelerated Service Testing (FAST).

1.4 Organization of Report

Section 2 provides a technical overview of the ANC and AVC systems.

Section 3 describes the setup and installation of the ANC and AVC hardware on the 2001 locomotive to evaluate ANC and AVC performance during stationary and on-track operation of the locomotive conducted during Phase I of the project.

Section 4 describes the activities carried out and results obtained during Phase II of the project.

Section 5 describes lessons learned during the conduct of this project along with a final summary of the results of the project.

2. ANC and AVC Technology Overview

The following subsections provide an overview of the ANC and ANV technologies evaluated in this project.

2.1 ANC Technical Overview

TechnoFirst active control is an adaptive active control approach. The benefit of adaptive active control is best understood by defining the concepts of *passive* and *active* control, and *fixed* and *adaptive* control.

Active control can be differentiated from *passive* control in that active control uses energy to destroy the energy present in a disturbance. *Passive* controllers merely dissipate energy by converting it into heat. *Adaptive* control can be differentiated from *fixed* control in that an adaptive controller continually "redesigns" itself to meet the instantaneous needs of a situation. *Fixed* controllers do the same thing, over and over, regardless of what noise is present. The non-stationary tonal nature of locomotive noise makes the use of fixed ANC methods, such as active headphones, less productive.

2.2 ANC Applications

The adaptive ANC technology that formed a basis of the heating, ventilation, and air-conditioning silencing product line was expanded for use in the locomotive cabin (Maguire, 2011).

2.3 ANC System Components

The simplest ANC system consists of a microphone and an audio speaker connected to a controller unit. The system detects the interior noise using the microphone, calculates the counteracting noise sequence required for reduction using a proprietary algorithm, and delivers that counteracting noise sequence using the speaker. This control action occurs thousands of times a second with the controller continually refining the reduction sequence.

Figure 2 depicts these components and a feed-forward sensor.

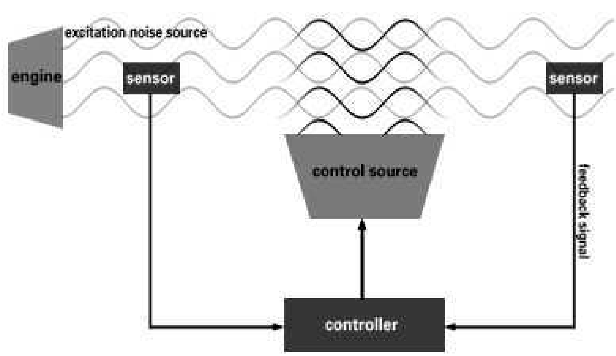

Figure 2. ANC System Components

2.4 ANC Exposure

The experience of being in the presence of an ANC system is one of both sound and feel for a low-frequency noise spectrum. Agricultural, construction, and rail transportation equipment produce low-frequency sound. This low-frequency excitation of air is experienced as pure sound and as a structural excitation of the body. The system, which is minimizing air-pressure variations, simultaneously produces the quieting effect often in conjunction with a reduction in low-frequency impact on the body.

Despite the reduction, there is sufficient noise content remaining so as not to disrupt the operation of a vehicle. The system is also unable to disrupt transient noises such as speech and similar radio traffic.

2.5 Sound and ANC Measurement Methodology – The Effect of Weighting

Sound levels and noise reductions are typically reported in terms of A-weighted sound pressure level (SPL) and C-weighted SPL. The A-weighted scale is accepted as a scale of average human perception and is distinctive for its de-emphasis of low frequencies. The C-weighted scale is also a scale of human perception but for higher loudness environments (Fletcher, 1933). A-weighted measurements are reported, but because the A-weighted scale has no correlation to either noise induced hearing loss or noise induced fatigue, C-weighted measurements are more indicative of any discomfort or damage experienced and reduction achieved.

"The Impact of A-weighting SPL during the Evaluation of Noise Exposure" (St. Pierre, 2004) is a more comprehensive analysis of the use of the A-weighting scale.

2.6 AVC Technical Overview

AVC shares the same technical approach as ANC. Force generating devices can destructively interfere with oscillatory motions, thus "freezing" a particular point in the inertial reference frame. An AVC, in its simplest form, consists of a controller, an actuator, and a sensor. Figure 3 shows these components arranged in a configuration for AVC of an engine. The identical concept can be applied to seat vibration.

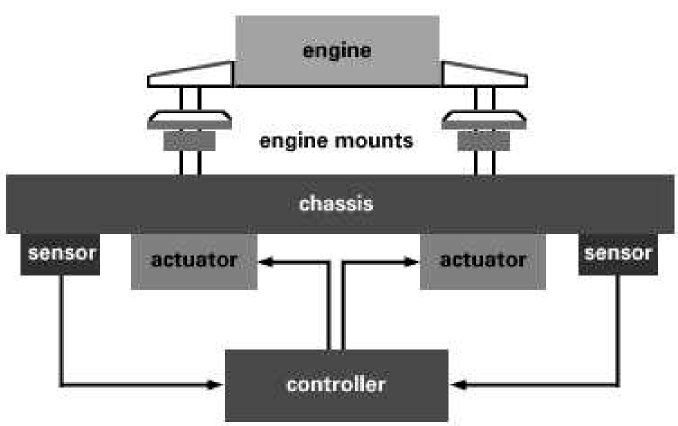

Figure 3. AVC System Components

3. Phase I Cursory Evaluation

On November 23 and November 24, 2009, a cursory evaluation of the ANC and AVC technologies was performed at TTC. During this phase of the project, the ANC and AVC systems were installed in the 2001 locomotive. The purpose of this installation was to plan the ANC speaker placement and to verify that the AVC vibration actuators being used were of sufficient capability to reduce seat vibration without distortion.

The original plan was to conduct the hardware installation and data collection task in two separate visits, but they were combined into a single visit as requested by the vendor.

3.1 Locomotive History

The 2001 locomotive has served the Milwaukee Road, Amtrak, and Helm Leasing with various unit numbers. It was built in 1966 by Electro Motive Diesel as No. 32302 for the Chicago, Milwaukee, St. Paul, and Pacific line. It was recently rebuilt by VMV Paducah built. Service is believed to have comprised:

1. Chicago Milwaukee St. Paul & Pacific No. 194
2. Chicago Milwaukee St. Paul & Pacific No. 2020 :2
3. Soo Line No. 2020
4. Amtrak No. 663
5. Helm Leasing No. 663
6. Helm Leasing No. 4202
7. 2001 Locomotive at TTC

3.2 Installation Specifics

The installation involved the following procedures:

- Transferring equipment to the locomotive
- Identifying suitable locations for the control hardware, speakers, and sensors
- Mounting or placing the control components
- Fastening the actuator mounting plates to the seat plates using fast-acting but strong two-part epoxy
- Mounting the actuators to the seat plate after sufficient drying time
- Running the locomotive to obtain measurements of sound and vibration levels
- Setting the internal gains and filters to match the portion of the noise and vibration to be controlled—taking into account the capability and placement of the speakers and actuators
- Shutting down the locomotive

- Calibrating the system
- Restarting the locomotive and completing the tuning process
- Measuring on-off performance
- Removing the equipment from the locomotive

3.3 Speaker/Actuator Mounting and Placement Details

The controller plate was placed ahead of the conductor’s seat. It rested on the floor and was secured with bungee cords.

Control wires were routed to the speakers, which were mounted on the front wall above the windscreens and in front of the respective conductor’s and engineer’s seats. The speakers were suspended using magnets and cloth straps.

Control wires were also routed to the actuators, which were mounted using brackets attached with epoxy to the seat plates of the conductor’s and engineer’s seats. They were difficult to attach, because of the shape of the seat plates.

3.4 Initial Cab General Condition and Sound/Vibration Levels

The cab was in good noise and vibration condition overall. Some noise present was due to loose electrical panels, primarily the panels on the back of the engineer’s control stand. Efforts were made to reduce the noise produced by these and other panels.

The sound levels in the cab at notch 8 under self-load static conditions were measured to be 85.2 dBA at the engineer’s position and 83.3 dBA at the conductor’s position.

3.5 Stationary Test Results

The on-off spectra for ANC and AVC systems are shown in Figure 4 and Figure 5. The results indicate there was some level of reduction in the noise level when the ANC was used. The results for the AVC system were less pronounced.

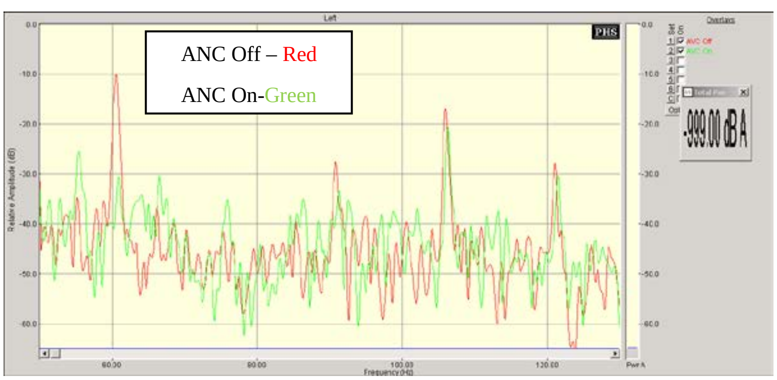

Figure 4. Noise Spectrum at Notch 8 – Uncontrolled and Controlled

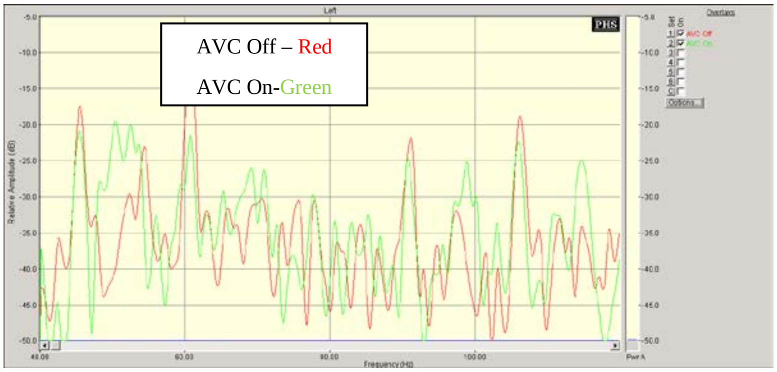

Figure 5. Vibration Spectrum at Notch 8 – Uncontrolled and Controlled

3.6 Additional Practical Information Obtained

Figures 6 through 12 show the inside of the locomotive after the ANC and AVC equipment was installed, and dimensions to aid in the design of the speakers and mounting fixtures required for a semi-permanent installation.

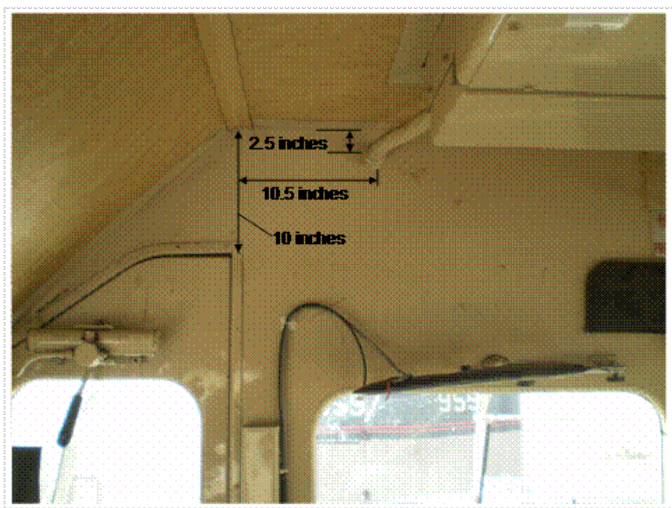

Figure 6. Left Overhead View

Figure 7. Overhead View

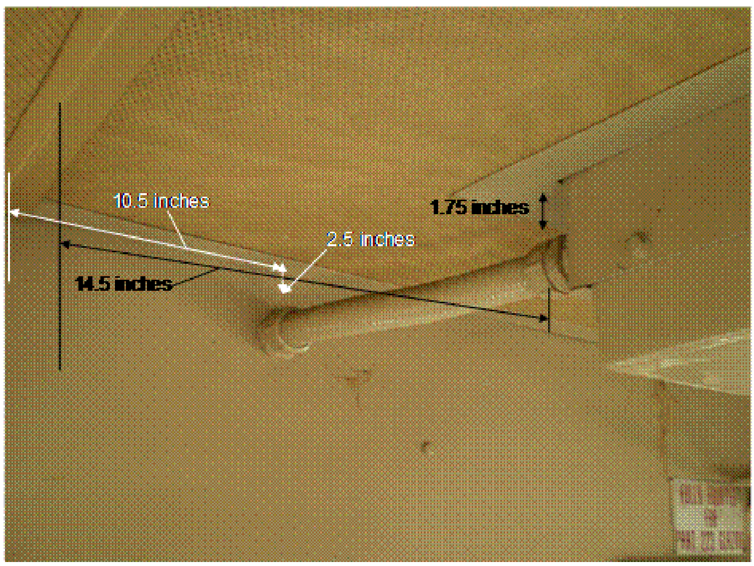

Figure 8. Overhead Piping View

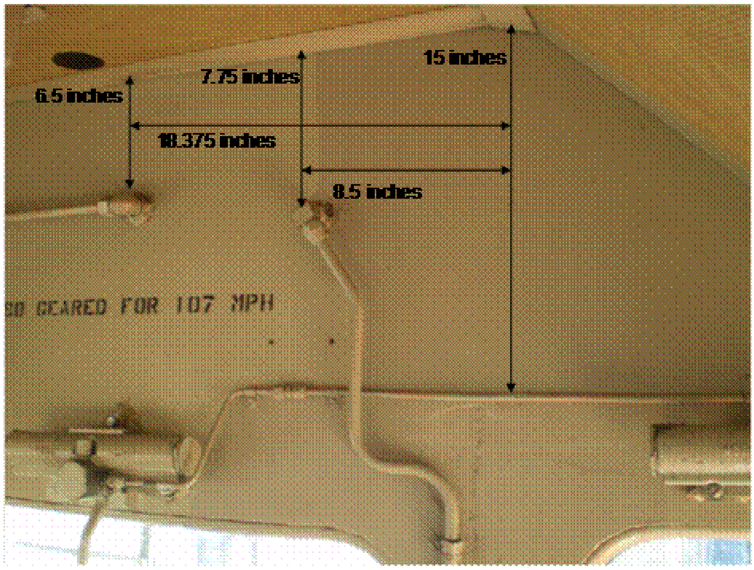

Figure 9. Overhead Piping View II

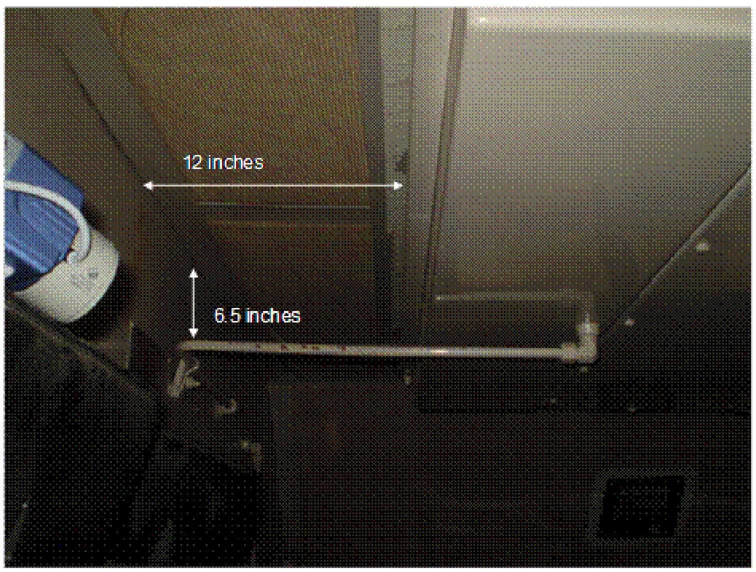

Figure 10. Overhead Piping Side View

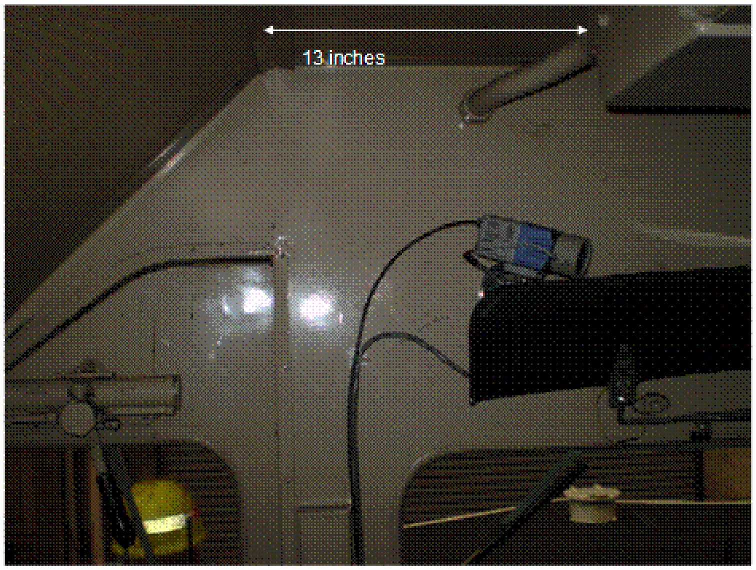

Figure 11. Left Overhead View II

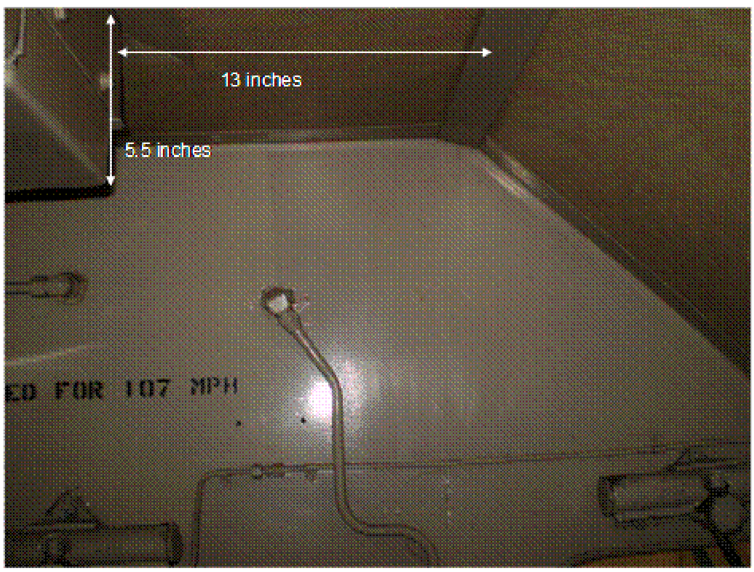

Figure 12. Right Overhead View

3.7 Conclusion

The Phase I evaluation provided useful information, which was then used to accelerate the test installation carried out in Phase II of the project.

4. Phase II System Evaluation

In March 2011, ANC and AVC hardware was installed in the 2001 locomotive, and evaluation data was collected while the 2001 locomotive was being operated as a part of the HAL train on the HTL at TTC.

4.1 Phase II Tasks

The following tasks were carried out during Phase II:

- TechnoFirst visited TTC to take preliminary data.
- TechnoFirst worked with TTCI to design speakers and speaker/actuator mounting.
- TTCI and TechnoFirst mounted the equipment and adjusted the system.
- Data was collected under static conditions with the locomotive operated in the self-load condition.
- The locomotive was operated as part of the HAL program test consist during nightly testing at FAST. Time-domain data was logged.
- Data was analyzed and presented.

4.2 Installation Chronology

The installation began with the mounting of control equipment inside the 2001 locomotive with the locomotive located in the Center Services Building at TTC. Figure 13 shows the locomotive in this location.

Figure 13. 2001 Locomotive in the Center Services Building

First, the control speakers were mounted. Figure 14 shows the locomotive control speakers. Then, the vibration actuators were mounted on the seat plate (Figure 15).

Figure 14. Left Control Speaker (right in background)

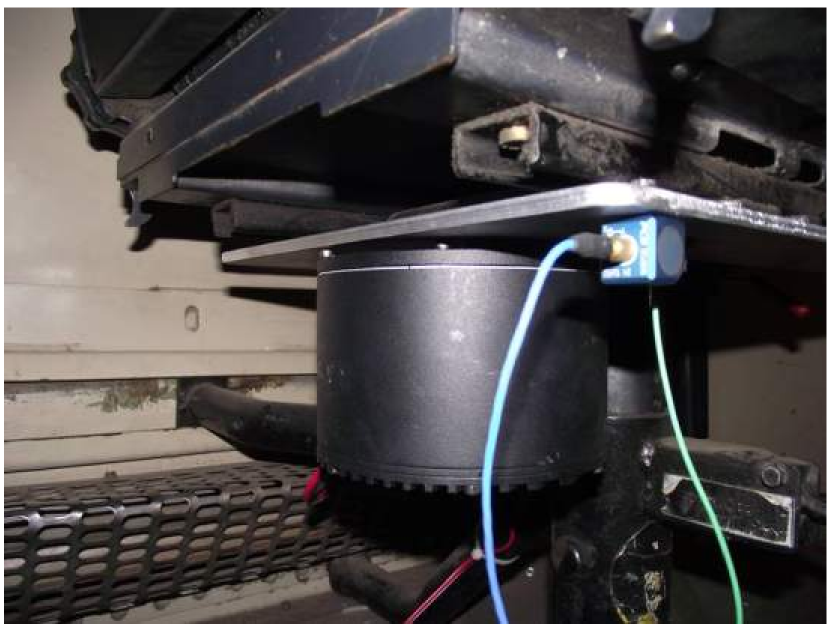

Figure 15. Left Control Vibration Actuator (with logging accelerometer)

Next, the controller hardware was mounted. Figure 16 shows the mounting in progress, and Figure 17 shows the final layout.

Figure 16. Wiring the Control Panel (ANC controller on left and AVC controller on right)

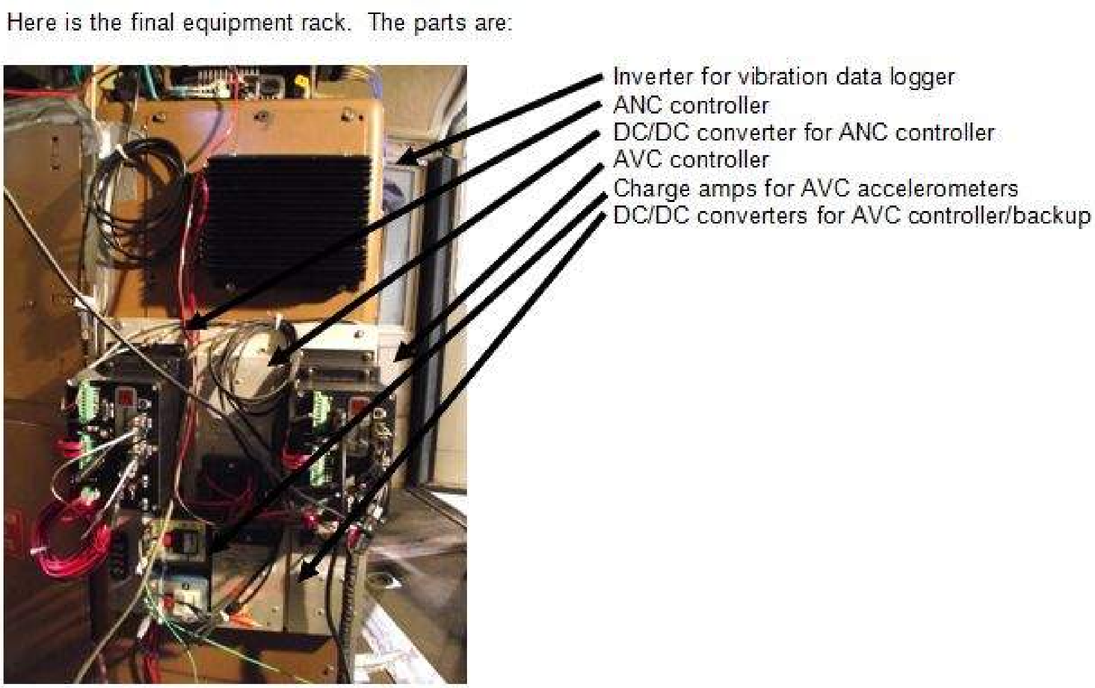

Figure 17. Final Control Panel Layout

The measurement equipment was then installed. Figure 18 shows the left side (conductor's seat) SPL data logger. (A representative mounting of the AVC performance sensor was shown in Figure 17).

Figure 18. SPL Data Logger (conductor's side)

The locomotive was then moved outside where it could be run under self-loading conditions, as Figure 19 shows. The 2001 locomotive is on the left.

Figure 19. The 2001 Locomotive during Self-Load Testing at TTC

After the system was adjusted, the locomotive was added to the HAL train for on-track operation on the HTL. Some additional adjustments and analysis were done while on the HTL. Figure 20 shows the unit at this location.

Figure 20. The 2001 Locomotive in the HAL Train on the HTL

4.2.1 ANC Stationary Test

Time domain and SPL measurements were made in the 2001 locomotive cab.

The time-domain recordings were made using a National Institute of Standards and Technology (NIST)-calibrated Head Acoustics SQuadriga dual-microphone headset recorder. The unit was placed on the head of a person sitting in the locomotive seat. As such, these recordings are representative of what would be experienced by a person occupying the locomotive seat.

The SPL measurements were made at a location on the locomotive sidewall near, but not directly at, the head area using Extech Model 477460 SPL Data Loggers. As such, the sound level measured by the SPL data loggers could differ from that obtained at the precise ear locations.

Figure 21 and Figure 22 show the time-domain recorded sequence – ANC off and on – for the engineer's and conductor's seats, left and right ears. The recordings were made on a calibrated Head Acoustics SQuadriga headset recording unit with the locomotive operating at notch 8 in the static, self-load condition.

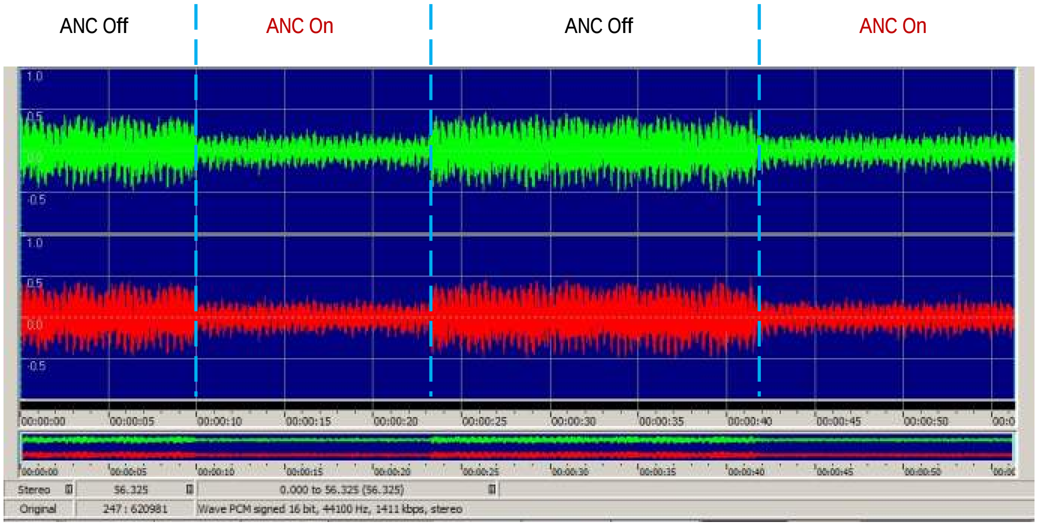

Figure 21. Engineer's Head Area ANC Off/On Sequence – Left Ear (green) and Right Ear (red)

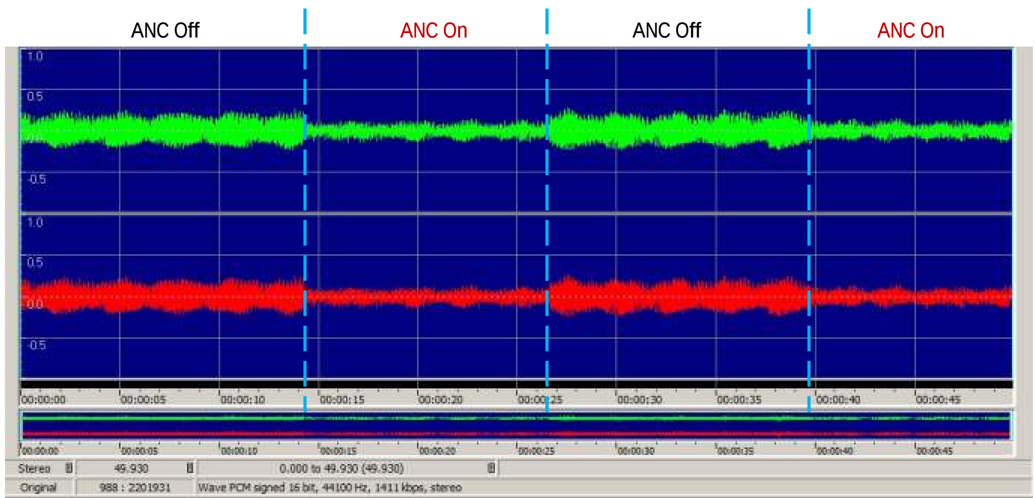

Figure 22. Conductor's Head Area ANC Off/On Sequence – Left Ear (green) and Right Ear (red)

Figure 23 shows an example of a NIST-calibrated Extech Model 477460 SPL data logger as mounted on the conductor's side.

Figure 23. Remote SPL Logging Device (Conductor side)

Figure 24 and Figure 25 show the time-domain recorded logged sequence – ANC Off/On – for the engineer and conductor remote SPL logger – dBA. The dBC data is presented Figure 26 and Figure 27. The reduction obtained with the ANC under static conditions was measureable. It should also be noted that the logged A-weighted SPL were obtained in the presence of significant noise coming from the locomotives self-load cooling fans. When locomotives are operated in self-load conditions, employees are required to wear hearing protection when exposed to a sound level that is equal to or exceeds an 8-hour time-weighted average of 85 dBA (U.S. Department of Labor, 1991).

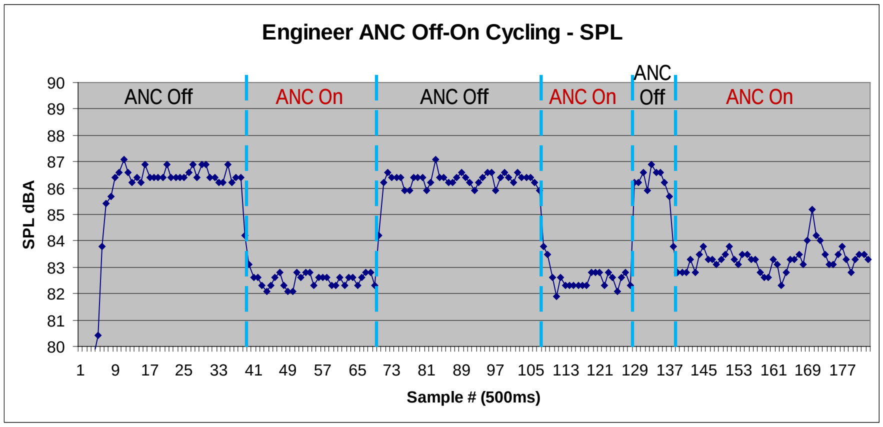

Figure 24. Engineer's Head Area ANC Off/On Sequence – SPL dBA

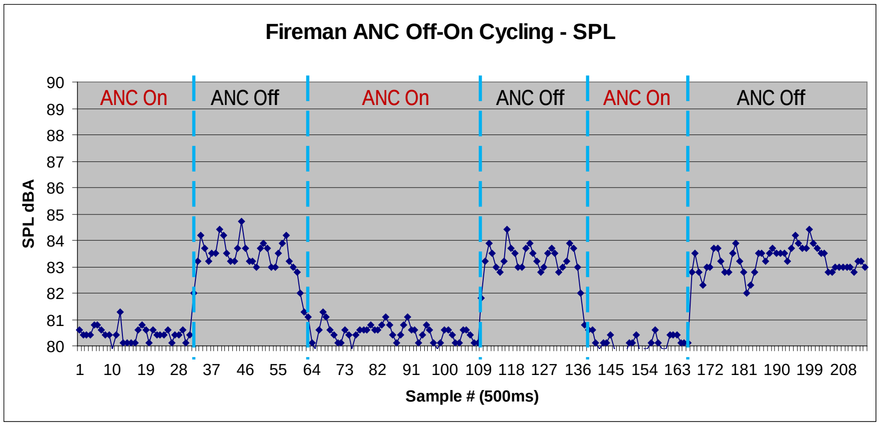

Figure 25. Conductor's Head Area ANC Off/On Sequence – SPL dBA

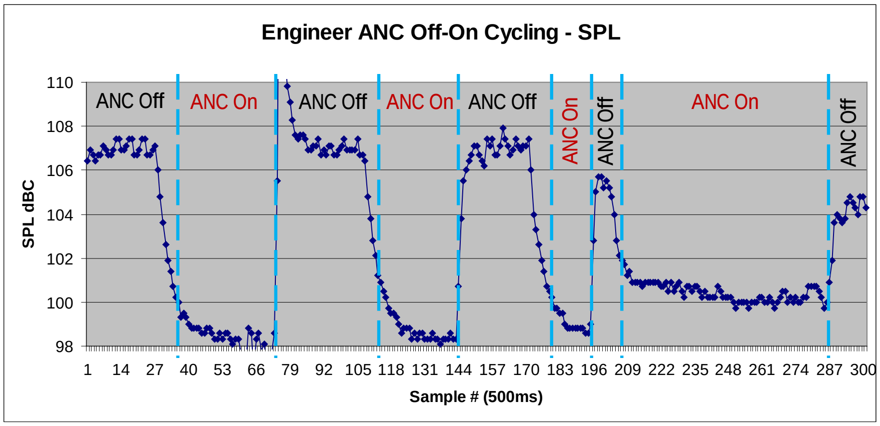

Figure 26. Engineer's Head Area ANC Off/On Sequence – SPL dBC

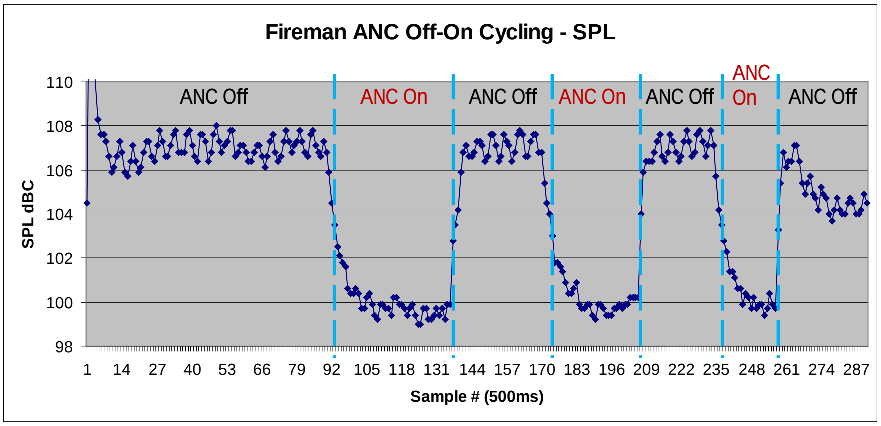

Figure 27. Conductor's Head Area ANC Off/On Sequence – SPL dBC

4.2.2 AVC Stationary Test

AVC performance was evaluated using the NIST-calibrated B&K Pulse LAN-XI Vibration Logger attached to two three-axis accelerometers.

Recordings were also made directly from the error sensor monitor port on the TechnoFirst Active Controller. The signal path for these measurements are not NIST-calibrated or certified. Any data shown is noted accordingly.

Figure 28 shows this time-domain recorded sequence – AVC Off/On – for the engineer's and conductor's seat z-axis acceleration as recorded at the time of initial tuning through the controller monitor port. This represents an approximate 8 decibels (dB) of un-weighted reduction in the pass band of the controller.

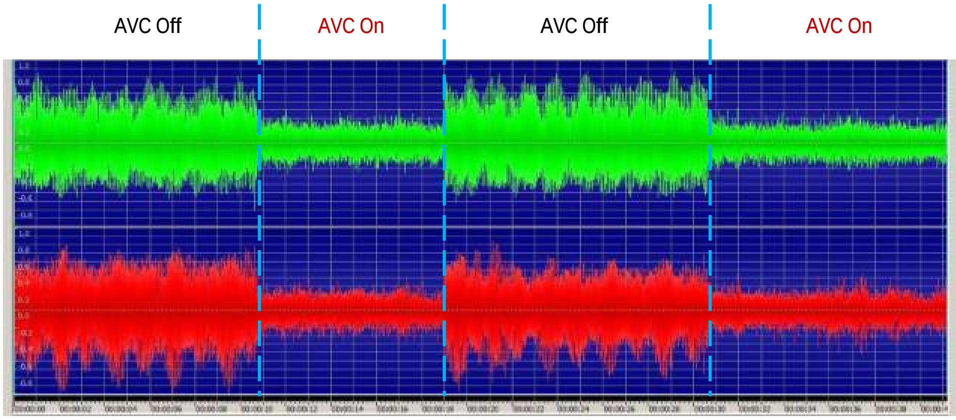

Figure 28. AVC Off/On Time-Domain Sequence from Controller – Non-NIST

On the first day of the on-track trials, the performance of the AVC system was recorded using the BK Pulse LAN-XI system. A reduction in the vibration measured at the z-axis of the engineer's seat was still measureable (Figure 29), but the reduction in vibration measured at the conductor's seat was greatly reduced (Figure 30). This was not noticed at the time of deployment, and the vibration data logged on-track was similarly degraded. The broadband and unweighted reduction logged at the engineer's seat for the AVC system was 3–4 dB.

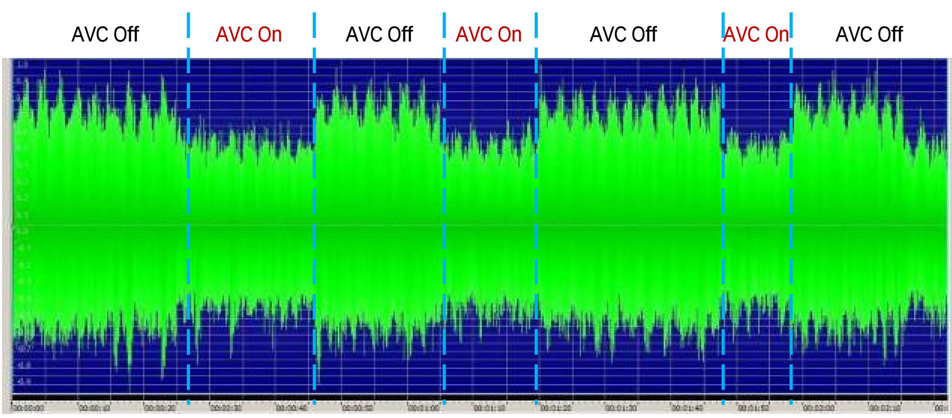

Figure 29. AVC Off/On Time-Domain Sequence on Day of Release – Engineer's Seat

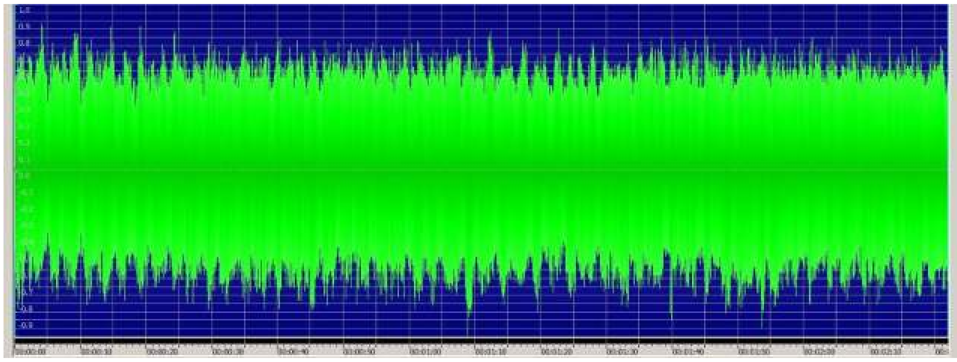

Figure 30. AVC Off/On Time-Domain Sequence on Day of Release – Conductor's Seat

4.2.3 ANC On-Track Test

SPL measurements were made near the head area in the 2001 locomotive cab during an on-track trial. The SPL measurements were made using the Extech Model 477460 SPL data loggers described previously.

The performance of the ANC was assessed by starting the on-track trial with the controller off. During the trial, the controller was engaged.

Figure 31 and Figure 32 show the time-domain recorded sequence – ANC Off/On – for the engineer and conductor remote SPL logger for the on-rail trial. A 10-point median filter was applied.

The low points in the Off case are the ebbs of the beating phenomenon present in the cab. The ANC reduced the overall average SPL but also stabilized the cab internally by counteracting the beating.

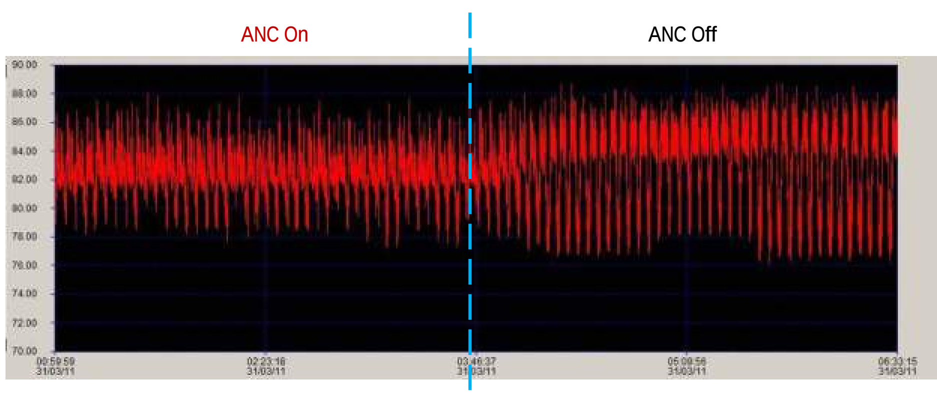

Figure 31. ANC On-Off Time-Domain Sequence On-Rail – Engineer

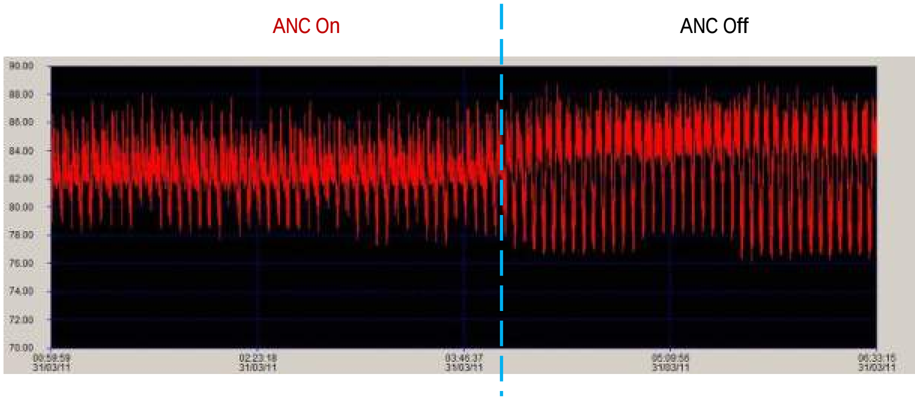

Figure 32. ANC On-Off Time-Domain Sequence On-Rail – Conductor

4.2.4 AVC On-Track Test

AVC performance was evaluated using the B&K Pulse LAN-XI Vibration Logger attached to two 3-axis accelerometers.

As previously noted, the AVC did not demonstrate peak performance during the static test condition on the day that the unit was deployed for on-track testing. The on-track data obtained shows no broadband reduction in the seat vibration in the z-axis.

5. Conclusions

The installation performed at TTC is one of the first U.S. on-track applications of the ANC and AVC technologies. Although the installation ultimately functioned as planned, there were some lessons learned.

5.1 Lessons Learned

There were three primary "lessons learned" during this installation. The first concerned the battery power of the SPL data loggers, the second pertained to the reset algorithm in the controller, and the third was related to AVC performance monitoring.

1. Battery Power for SPL data loggers — The SPL data loggers were new instrumentation that were purchased specifically for this installation. They performed satisfactorily and became recommended instruments. Although the unit's documentation indicated that the data loggers would run for a very long time on fresh batteries, no estimated duration was provided by the manufacturer. One night of data was lost because of a drained battery in the SPL data loggers. It turned out that the battery used in the system is not commonly used.
2. Controller Overload Algorithm — The controllers were programmed to respond to mathematical overloads by becoming less aggressive. For example, if a locomotive's loudness increases beyond a certain point, the controller would note that the internal calculations were overflowing and adjust its internal gain settings lower.

   During this installation, it was discovered that the use of the locomotive as a switch engine for car coupling operations caused the overload algorithm to lower the internal gain settings. Also, after a series of coupling operations, the controller had adjusted its internal gain settings to a level so low as to no longer reduce the cabin noise during non-switching operations. Therefore, the algorithm had to be modified during the test so that this unintended reduction in gain settings did not occur.
3. AVC Performance Monitoring — The B&K Pulse LAN-XI was an excellent means of recording vibration data, but the lack of an immediate view of performance made it difficult to determine whether the AVC system was operating properly. Future installations should include a method to view the performance of AVC during the test.

5.2 Final Summary

The use of the ANC during the static tests produced measurable results. ANC on-track operation also produced measurable reductions in the noise level, but the vibration data results showed little or no reduction. The data indicated that the noise level on average was reduced by approximately 4 dBA and by 7 to 9 dBC.

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Abbreviations and Acronyms

ANC	active noise control
AVC	active vibration control
dB	decibels
dBA	A-weighted decibels
dBC	C-weighted decibels
FAST	Facility for Accelerated Service Testing
HAL	heavy axle load
HTL	High Tonnage Loop
NIST	National Institute of Standards and Technology
SPL	sound pressure level
TTC	Transportation Technology Center (the site)
TTCI	Transportation Technology Center, Inc. (the company)