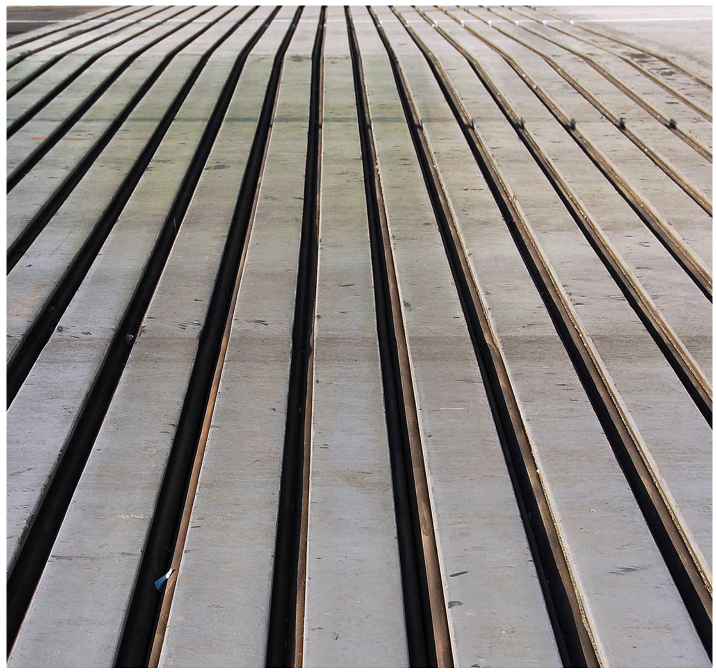
Expansion Joint Noise Reduction on the New Tacoma Narrows Bridge

WA-RD 785.1

Tim Sexton

December 2011



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16. ABSTRACT

Washington State Department of Transportation (WSDOT) responded to citizen complaints about expansion joint noise on the new Tacoma Narrows Bridge (TNB) by installing new wall coated in noise absorptive materials. The goal of the project was to reduce low frequency noise from the bridge. The report highlights the collaborative process used to develop the project design, the methodology used to evaluate the project's performance, and the project results. Lessons learned include suggestions for improving acoustic performance evaluation.

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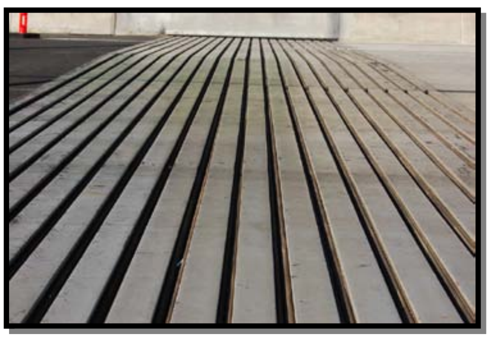

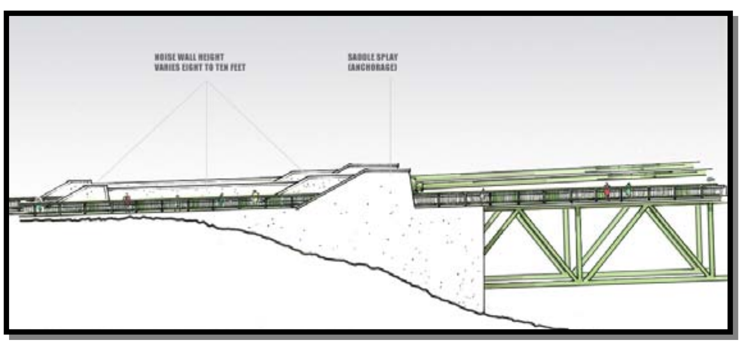

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EXECUTIVE SUMMARY

The Washington State Department of Transportation (WSDOT) Tacoma Narrows Bridge (TNB) office received complaints about the annoying noise coming from the new bridge as vehicles passed over the expansion joints that connect the bridge's approach to the its deck. The project was the first use of this type of expansion joint in Washington State and WSDOT had not heard of noise complaints with similar joints installed elsewhere. Although the area around the expansion joint did not qualify for traffic noise abatement when it was analyzed before construction, WSDOT attempted to reduce noise on the TNB because of the unique nature of the expansion joint noise and related annoyance it caused for nearby residents.

A number of constraints limited the available options for mitigating the expansion joint noise:

- Structural – vertical and wind loading;
- Safety – crash worthy, visual distraction;
- Aesthetic – maintain iconic profile, view for drivers and general public; and
- Acoustic – reducing of the unique expansion joint noise

Design of Noise Reduction Features

To address the project constraints, a collaborative process among WSDOT specialists and private industry was initiated to develop a possible solution to the problem. This collaboration designed concrete walls coated with a sound absorbing material extending from the joint out to the neighborhoods on both sides of the roadway. Adjacent crash barriers were also coated with sound absorptive material.

Research Designation

Highway-related noise continues to be a source of public annoyance and new solutions to reduce transportation noise need to be developed. This noise reduction strategy was treated as a research project because it was a seminal in many ways, including WSDOT's first use of absorptive materials to mitigate non-highway traffic-related noise and WSDOT's first bridge retrofit for noise reduction. This strategy for reducing bridge expansion joint noise had not been used previously anywhere in the world. In fact, globally, there are, currently, no best practices for reducing bridge expansion joint noise.

Evaluation Methodology

Sound levels and frequencies were measured before the project, after the new walls were constructed without absorptive treatment, and after sound absorptive treatment was added to the new walls. Measurements focused on changes in low frequency sound since these frequencies travel farthest. Low frequency sound was also believed to be the source of most public annoyance. Traffic noise in general was not expected to be reduced by the project.

Results and Conclusions

The measurement results suggest a reduction of low frequency sounds with the addition of the new walls and further reductions after sound absorptive treatment was added.

Complaints stopped after the noise reduction project was completed. Discussions with residents living near the project also suggest that the sound of the expansion joint was less annoying than before the noise reduction project.

A number of problems were encountered during design and construction of the noise reduction project. Staff changes at the product vendor lead to some misunderstandings during design and resulted in last minutes changes during installation. There were also some problems with adhesion of the sound absorptive product to the new barriers and existing crash barriers. These problems were resolved with limited effect to the project cost and schedule.

After analyzing the measurement results, it is recommended that an improved measurement methodology be developed for future bridge noise reduction projects. Since there are no accepted best practices for this type of analysis, WSDOT has submitted a research proposal to the National Cooperative Highway Research Program (NCHRP) to develop best practices for designing and evaluating bridge joint noise reduction.

BACKGROUND

Tacoma Narrows Bridge Project Description

The new TNB is parallel to and south of the existing 1950 TNB. It carries four 11-foot-wide lanes of eastbound traffic toward Tacoma. The left lane is a high-occupancy-vehicle (HOV) lane, the two center lanes are general purpose lanes open to all traffic, and the right lane is an "add/drop" lane that extends across the bridge to the Jackson Avenue exit.

In addition, the bridge has a 10-foot right shoulder for disabled vehicles and a 10-foot barrier-separated bicycle/pedestrian lane.

The new Tacoma Narrows Bridge was the first toll facility in western Washington in nearly five decades.

Why is WSDOT attempting to mitigate joint noise from the Tacoma Narrows Bridge?

Since the opening of the new TNB, residents adjacent to the bridge have complained about an irritating low-frequency “zipper” noise caused by vehicles’ tires passing over the new bridge’s expansion joint. In some cases, complaints were received from residents living approximately one-half mile from the expansion joints’ location. According to the numerous complaints, the expansion joint noise is more annoying than sounds from traffic on the regular highway (SR 16) or bridge deck. This is likely due to the impulsive (spikes in sound at certain frequencies) and intermittent nature of the low frequency joint noise compared to overall traffic noise. Highway traffic noise tends to be more consistent and broadband (similar across all audible frequencies). There is no record of complaints related to expansion joint noise on the existing bridge prior to the completion of the new bridge span.

This distinction between the types of sound from highway traffic and the joint is important because the area was analyzed for traffic noise impacts, as part of the National Environmental Policy Act (NEPA) process, and did not qualify for noise abatement according to FHWA and WSDOT noise policy. However, the analysis did not anticipate the uniquely annoying noise created by vehicle’s passing over the expansion joints. Also, FHWA’s Traffic Noise Model (TNM v2.5), the required model for federal-aid highway projects, cannot model expansion joint noise.

WSDOT typically focuses on reducing conventional traffic noise, because of legal and funding limitations to reducing other annoying sounds like truck compression-brakes, rumble strips, etc. These limitations are outlined in the WSDOT noise policy that complies with federal rule 23 CFR 772.

Standard traffic noise mitigation blocks the line-of-sight between the “source” (truck exhaust stack and/or tire/pavement interface) and the “receiver” (resident). The line-of-sight is normally blocked by a concrete noise barrier or earthen berm placed between homes and the highway. While barriers and berms can mitigate both direct *and* reflected noise, there are instances where alternative forms of noise reduction may be more effective, context appropriate, constructible, and/or cost effective.

Exhibit 1: Expansion Joint in Transit and Tacoma Narrows Bridge Overhead View

Left - new expansion joint being transported from Ohio. Right - overhead view of bridge from the East, with new joint location highlighted.

Has WSDOT addressed expansion joint noise in the past?

WSDOT has heard infrequent complaints about expansion joint noise in the past; there is no documentation of target efforts to reduce expansion joint noise. While no documentation was discovered, verbal recollections from WSDOT staff recall an attempt to reduce noise by filling the gaps between the plates of the expansion joints with rubber on I-90 over Lake Washington. Unfortunately, the rubber quickly fell apart under these conditions (over 120,000 AADT).

What makes this joint unique?

Existing Bridge

The expansion joints on the existing Tacoma Narrows Bridge span are a longitudinal finger joint design that provides an un-broken driving surface throughout its range of movement. There are four of these joints on the existing bridge.

The existing bridge span has a metal guardrail, as shown in Exhibit 2. The guardrail has some hard surface to reflect sound from traffic, but most sound is transmitted around the rails in a direct path out from the roadway.

New Parallel Bridge

The expansion joints on the new bridge are a transverse accordion design that provide for up to six feet of expansion/contraction. The new joint creates a broken driving surface during expansion and contraction. There are two joints on the new bridge that connect either approach to the bridge deck. This is the first time a transverse accordion expansion joint has been used by WSDOT.

On the new bridge span, concrete crash barriers and large cable housings are directly adjacent to the expansion joints. This concrete surface creates significantly more reflective surface for sound to “bounce” around and transmit out into adjacent neighborhoods than on the existing bridge span.

Expansion joint noise at nearby residences appears to come directly from the joint and from noise bouncing off the crash barrier and bridge walls and reflecting towards adjacent residences. Images of both joint types are shown in Exhibit 2.

The new bridge span has a concrete safety barrier near the expansion joint, as shown in Exhibit 3 (far right) and Exhibit 5. The concrete safety barrier has much more hard surface to reflect traffic noise from the roadway out into the adjacent neighborhood than the metal guardrail on the existing bridge.

Exhibit 2: Comparison of Expansion Joint on the Existing and New Tacoma Narrows Bridges

Left – one of four existing longitudinal finger joints on the existing bridge. Right – one of two new transverse accordion joints on the new bridge structure.

Who was involved in designing the project?

Given WSDOT's inexperience reducing this type of expansion joint noise, we inquired nationally and internationally to see if other acoustic experts were aware of similar situations. We were unable to find others who had addressed this type of expansion joint noise before and the literature reviewed on the subject was not directly relevant.

Since no national experts could be identified, WSDOT initiated a collaborative process to internally design and evaluate the project. WSDOT staff worked together with a local sound absorptive material supplier to address the following challenges:

- Structural – vertical and wind loading

  Tim Moore, PE, SE, Mega Projects Bridge Manager

- Safety – crash worthiness, visual distraction

  Tim Moore, PE, SE, Mega Projects Bridge Manager

- Aesthetic – maintain iconic profile, view for drivers and general public

Paul Kinderman, PE, AIA, State Bridge and Structures Architect

- Acoustic – reducing noise from the unique expansion joint

  Tim Sexton, WSDOT Air Quality, Noise, Energy Policy Manager

- Product Vendor – support project design to promote product performance

  Concrete Systems Northwest, Inc., Soundsorb™ sound absorptive material vender

  Everett Temme, formerly of Concrete Systems Northwest, Inc.

  Boone Bucher, Concrete Solutions, Inc.

Through this collaboration, WSDOT determined that adding sound absorptive treatment around the expansion joint could best address the acoustic, structural, and aesthetic needs of the project. WSDOT then worked with internal staff and the product vendor on the final project design.

RESEARCH DESIGNATION AND PRODUCT SELECTION

Given the complicated and uncertain nature of the project, WSDOT elected to advance the work as a research project and acquire the sound absorptive material through a sole-source material acquisition process. This was also WSDOT's first use of absorptive materials to mitigate an atypical highway-related noise and first retro-fitting of a bridge for noise reduction.

Potential Lessons Learned

While the proposed abatement has a number of features specific to this project, there were a number of more general lessons that WSDOT hoped to learn from this project to inform future projects. For example:

1) How effectively do absorptive materials mitigate traffic noise in general and the TNB expansion joint noise in particular?
2) What are the best practices for installing an absorptive finish on a high volume highway? What are the final material and installation costs and cost breakdown? Do/can installation practices affect the product's final installed appearance?
3) There are a number of structural and safety questions related to noise reduction on a bridge and bridge approach that will be addressed in this design. The relatively small amount of area affected by the project on the Tacoma Narrows Bridge could provide valuable data to help inform future noise reduction efforts on project such as I-5 Ship Canal Bridge, the SR 520 floating bridge, and the SR 99 Alaskan Way Viaduct.

4) How can public-private partnerships be created to foster creative solutions to unique and complex problems? Can informal partnerships without financial guarantees, such as the relationship between WSDOT and Concrete Systems Northwest, be practical in other applications?
5) Is the proposed monitoring plan for the TNB adequate? If not, what improvements can be made to ensure that the most accurate and informative statistics are collected?

Product Selection

There are many absorptive products on the market and they vary widely in appearance, effectiveness, installation procedures, and versatility. However, the many limitations on the TNB (safety, structural, aesthetic, etc) restrict the number of products that satisfy all the project's constraints. Soundsorb ™ was one of the products that met the product need.

WSDOT and its contractors had very limited experience with absorptive products so there was some concern that problems might arise during the installation of an absorptive product. WSDOT's contractor had a number of problems installing an absorptive material (a different product) on a recent WSDOT project on SR 17. Therefore, the sole source material acquisition process was used to ensure that a local vendor, *Concrete Systems Northwest, Inc.*, would be selected to provide timely engineering and product expertise for designing, fabricating, and installing the absorptive product.

In addition to satisfying all the needs of the project, Soundsorb™ was recommended for the following reasons:

1) *Produced and supported locally* – Concrete Systems Northwest, manufacturers of Soundsorb™, are located in Bellevue, WA, and have local technical support to improve the chances for success on this high-visibility project.
2) *Known to effectively reduce absorptive sound* – ASTM test results show the product absorbs between 95% and 100% of all the sound energy that hits the panel.
3) *Context sensitive* - Soundsorb™ is versatile enough that it can be textured to maintain the bridge's aesthetic vision and blends with the current design.

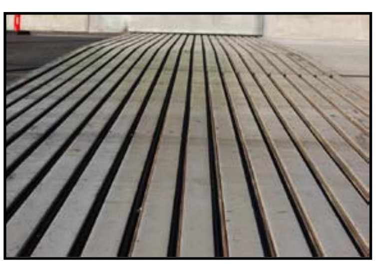
NOISE REDUCTION PROJECT DESIGN

What is the source of the joint noise experienced by adjacent residents?

Based on initial sound level measurement comparisons from above and below the joint, discussions with local residents, and the best professional judgment of the project team, including the product vendor, it was determined that most residents were experiencing the joint noise radiating from the top of the joint.

For residences with a direct line-of-sight to the joint, the noise appeared to be traveling both from a direct path from the joint and from reflected noise bouncing off the adjacent suspension cable housings and concrete safety barriers. Residences below the joint were thought to be experiencing reflected noise reflecting off the cable housings and crash barriers and refracting down into the neighborhoods. It is possible that structural noise and vibration were also contributing to noise heard at homes below the joint. However, evaluating structural noise and vibration was determined to be beyond a reasonable scope for this project because of the even greater uncertainties and unknowns associated with this type of noise.

Exhibit 3: Additional Views of new TNB Expansion Joint



From left to right: 1) topside - expansion joint, 2) underside - expansion joint, 3) view of the crash barrier and cable housing with joint location circled.

Could traditional mitigation measures, such as noise barriers, have been used?

Since the expansion joint was installed on an elevated bridge structure, WSDOT estimated that at-grade noise walls would need to be more than 40-feet tall to provide "feasible" noise reductions at some locations. Therefore, building at-grade traffic noise barriers along both sides of the bridge that were high enough to block the line-of-sight between homes and the expansion joint would be prohibitively expensive, block valuable views, and pose constructability issues because of steep slopes in many locations. For these reasons, this option was not selected.

Traditional reflective traffic noise walls placed directly on the bridge could reduce some of the direct path noise for receivers with a direct line-of-sight to the noise walls. However, reflective concrete walls would increase the amount of reflective surface and have the potential to increase the reflected expansion joint noise at some adjacent residential locations. There were also concerns about the ability of heavy concrete walls to comply with the bridge's structural weight and wind load limitations and safety standards, while maintaining the bridge's aesthetic qualities for passing motorists and the general public. Since reflected noise was presumed to contribute to the annoying noise in the adjacent neighborhoods, adding additional reflective surface was determined to not be a viable option for this project.

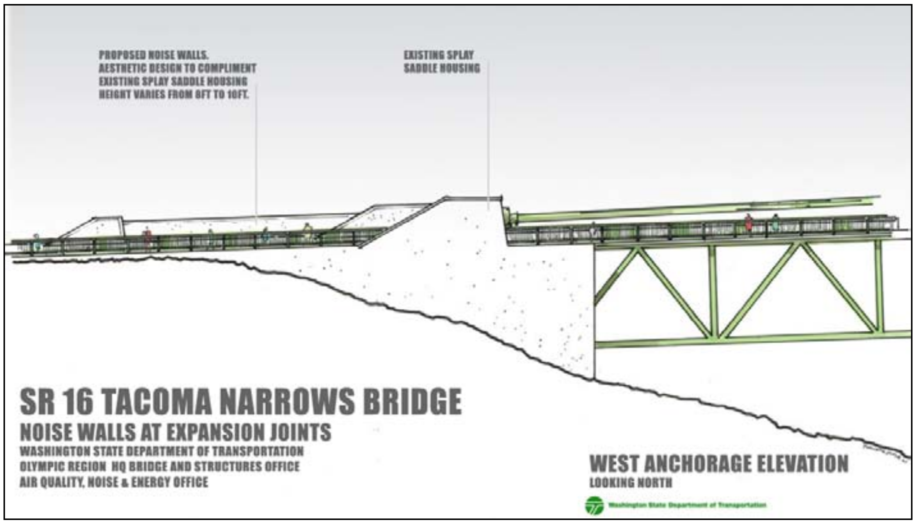
What was the final design for the noise reduction project on the new TNB?

The result of collaborative process between WSDOT and *Concrete Systems Northwest, Inc.* was the design of approximately 10-foot tall concrete walls coated with a sound absorbing material that extended from the expansion joint back towards the bridge approach. It was not possible to extend walls onto the bridge deck itself because of loading constraints on the bridge.

The crash barrier on both sides of the joint and the north side cable housings were also coated with absorptive material. Cable housings on the south side of the bridge were set back on the opposite side of the bicycle/pedestrian walkway and were not treated. The walls were designed to be tall enough to block the line-of-sight to the joint from some adjacent homes and the absorptive finish was added to reduce noise reflections.

All of the new elements “come from the same family of shapes” as the existing bridge, per AASHTO LRFD Bridge Design Specifications C2.5.5.

Exhibit 4: Artistic Rendering of Proposed Noise Reduction



Early artistic rendering (Kinderman, 2007): The above drawing depicts the new proposed wall only on the inside (south side) of SR 16. The final design had a similar wall on both sides of the roadway.

Exhibit 5: Images of New Walls - Post Construction

View from behind new wall structure from SW corner of bridge.

New walls with absorptive treatment, walls on NW corner of bridge. Cable housing circled in red for comparison with images below.

Close up view of sound absorptive panels attached to the new wall structures.

MEASUREMENT METHODOLOGY

How did WSDOT evaluate the effectiveness of the project?

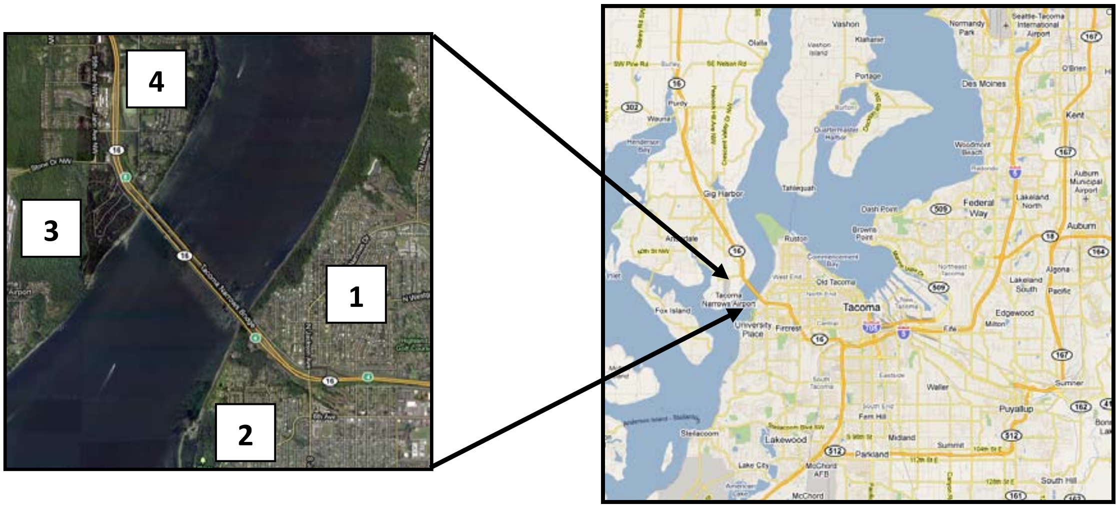
Overall traffic noise was not expected to be reduced by the project. Instead, the goal of measurements was to assess any reduction in the low frequency component of the sound coming from the bridge expansion joints. A series of measurements were taken to assess the efficacy of the project. The project area was divided into geographic “quadrants” reflecting the four areas directly affected by the expansion joint noise.

1. North of SR 16 in Tacoma
2. South of SR 16 in Tacoma
3. South of SR 16 in Gig Harbor
4. North of SR 16 in Gig Harbor

Measurements were collected at 26 total sites, with five to eight locations in each quadrant. Each location was measured pre-construction, after installation of the new walls without sound absorptive materials, and after absorptive materials were added and the project was complete. Some locations further from the expansion joints were selected because of complaints occurring at those approximate locations.

Potential changes in sound levels based on the amount of expansion/contraction of the bridge joint were not addressed.

Exhibit6: Noise Measurement Quadrants and Map



Left - Map of geographic measurement "quadrants", Right - Tacoma area map

Traffic

Traffic was not visible from many of the measurement locations so traffic information was not collected. We understood that differences between measurements in traffic volumes, vehicles mixes (heavy trucks, medium trucks, cars, and motorcycles), and vehicle speeds would create some variability in the reported results. Workforce limitations restricted staff to a single person per measurement period and simultaneous sound level measurements and traffic counts were not possible. To reduce variability based on traffic changes, measurements were collected during a similar day of the week and time for each location. No noticeable traffic events occurred during any of the measurements.

Measurement Metrics

All measurements were 10-15 minute time-weighted average L_{eq}, with a 1/3 octave band filter, using Ono Sokki 5560 ANSI Type 1 sound level meters with Fast time weighting. The 1/3 octave band filter allows individual frequency bands to be captured.

Exhibit 7: Receiver locations north of SR 16 in Tacoma

Exhibit 8: Receiver locations south of SR 16 in Tacoma

Exhibit 9: Receiver locations south of SR 16 in Gig Harbor

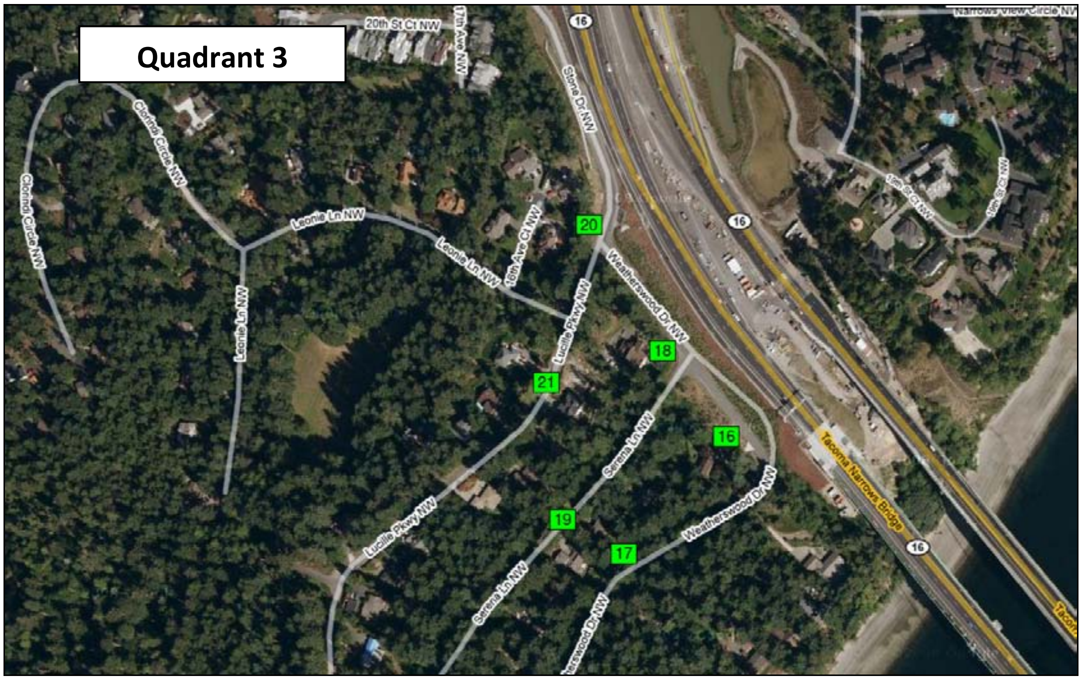
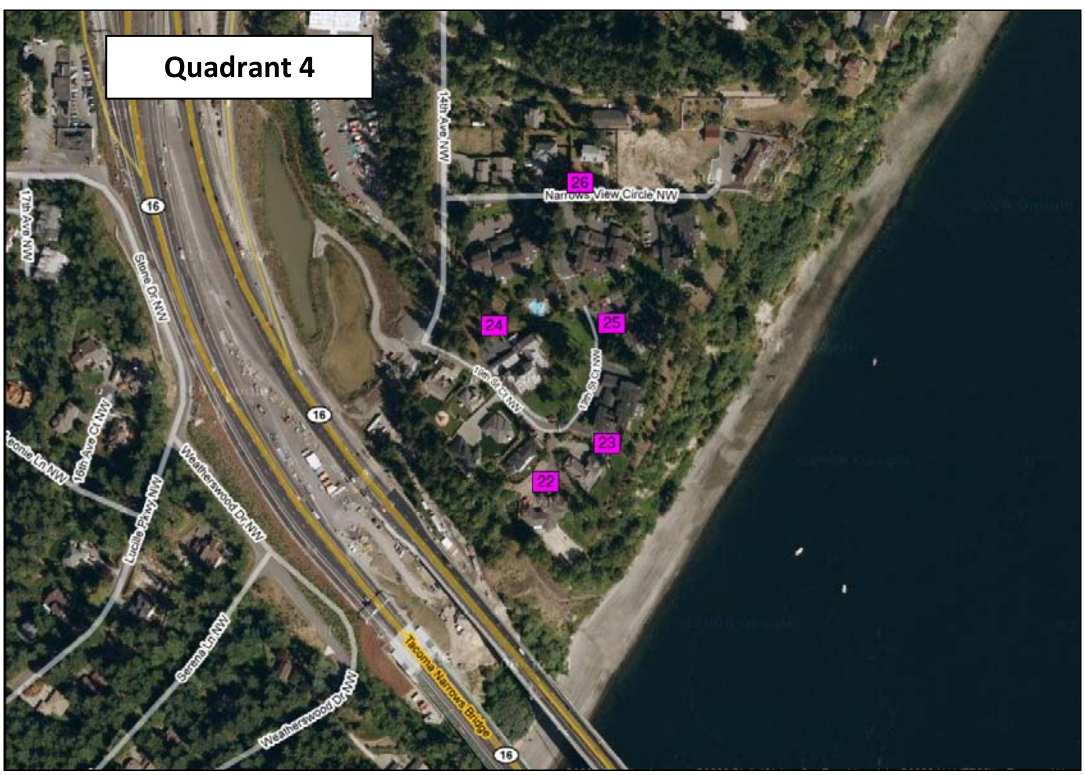


Exhibit 10: Receiver locations north of SR 16 in Gig Harbor



MEASUREMENT AND CONSTRUCTION CHALLENGES

There were a number of unexpected challenges encountered on the project after work had commenced. Challenges to both the measurement methodology and construction of the project are described below. All the challenges below will need to be addressed more comprehensively on future projects.

Performance Measurement

Measurement Equipment Issues

There were some technical problems with the pre-construction sound level measurements that were not discovered until after construction of the new walls had commenced. Specifically, the microphone diaphragm on one of the sound level meters appears to have been damaged. We suspect this damaged diaphragm contributed to some potentially "contaminated" results of the high frequency measurement levels throughout the project area, especially measurements on the north side of SR 16 in Gig Harbor (see Exhibit 10).

To address this challenge, the damaged meter was replaced and the final measurement trends appear to confirm the validity of the low frequency measurement levels targeted by this project.

Isolating the expansion joint noise from overall traffic noise and local sounds

Other area noise sources included airplane flyovers to/from the nearby Tacoma Narrows Airport, traffic on SR 16 and local streets, and neighborhood sounds including lawn mowers, car and house door banging, and barking dogs. At locations closer to the joint, traffic noise was the dominant source with the joint noise clearly audible and occurring with enough frequency to be captured with the L_{eq} metric. However, traffic and expansion joint noise were clearly audible at all locations, but other noise sources, such as passing vehicles on local roads, were intermittently dominate.

To address challenge of isolating the expansion joint noise, measurements were paused when non-traffic/expansion joint noise sources were clearly audible. Sound levels and frequency results between measurements and locations (above and below joint) were compared to determine whether measurements were contaminated. Even after discarding some of the clearly contaminated data, there remain some concerns about some of the measured results.

Exhibit 11: Example Measurement Location – Quadrant #3, South of SR 16 in Gig Harbor

SW bridge corner – pre-construction measurement location with cable housings in background. One of the few sites with a line-of-sight to expansion joint.

Restricted views to the top of the expansion joint

Staff limitations prevented traffic and vehicle mix counts from being collected. It was not possible to normalize data for traffic without this information. To address this challenge, measurements were taken during similar times of day to attempt to evaluate similar traffic volumes and vehicle mix compositions. However, even without obvious traffic events occurring, there is a high likelihood that some measurements reflected different traffic conditions that influenced measured results.

Determining effect of the project

Comparative measurements between the three measured scenarios give some indication of the project's performance. However, the challenges previously listed make it difficult to make a final quantitative determination of the results.

To address this challenge, a number of variables were analyzed to better understand the significance of the measured values. For example, comparing measured results at locations above and below the joint and Quadrant 1 and Quadrant 2 measured results suggest a clear trend towards reduced low frequency sound. Discussions with local residents and project team site visits also suggest that the project was successful at reducing low frequency noise

New Wall Structures

Cast-in-Place vs. Pre-Cast Concrete Wall Panels

The walls were originally planned to be cast-in-place so dowels could be drilled in at very close spacing. Since the architecture was complex, WSDOT didn't believe a pre-cast panel could be installed without a lot of field modifications and added risk that construction would be within allowable tolerances. However, the contractor was able to demonstrate their ability to pre-cast the panels and WSDOT accepted their proposed Cost Reduction Incentive Proposal (CRIP).

Sound Absorptive Treatment

Design Challenges

The contract omitted the joints in the concrete walls and safety barrier panels. These joints had to be saw-cut before/after installation to prevent the material from cracking and falling off the new wall structures when the walls expanded and contracted with heat/cold. This was a consequence of substituting pre-cast for the original cast-in-place wall panels. There were more joints with the precast alternative than had been envisioned with the CRIP.

Installing Absorptive Material – Steel Traffic Barriers

Soundsorb™ was attached to the steel traffic barrier cover plates, located directly above the modular expansion joint, by an epoxy skim coat. The manufacturer recommended that Soundsorb™ panels should be applied to sandblasted structural steel. However, the material effectively bound to the galvanized surface finished, which WSDOT elected to maintain.

Installing Absorptive Material – Concrete Panels

There were also challenges attaching the sound absorptive panels to the new precast panels and the existing cable-housing. The product was designed for application to concrete using an adhesive. Adhesion of the material to concrete proved difficult and required some trial and error before a proper bond could be formed between the two mediums.

Product Durability

The Soundsorb™ panels were also found to be more fragile than expected and additional panels had to be ordered to complete the project.

Since project completion, the Soundsorb™ panels have been struck and damaged by traffic. Extra barriers are kept on hand to repair any damaged sections.

MEASUREMENT RESULTS

What project goals were being evaluated?

The primary goal of this project was to reduce the low frequency noise generated by vehicles passing over the new expansion joint.

The following tables are a summary of the measured values for each quadrant, by frequency, for each of the measured conditions: pre-construction, with wall but without absorptive treatment, and walls and absorptive treatment installed. For the summaries below, any contaminated high frequency values (16 kHz – 20 kHz) for the pre-construction measurements have been removed.

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Exhibit 12: Summary numeric measured values and graph of frequency distribution for receiver locations in Quadrant 1 (north of SR 16 in Tacoma)

Frequency	Pre Construction (dBA)	Walls: No Absorption (dBA)	Walls with Absorption (dBA)	Change with Project (dBA)
	22.23	16.57	10.52	11.71
	22.73	19.95	14.63	8.11
	24.79	23.57	19.20	5.59
	27.84	27.69	25.36	2.48
	31.55	30.73	28.93	2.61
	38.33	37.05	36.61	1.72
	41.36	41.26	40.46	0.90
	42.48	39.74	40.56	1.91
	42.87	39.78	40.98	1.90
	42.20	40.25	40.77	1.43
	43.44	40.62	42.02	1.42
	44.76	42.16	44.26	0.50
	47.42	43.82	44.99	2.43
	48.32	45.50	46.54	1.78
	50.35	47.51	48.20	2.15
	51.97	49.16	49.57	2.40
	53.22	51.29	51.09	2.13
	52.27	51.60	51.22	1.05
	50.97	50.04	49.79	1.18
	49.21	47.83	47.41	1.79
	46.65	44.77	44.69	1.96
	44.32	42.32	42.30	2.01
	42.67	39.61	40.99	1.68
	40.46	37.77	39.31	1.15
	36.63	35.58	35.13	1.50
	33.38	32.86	30.77	2.61
	28.05	29.72	26.02	2.03
	24.06	24.09	20.37	3.69
	22.79	18.18	14.13	8.66
	22.51	14.28	9.43	13.07
	22.49	15.38	7.36	15.14

Contaminated 16 kHz -20 kHz measurements removed for pre-mitigation measurements.

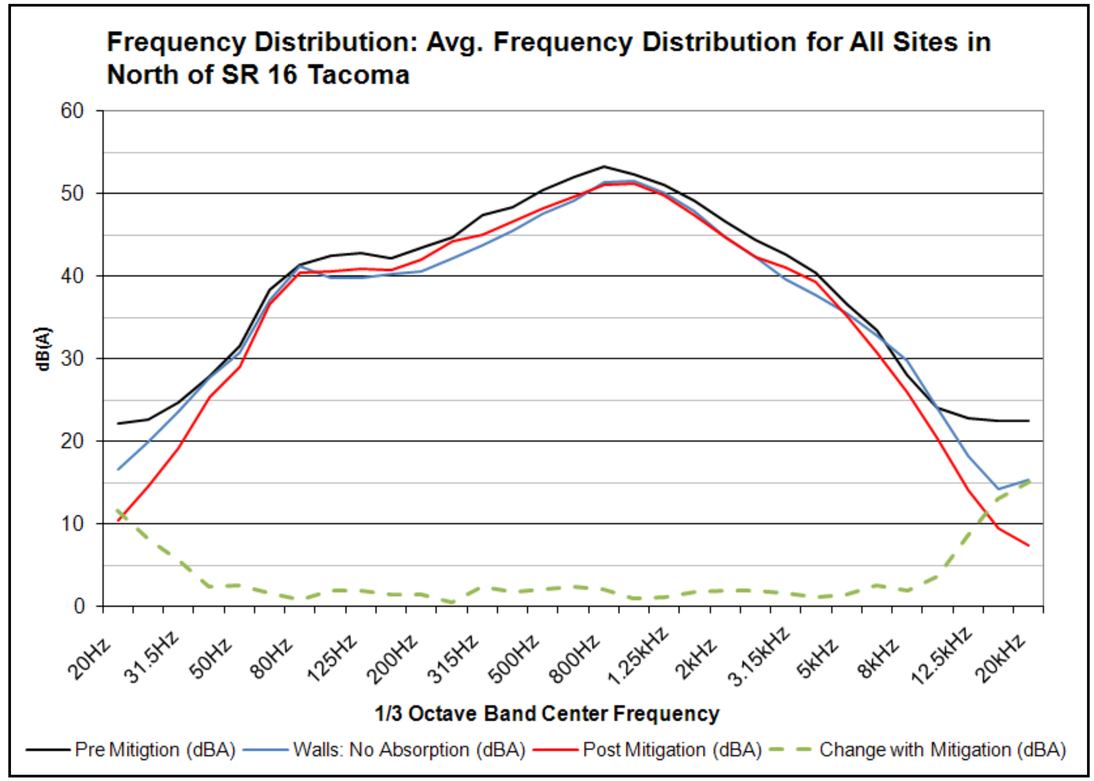


Exhibit 13: Summary numeric measured values and graph of frequency distribution for receiver locations in Quadrant 2 (south of SR 16 in Tacoma)

Frequency	Pre Construction (dBA)	Walls: No Absorption (dBA)	Walls with Absorption (dBA)	Change with Project (dBA)
	12.5	17.4	12.3	0.2
	13.2	18.4	13.8	-0.7
	18.3	21.1	16.8	1.5
	20.5	25.7	21.7	-1.2
	25.0	29.0	25.8	-0.8
	29.0	34.4	32.5	-3.4
	33.1	38.7	35.9	-2.8
	34.2	39.1	36.4	-2.2
	38.7	38.8	37.6	1.1
	35.4	38.0	38.0	-2.5
	35.3	38.0	37.7	-2.3
	39.0	39.2	39.4	-0.4
	38.3	40.9	41.3	-2.9
	42.5	42.6	42.1	0.4
	43.5	46.0	43.6	-0.1
	45.8	49.6	45.8	0.1
	49.4	51.7	47.6	1.8
	46.9	51.1	47.6	-0.6
	46.3	48.9	46.2	0.1
	44.6	46.3	44.1	0.5
	39.8	42.7	40.9	-1.1
	38.4	38.7	38.5	0.0
	36.2	34.9	35.8	0.3
	32.9	31.2	33.1	-0.2
	30.7	27.7	30.5	0.2
	29.3	23.7	28.1	1.3
	26.2	21.4	23.5	2.7
	20.8	16.6	19.0	1.9
	20.1	14.1	16.1	4.0
	20.0	12.3	14.2	5.8
	20.0	11.8	14.5	5.5

Contaminated 16 kHz -20 kHz measurements removed for pre-mitigation measurements.

Exhibit 14: Summary numeric measured values and graph of frequency distribution for receiver locations in Quadrant 3 (south of SR 16 in Gig Harbor)

Frequency	Pre Construction (dBA)	Walls: No Absorption (dBA)	Walls with Absorption (dBA)	Change with Project (dBA)
	16.0	14.6	11.5	4.5
	18.5	17.9	14.1	4.3
	22.0	22.7	18.7	3.4
	24.7	27.6	24.6	0.1
	28.0	30.7	29.3	-1.3
	33.4	37.8	35.4	-2.0
	38.2	40.7	38.7	-0.5
	38.6	40.8	38.3	0.3
	39.0	41.8	38.6	0.5
	39.3	41.3	38.9	0.5
	40.6	42.7	40.4	0.2
	41.9	45.2	42.8	-0.9
	45.5	47.7	45.5	0.0
	49.1	49.0	46.5	2.6
	52.2	51.9	48.5	3.7
	54.9	55.1	51.7	3.2
	57.1	57.1	54.2	2.9
	56.9	56.8	54.5	2.4
	56.0	55.5	53.3	2.7
	54.1	53.2	50.7	3.5
	51.3	50.0	47.1	4.1
	48.3	46.3	44.1	4.2
	45.4	42.7	40.8	4.6
	42.0	38.9	37.3	4.7
	38.6	34.9	34.4	4.2
	34.9	31.6	31.2	3.8
	30.8	28.3	27.7	3.1
	24.9	22.3	21.7	3.2
	18.5	17.5	16.5	2.0
	20.7	13.6	13.0	7.7
	20.4	11.9	11.7	8.7

Contaminated 16 kHz -20 kHz measurements removed for pre-mitigation measurements.

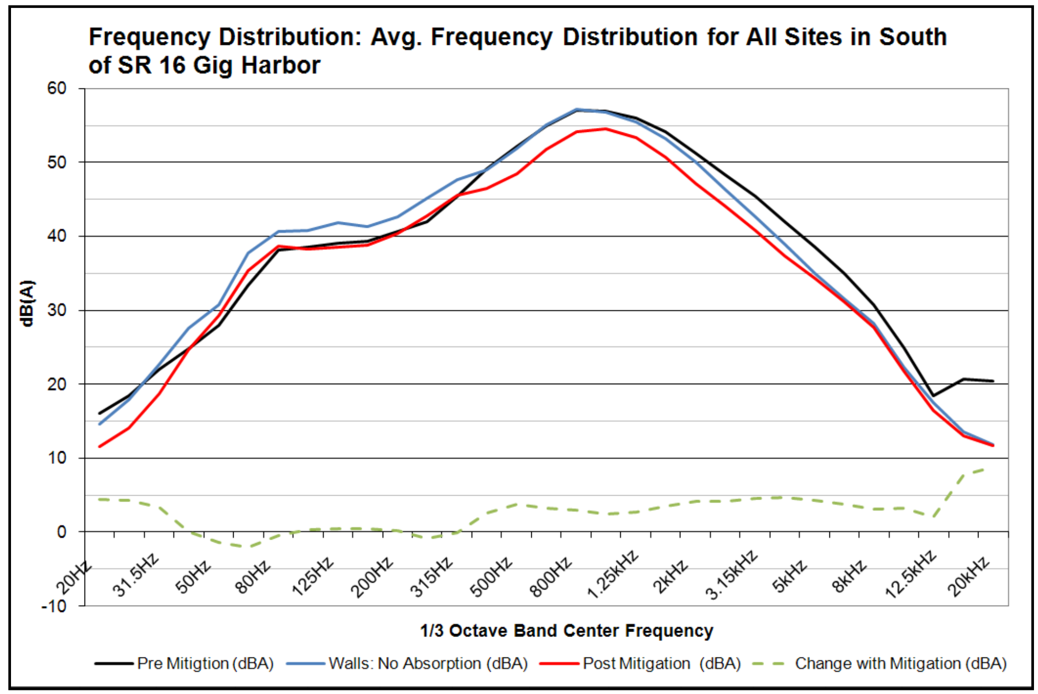
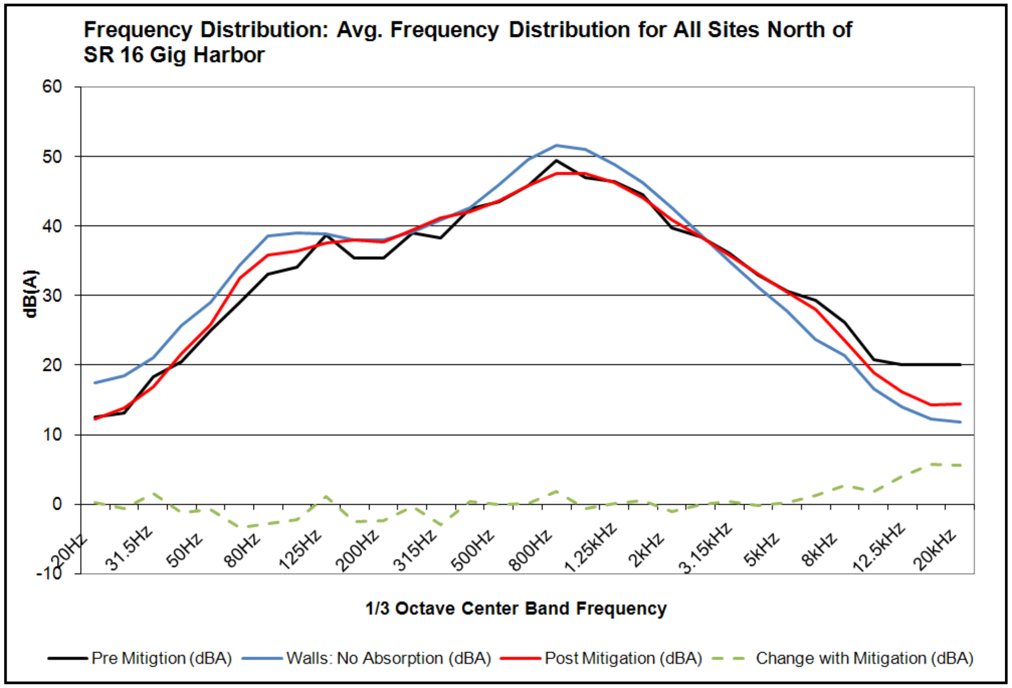


Exhibit 15: Summary numeric measured values and graph of frequency distribution for receiver locations in Quadrant 4 (north of SR 16 in Gig Harbor)

Frequency	Pre Construction (dBA)	Walls: No Absorption (dBA)	Walls with Absorption (dBA)	Change with Project (dBA)
	12.5	17.4	12.3	0.2
	13.2	18.4	13.8	-0.7
	18.3	21.1	16.8	1.5
	20.5	25.7	21.7	-1.2
	25.0	29.0	25.8	-0.8
	29.0	34.4	32.5	-3.4
	33.1	38.7	35.9	-2.8
	34.2	39.1	36.4	-2.2
	38.7	38.8	37.6	1.1
	35.4	38.0	38.0	-2.5
	35.3	38.0	37.7	-2.3
	39.0	39.2	39.4	-0.4
	38.3	40.9	41.3	-2.9
	42.5	42.6	42.1	0.4
	43.5	46.0	43.6	-0.1
	45.8	49.6	45.8	0.1
	49.4	51.7	47.6	1.8
	46.9	51.1	47.6	-0.6
	46.3	48.9	46.2	0.1
	44.6	46.3	44.1	0.5
	39.8	42.7	40.9	-1.1
	38.4	38.7	38.5	0.0
	36.2	34.9	35.8	0.3
	32.9	31.2	33.1	-0.2
	30.7	27.7	30.5	0.2
	29.3	23.7	28.1	1.3
	26.2	21.4	23.5	2.7
	20.8	16.6	19.0	1.9
	20.1	14.1	16.1	4.0
	20.0	12.3	14.2	5.8
	20.0	11.8	14.5	5.5

Contaminated measurements removed for pre-mitigation measurements.



CONCLUSIONS

The project was successful and taught WSDOT a number of lessons about the design and evaluation of future noise pilot studies. So despite the problems with data collection and noise interference from other sources, apparently the measurement data from before and after is significant enough to be conclusive about this?

Measurements suggest that the project reduced low frequency noise from the expansion joint

As expected, there is very little difference in the overall sound levels between the pre- and post- noise reduction project conditions. This is shown by the similar overall values for the measured results. However, comparisons of measurements by frequency suggest that the project effectively reduced low frequency noise from the expansion joint in many locations. Again, the low frequency noise was the source of complaints. The measured results also show a reduction of the high frequency sound that may have also contributed to public annoyance.

For nearly all of the measured locations, the low and high frequency measured sounds are lower after the project was constructed compared to the pre-construction condition. There is also a measurable decrease in the low and high frequency sound with the absorptive treatment added compared to the new walls alone, before absorptive treatment was added.

Public feedback suggests the project was effective

In addition to the quantitative description of results included in this report, positive comments were heard from residents by WSDOT staff while in the field. Approximately five people commented positively on the project, with at least one person commenting from each of the measured quadrants, except from Quadrant #3, south of SR 16, in Gig Harbor. No negative comments from the public in the field after the new walls were constructed. In some cases, the positive comments were from the same people that complained about the joint noise during the pre-construction measurements. Formal public complaints also stopped after the project was completed.

WSDOT learned a number of lessons to apply on future noise pilot studies

The challenges encountered during the measurements and construction on this project must be addressed in future projects.

- Future research is needed improve measurement methods for this type of evaluation to improve the quality of the results. Research to this effect has been proposed to the National Cooperative Highway Research Program (NCHRP) and WSDOT is encouraged to support this and other related efforts.
- The challenges encountered during construction of this project may also be resolved through additional research and experience with absorptive materials. There may also be a benefit to clarifying specifications (construction and aesthetic) for absorptive materials before considering their use on future WSDOT projects.

POTENTIAL LESSONS LEARNED - RESPSONSES

Although the proposed abatement has a number of features specific to this project only, there are many more lessons that could be learned from this project and transferred to other WSDOT projects. For example:

1) *How effectively do absorptive materials mitigate traffic noise in general and the TNB expansion joint noise in particular?*

   The results of this study show that targeted use of absorptive materials may be effective for reducing reflective noise is some situations, especially bridge expansion joints.

2) *What are the best practices and costs for installing an absorptive finish on a high volume highway?*

   The Manufactures Representative specified a cement based adhesive but the Contractor had better success using a two part epoxy.

   The total cost for this noise wall project was $878,302.22, the Soundsorb™ acoustical treatment bid amount was $60.00 per square foot or $192,678.00. The small amount of material resulted in higher per unit costs.

3) *Do/can installation practices affect the product's final installed appearance?*

   The Soundsorb™ panels were made of a light weight concrete material with high air voids. The panels provide no structural strength and must be attached to a structural wall. No additional insight was gained on the affect of installation practices on final product appearance.

4) *There are a number of structural and safety questions related to noise abatement on a bridge and bridge approach that were addressed in this design. The*

relatively small amount of area proposed for abatement of the Tacoma Narrows Bridge could provide valuable information to help inform future abatement on the I-5 Ship Canal Bridge, the SR 520 floating bridge, and the SR 99 Alaskan Way Viaduct.

The project design did not introduce any new safety concerns. The location of the new walls on the bridge approach, at less than 10 feet tall, was not a concern for dead loading or wind loading. Retrofitting bridges with noise reducing features could create new challenges that were not encountered on this project.

5) *How can public-private collaborations be created to foster creative solutions to unique and complex problems? Can informal partnerships without financial guarantees, such as the relationship between WSDOT and Concrete Systems Northwest, be practical in other applications?*

The vendor provided design assistance, including sketch drawings, which supported the final project design. The design assistance and related collaboration resulting from the informal public-private relationship was beneficial. Unfortunately, there were some internal problems between the vendor and the material patent holder that caused a moderate delay on the project. There is no indication that this type of conflict would have been avoided had a more formal partnership agreement existed between WSDOT and the vendor.

6) *Is the proposed monitoring plan for the TNB adequate? If not, what improvements can be made to ensure that the most accurate and informative statistics are collected?*

The monitoring plan for this project could have been improved in the following ways.

- Traffic counts and vehicle mix information would have further informed the comparison of the measurements.
- Community measurements were useful to describe the situation experienced by residents, but near-field measurements immediately adjacent to the project would have provided additional information on the performance of the product and insight on the application of absorptive treatments for future projects.
- Modeling the design to evaluate the performance effects of various dimensions of the design. For example, various wall heights and lengths could have been compared on the TNB project to optimize potential noise reductions from the design.