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SMART SENSOR FOR AUTONOMOUS NOISE MONITORING (SSAM)

Final Report for Highway IDEA Project 131

Prepared by:
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SMART SENSOR FOR AUTONOMOUS NOISE MONITORING (SSAM)

IDEA PROGRAM FINAL REPORT

FOR THE PERIOD DECEMBER 2007 THROUGH JULY 2009

NCHRP-131

Prepared for the IDEA Program

Transportation Research Board

National Research Council

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1. EXECUTIVE SUMMARY

This project involves the development of a cost-effective sensor for long-range wireless, autonomous traffic noise monitoring. The noise monitoring device provides a highly efficient means of monitoring and reporting noise such as highway noise, airport noise, construction noise, and many other scenarios where noise monitoring is needed. The device reports noise measurements periodically (e.g., hourly or daily as desired) to a receiver that may be located more than a mile away. At a fraction of the cost of a typical data logging sound level meter, SSAM provides a cost-effective method to monitor noise at many locations simultaneously.

The compact size, ease of use, and low cost of the SSAM sensor offer unique benefits for traffic noise monitoring. For example, tens or even hundreds of SSAMs can be distributed along many miles of roadway for continuous, long-term monitoring. The concept for the device and a photo is shown in Figure 1. The resulting technology provides reduced overall noise testing costs and greatly increased data gathering and analysis capabilities for agencies. The increased data gathering capability can provide improved understanding of highway noise sources, airport noise sources, and their variation as a function of location, time-of-day, day-of-week, weather conditions, and other parameters that effect traffic noise levels.

In this report, we describe the results of the project as was conducted in two Stages. Work in Stage 1 focused on the design and development of the Smart Sensor for Autonomous Noise Monitoring (SSAM). Embedded processing software was developed to provide the capability to measure sound in averaging modes, apply frequency weightings, and compute octave band analyses with the goal of achieving ANSI standards for Type 1 ratings. Sensor enclosures were fabricated and testing of the noise analysis software was completed. The electronics for the wireless connection was designed, circuit boards were fabricated and transmission ranges of up to 1.2 miles were demonstrated through controlled testing. Work in Stage 2 involved testing, refinement, and demonstration of the technology for Ohio and California departments of transportation. Tests included noise barrier insertion loss and wayside traffic noise measurements.

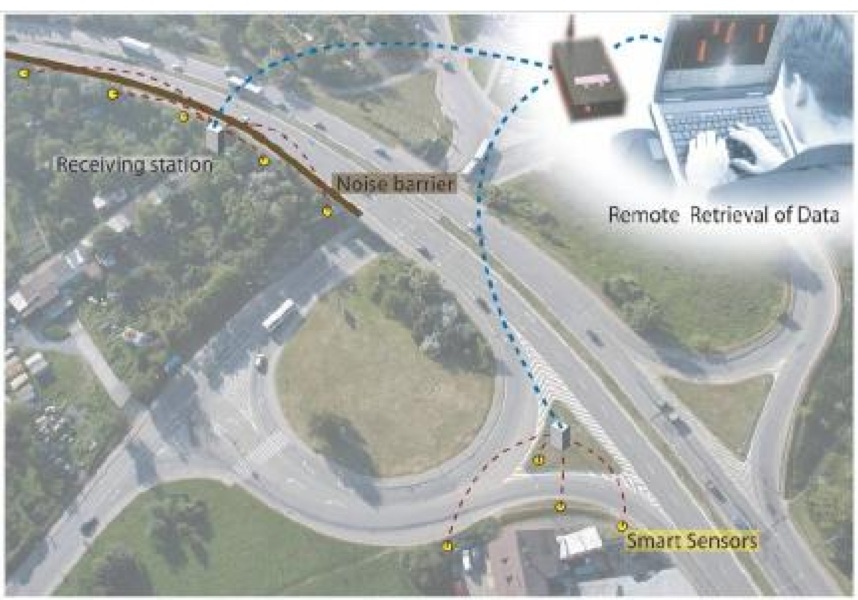

FIGURE 1: LEFT—Illustration of the SSAM Concept . The compact device autonomously monitors noise at many locations and wirelessly reports the standardized noise metrics. RIGHT—Photograph of the prototype SSAM device.

2. IDEA PRODUCT

A new approach to noise measurement and monitoring was developed here. As illustrated in Figure 1, the approach provides simultaneous noise measurements at tens, hundreds, or thousands of points along extended lengths of highways and/or communities in a cost-effective manner—in other words, more data at a fraction of the cost. The basic idea is to install many small, inexpensive wireless acoustic smart sensors at positions of interest. Each of these sensors, referred to as Smart Sensor for Autonomous noise Monitoring (SSAM), incorporate a microphone and related microelectronics that analyze acoustic data in real-time to provide the desired noise related metrics. During their operation, each sensor periodically (e.g., once per minute) reports the noise metrics to a central receiving station via a long-range wireless connection. The central receiving station generates data files containing noise time histories and a provides a near real-time graphical display overlaid on a map to indicate the level of noise at the various sensor locations. The data can be visualized as it is collected or at a later time via a playback function to provide a wealth of information such as identification of noise hot-spots or enforcement needs.

The objective of the work reported here was to design, fabricate and test a set of prototype SSAM devices and demonstrate their use and advantages as compared to existing methods of traffic noise monitoring. While the technology has numerous potential applications, particular attention has been paid to specific traffic noise tests of interest to Ohio Department of Transportation and California Department of Transportation, including traffic noise barrier insertion loss and wayside measurements.

3. CONCEPT AND INNOVATION

Transportation noise has become a major source of environmental pollution. Homeowners and businesses located near major highway corridors and airports have become intolerant of traffic-related noise, prompting transportation agencies to install noise barriers, develop quite pavement technologies, and closely scrutinize plans for infrastructure construction. To establish existing noise levels and evaluate the true impact of roadway or airport modifications, it is necessary to measure and monitor the associated noise carefully and understand the sources and propagation of noise.

SSAM facilitates the cost-effective measurement and monitoring of noise in several scenarios and at multiple locations over extended periods of time. This capability allows transportation and other agencies to gain a deeper understanding of noise sources and propagation that can facilitate effective decision making with regard to noise mitigation or enforcement. SSAM's approach to noise measurement can also provide a cost-effective method to collect the data needed to refine noise models such as the Federal Highway Administration's (FHWA) Traffic Noise Model (TNM) or the Federal Aviation Administration's (FAA) Integrated Noise Model (INM).

The concept for SSAM spawned from a related acoustic sensor technology that Applied Research Associates, Inc. (ARA) recently developed for a Department of Defense (DoD) application under a multi-million dollar effort (Government and ARA internal research and development funds). The DoD acoustic sensor is water resistant, and includes an integrated wind screen, calibrated microphone, microprocessor, and wireless communication in a small, inexpensive handheld package. The acoustic sensor was designed around commercial off-the-shelf (COTS) hardware in an effort to minimize costs when manufactured in large quantities. Several novel technologies were incorporated in the sensor. For example, the microphone element is a commercial off-the-shelf hearing aid element that has frequency-response characteristics similar to research grade microphones, at a fraction of their cost. An on-board microprocessor performs customized real-time analysis of the incoming acoustic data stream. The device was designed to be inexpensive in large quantities, provide customized acoustic data according to the application, operate for an extended period of time with little maintenance, and communicate information wirelessly using a simple and intuitive software interface.

Using this prior technology as inspiration for the development of SSAM has allowed the team at ARA to efficiently develop a technology to fit the needs of transportation agencies, specifically with regards to traffic noise monitoring. Like the prior ARA technology, SSAM is based on low-cost components, on-board microprocessing, and wireless data transfer. Unlike the prior ARA technology, SSAM was developed to accommodate precision calibration and use for ANSI standard noise measurements, such as traffic noise barrier insertion loss.

A related technology known as Sensor Network with Delay Tolerance (SeNDT) was recently developed*. The SeNDT technology uses an 803.11b wireless technology for wireless noise data transfer (803.11b is known to have a typical wireless range of 100 meters). The dimensions of the SeNDT device is approximately 8"x8"x3" and has two protruding antennas. The device is based on a Triton XXS processor (typically costs for the Triton development boards are $350 in small quantities). The cost of the additional SeNDT components including housing, microphone, etc. are not known. The device samples data at 49 kSamples/sec at 16 bit, thereby providing wide dynamic range acoustic measurements over the full audio bandwidth. The device outputs A-weighted sound pressure levels.

The SSAM technology developed here differs from the SeNDT technology in several ways. SSAM was developed to be very low cost (e.g., $114 in parts), provide extensive functionality comparable to high-end sound level meters (including flat-weighted, A-weighted, and ANSI octave band measurements), provide a compact and unobtrusive appearance (e.g., 4"x3"x3", resembling a telephone pole junction box, with no exposed antennas), and provide a minimum of 1 mile of wireless transmission range.

4. INVESTIGATION

The work completed under this project involved Design and Development (Stage 1) and Traffic Noise Measurements and Demonstrations (Stage 2). The results and technical details are described below.

4.1 DESIGN AND DEVELOPMENT

The development of SSAM involved packaging design (the enclosure), hardware development (microelectronics, wireless connectivity, microphone selection and housing), and software development (embedded microprocessor in the sensor and graphical interface and data processing on the base station). The specific designs and features are described in the following subsections.

4.1.1 Packaging Design

Three packaging designs were considered for SSAM. The first package design closely resembled common sound level meters including a long microphone boom. A second package design accommodated a large battery pack for testing over extended periods of time (several months). A third package design was intended to be small and inconspicuous. After review by several transportation agency personnel, the vast majority choose the small and inconspicuous design because of concerns of theft, vandalism and undesired attention that the other designs may attract.

* P. McDonald *et al.*, "Assessing the environmental impact of transport noise using wireless sensor networks," *Proc. TRB 2008 Annual Meeting* (2008).

The resulting SSAM package design is shown in Figure 2. The design permits mounting on a tripod as is convenient for various ANSI noise tests. The design also accommodates strapping to a telephone pole or sign post for more general noise monitoring. When mounted to a telephone pole, the SSAM's shape and color resemble a common electrical junction box. Therefore, SSAM can be deployed in an inconspicuous manner for unattended testing over longer periods of time.

The microphone positioning in the SSAM sensor was designed, tested, and redesigned to assure that the frequency response of the microphone was unaffected by the housing. Specifically, frequency response testing was completed to assure that a meaningful calibration can be achieved with a IEC942 standardized calibrator.

The SSAM packaging was fabricated by a sintered nylon rapid prototyping method. The resulting package is very strong and durable (sintered nylon retains at least 90% the strength of injection molded nylon). A photograph of a SSAM package is shown in Figure 3 on the left. On the right side of Figure 3, the SSAM has been inconspicuously mounted to a light pole.

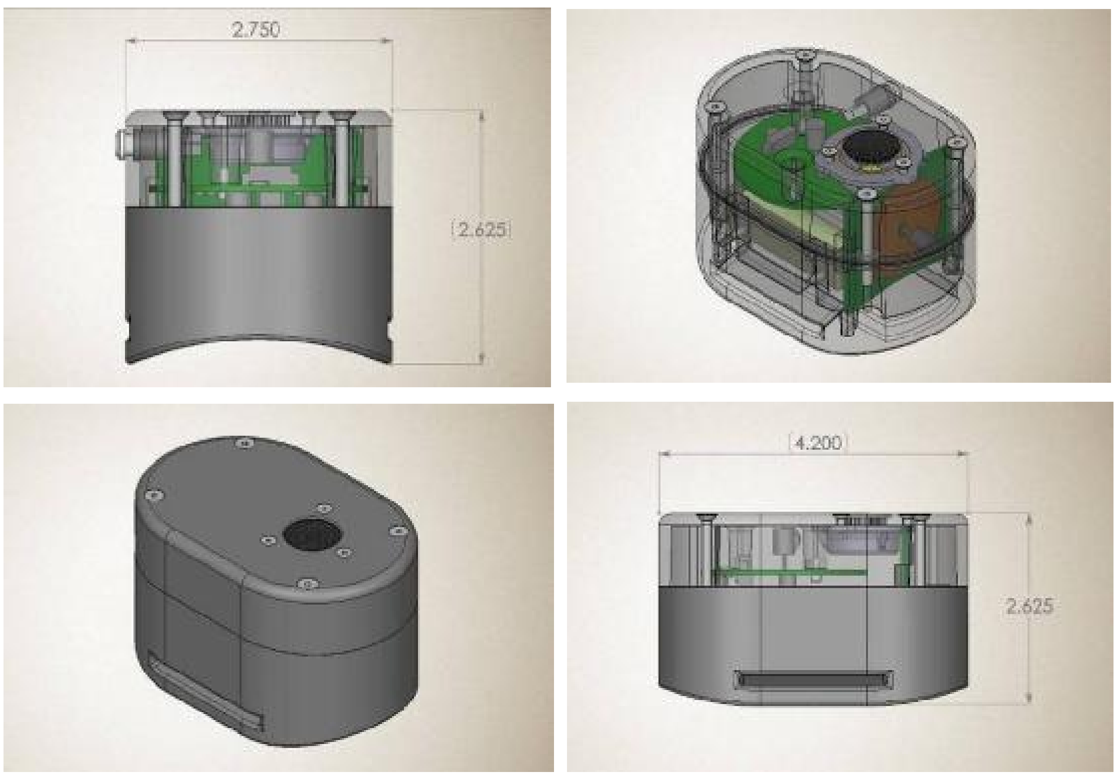

FIGURE 2: Design of the SSAM packaging for a small and inconspicuous appearance.

4.1.2 Hardware Development

The key hardware design challenge in developing SSAM was to achieve high-quality noise measurements while keeping the components costs as low as possible. The design goals for SSAM included:

- Provide on-board, real-time flat-weighted sound pressure levels (to Type 1 frequency-response specifications);
- Provide on-board, real-time A-weighted sound pressure levels (to Type 1 frequency-response specifications);
- Provide on-board, real-time octave band analysis (to Type 1 bandwidth and roll-off specifications);

- Achieve a large measurement dynamic range (e.g., 40 dB to 120 dB);
- Achieve long range wireless transmission while staying below FCC regulated transmission powers;
- Permit simultaneous operation of ten or more SSAM units transmitting to a single base station with graphical user interface.

A photograph of the final hardware installed in a SSAM enclosure is shown in Figure 4. The back half of the SSAM packaging contains a battery chassis and the front half of the SSAM packaging contains the microphone enclosure, and two circuit boards that accommodate signal conditioning, pre-amplification (gain), octave band filters, analog-to-digital converters, microprocessor, wireless transmitter, and other components. The specific components and board layout are not discussed here. The batteries can be user-replaced if proper care is taken to avoid damage to the circuit board.

The estimated production cost of the SSAM sensor is described in Table 1. In production, the parts cost total is estimated at $114 per SSAM sensor unit, not including the costs of assembly. Compared to a data logging sound level meter with octave band analysis (typically purchase cost of about $2000), the potential cost savings provided by the SSAM sensor is significant.

The SSAM base station consists of a dedicated laptop computer with USB interface to the receiver module and antenna (total parts cost of the base station is approximately $1000). Photographs of the entire SSAM system, including ten sensors and a base station, packaged in a travel case are shown in Figure 5. The base station software is described in the following section of this report.

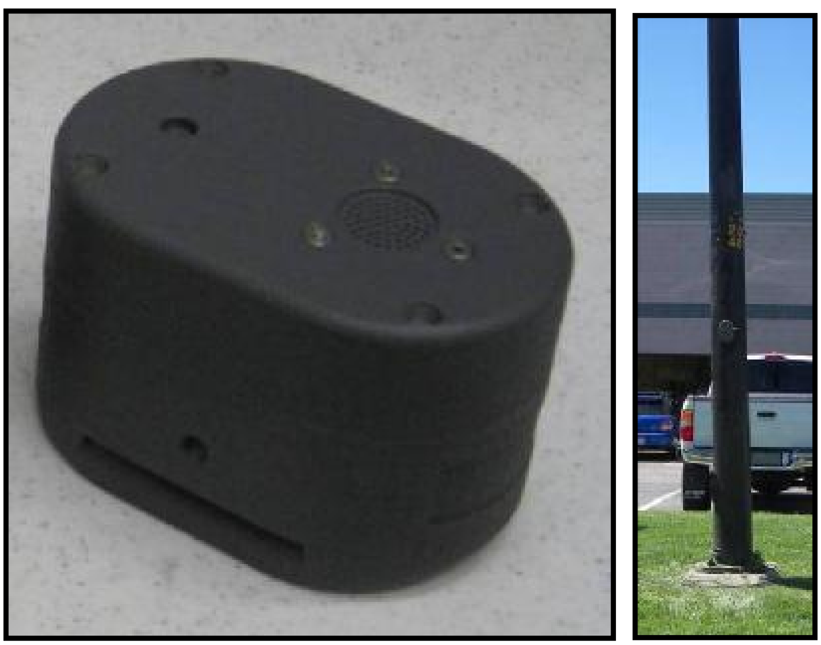

FIGURE 3: LEFT—water resistant sintered nylon SSAM enclosure. RIGHT—When SSAM is installed on a telephone pole, it is inconspicuous because it resembles a common electrical junction box.

FIGURE 4: Photos of the SSAM units. LEFT—Inside the enclosure is housed four batteries and the circuit board. RIGHT—Top and bottom views of the SSAM sensor.

TABLE 1: Cost of the SSAM sensor—In production, the total parts cost per SSAM sensor is approximately $114.

SSAM Sensor Part	Small Quantity Cost	Production Quantity Cost
Microphone	$36.12	$20.15
Housing	$5.50	$3.30
Filters	$47.20	$28.32
Microprocessors	$38.86	$23.32
Digitizer	$11.07	$6.64
Various electronics components	$50.87	$30.52
Total Parts Cost	$189.62	$113.77

FIGURE 5: Photograph of the completed sensors and base station stored in their travel case. The case contents include: laptop, ten SSAMs, one USB receiver module with short range receiver antenna, cord and power supplies, and replacement batteries. Not shown is the larger optional receiver antenna used for longer range wireless reception.

4.1.3 Software Development

Software development for the SSAM system consisted of code for the embedded microprocessor in the SSAM sensors plus development of software for the base station. The software that resides on the SSAM sensors is embedded c-code that serves the following functions:

- General system timing controls,
- Control of analog-to-digital conversion rates, programmable amplifier gain settings, frequency of wireless transmissions,
- Digital signal processing including exponential time averages, A-weighting digital filter calculations, and time averages,
- Control of startup calibrations, and wireless transmission of sensor data.

The software that resides on the base station (a Dell Vostra laptop computer) is written in National Instrument's LabVIEW™ software environment. The base station software provides the following functions:

- Provides a graphical user interface to control the SSAM system and data logging,
- Coordinates data logging from up to ten SSAM units via the universal serial bus (USB) interface to the receiver module,

- Provides final signal processing of the data streams to convert data to calibrated units and associated displays,
- Provides graphical display of SSAM data via a map overlay of flat-weighted sound pressure levels,
- Provides graphical display of octave bands at a given sensor location,
- Provides the ability to "play back" a data set to visualize changes in noise characteristics as a function of time.

Figure 6 shows the two main displays from the base station including the map overlay (left) and the octave band analysis (right).

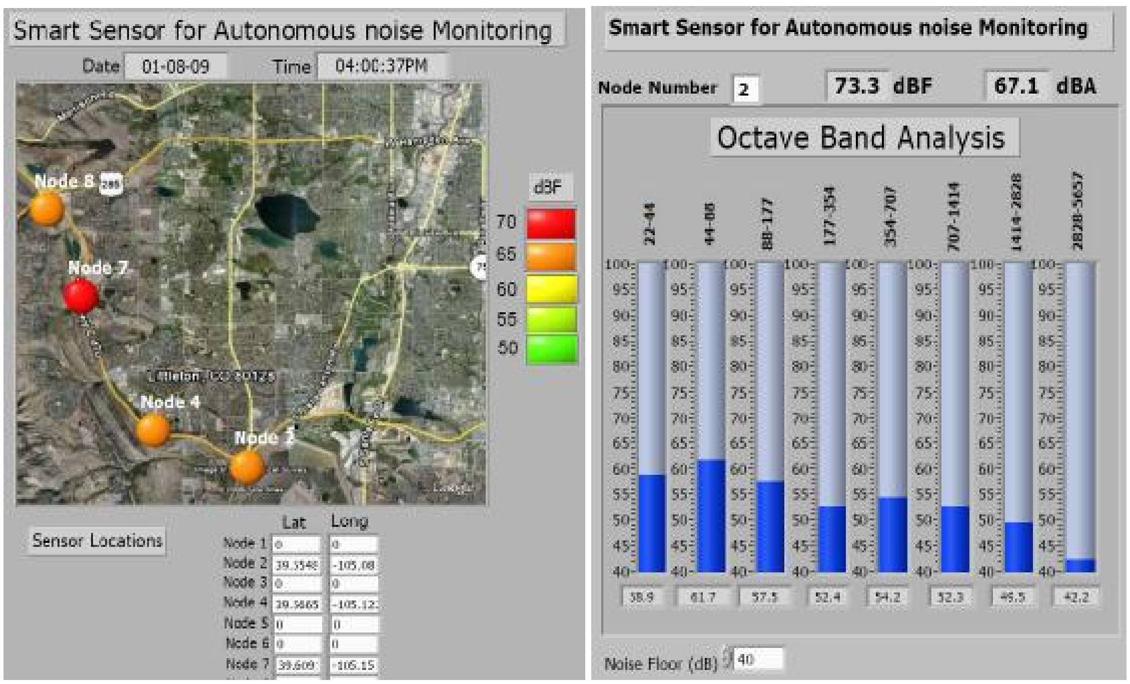

FIGURE 6: Screenshots from the base station user interface. Left—the main map view showing the location of four deployed SSAM sensors with color coding to indicate flat-weighted sound pressure levels. Right—the data (flat and A-weighted sound pressure levels, octave band levels) from a single SSAM.

4.1.4 Electronics Evaluation

Following the development of the SSAM system, a series of laboratory tests were performed to verify proper functioning of the hardware and software, to determine the calibrated system parameters required to conform with specifications for sound level meters (ANSI S1.4-1983 and ANSI S1.4a-1985), and to simulate a typical noise barrier test.

A system functionality test of each SSAM sensor was performed to determine:

- noise floor,
- proper functioning of the octave band filters.

The noise floor was determined by placing each SSAM unit inside a sound isolation chamber and measuring the received signal. Inside the sound isolation booth, the SSAM units were powered on and the receiver station displayed the raw data transmitted from the SSAM. A relatively constant noise floor was typically observed at the receiver station. All

SSAM sensors were tested and found to have noise floors less than approximately 65 dB for the typical 100x gain setting—this was higher than the as-designed 40 dB noise floor. The excess noise floor was likely due to circuit board re-works that can be easily eliminated in future versions of SSAM.

To verify that each microphone was working properly and the octave band filters were functioning, a tone corresponding to the center frequency of each octave band was generated in the chamber. Proper functionality was demonstrated by measurement of acoustic response in the appropriate octave band.

4.1.5 Wireless Range Testing

Wireless range testing was conducted by transmitting over line-of-sight distances along the ground. The SSAM device transmitted to a maximum ground-to-ground range of 1.2 miles in an urban environment (Golden, CO).

4.1.6 Frequency Response Testing

Frequency response testing of the SSAM unit was conducted as shown in Figure 7. The resulting data is presented in Figure 8. The response is typically less than +/- 0.5 dB with flat response over the range of 1000 Hz to 5000 Hz. Similar flat response is achieved over the range 20 Hz to 5000 Hz.

As mentioned above, the SSAM enclosure was redesigned to assure that the housing did not have an effect on the microphone's frequency response. In the original design, the microphone was recessed behind the screen and we found that this caused some significant frequency dependence. By repositioning the miniature microphone nearly flush, a flat frequency response was obtained (as seen in Figure 7). Furthermore, side-by-side testing with a Type 1 reference microphone and reference sound source was evaluated to assure that the SSAM sensor can be accurately calibrated by placing a piston phone calibrator on the face of the SSAM unit. It should be noted that the lack of a microphone boom on the SSAM unit implies that some directionality may occur at higher frequencies. However, the SSAM does not operate above 6 kHz and, therefore, the SSAM is quite omni-directional.

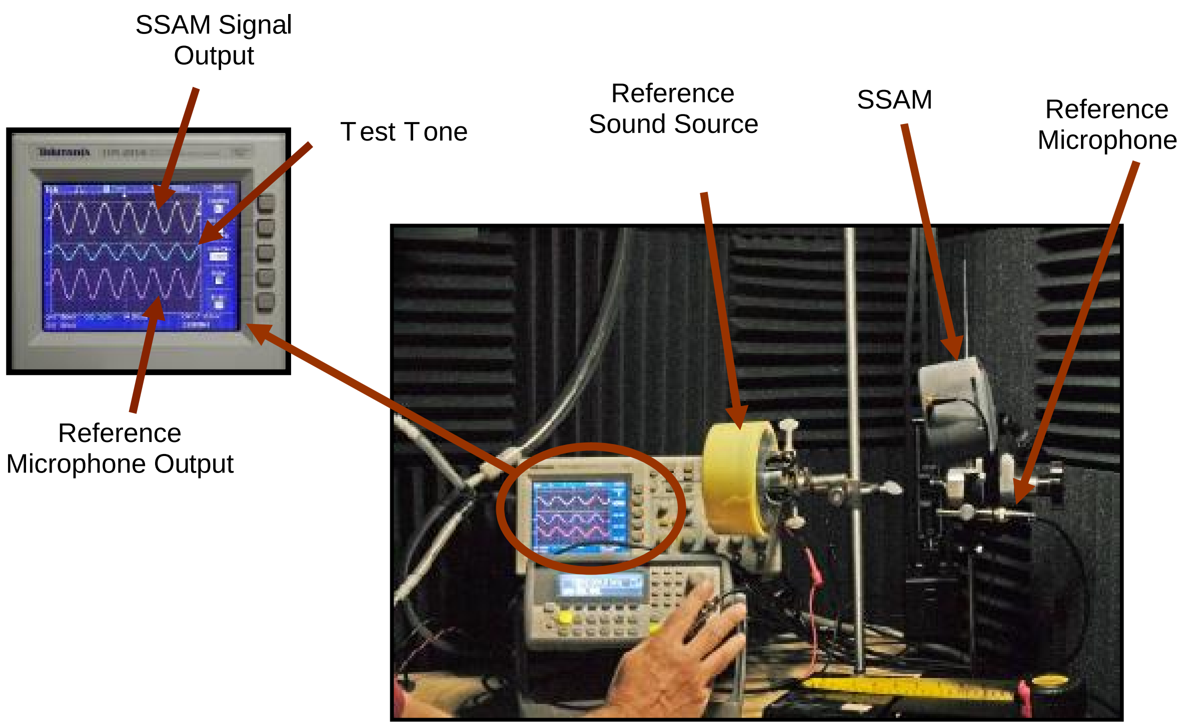

FIGURE 7: Photograph of laboratory testing and calibration of SSAM.

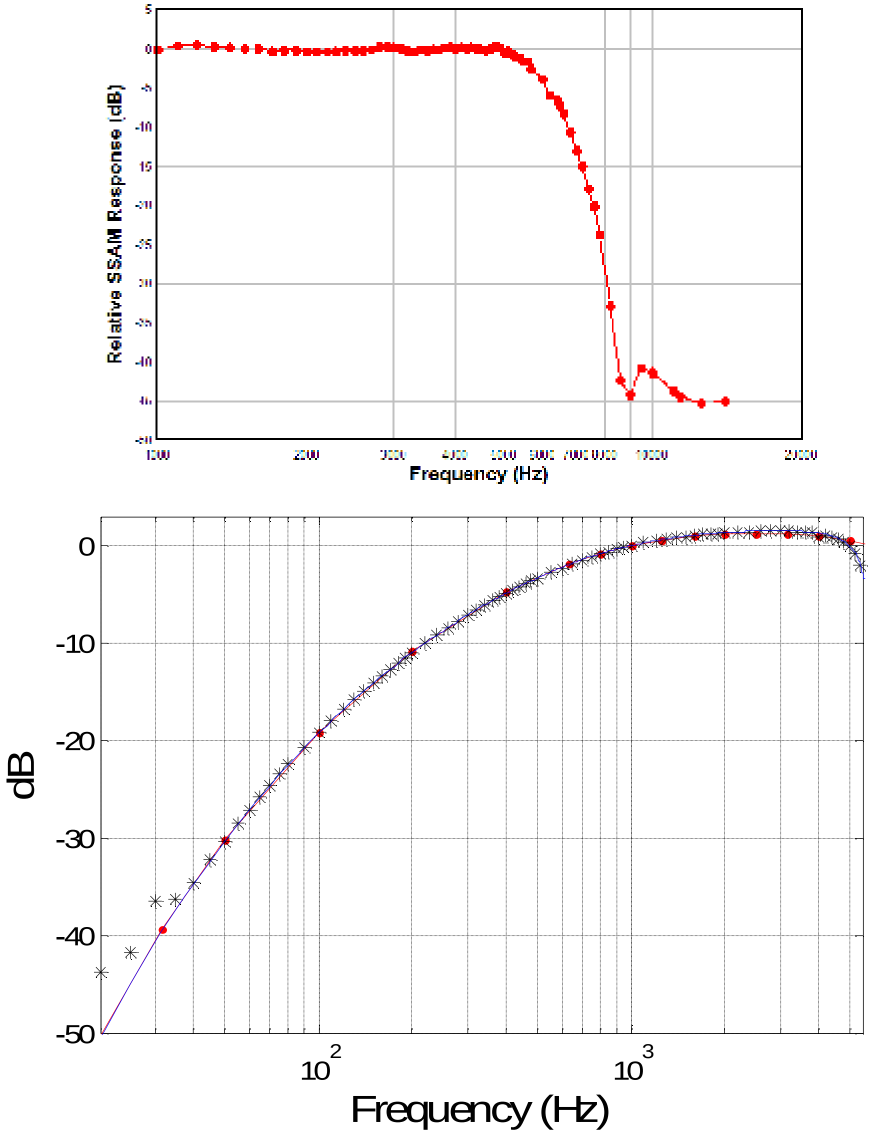

FIGURE 8: Frequency response of the SSAM device. The device's response meets or exceeds ANSI Type 1 microphone response requirements over the frequency range 20 Hz to 5000 Hz. BOTTOM—A-weighted SSAM frequency response (blue) compared to the ANSI standard (red circles).

4.2 TRAFFIC NOISE MEASUREMENT TESTS AND DEMONSTRATIONS

An initial field test was performed at a local highway noise barrier along highway C470 in Littleton, CO. More extensive noise barrier testing was conducted in Troy, OH. In addition, wayside traffic noise measurements were conducted in Sacamento, CA. A description of these tests is presented in the following subsections of this report.

4.2.1 Colorado Traffic Noise Tests

An initial noise barrier insertion loss test was performed at a test site along highway C470 in Littleton, CO. The purpose of this test was to determine the functionality of the SSAM units in a realistic test environment. As described in the remainder of this section, the tests demonstrated the basic functionality including:

- Wireless Data Transfer: wireless transfer of data from multiple SSAM sensors to the SSAM base station located in a nearby vehicle was demonstrated;
- Real-Time Remote Noise Monitoring: the ability to observe, in near real time, the relative quiet behind the noise barrier, as compared to the control site without the noise barrier was demonstrated.

During these tests, nine minute arithmetic averages of fast time-weighted acoustical descriptors were calculated: A-frequency weighting, flat frequency weighting, and flat weighted octave bands spanning 22 Hz to 6 kHz were measured. Four SSAM units were operated simultaneously at two site locations near the cul-de-sac at the end of S. Newland Ct. Two SSAM units were placed at a site location where the noise barrier was present. The remaining two SSAM units were placed at a location 15 m beyond the termination of the barrier. Calibration of the SSAM units was completed before and after the tests, in accordance with ANSI standards. A birds eye image of the location is shown in Figure 9.

Each SSAM unit was placed on a tripod at a height of 1.5 m above the ground with the exception of the reference sensor that was mounted approximately 2 meters above the noise barrier. The noise barrier is 4.3 m high at the est site and is 16.4 m from the center of the nearest traffic lane. Photographs of the SSAM test locations are shown in Figure 10 and Figure 11.

The SSAM system performed well under the conditions of the test. The primary advantage of SSAM in this test is the absolute acoustic equivalence between the "before" site location (no noise barrier) and the "after" site location (with noise barrier). The resulting data is presented in Table 2. The data has an experimental uncertainty of about +/- 3 dB with the exception of frequencies between 44 and 177 Hz where the experimental uncertainty was as much as +/- 9 dB. The experimental uncertainty is likely due to variations in traffic volume and wind conditions. In the low frequency bands, the noise barrier provides very little noise reduction. For example, the 22-44 Hz band insertion loss was within experimental uncertainty of zero (insertion loss was -1.9 dB +/- 3.1 dB) indicating that the noise barrier has little or no effect on these very low frequencies.

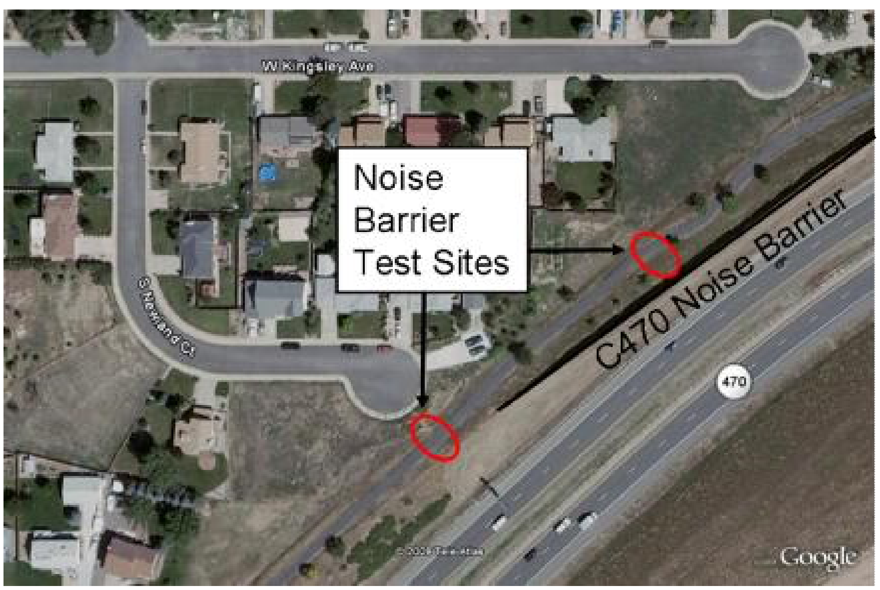

FIGURE 9: Google Earth® image of the C470 test site locations.

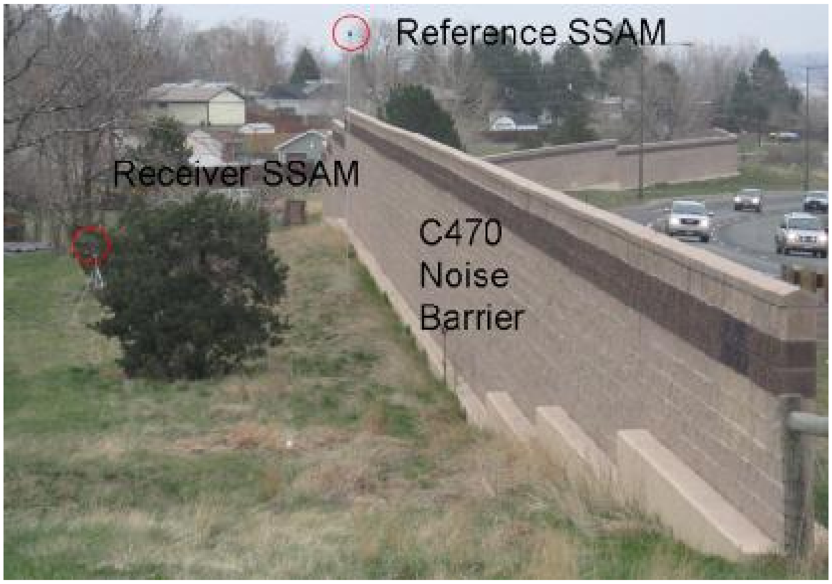

FIGURE 10: After site SSAM configuration. The reference SSAM unit is 1.7 m above the sound barrier. The receiver SSAM unit is 1.5 m the ground.

FIGURE 11: Equivalent before site reference microphone position. The reference SSAM is 1.5 m above the ground and about 4 m above the nominal plane of the sound source.

TABLE 2: C470 test results.

C470 Noise Barrier Insertion Loss & Error										
Standoff Distance (m)	dBA	dBF	2828-5656 Hz (dB)	1414-2828 Hz (dB)	707-1414 Hz (dB)	354-707 Hz (dB)	177-354 Hz (dB)	88-177 Hz (dB)	44-88 Hz (dB)	22-44 Hz (dB)
5	11.4 +/- 3.2	5.5 +/- 2.6	7.4 +/- 2.8	11.7 +/- 3.7	15.2 +/- 4.1	14.2 +/- 5.7	13.0 +/- 3.7	8.3 +/- 9.0	1.7 +/- 6.7	-1.9 +/- 3.1

4.2.2 Ohio Traffic Noise Barrier Tests

The Troy, Ohio noise barrier insertion loss test demonstrated the usefulness of SSAM in the following ways:

- SSAM provides simultaneous measurements at several sites: Several SSAM monitors were simultaneously deployed at locations with and without the noise barrier thereby reducing or eliminating traffic variations (noise source variability). Such simultaneous measurements would be difficult using standard sound level meters because of the high expense associated with deploying six sound level meters (for example) at two sites.
- SSAM wireless link provides immediate noise barrier insertion loss evaluation: By deploying the SSAM units simultaneously at locations with and without the noise barrier, the operator can make an in-field preliminary assessment of noise barrier insertion loss by viewing the real-time data from all SSAM sensors on the SSAM base station. In one test case, for example, the traffic volume and speed was identical at both locations, and the base station provided calibrated, time averaged sound level measurements in near real-time. The difference in sound pressure levels can be observed at the SSAM base station in near-real time, providing a rapid (although preliminary) immediate noise barrier insertion loss assessment.

This remainder of this section details the measurement and calculation of acoustic insertion loss for a noise barrier located along the I-75 corridor in Troy, Ohio according to the ANSI S12.8-1998 standard, with the use of the SSAM sensors.

The Troy, Ohio test sight involved free flowing traffic in a 65 mph zone along the I-75 corridor. Photographs of the site are shown in Figures 12 through 14. The acoustical descriptors (see Section 8.1 of S12.8-1998) included time averaged A-weighted sound pressure levels (dBA), time averaged flat-weighted sound pressure levels (dBF), and eight time-averaged octave band levels (spanning 22 Hz to 6 kHz). Continuous fast time-weighted exponential averages were arithmetically averaged over approximately 15 minute time intervals. Since the sound source could not be removed, background noise was determined by the fast time-weighted measurement obtained for each acoustical descriptor at the minimum measured A-weighted sound level. An indirect measured method, described in Section 4.2 of S12.8-1998, was used to determine the noise barrier insertion loss. Some exceptions to the standard did occur and are described in ODOT Report Number FHWA/OH-2009/6.

The noise barrier tests were conducted at five independent locations over two days of measurement: Tuesday May 5th and Wednesday May 6th of 2009. Calibration of the SSAM units was completed before and after all tests, in accordance with ANSI standards. Four sites were located along portions of the noise barrier and the fifth location was south of the barrier termination. At each location, three receiver microphones were used. Microphone 1 was located 5 m from the noise barrier (or nominal noise barrier location Site E). Microphone 2 was 25 m from the noise barrier. Microphone 3 was 50 m from the noise barrier. Each of the receiver microphones was placed on a tripod approximately 1.5 m in height. For sites A-D, a reference microphone was placed on a fiberglass boom and raised at least 3.5 m above the noise barrier (ANSI S12.8-1998 requires the microphone be placed at least 1.5 m above the barrier). Details of the site description are provided in ODOT Report Number FHWA/OH-2009/6.

Acoustical and meteorological equipment was required to perform the noise insertion loss measurements. The acoustical equipment provided information about the sound source and background noise at each test location. The meteorological data ensured that each test site falls within comparable environmental conditions to assure acoustical equivalence between the measurement locations. Acoustical equipment included the following:

- Six SSAM Sensors for Autonomous noise Monitoring were used over the course of this two day study. Each sensor is a self contained sound level meter complete with microphone, amplifier, analog/digital filters, microprocessor, and wireless transmission technology. Serial numbers of the SSAM units are: 4,6,7,11,19.
- One SSAM base station to receive individual sensor transmissions and export them via USB to a computer.
- An ND9 Acoustic Calibrator (94/114 dB @ 1000 Hz), Serial Number N414220 satisfying IEC942 Class 1 standards for acoustic calibrators. A small rubber seal has been added to the unit to allow for calibration of the SSAM unit.
- Six wind screens (Parts Express 242-030).
- Dell Vostro 1310 Laptop for data recording.
- Proprietary software developed in LabView® for retrieving and processing SSAM data transmissions.

Meteorological equipment included the following:

- Extech 45158 Mini Thermo-Anemometer, serial number 20908, for measuring average wind speed and temperature.
- Engineer Lensatic Compass for determining prevailing wind direction and direction between source and receiver.

In addition to acoustical and meteorological data, a video recording of the traffic flow was made for each measurement location and duration.

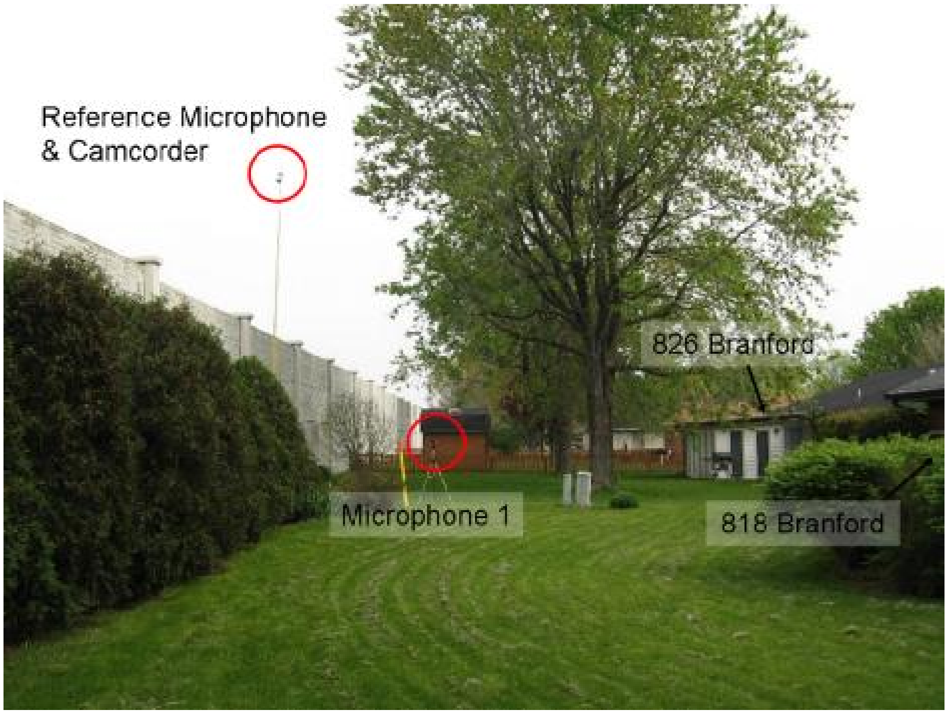

FIGURE 12: Photograph taken from the south side of the measurement site in the backyard of 818 Branford.

FIGURE 13: Photograph taken from behind microphone 3 facing the noise barrier.

FIGURE 14: Photograph taken from the North East side of Site D facing the McKaig Avenue/I-75 overpass.

A summary of the test results indicating the minimum noise insertion loss number for the ten acoustic descriptors, and three noise barrier standoff distances is presented in Tables 3 through 6. The mean insertion loss represents the minimum insertion loss that the noise barrier provides. The calculations used to obtain these results can be reviewed in ANSI S12.8-1998. The field data worksheets for each microphone location are included in Appendix A of ODOT Report Number FHWA/OH-2009/6.

For each site location, the tabulated results include (a) measurement conditions, (b) insertion loss, and (c) measurement uncertainty.

(a) The measurement conditions include time and duration of measurement, wind conditions, cloud cover conditions, temperature, and traffic data. Traffic data is obtained by counting vehicles passing on both sides of the highway during the measurement. Vehicles are classified in five categories: automobiles (A), medium trucks (MT), heavy trucks (HT), buses (B), and motorcycles (M).
(b) The mean insertion loss was determined for each source receiver pair.
(c) The total experimental uncertainty calculated for each measurement is provided. Values given in the tables have units of decibels referenced to 20 μPa.

The results in Tables 3 through 6 are generally reasonable with some exceptions. In general, the octave band insertion loss data shows that the noise barriers are most effective at reducing higher frequency noise components, as may be expected. The data as a function of distance behind the noise barrier shows that the insertion loss is highest closest to the barrier, as may be expected.

In some cases, however, the insertion loss calculations show an increase in noise in the 22-44 Hz band. At this time it is not clear if this is a real effect or perhaps a noise floor issue in that particular octave band, for example. It is also noted that the mean insertion losses reported for Site C (17.0 dBA, 16.4 dBA, 10.1 dBA) seem high compared to the insertion loss values obtained at Sites A and B.

TABLE 3: Site A test results.

Measurement Data									
Run	Start Time (MST)	End Time (MST)	Duration	Wind Speed (m/s)	Wind Dir. °	Wind Class	Temp (°F)	Cloud Cover Class	Source Operating Data A MT HT M B
1	9:31:06	9:46:37	0:15:31	0.1	31°	Calm	70°	2	441 52 153 3 0
2	9:49:08	10:04:39	0:15:31	0.5	31°	Calm	71.1°	2	434 40 138 0 0
3	10:07:10	10:22:41	0:15:31	0.2	31°	Calm	72°	2	507 35 148 1 1

Site A: Mean Insertion Loss										
Standoff Distance (m)	dBA	dBF	2828-5656 Hz (dB)	1414-2828 Hz (dB)	707-1414 Hz (dB)	354-707 Hz (dB)	177-354 Hz (dB)	88-177 Hz (dB)	44-88 Hz (dB)	22-44 Hz (dB)
5	13.0	9.6	15.6	17.3	19.2	22.8	16.4	12.8	4.3	-4.1
25	10.9	7.4	11.9	16.0	15.9	18.9	16.0	10.3	3.9	-5.1
50	8.8	7.2	4.2	9.6	11.1	14.7	14.8	11.4	5.0	-4.0

Site A: Mean Insertion Loss Uncertainty										
Standoff Distance (m)	dBA	dBF	2828-5656 Hz (dB)	1414-2828 Hz (dB)	707-1414 Hz (dB)	354-707 Hz (dB)	177-354 Hz (dB)	88-177 Hz (dB)	44-88 Hz (dB)	22-44 Hz (dB)
5	4.3	2.1	2.6	5.4	8.4	6.8	4.4	3.7	5.9	3.7
25	4.5	2.3	2.8	5.6	8.9	6.8	4.5	4.6	8.1	3.1
50	4.1	3.3	3.0	5.9	8.2	6.8	4.4	4.8	6.3	4.3

Measurement Notes:

- A dog inside 1088 Dorchester barked intermittently through each of the measurement intervals. The sound was undetectable at microphone 1, detectable only during quieter traffic periods at microphone, and detectable at most levels at microphone 3. The author does not believe the dog affected the integrity of the data.
- Ambient bird chirping was present through most of the measurement period. A significant flock of birds landed near microphone 2 during the second measurement interval for approximately 1 minute. Standing near the microphone caused the birds to retreat.
- A lawnmower more than 100 m away was semi-audible at Microphone 3 during the third measurement interval.

TABLE 4: Site B test results.

Measurement Data										
Run	Start Time (MST)	End Time (MST)	Duration	Wind Speed (m/s)	Wind Dir. °	Wind Class	Temp (°F)	Cloud Cover Class	Source Operating Data A MT HT M B	
1	7:30:32	7:46:06	0:15:34	0.2	N/A	Calm	64	2	455 50 137 1 2	
2	7:46:21	8:01:53	0:15:32	0.8	N/A	Calm	66	2	505 45 143 2 2	
3	8:04:23	8:13:13	0:08:50	0.6	N/A	Calm	68	2	24 18 70 0 0	

Site B: Mean Insertion Loss										
Standoff Distance (m)	dBA	dBF	2828-5656 Hz (dB)	1414-2828 Hz (dB)	707-1414 Hz (dB)	354-707 Hz (dB)	177-354 Hz (dB)	88-177 Hz (dB)	44-88 Hz (dB)	22-44 Hz (dB)
5	15.5	10.7	18.2	20.5	21.7	22.9	15.8	12.0	6.0	-3.1
25	15.3	8.4	14.6	21.4	22.4	22.2	16.4	13.1	7.3	-5.0
50	9.2	7.6	6.9	10.0	11.9	15.3	12.4	9.6	6.0	-2.6

Site B: Mean Insertion Loss Uncertainty										
Standoff Distance (m)	dBA	dBF	2828-5656 Hz (dB)	1414-2828 Hz (dB)	707-1414 Hz (dB)	354-707 Hz (dB)	177-354 Hz (dB)	88-177 Hz (dB)	44-88 Hz (dB)	22-44 Hz (dB)
5	3.8	2.6	2.4	5.2	6.7	1.9	3.3	8.5	3.9	1.9
25	3.8	2.7	2.5	5.3	6.5	2.3	3.4	3.1	4.3	2.3
50	3.9	2.5	2.9	5.7	6.6	2.2	3.3	4.9	5.3	1.6

Measurement Notes:

- Between five and seven cars passed on the road in front of Microphone 3 during each measurement interval. Each was driving around the speed limit of 30 mph. The noise from this traffic was inaudible at Microphone 1 and only semi-audible at Microphone 2.
- Some residents were playing fetch with a small dog within 10 m of Microphone 2 during the second and third interval, however the sound was no louder than a conversation level and noticeably quieter than the highway noise.
- Each of the measurement intervals were cut short by at least a 2 minute interval to accommodate a lawn contractor that agreed to take a break from mowing near microphone 3 to allow us to take measurements. The contractor began work again 12 minutes into the third measurement interval. All data beyond this point was omitted from analysis.

TABLE 5: Site C test results.

Measurement Data														
Run	Start Time (MST)	End Time (MST)	Duration	Wind Speed (m/s)	Wind Dir. °	Wind Class	Temp (°F)	Cloud Cover Class	Source Operating Data A	MT	HT	M	B
1	1:03:39	1:19:11	0:15:32	1.5	358	Calm	72	3	773	46	135	8	3
2	1:21:41	1:37:13	0:15:32	1.5	358	Calm	72.5	3	823	45	176	2	2
3	1:39:44	1:50:45	0:11:01	1	358	Calm	73	3	712	32	107	1	1

Site C: Mean Insertion Loss										
Standoff Distance (m)	dBA	dBF	2828-5656 Hz (dB)	1414-2828 Hz (dB)	707-1414 Hz (dB)	354-707 Hz (dB)	177-354 Hz (dB)	88-177 Hz (dB)	44-88 Hz (dB)	22-44 Hz (dB)
5	17.0	9.7	21.0	25.4	24.7	21.3	13.0	7.1	2.6	-1.9
25	16.4	10.2	14.6	23.1	22.2	20.6	16.9	10.8	5.5	0.2
50	10.1	8.7	6.9	11.5	13.6	15.5	14.5	9.3	5.5	0.3

Site C: Mean Insertion Loss Uncertainty										
Standoff Distance (m)	dBA	dBF	2828-5656 Hz (dB)	1414-2828 Hz (dB)	707-1414 Hz (dB)	354-707 Hz (dB)	177-354 Hz (dB)	88-177 Hz (dB)	44-88 Hz (dB)	22-44 Hz (dB)
5	5.0	3.0	3.2	7.1	9.1	2.1	5.0	3.9	4.2	3.8
25	4.4	2.6	2.8	5.5	7.6	1.7	4.0	3.9	5.5	4.4
50	4.6	2.4	3.3	6.2	8.3	1.9	4.1	3.7	5.4	4.0

Measurement Notes:

- Between four and six vehicles passed by Microphone 3 during each measurement interval. During the second interval, a bus and a UPS truck passed.
- The wind picked up some during the second measurement interval. For a 10 s period, the wind gusts approached 2.9 m/s from 350° from due North.

TABLE 6: Site D test results.

Measurement Data									
Run	Start Time (MST)	End Time (MST)	Duration	Wind Speed (m/s)	Wind Dir. °	Wind Class	Temp (°F)	Cloud Cover Class	Source Operating Data A MT HT M B
1	1:03:39	1:19:11	0:15:32	1.5	358	Calm	72	3	773 46 135 8 3
2	1:21:41	1:37:13	0:15:32	1.5	358	Calm	72.5	3	823 45 176 2 2
3	1:39:44	1:50:45	0:11:01	1	358	Calm	73	3	712 32 107 1 1

Site D: Insertion Loss										
Standoff Distance (m)	dBA	dBF	2828-5656 Hz (dB)	1414-2828 Hz (dB)	707-1414 Hz (dB)	354-707 Hz (dB)	177-354 Hz (dB)	88-177 Hz (dB)	44-88 Hz (dB)	22-44 Hz (dB)
28	9.4	5.2	12.8	15.0	14.2	14.0	10.2	4.2	0.3	-3.6

Site D: Insertion Loss Uncertainty										
Standoff Distance (m)	dBA	dBF	2828-5656 Hz (dB)	1414-2828 Hz (dB)	707-1414 Hz (dB)	354-707 Hz (dB)	177-354 Hz (dB)	88-177 Hz (dB)	44-88 Hz (dB)	22-44 Hz (dB)
28	4.5	2.4	4.3	6.2	7.6	2.8	4.7	4.6	5.6	5.2

Measurement Notes:

- A man was edging his yard with a weed eater within 10 m of microphone 1 during the first measurement interval. The sound lasted approximately 3-4 minutes. No data was omitted since the microphones at site C were not experiencing any noise fluctuations.
- Sounds from McKaig Ave. were inaudible during the measurement period.

4.2.3 California Wayside Traffic Noise Measurements

On June 8, 2009 a set of 13 SSAM units were tested along the edge of highway I-80 just outside Davis, California. The Davis tests demonstrated usefulness of the SSAM system in the following ways:

- Large Number of Simultaneous Noise Measurements: A total of 13 SSAM sensors were deployed for the simultaneous measurement on noise levels along two linear arrays. This measurement would be difficult with standard methods because of the significant expense of owning or operating such a large number of sound level meters.
- Near Real-Time Spatial Variations of Noise: The data from the 13 SSAM sensors was monitored in near-real time from the base station located about 1/4/ mile away. By monitoring the sensors in near real-time from a centralized location, the operator was able to immediately see the variations in noise levels as a function of position away from I-80.
- Rapid Set-Up of a Noise Monitoring Array: These tests also demonstrated the ability to rapidly set-up an array of many SAAM sensors. The SSAM sensors were attached to inexpensive stakes and existing posts with zip-ties.

An aerial view of the Davis, California test site is shown in Figure 15. The test coincided with a scheduled Caltrans noise monitoring project. The measurement provided the opportunity to compare the performance of the SSAM to standard noise monitoring equipment during simultaneous measurements.

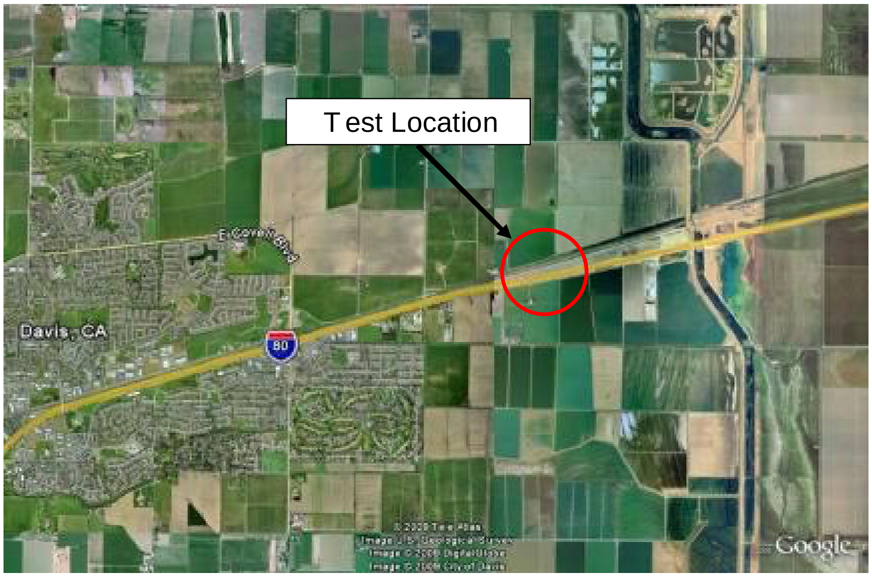

FIGURE 15: Google Earth® image of I-80 test location outside Davis, California

Acoustic contractors from Illingworth & Rodkin, Inc. (I&R) performed a four hour noise measurement using standard Larson Davis sound level meters and real time 1/3 octave band analyzers. At the test location, I&R deployed 4 sound level meters which measured 5 minute averages over a four hour period. An aerial site image including I&R sound level meter locations and SSAM locations is shown in Figure 16.

A total of 13 SSAM units were deployed in two evenly spaced arrays on the north and south sides of I-80. Four of the SSAM units were placed in close proximity to the I&R sound level meters for comparison purposes. The remaining SSAM units were installed in two linear arrays as shown in Figure 16. Each SSAM unit was programmed to report 5-min averages for each slow time-weighted noise descriptor: dBA, dBF, and eight octave bands spanning 22-5656 Hz. Calibration of the SSAM units was completed before and after the tests, in accordance with ANSI standards. The SSAM data was collected at a single centralized base station during the same four hour time window as the I&R measurement.

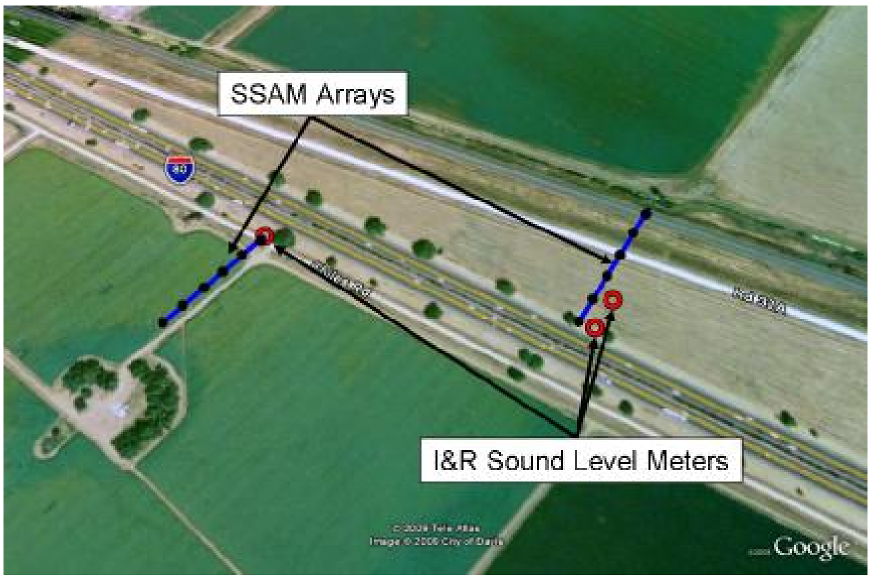

FIGURE 16: Google Earth® image of I-80 test location outside Davis, California with noise monitoring locations.

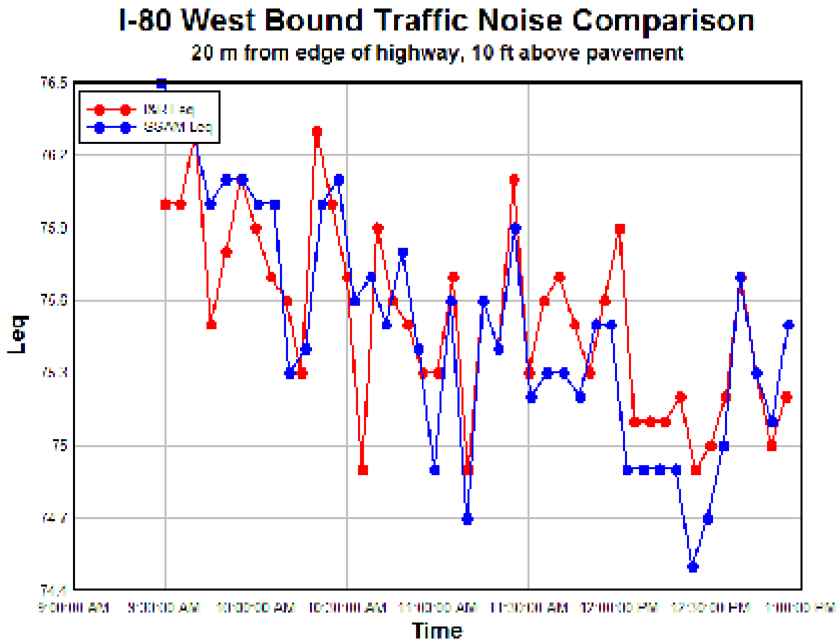

FIGURE 17: Five-minute Leq over the duration of the I-80 test at the collocated reference position 20 m from the highway and 10 ft above the pavement.

Figure 17 shows a comparison of the 5 minute Leq as measured at the reference microphone location 20 m from the highway and 10 ft above the pavement—the SSAM and I&R data agree within a few tenth of a decibal. By comparing the difference between the I&R Leq data and the SSAM Leq data, the accuracy of SSAM was evaluated. Table 7 presents the average Leq difference (SSAM data minus I&R data) over a four hour period for each of the collocated measurement sites. The largest discrepancy occurred at the 20 m standoff distance at 5 ft above the pavement. Given the ratio of the standard deviation to the average difference of the measurement, it appears a poor calibration was applied to that specific SSAM unit. The remaining SSAM units provided data that agreed with the I&R results within the measurement uncertainty (standard deviation).

At each of the collocated sites, octave band measurements were also compared. I&R reported 1/3 octave band data which was processed to obtain octave band measurements for comparison with the SSAM octave band results. Laboratory tests revealed that the electronic noise floor in the two highest SSAM octave bands was the major contributor to the increased noise floor. Figure 18 shows the octave band data comparison excluding two highest octave bands of the SSAM. Over this frequency range, the SSAM octave band measurements agree within about 2 dB of the reported data from I&R. The cause of the excessive high-frequency noise floor has been identified and can be easily corrected in a future SSAM revision.

Noise levels measured by SSAM array were also displayed as a function of distance away from westbound I-80 as shown in Figure 19. The data in Figure 19 is shown along with theoretical curves for cylindrical and spherical spreading. As may be expected, the measurements fall between the two extremes of spherical and cylindrical spreading. At the larger distances (greater than 100 m from the highway), the noise floor of the SSAM units become apparent at approximately 63 dB. This noise floor is in excess of the designed 40 dB noise floor and is likely due to electronic noise resulting from circuit board re-works.

TABLE 7: Leq comparison between SSAM and I&R for each common test location.

I&R vs. SSAM Leq Comparison		
Location	**Average Leq Difference**	**Standard Deviation**
20m, 5ft	-0.99	0.48
20m, 10ft	-0.03	0.21
43m, 5 ft	0.53	0.46

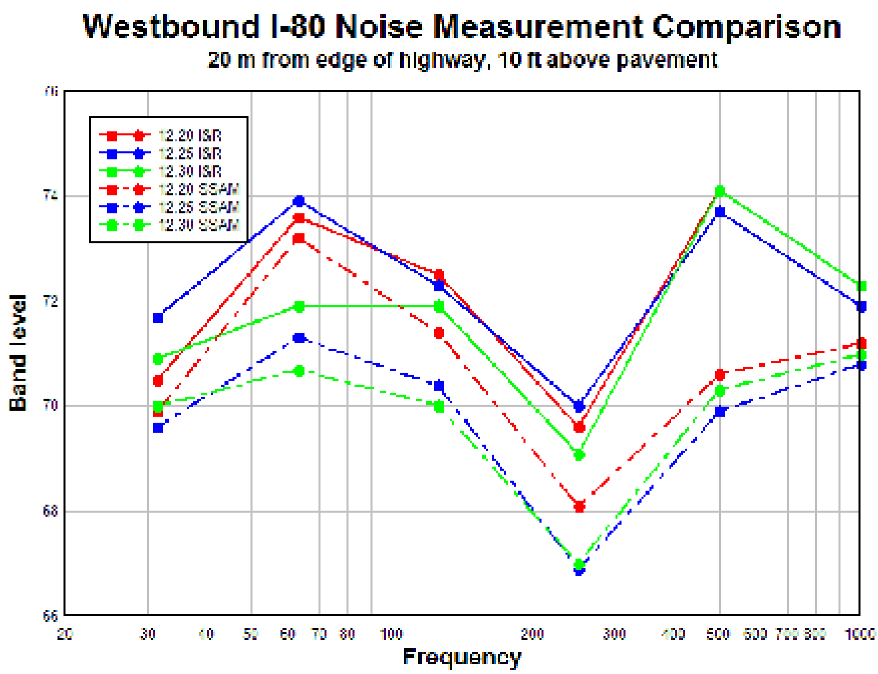

FIGURE 18: Octave band data comparison between I&R and SSAM at westbound reference location (20 m from edge of highway, 10 ft above pavement) excluding data below SSAM noise floor.

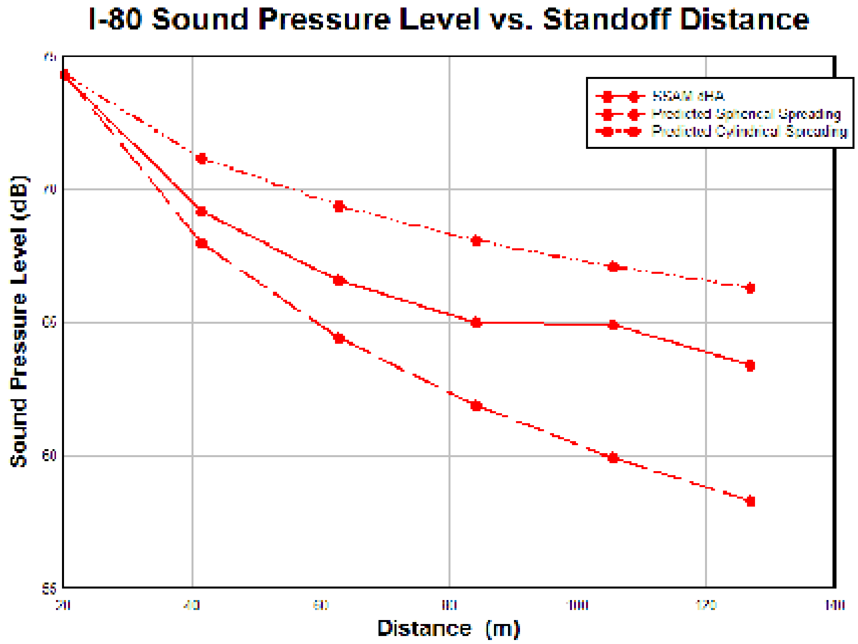

FIGURE 19: I-80 dBA SPL as a function of distance from the highway.

5. PLANS FOR IMPLEMENTATION

This project has transitioned SSAM from concept through demonstration of a working prototype system for multipoint wireless noise monitoring. The use of SSAM in future transportation noise studies is encouraged in order to

- Gain exposure and acceptance in the transportation community,
- Identify needed improvements or desired features,
- Establish a substantial data base of SSAM measurements validated against simultaneous standard noise methods.

By advocating the use of SSAM and incorporating the use of SSAM in future noise studies, the technology can transition from prototype, to a mature, accepted system with well established performance characteristics. Once this transition is made, the substantial cost-effectiveness of the technology can be realized as automated noise monitoring and testing becomes the accepted norm. Ultimately, SSAM will be available for sale or lease as a commercial product or service.

6. CONCLUSIONS

The compact size, ease of use, and low cost of the SSAM sensors offer a unique benefit to traffic noise monitoring. For example, tens or even hundreds of SSAMs could be distributed along many miles of roadway for continuous, long-term monitoring. The resulting technology can provide reduced overall noise test costs and a great increase in data gathering and automated analysis. The added information can provide improved understanding of highway noise sources, airport noise sources, and their variation as a function of location, time-of-day, day-of-week, weather conditions, and other parameters that effect traffic noise levels.

The potential payoff of this project is best realized by considering current traffic noise monitoring and evaluation methods. Although the current wayside techniques provide transportation agencies with valid, accurate data, they are time consuming, cumbersome, and costly to operate. The resulting data must be post-processed, sometimes requiring several additional days before the desired noise metrics are available. In addition, agencies are reluctant to leave noise equipment unattended for extended period of time due to risk of vandalism or theft. The prototype SSAM system provides the ability to perform long-term wayside measurements that can supplement standardized methods or provide a lower-cost alternative to standard noise measurement methods. Further, SSAMs can directly measure noise characteristics along roadways, in front of and behind traffic noise barriers, over/through rows of buildings and vegetation, and other scenarios that the FHWA's Traffic Noise Model cannot currently predict. SSAM may therefore facilitate validation and improvement of the TNM, or direct measurement of the desired noise contours.

This report compares the precision and accuracy of SSAM to that of conventional noise measurement methods through laboratory testing and wayside traffic noise measurements. The data shows that SSAM can provide accurate noise measurements, comparable to typical Type 1 data logging sound level meters. The additional provision for long-term installation of SSAM with long-range wireless transmission of data provides a great capability that has not previously existed. The field tests conducted demonstrate the usefulness of SSAM as follows:

- Wireless Data Transfer
- Near Real-Time Remote Noise Monitoring
- Simultaneous Measurements at Several Sites
- SSAM Wireless Link for Immediate Noise Barrier Assessment
- Near Real-Time Spatial Variations of Noise
- Rapid Set-Up of a Noise Monitoring Array

The SSAM system provides a flexible technology that can be adapted to many other noise monitoring applications of interest to DOTs. For example, the SSAM technology can be modified (through additional research) for use in other areas such as bridge vibration monitoring, underwater noise monitoring, forestry applications, etc. Now that the basic technology has been completed, various improvements to SSAM can be implemented through modest investments.

6.1 RECCOMENDATIONS FOR FURTHER WORK

This project resulted in the creation of a prototype system for low-cost, multi-node noise monitoring. The field tests completed demonstrate some of the utility of the technology; however, additional field testing is needed to provide a full understanding of the technology benefit as applied to transportation. Therefore, continued field testing, in collaboration with standard and non-standard noise measurements is recommended. The additional testing will serve to further assess the accuracy of the SSAM measurements while also provided the ability to collect data from up to 20 locations simultaneously.

Several possible enhancements and refinements to the SSAM hardware and are envisioned in order to improve the performance and utility of the technology. Potential revisions and improvements are as follows:

1. Develop and implement a robust calibration scheme to permit use over a wide range of environmental conditions. Two approaches to self-calibration are possible:
    a. incorporate and integrated self-calibration,
    b. incorporate humidity and temperature sensors and apply calibration corrections based on empirical relationships.

2. Add transmit functionality to base station:
    a. remote on/off, calibration, and battery check,
    b. remote slow/fast control, query state, adjust the preamplifier setting,
    c. remote adjustment of the average/report time.
3. Add calibration, slow/fast/transient switch/button to exterior.
4. Improve/correct filter network:
    a. evaluate current implementation vs. FFT chipset (power vs. performance),
    b. replace capacitors at output of filters (currently out of spec),
    c. develop an electronic test bed for "factory calibration" of the octave band filters.
5. Update printed circuit board to eliminate re-works and thereby reduce the electronic and acoustic noise floor.
6. Create optional microphone attachments (inset or boom).
7. Create microphone replacement attachment (for electronic noise test; required by ANSI).
8. Pursue ANSI certification.
9. Implement weather monitoring software to automatically exclude data during high winds.
10. Implement automatic Google Earth and/or GIS mapping.
11. Increase acoustic measurement functionality (e.g., construction noise , airplane counting, long-term traffic noise monitoring).