APPENDIX J3

NOISE

Date	Reference
October 31, 2008	Transit Train Horns and Bells Simulation at Minnesota Public Radio (MPR)
November 25, 2008	Construction Noise Memorandum
January 7, 2009	Field Measurements to Determine Reference Sound Exposure Level
March 11, 2009	Transit Train Horn and Bell Simulation at Central Presbyterian Church and St. Louis King of France Church
March 23, 2009	Light Rail Horn and Bell Simulation at MPR Studios H, I, and P
March 30, 2009	Sound Insulation Testing at MPR Studios MMW and P
May 1, 2009	Background Noise Measurements on February 11, 2009, in MPR Studios MMW and P
N/A	Noise Contour Figures
N/A	Detailed Noise Impact Table
N/A	HDR Assessment of Central Presbyterian Church

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Memo

To:	Kathryn O'Brien		
From:	Tim Casey and Elliott B. Dick	Project:	Central Corridor Light Rail Transit
cc:			
Date:	October 31, 2008	Job No:	65891

Re: Transit train horns and bells simulation at Minnesota Public Radio

BACKGROUND

The building which houses *Minnesota Public Radio* (MPR) is located in downtown St. Paul, along the *Central Corridor Light Rail Transit* (CCLRT) route on Cedar Street. Some noise-sensitive interior spaces at MPR may be affected by the introduction of Light Rail Transit on Cedar Street. The *Light Rail Vehicles* (LRV) are expected to sound horns and bells under certain operational circumstances.

Minnesota Public Radio Interior Spaces

The main building occupied by MPR has several additions, each of different vintages. The original building was a two-story bank. One renovation added two stories atop the original bank and houses two studios of particular interest: *Studio M*, also known as Maud Moon Weyerhaeuser Studio, and *Studio P*, also known as the Atrium Studio.

The most recent renovation (2006) included an atrium and a new building to the north of the original bank. This new building houses several studio spaces including one assessed as part of the ESI simulation, *Studio 443*. This building also had several offices with windows onto Cedar Street, some of which were also assessed as part of the ESI simulation.

Studio M: Maud Moon Weyerhaeuser Studio

Studio M was assessed in both the ESI simulation and the HDR simulation. Studio M is a large shoebox-shaped recording studio. One of the long-dimension walls is the exterior wall adjacent to Cedar Street. There is a semicircle window in this wall, made up of two quarter-circle windows. The window in Studio M is just an ordinary window; it has an assembly of clear plastic half-cylinders placed over the windows, which do not appear to be acoustically designed for use in a recording studio. This half-cylinder surface is intended to increase the window isolation by adding mass and an airspace, and additionally to prevent reflections (echoes) by eliminating the flat window surface. There was internal ventilation at the top and bottom of the confined airspace, presumably to prevent condensation.

Studio P: The Atrium Studio

Studio P was assessed in the ESI simulation, but was not assessed as part of the HDR simulation. Studio P is quite a bit smaller than Studio M, and is located above the Northwest corner of the original bank building. It has two windows: a tall, narrow window looks out on Cedar Street, and a quarter-circle window looks out into the new atrium. The windows in Studio P are acoustically designed for use in recording studios, with a thick airspace between the panes of glass and absorption around the airspace perimeter.

Forum

The Forum was assessed in the HDR simulation. The Forum is a large room, half occupied by audience risers. There are two, two-story windows looking out onto a rooftop patio, with two separate doors in the window assembly. These windows, like the windows in Studio P, are designed for studio use, with a thick airspace between two thick layers of glass.

By the description of MPR personnel, the Forum does not have isolation normally associated with a recording studio, aside from the exterior windows. There are single-entry doors; there is no sound-lock arrangement of doors. The floor slab is reportedly not ‘floating’, a method of mechanically separating the floor with the rest of the building. It was also reported that bands playing in the forum could be heard elsewhere in the building, whereas most recording studios are acoustically isolated from the rest of the building in which they reside.

Fitzgerald Theatre

The Fitzgerald Theater is separate from the MPR building, located approximately a half-block away on Exchange Street. This is a theater, originally built in 1910; MPR purchased it in 1980 and subsequently renovated it to its current state. MPR uses this theater regularly for performances and broadcasts, such as, “A Prairie Home Companion.” The lobby is located on Exchange Street, and would have a clear view of LRV’s as they travel Cedar Street due to its glass doors. The stage door opens into an alley, but LRV's will pass by the end of the alley on Cedar Street.

Light Rail Vehicle Bells and Horns

According to Metro Transit standard operating procedures, current LRV horn and bell noise level standards are as follows.

Table 1

Metro Transit LRV Horn and Bell Noise Level Criteria

	Target Level	Measurement Distance
Bells	79 dBA	50 ft
Low-Horn	90 dBA	100 ft
High-Horn	95 dBA	100 ft

LRV horns and bells are currently calibrated when maintenance is performed on the LRV warning system. Metro Transit staff performs the calibration procedure inside the maintenance building, at the prescribed distance from the front of the train, and measures the noise level on a hand-held sound-level-meter.

Metro Transit has adopted standard operating procedures for the sounding of bells and horns, which are attached. Bells are sounded when entering and leaving an LRT station platform. High horns are sounded in emergency situations when operators believe a loud warning is required to alert persons outside the LRV to a hazard. The high horns (2 short blasts) is also sounded when two trains pass each other at a grade crossing. Low horns are typically used only at the Franklin yard and shops as part of LRV operations and maintenance occurring there.

LRT AIRBORNE NOISE TESTING

On September 22, 2008, MPR's consultant, ESI Engineering conducted a simulation of LRT horn and bell use outside MPR in downtown St. Paul. This simulation was attended by an observer from HDR Engineering, which is a consultant under contract to the Central Corridor Project Office. On October 22, 2008, HDR conducted a second simulation, with a more accurate representation of horn and bell noise levels and audible signal use. An observation of the ESI testing and a summary of preliminary findings of the HDR testing follows.

ESI SIMULATION OBSERVATIONS

This test was conducted by Tony Baxter and Bret Peterson, both with ESI Engineering. Steve Griffith represented MPR. A sound engineer for MPR was also present at times during the simulation. ESI reported that this simulation was intended to investigate the potential of noise intrusion from light rail transit train horns and bells into the MPR building.

ESI Simulation Method

The transit horn and bell source was simulated with a DAT recording played with a TEAK RD130TE to a Mackie SRM450 two-way powered loudspeaker. The loudspeaker was lifted to 11 ft from the roadway (measured from the bottom of the loudspeaker). The loudspeaker faced down the road, so the loudspeaker axis was parallel with the centerline of the track. The environment at the simulation site was a typical urban canyon, except for a lawn across from the old portion of the building.

The recordings included a high-horn, a low-horn, and bells. The high-horn seemed to be similar in frequencies, but higher in level with the low horn. The recordings were made by ESI, outside the Hiawatha maintenance building. The recording environment would be free of buildings and the ground would be ties on ballast. Reference levels were also measured at the time of recording. Measurements by ESI were 80 dBA at 25 ft on-axis with the bell source, directly in front of the stationary train, and 78 dBA at 50 ft from the bell source.

The playback level was calibrated to match the measured reference levels. The reference recordings and measurements were made at 25 ft on-axis with the bell sound source, as were the calibration measurements. ESI reported that the high horn was 3 dB too low, but that increasing the level would introduce distortion in the loudspeaker. Calibration of the bells had to be delayed due to a lawnmower initially interfering with the measurement, but the bells were calibrated successfully once the engine noise ceased.

Measurement Equipment

Noise levels of the high-horn, low-horn, and bells were measured in each location with a Larson Davis 824 handheld analyzer. It was calibrated at the beginning and end of the measurement, and the background level was measured in each location.

A second measurement was made in some locations through a studio microphone belonging to MPR. This microphone signal was split; one signal was sent to a PC-based analyzer, also operated by ESI, while the other simultaneous signal was recorded by MPR and monitored by headphones. The available calibrator would not fit on this microphone, so the level on the PC-based analyzer was adjusted to match the level on the calibrated meter (the direct output of the meter was also sent into the PC-based analyzer).

The studio microphone signal recorded by MPR, was also monitored on headphones. The signal gain on the headphones was adjusted so inaudible signals became audible on the headphones. While this may not represent what a human ear hears within the studio space, it nonetheless reveals signals that would be captured on an audio recording. Such signals at or near the noise floor may or may not present a problem; it depends on the recording and mixing of an end-product.

ESI SIMULATION MEASUREMENTS

Measurements occurred within three studios, and several offices. This portion will describe and address each studio individually, and all the office measurements as a group.

Studio M: Maud Moon Weyerhaeuser Studio

There was studio equipment and furnishings stored around much of the room perimeter, but there was still a large area of free floor space in the studio. An isolation booth sat in the corner. The microphones were set up on an axis normal to the center of the exterior window. Subjective impressions of the HDR observer during the simulation of each source were:

- **High Horn:** filtered, but clearly audible.
- **Low Horn:** unmistakably audible, but very quiet.
- **Bells:** Nearly inaudible, but still distinctly present.

The window in this room was clearly the weak point in the overall acoustical isolation from the outside. The HDR observer could not discern if there was a specific sound leak, or if the sound was just passing though the window assembly.

Studio P: The Atrium Studio

There was studio equipment and furnishings stored around much of the room perimeter, constraining the free floor space to a relatively small area. A single microphone and desk were set up for voice recording in front of the control room window. The measurement microphones were set up in the middle of the studio, near the desk. Subjective impressions of the HDR observer during the simulation of each source were:

- **High Horn:** barely audible, but distinct. It could be localized to the narrow window looking out on Cedar Street.
- **Low Horn:** inaudible to the HDR observer, but the ESI test operator reported hearing it faintly.
- **Bells:** inaudible, even to the MPR observer listening on headphones with gain.

The MPR observer was listening on the headphones with gain while the test operator was in the studio, and reported stomach gurgling, picked-up on the studio microphone that was at least as loud as the horns.

Studio 443

Studio 443 is one of the most recently-built studios. Only the handheld meter was used to measure sound in this space. Nothing was audible from the outside of the studio, not the high horn or any other noise from the LRV. Even when a door closed in a wall adjoining the studio (outside the studio), the impact vibration was not transmitted into the studio space. Based on these observations, these studios seemed well-designed and the space seems acoustically isolated from the spaces outside of it.

Office Measurements

Only the handheld meter was used to measure the simulated sound in offices. HDR notes that offices are not assessed for potential noise impact according to FTA standards, although some offices are assessed for vibration. However, the HDR observer noted the following points somewhat relevant:

- The horns and bells alike were clearly audible in every office facing Cedar Street. The new building was not notably quieter than the old building.
- The walls between offices did not provide much privacy, but the horns and bells were still significantly louder than talking heard through the walls.
- At one office in the newest part of the building, the bells from Louis, King of France Church were clearly audible (they sound every quarter-hour). This event did not get measured.

ESI SIMULATION SUMMARY

The simulation of transit horns and bells was not a perfect simulation: ESI reported this was a preliminary investigation. The horns and bells simulation was clearly audible in the offices facing Cedar Street, however the regular church bells were also clearly audible. The simulation did not affect the background noise of the newest studios at MPR, but the simulation did affect two of the older studios facing Cedar Street.

The effect of the horns and bells simulation on Studio M was very apparent. Transit trains will be sounding bells at every passing through the grade-crossing at Seventh Street, and so will likely be audible on some recordings in Studio M. Transit train horns could be expected less frequently, but their occurrence will likely be noticeable.

Based on observations in Studio M, one might expect other sounds to be audible through the window. For instance, the lawnmower that interfered with calibrating the bell simulation, though this event was not measured, could be expected to be audible at some level in Studio M. Likewise any other sounds that are at least as loud as the transit train bells would intrude into the studio, including common traffic sounds (brake screech, honking horns, loud vehicles, emergency sirens, etc.). The church bells from down the street chime every 15 minutes but weren't quite as loud as the simulated transit train bells.

During ESI's simulation, LRV horn and bell noise was barely audible in Studio P. Some recordings in Studio P may exhibit low levels of transit horn noise, as simulated. Based on the observations during the simulation, Studio P is more effectively isolated than Studio M from the sounds of train horns and bells. While not conclusive, this suggests that Studio P has more effective acoustic isolation than Studio M.

HDR SIMULATION METHOD

The HDR simulation and measurement was lead by Tim Casey and Elliott Dick, both with HDR, and assisted by a team of four other attendants. Kathryn O'Brien of the Central Corridor Project Office, and Tony Baxter of ESI, were also present to observe the measurements. LRV horns and bells noise was measured by HDR staff during a series of simulated pass-bys of a Metro Transit vehicle operating horns, bells, or both. Measurements of the simulated horns and bells occurred at several locations: one inside Studio M, one inside the Forum, two locations inside the Fitzgerald Theater, and one location outside MPR. ESI did not perform measurements inside Studio P because ESI determined that Studio P has better acoustic isolation against the LRV horns and bells than Studio M. Studio M is the worst-case scenario for MPR's studios' acoustic isolation

Data collected during measurements allows HDR to assess the anticipated affect of the LRV horns and bells within these interior spaces. Ultimately, HDR intends to compare the interior noise levels without LRT horns or bells, against the noise levels in the studio with LRT horns, and the levels with LRT bells.

Data acquired by the sound level meters was stored in the meters, and later downloaded for post-measurement analysis of data. The time histories were examined to differentiate levels during LRV horns or bells sounds, versus during pauses between LRV sounds. Sounds of LRV horns and bells, at each measurement location, are compared to the measured natural ambient sound of the location (in the absence of simulated LRV horn and bell noise).

Characteristics of Sound Measurement Equipment

The measurement equipment HDR used included digital Sound Level Meters (SLM) with the capability to store analysis results, at least a 60-dB dynamic range; Type 1 as defined by ANSI S1.4. HDR used a Larson Davis (LD) 2900 analyzer to measure noise levels inside studios in MPR. HDR also used LD 824 analyzers at other monitoring locations. Sound pressure levels were measured in 1/3 octave bands inside MPR: at all other locations HDR measured broad-band sound pressure levels. The octave-band filters HDR used during the simulations meet the requirements of ANSI S1.11.1985. The microphones selected for the measurements have a nominal frequency response range that includes the range of frequencies from 10 Hz to 10 kHz. HDR used either a free-field or a diffuse-field microphone; the directional response is not significantly different below 10 kHz on either type of microphone. Nonetheless, directional response of microphones was selected appropriate to the measurement environment, identified below.

For measurements performed inside MPR, HDR configured the LD2900 analyzer to use A-weighting; octave band sound level weighting is set at FLAT. All LD824 SLM's were also configured to apply A-weighting. The measurement systems for interior spaces interior include the capability to measure fast-average sound level with exponential decay over consecutive time intervals, stored independently to produce a time history. The measurement systems for exterior locations include the capability to measure the time-average sound level (L_{eq}), simultaneously over one or more prescribed periods of time. The overall measurement duration is determined by a manual run/stop triggered by the operator. Each measurement is stored within each meter.

Calibration of Sound Measurement Equipment

HDR SLM's and analyzers are calibrated on an annual basis by an independent laboratory using standards traceable to the National Institute of Standards and Technology. Rented equipment is likewise calibrated annually. Calibration certificates of HDR equipment and rented equipment are available to the client upon request.

The sound measurement equipment is adjusted to a reference level traceable to the National Institute of Standards and Technology, using a battery-operated precision microphone calibrator meeting ANSI S1.40 and IEC 60942, Class 1 Sound Calibrators. Sound measurement equipment is calibrated and adjusted in HDR's office prior to transportation to the measurement site. Calibration checks are performed in the field before the first measurement and after completion of the series of measurements.

Testing of mock-up equipment and validation

Metro Transit operations and maintenance personnel arranged a mock-up to simulate LRV horns and bells. HDR staff were present along with Metro Transit personnel at the Franklin yards and shop to test and validate the mock-up to ensure consistency with actual HLRT bells and horns. This validation was conducted by setting up the mock-up equipment and an actual Hiawatha LRV side-by-side. The levels of bells and horns were measured for the mock-up and the actual ligh rail vehicle.

The first audible warning simulation device tested in the manner described above was inconsistent with the actual LRV. Specifically the noise levels matched reasonably well, but the horn pitch sounded somewhat different, and the measured spectrum content was notably different. HDR observed a slight frequency shift between the two signal sources which may present a minor problem, but more concerning was that the mock-up's horn emitted a narrow-band tone compared with the actual horn in use, which spans at least two whole octaves. The explanation was that the mock-up was originally made before Metro Transit bought any trains for HLRT, and it used a signal generator for another transit system. Consequently the signal generator in the mock-up was different from the ones in trains. This mock-up was rejected and Metro Transit staff set about the task of building a second mock-up using actual HLRT components.

The second mock-up used a spare signal generator for the vehicles in service on the HLRT line and the actual horn device currently in use on the HLRT fleet. Noise levels emitted by this mock-up measured much more consistently with the measured LRV. The following table shows measured SPL's at 50 ft from the LRV and the mock-up. Data in the table shows close agreement between the audible signal on the LRV and the mock-up. This second mock-up was accepted for use in testing at MPR.

Table 2

LRV Horn and Bell Noise Level Validation Data

	Light Rail Vehicle	Mock-Up
Bells	78.9 dBA	79.8 dBA
Low-Horn	88.3 dBA	88.5 dBA
High-Horn	94.8 dBA	94.3 dBA

One measurement of the LRV high horn demonstrates the directivity of the horn and bell source; it is 19.2 dBA down at 90° from on-axis.

HDR previously performed reference measurements of LRV bells sounding during a train pass-by event, 50ft perpendicular from the track centerline. Comparing to the on-axis measurements, the HDR reference measurements differed in that the train was moving, and the measurement was 90° off-axis from the bell source. The HDR measurement results ranged from 73 dBA to 78 dBA, and averaged 76 dBA. Given the difference in measurement conditions, the measurements of the transit bells are reasonably comparable.

LRV Horn and Bell Pass-by Simulation Measurement

The accepted mock-up was constructed from spare parts of actual LRV audible warning devices, including a signal source box with adjustable levels, normally located behind a locked access panel in the LRV, and an Atlas-brand "wide-dispersion" horn, normally mounted atop the vehicle. The mock-up was mounted on a truck, and driven down Cedar Street along the planned CCLRT track alignment. A Hiawatha LRV operation trainer sat in the truck cab to trigger the sounding of horns, bells, or both, appropriate to standard operation of the vehicles. The photograph below shows the Metro Transit vehicle with the LRV horn; the horn control unit was in the back seat of the truck cab.

Figure 1

Metro Transit LRV Horn and Bell Simulation Vehicle

HDR measured horn and bell noise levels during pass-by events outdoors: these SLM's were located on the east side of Cedar Street. This placed microphones in proximity to acoustically reflective surfaces (the buildings). Any reflections present in the measurement represent the acoustic environment of that locale, specifically urban canyons. The SLM microphones were placed at a point that is away from any such non-normal acoustically reflective surface by at least 0.75 m (2.5 ft), to meet guidance in ASTM standards.

HDR positioned the microphone between 4 ft and 6 ft above the ground, mounted on a mast sufficiently strong to support the weight of the microphone and protective equipment mounted on it, and which is resistant to being upset by the wind or other disturbances.

Table 3

Equipment for Exterior Locations

Microphone	PCB Type 377B41 free-field microphone
Measurement Equipment	Larson Davis Type 824 analyzer
Microphone Protection	Environmental microphone mounting assembly

The directional response of the exterior microphone locations are free-field. The self-noise of the microphones is less than 30 dBA (re. 20 μPa) to ensure adequate signal-to-noise when the signal is the ambient sound level of the outdoor soundscape. An environmental microphone protection kit was utilized for outdoor microphones, consisting of a microphone rain shield, windscreen, bird deterrent accessory, and desiccant system, compatible with the microphone system.

Studio M measurement

The low-noise microphone was located in line with the window facing Cedar Street, close to the middle of the room, but not in the exact center of the room.

The measurement environment inside the studio at MPR is very quiet. Operator-generated noise may constitute an interference of the measurement of sound levels, including operator movement or even breathing. An extension cable allowed the test operator and observers to work away from the low-noise microphone system, so the operator and other observers do not influence the measurement with movement, breathing, or other operator-generated noise.

Within the interior studio space, the level in some frequency bands of interest may be less than 10 dB above the electrical self-noise of the microphone and measurement system. The self-noise of the measurement system (including the microphone and microphone preamplifier system) including each band of interest, was measured by covering the microphone with a calibrator with a tight seal.

Table 4

Equipment for Interior Studio Location

Microphone	Brüel & Kjær Type 4955 low noise free-field microphone
Measurement Equipment	Larson Davis Type 2900B analyzer
Microphone Protection	None
Accessories	Brüel & Kjær Nexus conditioning amplifier
	BNC to Switchcraft adapter
	100ft BNC extension cable

The measurement environment inside the studio at MPR was very quiet. To avoid microphone self-noise as interference in the measurement of sound levels, the self-noise of the low-noise microphones was less than 10 dBA (re. 20 μPa) to ensure adequate signal-to-noise when the signal is the ambient sound level of the studio. The low reverberation of the MPR studio suggests use of an interior free-field microphone, oriented to face the incident noise (the window), where the orientation vector is normal to the microphone diaphragm.

Forum/Fitzgerald measurement

The Forum, although quite dry (low reverberation), is more or less a typical large-volume space with a diffuse field; The Fitzgerald Theatre measurement locations were typical interior spaces with diffuse field characteristics. Analyzers and microphones were mounted on tripods, or handheld by experienced operators.

Table 5

Equipment for Forum and Fitzgerald Locations

Microphone	Larson Davis Type 2560 diffuse-field microphone
Measurement Equipment	Larson Davis Type 824 analyzer
Microphone Protection	Windscreen

A diffuse-field microphone was utilized in a vertical orientation (straight up), customary for typical interior spaces. The self-noise of the microphones was less than 30 dBA (re. 20 μPa) to ensure adequate signal-to-noise when the signal is the ambient sound level of the interior spaces. Environmental protection of interior tripod-mounted microphones was an interior windscreen to prevent interference from air movement.

HDR SIMULATION RESULTS

Preliminary results and some on-site observations are reported here. Full analysis of measurement data is forthcoming.

Studio M

The background noise level of the room, using the low-noise microphone, is 20-22 dBA. The noise of the high-horn is as high as 30 dBA inside the studio.

HDR performed an experiment to determine the highest level of horn noise that is inaudible in Studio M, and therefore also has least potential to interfere with recordings inside studio M. The mock-up was positioned stationary and at a position north of the centerline of the window, along the Cedar Street alignment and facing south. Metro Transit staff reduced the horn volume level three times, and after the third adjustment, the horn noise was inaudible in studio M. According to this experiment, a high-horn maximum sound pressure level of 79 to 80 dBA at 25 ft is not audible or detectable in Studio M (Tony Baxter of ESI confirmed this SPL and also that at this level the horn noise was inaudible in Studio M). This horn noise level was also only faintly heard on the recording equipment. It was difficult for the studio engineer to discern while listening with high gain on the signal, but he thought he could barely distinguish it from the background noise.

This experiment was not repeated with the LRV bells. The bell sound pressure level specification (extrapolated from 50 ft using a typical point-source 6 dB decrease per distance doubled) is 85 dBA at 25 ft, higher than the maximum horn sound pressure level determined in the experiment. Based on the horn noise level experiment results, the volume level of the LRV bells needs to be similarly reduced to a level that is comparable to the horn maximum sound pressure level of 79 to 80 dBA at 25 ft.

These experiment results also apply to Studio P due to its higher acoustic isolation. The high horn was less audible and less detectable in Studio P during the ESI simulation. Therefore it is likely that the maximum horn sound pressure level determined in the experiment (79 to 80 dBA at 25 ft) will be less detectable in Studio P than the already barely detectable signal in Studio M.

Forum

The background level in the forum is around 30 dBA. The level of the horn, after adjustment to a level acceptable in studio M, is as high as 35 dBA.

Fitzgerald

HDR measured noise levels during two pass-bys with high-horns, one northbound and one southbound, simultaneously in two locations, the lobby area and the stage. The measurement location in the theatre lobby area was separated from the street by an enclosed glass entryway. Horns were audible in the lobby, but barely measurable. The ambient background noise level without the horns is around 50 dBA, and the A-weighted level of the horn pass-by measurements did not increase from the ambient more than one-half of a decibel.

The horn was not measurable and barely audible on the stage, if audible at all. The door between the 2^{nd} lobby and the house seating was open during these measurements, but it was not possible to localize the very faint signal by ear to determine if it came through the lobby door, or the stage door or wall. This despite the northbound passby was a constant-running high-horn as it passed by the alley, a very unlikely situation.

V. MITIGATION

Metropolitan Council has two categories of options to mitigate LRT horn and bell noise in this portion of the project area. The first mitigation category is administrative, which refers to adjustments to operational practices. The second mitigation category is structural, which refers to physically implementing a mitigation measure (like constructing a noise wall next to a highway). Potential options within each category are discussed below.

Administrative Mitigation Measures

Following are potential administrative mitigation measures available to Metropolitan Council.

- Reduce the level of the high-horn for the entire fleet. Results of these activities determined that a high-horn maximum sound pressure level of 79 to 80 dBA at 25 ft was not audible or detectable in Studio M and Studio P. This sound pressure level is much lower than current standard operating procedures. Metropolitan Council should consider surveying LRT systems in other cities and determining their horn and bell sound pressure level: reducing high-horn noise levels throughout the LRT fleet should also be considered.

- Institute a more rigorous calibration standard/procedure to ensure consistency of horn and bell sound pressure level throughout the fleet. The uniformity this provides will ensure that LRT horn and bell noise to not interfere with activities in the most noise-sensitive portions of the project area. HDR recommends Metro Transit hire an acoustical consultant to perform these measurements, to ensure they are performed correctly.

Structural Mitigation Measures

Following are potential structural mitigation measures available to Metropolitan Council.

- Acoustically isolate Studio M from Cedar Street. The isolation of the exterior wall can be improved by constructing a new wall inside the existing exterior wall along Cedar Street. The new wall should be acoustically isolated from the floor, ceiling and walls, to minimize the transmission of acoustic energy from Cedar Street into the recording space. The new wall should be designed to with adequate transmission loss to ensure that traffic noise (including emergency sirens) does not leak into the recording space. Compared to the rest of the exterior wall of Studio M, the window is the weakest point of isolation and it must be improved to realize any other isolation improvement. The existing window can be left in place, however a new acoustically designed window should be incorporated into the new wall partition to maintain ambiance and allow natural light into the space. The Studio M window is semicircular; if the new window is also semicircular, it may have to be a custom window order.

- Similar measures could be constructed into Studio P.
- Similar measures of mitigation as recommended for Studios M and P would not be appropriate for the Forum since this space was not designed, and does not serve as a critical listening/critical recording facility. Meetings do occur in this space and according to MPR staff, they are recorded. However, the Forum was designed to provide an amount of outdoor to indoor noise reduction commensurate with the room's intended purpose, viz., a public meeting space. With the potential institution of administrative mitigation measures, as described above, the Forum would experience lessened LRT-related noise intrusion.

Memo

To:	Tim Casey		
From:	Kent Peterson	Project:	**Construction Noise for CCLRT**
cc:			
Date:	11/25/08	Job No:	68591

Construction Noise for CCLRT

While both Minneapolis and St. Paul have noise ordinances, both cities rely on the Minnesota Pollution Control Agency (MPCA) Noise Standards (Minnesota Rules, Chapter 7030) to establish maximum allowable noise levels for construction activities. MPCA noise standards regulate environmental noise using the L10 and L50 descriptors that represent noise levels exceeded 10% and 50% of the time. MPCA regulates noise during daytime (7:00 am to 10:00 pm) and also during nighttime (10:00 pm to 7:00 am) using different limits for each time period. MPCA noise standards establish different maximum allowable noise levels for three different categories of land use or Noise Area Classification (NAC), with residential lands included in NAC 1. Table 1 details the MPCA Noise Area Classification limits.

Table 1
MPCA Noise Area Classification

Noise Area Classification (NAC)	Daytime		Nighttime	
	L10 (dBA)	L50 (dBA)	L10 (dBA)	L50 (dBA)
1	65	60	55	50
2	70	65	70	65
3	80	75	80	75

Source: “A Guide to Noise in Minnesota”, MPCA, 2008

While environmental noise is subject to MPCA standards, the MPCA typically does not regulate construction noise. This analysis is based on FTA construction noise impact thresholds as provided within chapter 12 of the “Transit Noise and Vibration Impact Assessment” manual (FTA, Office of Planning and Environment, May 2006).

The Metropolitan Council propose to create a new light rail line, therefore construction activities will occur at different times and in different locations throughout the Study Area. Construction activities often generate noise and sometimes ground-borne vibration; however these emissions vary greatly depending upon the duration and complexity of the project.

It is unlikely that each piece of construction equipment would be used throughout the entire duration of a construction project. Rather, each phase of a construction project may require use of certain pieces of equipment, and some equipment may be unique to that phase. Therefore, each phase of any construction project could have unique noise characteristics.

Construction noise effects related to the Proposed Action would be temporary and localized around the track and proposed stations. The FTA guidance manual "Transit Noise and Vibration Impact Assessment", Chapter 12; "Noise and Vibration during Construction", the FTA provides guidance for assessing the potential for construction noise impacts on different land uses as shown in Table 2 below. These construction noise impact thresholds were used to assess the potential for construction noise impacts on the Central Corridor LRT project.

Table 2,
FTA Construction Noise Impact Thresholds

Land Use	8-hour L_{eq} (dBA)	
	Day	Night
Residential	80	70
Commercial	85	85
Industrial	90	90

Source: "Transit Noise and Vibration Impact Assessment, FTA, May 2006

The majority of land uses immediately adjacent to the Central Corridor are commercial. However, residential land uses occur throughout the project area, including dormitories at the University of Minnesota, and residences and apartments which are nearby the project corridor. In some cases, residential land uses exist immediately adjacent to the Central Corridor. Additionally, other noise and vibration sensitive receptors along the project corridor may be affected by construction noise and vibration. Therefore a detailed assessment of the noise and vibration was performed to better understand how construction-induced noise and vibration may affect nearby land uses.

Construction Noise Detailed Assessment

The Federal Highway Administration Roadway Construction Noise Model (RCNM), was used to assess noise from various pieces of construction equipment and their affect on both commercial and residential locations. This model expressed calculated noise levels using the L_{eq} descriptor specified by the FTA. Noise-sensitive receptors evaluated in this analysis include the U of M dormitories, the University of Minnesota's Nuclear Magnetic Resonance Lab at Hasselmo Hall, KSTP television station, Twin Cities Public

Television (TPT), Minnesota Public Radio (MPR), Saint Louis King of France and Central Presbyterian Churches, and various media production and theatrical locations. Use of this model is appropriate due to the similarity of equipment used when building roadways and rails systems, and the more refined analytical capabilities of RCNM in comparison to spreadsheet-based FTA methods. RCNM was developed during Boston's Big Dig project and has become the standard model when assessing transportation construction noise. Table 2, presents noise levels associated with typical construction equipment, as published by FTA and used within the modeling.

The construction equipment shown in Table 3 below is representative of the types of equipment likely to be used during the CCLRT construction phase. These noise levels and usage factors represent worse-case usage and it is not anticipated that all of this machinery will be used at any one particular location at the same time.

Table 3,
Construction Equipment Noise Levels

Equipment	Impact Device (impulse and vibration)	Acoustical Use Factor %	Typical Noise Level (dBA) 50 feet from Source
Backhoe	No	40	80
Ballast Equalizer	No	20	82
Ballast Tamper	Yes	10	83
Compressor (air)	No	40	81
Compactor (ground)	No	20	82
Concrete Mixer Truck	No	40	85
Concrete Saw	No	20	76
Crane	No	16	83
Dozer	No	40	85
Dump Truck	No	40	88
Front End Loader	No	40	85
Generator	No	50	81
Grader	Yes	10	85
Impact Pile Driver	Yes	20	101
Impact Wrench	Yes	20	85
Jackhammer	Yes	20	88
Paver	No	50	89
Pneumatic Tools	No	50	85
Roller	No	20	74
Scraper	No	40	89

Rail Saw	No	40	90
Rock Drill	No	20	98
Scarifier	No	20	83
Spike Driver	No	30	77
Tie Inserter	Yes	15	85
Tie Cutter	No	20	84
Tie Handler	No	20	80

Source: “Transit Noise and Vibration Impact Assessment, FTA, May 2006,
and FHWA, Roadway Construction Noise Model V1.0 February 2, 2006

Construction Noise Detailed Assessment Results

This analysis used aerial photographs and design documents to determine the distance between noise-sensitive land uses and construction areas. Receptors were modeled at distances between 30 and 200 feet, with shielding inserted to account for structures between the construction area and receiving land uses in the 2nd and subsequent rows. The U of M dormitories (Comstock, Centennial and Territorial Halls) nearest to the CCLRT construction areas were also modeled.

Tables 4 and 5 below, detail the daytime and nighttime affects associated with various receptors and distances with respect to machinery.

Table 4,
Construction Noise Impacts at Receptors
(Daytime)

	Receptors												
Equipment	Hasselmo Hall	U of M Dorms	2506 University (Apts)	Homes at 30'	Homes at 60'	Homes at 120'	KSTP	1951 University	Louis King of France	Central Pres	Cedar St. (30')	Fuzzy Slippers Studio	TPT
Backhoe	None	None	None	None	None	None	None	None	None	None	None	None	None
Ballast Equalizer	None	None	None	None	None	None	None	None	None	None	None	None	None
Ballast Tamper	None	None	None	None	None	None	None	None	None	None	None	None	None
Compressor (air)	None	None	None	None	None	None	None	None	None	None	None	None	None
Compactor (ground)	None	None	None	None	None	None	None	None	None	None	None	None	None
Concrete Mixer Truck	None	None	None	None	None	None	None	None	None	None	None	None	None
Concrete Saw	None	None	None	◆	None	None	None	◆	◆	◆	◆	None	◆
Crane	None	None	None	None	None	None	None	None	None	None	None	None	None
Dozer	None	None	None	None	None	None	None	None	◆	◆	◆	None	◆
Dump Truck	None	None	None	None	None	None	None	None	None	None	None	None	None
Front End Loader	None	None	None	None	None	None	None	None	None	None	None	None	None
Generator	None	None	None	None	None	None	None	None	◆	◆	◆	None	◆
Grader	None	None	None	◆	None	None	None	None	◆	◆	◆	None	◆
Impact Pile Driver	None	None	◆	◆	◆	None	◆	◆	◆	◆	◆	◆	◆
Impact Wrench	None	None	None	None	None	None	None	None	None	None	None	None	None
Jackhammer	None	None	None	None	None	None	None	◆	◆	◆	◆	None	◆
Paver	None	None	None	None	None	None	None	None	None	None	None	None	None
Pneumatic Tools	None	None	None	◆	None	None	None	◆	◆	◆	◆	None	◆
Roller	None	None	None	None	None	None	None	None	None	None	None	None	None
Scraper	None	None	None	◆	None	None	None	◆	◆	◆	◆	None	◆
Rail Saw	None	None	None	◆	None	None	None	◆	◆	◆	◆	None	◆
Rock Drill	None	None	None	None	None	None	None	None	None	None	None	None	None
Scarifier	None	None	None	None	None	None	None	◆	◆	◆	◆	None	◆

	Spike Driver	None	None	None	None	None	None	None	◆	None	None	None	None	None
	Tie Inserter	None	None	None	None	None	None	None	None	◆	◆	◆	None	◆
	Tie Cutter	None	None	None	None	None	None	None	None	◆	◆	◆	None	◆
	Tie Handler	None	None	None	None	None	None	None	None	None	None	None	None	None

◆ Denotes a noise impact

Table 5,
Construction Noise Impacts at Receptors
(Night)

		Receptors												
		Hasselmo Hall	U of M Dorms	2506 University (Apts)	Homes at 30'	Homes at 60'	Homes at 120'	KSTP	1951 University	Louis King of France	Central Pres	Cedar St. (30')	Fuzzy Slippers Studio	TPT
Equipment	Backhoe	None	None	None	◆	None	None	None	None	None	None	None	None	None
	Ballast Equalizer	None	None	None	◆	None	None	None	None	None	None	None	None	None
	Ballast Tamper	None	None	None	None	None	None	None	None	None	None	None	None	None
	Compressor (air)	None	None	None	◆	None	None	None	None	None	None	None	None	None
	Compactor (ground)	None	None	None	◆	None	None	None	None	None	None	None	None	None
	Concrete Mixer Truck	None	None	None	◆	None	None	None	None	None	None	None	None	None
	Concrete Saw	None	None	◆	◆	◆	None	None	◆	◆	◆	◆	None	◆
	Crane	None	None	None	◆	None	None	None	None	None	None	None	None	None
	Dozer	None	None	None	◆	None	None	None	None	◆	◆	◆	None	◆
	Dump Truck	None	None	None	◆	None	None	None	None	None	None	None	None	None
	Front End Loader	None	None	None	◆	None	None	None	None	None	None	None	None	None
	Generator	None	None	None	◆	None	None	None	None	◆	◆	◆	None	◆
	Grader	None	None	◆	◆	◆	None	None	None	◆	◆	◆	None	◆

	Impact Pile Driver	None	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
	Impact Wrench	None	None	None	◆	None	None	None	None	None	None	None	None	None
	Jackhammer	None	None	None	◆	None	None	None	◆	◆	◆	◆	None	◆
	Paver	None	None	None	◆	None	None	None	None	None	None	None	None	None
	Pneumatic Tools	None	None	◆	◆	◆	None	None	◆	◆	◆	◆	None	◆
	Roller	None	None	None	◆	None	None	None	None	None	None	None	None	None
	Scraper	None	None	◆	◆	◆	None	None	◆	◆	◆	◆	None	◆
	Rail Saw	None	None	◆	◆	◆	None	None	◆	◆	◆	◆	None	◆
	Rock Drill	None	None	None	◆	None	None	None	None	None	None	None	None	None
	Scarifier	None	None	None	◆	None	None	None	◆	◆	◆	◆	None	◆
	Spike Driver	None	None	None	None	None	None	None	◆	None	None	None	None	None
	Tie Inserter	None	None	None	◆	None	None	None	None	◆	◆	◆	None	◆
	Tie Cutter	None	None	None	◆	None	None	None	None	◆	◆	◆	None	◆
	Tie Handler	◆	None	None	◆	None	None	None	None	None	None	None	None	None

◆ Denotes a noise impact

There are 13 types of machinery that may result in exceedance of both the daytime and the nighttime FTA construction noise limits identified within these tables. The most intrusive of these are the impact pile driver and the jackhammer due to their impulsive (loud, short duration) nature.

Analysis results indicate that noise from nighttime use of impact pile drivers near the U of M dormitories will exceed FTA construction noise limits. Noise from additional construction equipment types will also reach impact levels at the apartments located at 2506 University and homes within 30 feet of the construction limits.

Construction Noise Mitigation

Analysis results indicate that the most effective construction noise mitigation measure is scheduling the loudest activities during daytime hours, and limiting their use in evenings and at nighttime in. Prohibition of loud construction activities during nighttime should be implemented near the U of M dormitories along Washington Avenue, near student housing apartments and residences along University Avenue.

Construction noise mitigation measures for Cedar Street in downtown St. Paul must be much more detailed as impacts are predicted for both the daytime and nighttime, and for multiple types of machinery. Also, a variety of activities occur in Saint Louis King of France Church and Central Presbyterian Church throughout the morning, afternoon, and evening. Use of loud construction equipment in the immediate vicinity of these two churches should be coordinated with the churches to ensure minimal disruption of activities inside the churches. A nearby residential (condominium) building may preclude late-night construction activities.

Additional coordination with Minnesota Public Radio is necessary to ensure that construction activities do not disrupt use of Studio M, a recording studio adjacent to Cedar Street. Broadcast facilities at MPR are less susceptible to construction noise.

Construction contractors should be required to develop a noise mitigation plan that includes;

- Minimization of noise impacts on adjacent noise-sensitive stakeholders while maintaining construction progress.
- An outline of the project's noise control objectives and potential components.
- An approach for deciding the appropriateness of mitigation.
- A summary of noise related criteria for construction contractors to abide by.

Construction Noise Mitigation Controls

Although no detailed construction documents or excavation plans are available which may detail times and usage of machinery, best management practices should also be included within any Mitigation Plan. These may include;

- Requiring OEM (original equipment manufacturer) or higher-performing mufflers on equipment.
- Requiring the regular maintenance and inspection of construction machinery to allow for quieter operation.
- Limiting the hours of construction activities to correspond with the core of business activities along Cedar St.
- Augmented back up alarms coupled with contractor observation to minimize alarm noise, a consistent area of concern and complaint on most construction projects.
- Limiting equipment on-site to only those machines which need to be within the construction zone.
- Performing nosier activities off-site until such a time when it can no longer be avoided.
- Specifying the proper usage and power for the particular construction procedure- no machinery over-kill.
- Specifying noise barriers and machinery enclosures where feasible.
- Implementing a noise complaint process for stakeholders which will be monitored and acted upon in a reasonable amount of time.
- Maintain a "noise hotline" to allow stakeholders an outlet for complaints, which would be followed up and investigated in a reasonable amount of time.

HDR also recommends maintaining a web-based work schedule to allow contractors and stakeholders to schedule noisier events in avoidance of noise sensitive activities. This could serve as an ongoing database throughout the life of the project and be a valuable source of stakeholder and contractor information.

While it is unlikely that work can commence without the use of some equipment listed, it is imperative that contractors coordinate the usage times and duration of noisy equipment outside of the recommended usage. Table 6 summarizes the noise sensitive areas and machinery restrictions for those pieces of equipment which are sources of a noise impact, whether day or night.

Through these measures and commitments, and by consistently implementing processes and over-sight, implementing a detailed construction noise mitigation plan can be a successful in minimizing noise impacts and stakeholder surprises, while keeping construction delays to a minimum.

Table 6, Construction Machinery Restrictions per Segment and Time

	Metro Dome Station To Washington Bridge		Washington Bridge to Westgate Station (to 200')		Westgate Station to Fairview Station (to 200')		Fairview Station to Rice St. Station (to 30')		Fairview Station to Rice St. Station (to 60')		Rice St. Station to Capital East Station (to 200')		Capital East Station to Union Depot (to 20')	
Equipment	**Day**	**Night**	**Day**	**Night**	**Day**	**Night**	**Day**	**Night**	**Day**	**Night**	**Day**	**Night**	**Day**	**Night**
Backhoe	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**NO**	Yes	Yes	Yes	Yes	Yes	Yes
Ballast Equalizer	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**NO**	Yes	Yes	Yes	Yes	Yes	Yes
Ballast Tamper	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Compressor (air)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**NO**	Yes	Yes	Yes	Yes	Yes	Yes
Compactor (ground)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**NO**	Yes	Yes	Yes	Yes	Yes	Yes
Concrete Mixer Truck	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**NO**	Yes	Yes	Yes	Yes	Yes	Yes
Concrete Saw	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**NO**	Yes	**NO**	Yes	Yes	**NO**	**NO**
Crane	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**NO**	Yes	Yes	Yes	Yes	Yes	Yes
Dozer	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**NO**	Yes	Yes	Yes	Yes	**NO**	**NO**
Dump Truck	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**NO**	Yes	Yes	Yes	Yes	Yes	Yes
Front End Loader	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**NO**	Yes	Yes	Yes	Yes	Yes	Yes
Generator	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**NO**	Yes	Yes	Yes	Yes	**NO**	**NO**
Grader	Yes	Yes	Yes	Yes	Yes	**NO**	Yes	**NO**	Yes	**NO**	Yes	Yes	**NO**	**NO**
Impact Pile Driver	Yes	Yes	Yes	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**
Impact Wrench	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**NO**	Yes	Yes	Yes	Yes	Yes	Yes
Jackhammer	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**NO**	Yes	Yes	Yes	Yes	**NO**	**NO**
Paver	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**NO**	Yes	Yes	Yes	Yes	Yes	Yes
Pneumatic Tools	Yes	Yes	Yes	Yes	Yes	**NO**	Yes	**NO**	Yes	**NO**	Yes	Yes	**NO**	**NO**
Roller	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**NO**	Yes	Yes	Yes	Yes	Yes	Yes
Scraper	Yes	Yes	Yes	Yes	Yes	**NO**	Yes	**NO**	Yes	**NO**	Yes	Yes	**NO**	**NO**
Rail Saw	Yes	Yes	Yes	Yes	Yes	**NO**	Yes	**NO**	Yes	**NO**	Yes	Yes	**NO**	**NO**
Rock Drill	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**NO**	Yes	Yes	Yes	Yes	Yes	Yes
Scarifier	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**NO**	Yes	Yes	Yes	Yes	**NO**	**NO**
Spike Driver	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Tie Inserter	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**NO**	Yes	Yes	Yes	Yes	**NO**	**NO**
Tie Cutter	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**NO**	Yes	Yes	Yes	Yes	**NO**	**NO**
Tie Handler	Yes	Yes	Yes	**NO**	Yes	Yes	Yes	**NO**	Yes	Yes	Yes	Yes	Yes	Yes

"Yes" indicates usage of specific machinery. "No" indicates usage within specified distance without special provision and communication.

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Memo

To:	Tim Casey		
From:	Elliott B. Dick	Project:	Central Corridor LRT
cc:			
Date:	Jan 7, 2009	Job No:	65891

Re: Field Measurements to Determine Reference SEL

Introduction

HDR determined a reference *sound exposure level* (SEL) for each noise source anticipated in the *Central Corridor Light-Rail Transit* (CCLRT) project. These reference levels are used in formulae to model the project-related noise sources. They are the basis for the noise emission level of each source, under certain reference conditions.

Reference measurements and calculations were performed as outlined in "Appendix E: Computing Source Reference Levels from Measurements" in the Federal Transit Administration's *Transit Noise and Vibration Impact Assessment* (May, 2006), hereafter referred to as the FTA Manual.

Measurement Locations

Measurements occurred on July 26, 2008, on running trains carrying passengers, without coordination. Events such as bells, therefore, were captured as they would be used naturally by individual operators. Horn events were not observed during or between the measurements. These events were captured between the Mall of America and the airport. Some measurements were discarded due to the sound of aircraft flyovers approaching the nearby airport.

The wayside noise on embedded track was measured between Bloomington Central Station and the 28th Avenue Station. The track runs between two large parking lots, offering an environment free of vertical reflecting surfaces.

Wheel squeal was measured at the corner of 28th Avenue and Old Shakopee Road, 50' perpendicular from the outside (eastbound) track, at the middle of the curve. Curve squeal only occurred on the inside (westbound) track.

Train speeds were measured for each pass-by event. All trains consisted of two cars. The track and the direction of travel were also noted, to indicate the distance from the track to use. The microphone was set up 50' from the nearest track.

Background Noise Correction

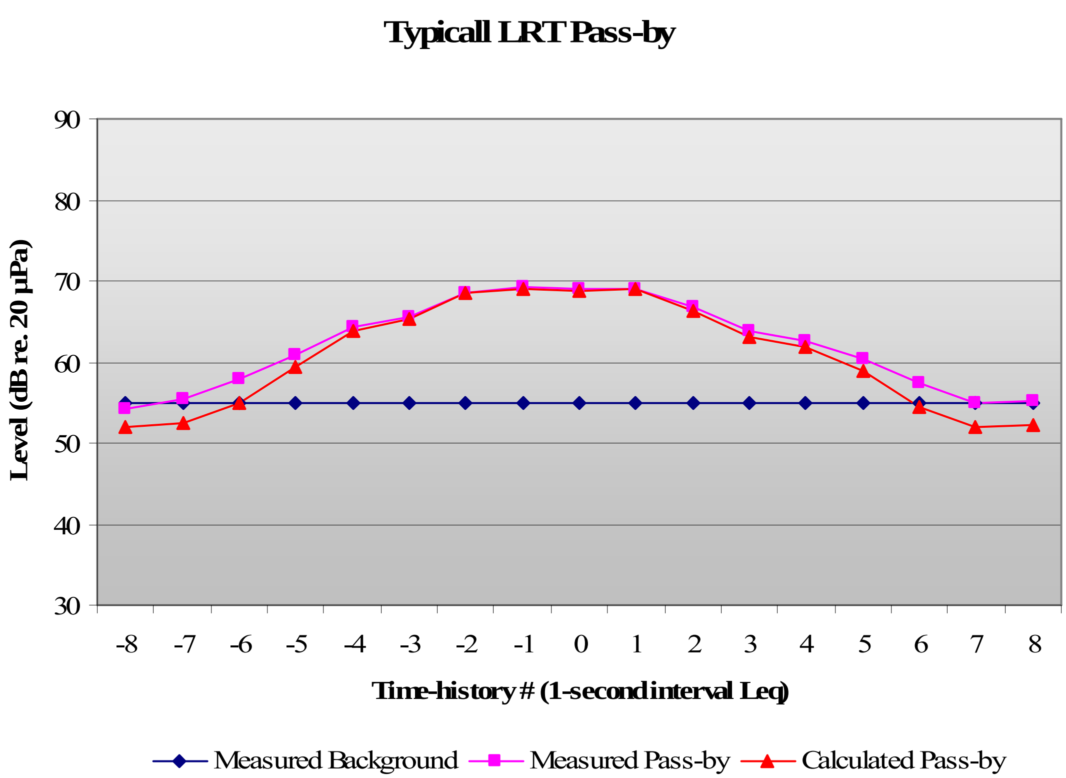
Since the measured level is the combined levels of the site's ambient background noise and the measurement noise event, the measurements were corrected for background noise. There are several valid methods to remove background noise from a measurement, including the method described in ISO 3744. In this international standard the correction term K_1 is subtracted from the measured level, and determined thus:

$$K_1 = \begin{cases} 0 & \text{dB} \quad \Delta L > 15 \\ -10\,\lg\left(1-10^{-0.1\Delta L}\right) & \text{dB} \quad 6 \le \Delta L \le 15 \\ 3 & \text{dB} \quad \Delta L < 6 \end{cases}$$

Where lg is the common logarithm (base 10), and ΔL is the background level subtracted from each measured level. Background noise was measured at each measurement location and every equivalent level (L_{eq}) was corrected for its corresponding background noise.

Measurement Results

Time histories of each pass-by measurement were evaluated for extraneous, unrelated noise events. The bounds of each time history were hand-picked for each pass-by, to reflect a reasonable event time history. An example of a pass-by is shown below, along with the background noise and the final corrected level.



The exposure level is symbolized as L_{ex} in Kinlser & Frey (4th edition, 2000, pp. 368) and defined therein as "The level of the time integral of the squared A-weighted sound pressure over a stated time referenced to $(1\,\text{s}) \times (20\,\mu\text{Pa})^2$." Because the time history was measured in 1-second intervals, this simplified the calculation of SEL from L_{eq} – simply the energy sum of the time history. This was used as the overall SEL of the event.

Each type of noise had two to three valid measurements. The SEL of each valid measured event was calculated, and then the reference measurements were determined according to Table E1 of the FTA Manual. The calculated reference levels were arithmetically averaged for each type of noise. Results are shown below.

	Meas. #1	Meas. #2	Meas. #3	Mean
Wayside noise (embedded track)	84.5	82.3	84.4	**84**
Wheel squeal	109.8	115.9	116.3	**114**

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Memo

To:	Kathryn O'Brien		
From:	Tim Casey	Project:	Central Corridor Light Rail Transit
cc:	file		
Date:	March 11, 2009	Job No:	65891

Re: Transit train horn and bell simulation at Central Presbyterian and St. Louis King of France Churches

BACKGROUND

Central Presbyterian Church and St. Louis King of France are located in downtown St. Paul, along the *Central Corridor Light Rail Transit* (CCLRT) route on Cedar Street. The *Light Rail Vehicles* (LRV) are expected to sound horns and bells under certain operational circumstances. Testing of LRV airborne noise impacts was conducted in October 2008, using a simulation of an LRV bell and horn, at Central Presbyterian Church and at St. Louis King of France Church.

Central Presbyterian Church Interior Spaces

Central Presbyterian Church was assessed in the HDR horn and bell simulation. The sanctuary of the church is a large room, mostly occupied by audience seating. The sanctuary inside of Central Presbyterian is not air conditioned, therefore the church's front doors, which open directly to Cedar Street, are often left open during the spring and summer seasons.

There are several large stained-glass windows inside of the sanctuary looking out onto Cedar Street, which provide natural light into the sanctuary and enhance the aesthetics of the church.

Church of St. Louis King of France

St. Louis King of France Church was also assessed in the HDR horn and bell simulation. The sanctuary of the church is a large room, mostly occupied by audience seating and a choir loft. There are several large stained-glass windows facing northwest, toward 10th Street. These windows, much like those in Central Presbyterian, provide natural light into the sanctuary and enhance the aesthetics of the church.

LRV Horn and Bell Use

Metro Transit has adopted standard operating procedures for the sounding of bells and horns on the Hiawatha Light Rail line. Bells are sounded when entering and leaving an LRT station platform. High horns are sounded in emergency situations when operators believe a loud warning is required to alert persons outside the LRV to a hazard. The high horns (2 short blasts) are also sounded when two trains pass each other at a grade crossing. Low horns are typically used only at the Franklin yard and shops as part of LRV operations and maintenance occurring there. These standard audible warning system procedures will be modified for use on CCLRT. In the vicinity of Cedar Street, horn use will be limited to emergency situations – similar to sirens on emergency service vehicles (fire, police, etc.).

SIMULATION MEASUREMENT

On October 22, 2008, HDR Engineering conducted a simulation of LRT horn and bell use on Cedar Street in downtown St. Paul. The HDR simulation and measurement was lead by Tim Casey and Elliott Dick, both with HDR, and assisted by a team of four other attendants. Kathryn O'Brien of the Central Corridor Project Office, and Tony Baxter of ESI, were also present to observe the measurements.

The LRV horn and bell sound-source mock-up was constructed from spare parts of actual LRV audible warning devices, including a signal source box with adjustable levels, normally located behind a locked access panel in the LRV, and an Atlas-brand "wide-dispersion" horn, normally mounted atop the LRV. The mock-up was mounted on a truck, and driven down Cedar Street along the planned CCLRT track alignment. A Metro Transit LRT operator sat in the truck cab to trigger the sounding of horns, bells, or both, appropriate to standard operation of the vehicles. Attachment A to this memorandum describes further details of the LRV horn and bell sound-source mock-up levels and validation.

LRV horn and bell noise was measured by HDR staff during a series of simulated pass-bys of a Metro Transit vehicle operating horns, bells, or both. Measurements of the simulated horns and bells occurred at several locations: in front of Central Presbyterian Church on the sidewalk, inside Central Presbyterian Church approximately 5 feet from the door, inside Central

Presbyterian Church in the center of the sanctuary (in the aisle by the center row), and inside St. Louis King of France Church in the center of the sanctuary (in the aisle by the center row).

Data collected during measurements allows HDR to assess the anticipated affect of the LRV horns and bells within these interior spaces. HDR compared the interior noise levels without LRT horns or bells against the noise levels in churches with LRT horns, and the levels with LRT bells. Attachment B of this memorandum contains details of the measurement instrumentation and procedures.

The noise measurement time histories were examined to differentiate noise levels with and without LRV horns or bells sounds. Sounds of LRV horns and bells, at each measurement location, are compared to the measured natural ambient sound of the location (in the absence of simulated LRV horn and bell noise).

HDR also measured horn and bell noise levels during pass-by events outdoors: these sound level meters (SLM's) were located on the east side of Cedar Street in close proximity to acoustically reflective surfaces (the buildings). Any reflections present in the measurement represent the acoustic environment of that locale, specifically urban canyons.

HDR SIMULATION RESULTS

Results of HDR horn and bell simulation for Central Presbyterian Church and St. Louis King of France found that horns are clearly audible inside both church sanctuaries; bells, as currently calibrated on the Hiawatha LRT, are also audible in both churches. It should be noted that both churches were unoccupied during the simulation measurements. Therefore background noise levels are somewhat unrepresentative of the churches when they are in use. It is very reasonable to expect that background noise levels would be higher when the church sanctuaries are occupied due to organ music, singers, speakers, and normal sounds generated by a congregation worshiping. Data collected during the bell and horn simulation is included as Attachment C to this memorandum. As shown in Attachment C, the sound level meters collect data every ¼ of a second. HDR processed the data, and evaluated it in terms of the change in hourly equivalent sound level, or Leq(h) inside the two churches.

These data indicate the following in regard to Central Presbyterian Church:

- The sound level of LRV bell passbys during a peak hour is anticipated to increase the average Leq(h) less than 1 dBA above the interior ambient noise floor with the church doors closed.

- The sound level of LRV bell passbys and one horn passby during a peak hour is anticipated to increase the average Leq(h) approximately 1 dBA above the interior ambient noise floor with the church doors closed.

- The sound level of the simulated LRV bells is on average 7 dBA above the interior ambient noise floor with the church doors open. It is important to note that this estimate is based on measurements conducted October 22, 2008 when there were no people in the sanctuary and when background noise levels were consequently lower than they would be when the church is in use.[1]

- The sound level of the simulated LRV horn passbys are on average 20 dBA above the interior ambient noise floor with the church doors open and no people in the sanctuary. When the church is occupied, and background noise levels are higher than measured during this simulation, the LRV horn noise is not expected to be as high above the background ambient noise levels.

- The simulated horns and bells mainly affect the 500 Hz and 1 kHz octave-bands with the church doors open.

- A vehicle with an emergency siren which passed at least a block away and was measured as being at least 20 dBA above the interior ambient noise floor with the church doors open. This siren event was from a vehicle that did not pass by the front of the church – its path was not visually confirmed.

[1] Doors closed are assessed in relation to the ambient level in the church when doors are closed and doors open are compared with ambient levels taken with doors open. Closing the door attenuates all noise including bells and other exterior sources (traffic noise) equally. Therefore because lower bell levels are being compared to a lower ambient level the overall increase in dB is very similar with doors open and doors closed.

The data in Attachment C indicate the following in regard to the Church of St. Louis King of France:

- The sound level of LRV bell passbys during a peak hour is anticipated to increase the average Leq(h) less than 1 dBA above the interior ambient noise floor with the church doors closed.
- The sound level of LRV bell passbys and one horn passby during a peak hour is anticipated to increase the average Leq(h) 1 dBA above the interior ambient noise floor with the church doors closed.
- The sound level of the simulated LRV bells alone is 0 dBA to 3 dBA above the ambient interior noise floor with the church doors closed.
- The sound level of the simulated LRV horns is up to 25 dBA above the ambient interior noise floor with the church doors closed.

Based on this information, and observations from the simulation events, HDR believes that St. Louis King of France Church is better insulated (and therefore better isolated from outdoor noise) than Central Presbyterian Church, which accounts for the differing amount of audible bell noise. The background level in St. Louis King of France is more than 5 dB lower than Central Presbyterian which can be an indicator of lower HVAC noise and less exterior traffic noise intruding into the sanctuary as compared to noise levels inside Central Presbyterian Church.

HDR notes that audibility, as discussed above, is not a criterion in the assessment of potential noise impacts using FTA methodologies. Rather, its use in this context is informational only. The LRT simulations are not a component of the FTA's Transit Noise and Vibration Impact Assessment methods, and are not a component of the impact assessment (Detailed Noise Assessment) performed for CCLRT.

MITIGATION

Metropolitan Council has two categories of mitigation concerning LRT horn and bell noise in this portion of the project area. The first mitigation category is administrative, which refers to adjustments to operational practices. The second mitigation category is structural, which refers to physically implementing a mitigation measure (like constructing a noise wall next to a highway). Potential options within each category are discussed below.

Administrative Mitigation Measures

Following are voluntary administrative mitigation measures committed by Metropolitan Council.

- Metropolitan Council has committed to revising standard operating procedure for the Central Corridor Light Rail project on Cedar Street near Central Presbyterian Church and the St. Louis King of France Church. Revisions include refraining from routine horn use, and limiting horn use to emergency circumstances.
- Metropolitan Council has committed to reducing standard bell SEL, sound exposure level. This can be done by either reducing the calibrated sound level of the bell or through the reduction of bell duration.

HDR Recommended Mitigation

- Institute a more rigorous calibration standard/procedure to ensure consistency of horn and bell sound pressure level throughout the fleet. The uniformity this provides will ensure LRT horn and bell noise does not interfere with activities in the most noise-sensitive portions of the project area. HDR recommends Metro Transit hire an acoustical consultant to perform these measurements, to ensure they are performed correctly.

ATTATCHMENT A – LRV BELL AND HORN MOCK-UP

According to Metro Transit standard operating procedures, current LRV horn and bell noise level standards are as follows.

Table B.1

Metro Transit LRV Horn and Bell Noise Level Criteria

	Target Level	Measurement Distance
Bells	79 dBA	50 ft
Low-Horn	90 dBA	100 ft
High-Horn	95 dBA	100 ft

LRV horns and bells are currently calibrated when maintenance is performed on the LRV warning system. Metro Transit staff performs the calibration procedure inside the maintenance building, at the prescribed distance from the front of the train, and measures the noise level on a hand-held sound-level-meter.

Testing and validation of mock-up equipment

Metro Transit operations and maintenance personnel arranged a mock-up to simulate LRV horns and bells. HDR staff were present along with Metro Transit personnel at the Franklin yards and shop to test and validate the mock-up to ensure consistency with actual HLRT bells and horns. This validation was conducted by setting up the mock-up equipment and an actual Hiawatha LRV side-by-side. The levels of bells and horns were measured for the mock-up and the actual light rail vehicle.

The first audible warning simulation device tested in the manner described above was inconsistent with the actual LRV. Specifically the noise levels matched reasonably well, but the horn pitch sounded somewhat different, and the measured spectrum content was notably different. HDR observed a slight frequency shift between the two signal sources which may present a minor problem, but more concerning was that the mock-up's horn emitted a narrow-band tone compared with the actual horn in use, which spans at least two whole octaves. The explanation was that the mock-up was originally made before Metro Transit bought any trains for HLRT, and it used a signal generator for another transit system. Consequently the signal generator in the mock-up was different from the ones in trains. This mock-up was rejected and Metro Transit staff set about the task of building a second mock-up using actual HLRT components.

The second mock-up used a spare signal generator for the vehicles in service on the HLRT line and the actual horn device currently in use on the HLRT fleet. Noise levels emitted by this mock-up measured much more consistently with the measured LRV. The following table shows measured SPL's at 50 ft from the LRV and the mock-up. Data in the table shows close agreement between the audible signal on the LRV and the mock-up. This second mock-up was accepted for use in testing at the churches.

Table B.2

LRV Horn and Bell Noise Level Validation Data

	Light Rail Vehicle	**Mock-Up**
Bells	78.9 dBA	79.8 dBA
Low-Horn	88.3 dBA	88.5 dBA
High-Horn	94.8 dBA	94.3 dBA

The photograph below shows the Metro Transit vehicle with the LRV horn; the horn control unit was in the back seat of the truck cab.

Figure A.1

Metro Transit LRV Horn and Bell Simulation Vehicle

One measurement of the LRV high horn demonstrates the directivity of the horn and bell source; it is 19.2 dBA down at 90° from on-axis.

HDR previously performed reference measurements of LRV bells sounding during a train pass-by event, 50ft perpendicular from the track centerline. Comparing to the on-axis measurements, the HDR reference measurements differed in that the train was moving, and the measurement was 90° off-axis from the bell source. The HDR measurement results ranged from 73 dBA to 78 dBA, and averaged 76 dBA. Given the difference in measurement conditions, the measurements of the transit bells are reasonably comparable.

ATTATCHEMENT B – MEASUREMENT EQUIPMENT AND PROCEDURES

The measurement equipment HDR used included Larson Davis 824 (LD824) analyzers. HDR measured broad-band sound pressure levels at the churches. The microphones selected for the measurements have a nominal frequency response range that includes the range of frequencies from 10 Hz to 10 kHz. The directional response of the microphone was selected appropriate to the measurement environment, identified below.

All LD824 SLM's were configured to apply A-weighting. The measurement systems include the capability to measure the time-average sound level (L_{eq}), simultaneously over one or more prescribed periods of time. The overall measurement duration is determined by a manual run/stop triggered by the operator. Each measurement is stored within each meter. Data acquired by the sound level meters was stored in the meters, and later downloaded for post-measurement analysis of data.

Calibration of Sound Measurement Equipment

HDR SLM's and analyzers are calibrated on an annual basis by an independent laboratory using standards traceable to the National Institute of Standards and Technology. Rented equipment is likewise calibrated annually. Calibration certificates of HDR equipment and rented equipment are available to the client upon request.

The sound measurement equipment is adjusted to a reference level traceable to the National Institute of Standards and Technology, using a battery-operated precision microphone calibrator meeting ANSI S1.40 and IEC 60942, Class 1 Sound Calibrators. Sound measurement equipment is calibrated and adjusted in HDR's office prior to transportation to the measurement site. Calibration checks are performed in the field before the first measurement and after completion of the series of measurements.

Exterior Monitor Equipment

HDR positioned the microphone between 4 ft and 6 ft above the ground, mounted on a mast sufficiently strong to support the weight of the microphone and protective equipment mounted on it, and which is resistant to being upset by the wind or other disturbances. The microphones were placed at a point that is away from any such non-normal acoustically reflective surface by at least 0.75 m (2.5 ft), to meet guidance in ASTM standards.

Table A.1

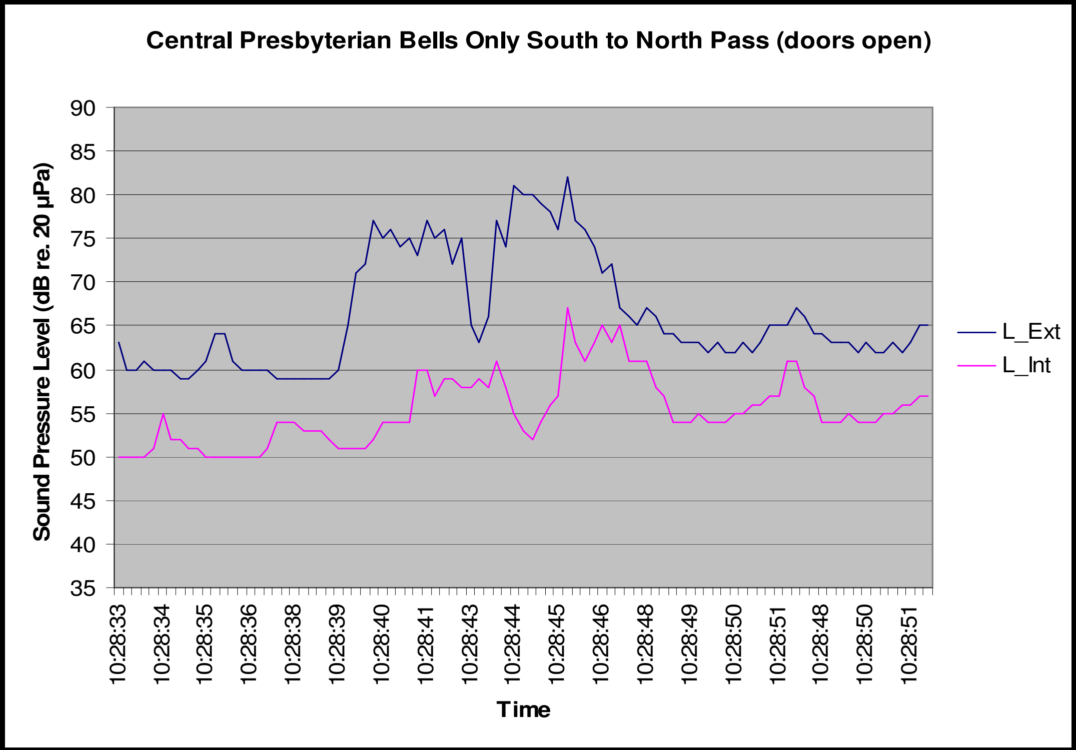
Equipment for Exterior Locations

Microphone	PCB Type 377B41 free-field microphone
Measurement Equipment	Larson Davis Type 824 analyzer
Microphone Protection	Environmental microphone mounting assembly

The directional response of the exterior microphone locations are free-field. The self-noise of the microphones is less than 30 dBA (re. 20 μPa) to ensure adequate signal-to-noise when the signal is the ambient sound level of the outdoor soundscape. An environmental microphone protection kit was utilized for outdoor microphones, consisting of a microphone rain shield, windscreen, bird deterrent accessory, and desiccant system, compatible with the microphone system.

ATTACHMENT C – NOISE MONITORING DATA

Results from Central Pres, Bells Only, Doors Open



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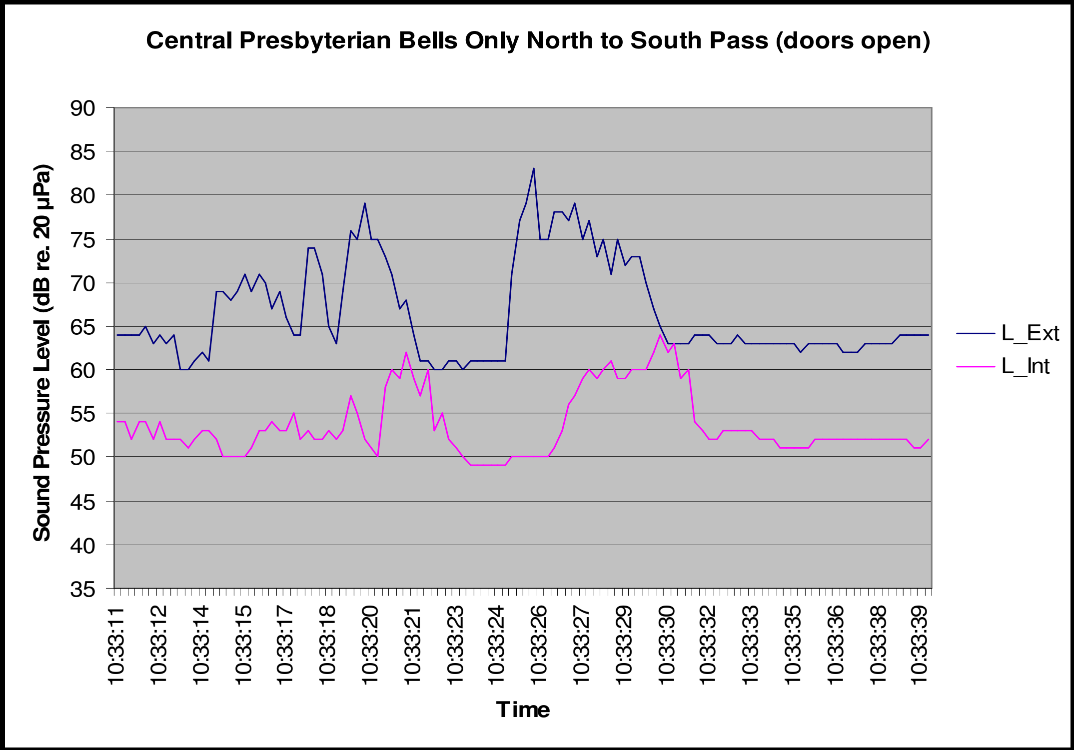
Results from Central Pres, Bells Only, Doors Open



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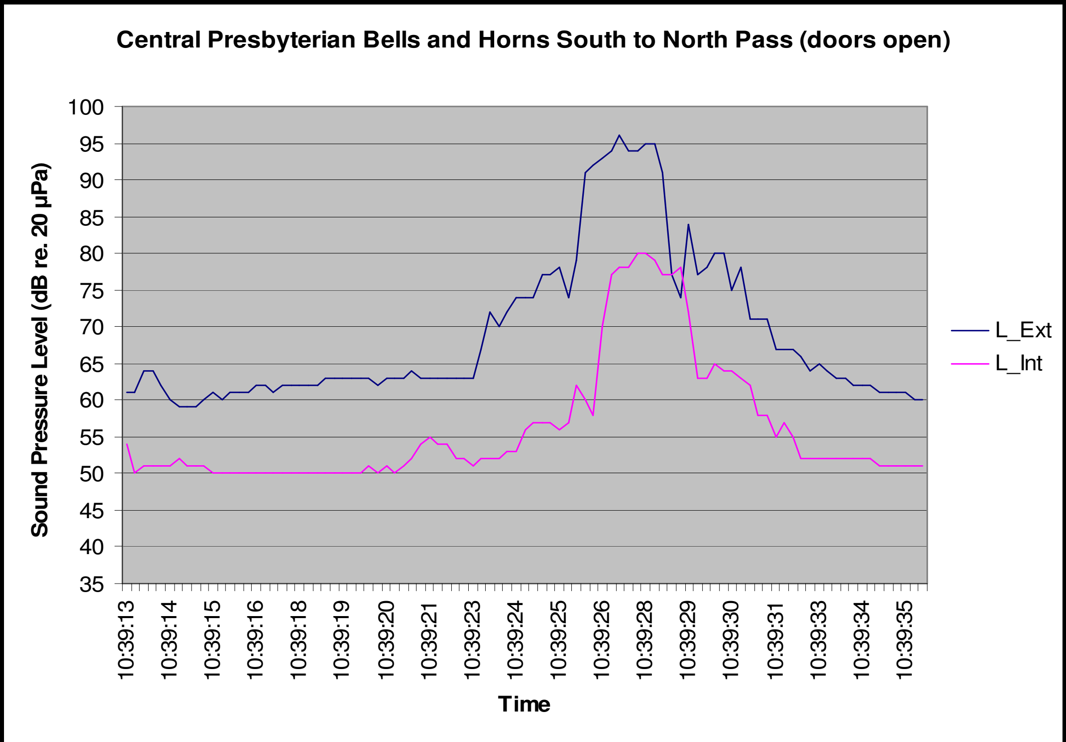
Results from Central Pres, Bells and Horns, Doors Open



HDR

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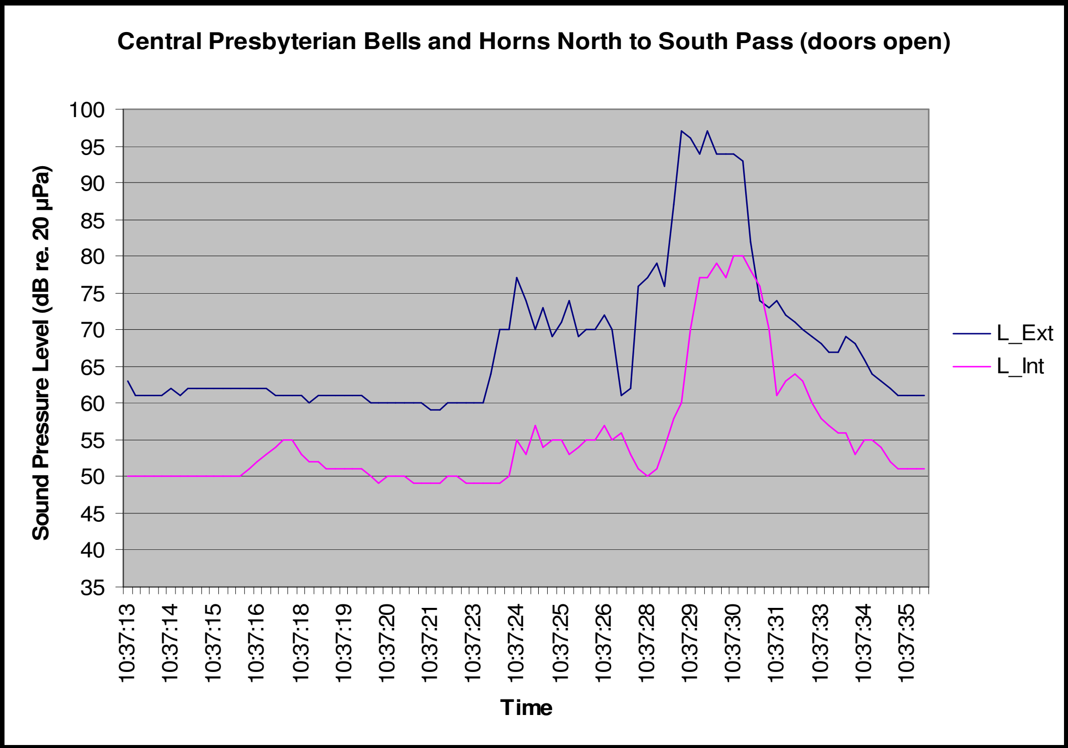
Results from Central Pres, Bells and Horns, Doors Open



HDR

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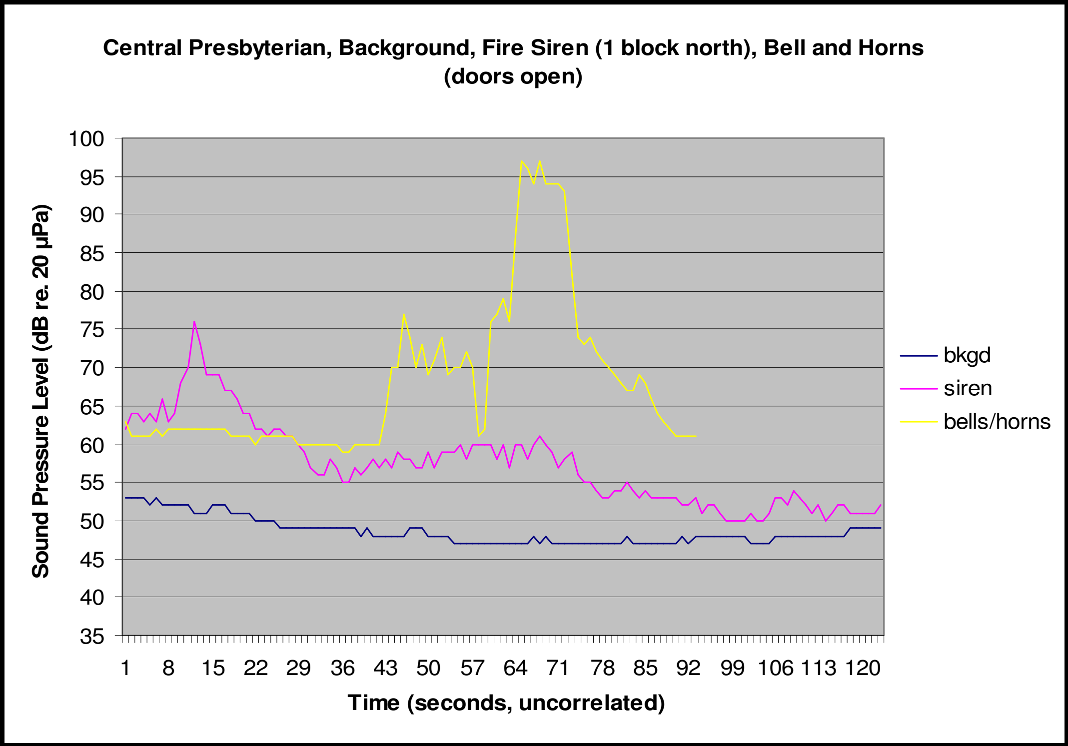
Results from Central Pres, Composite (no time correlation)



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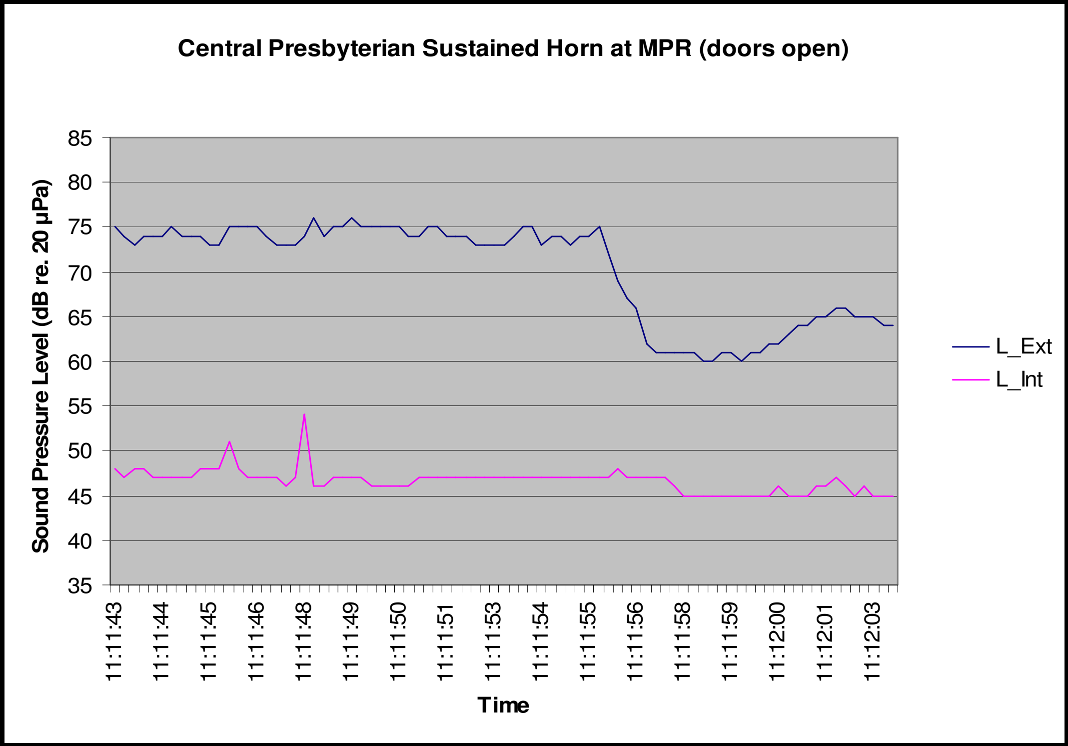
Results from Central Pres, Sustained Horn at MPR, Doors Open



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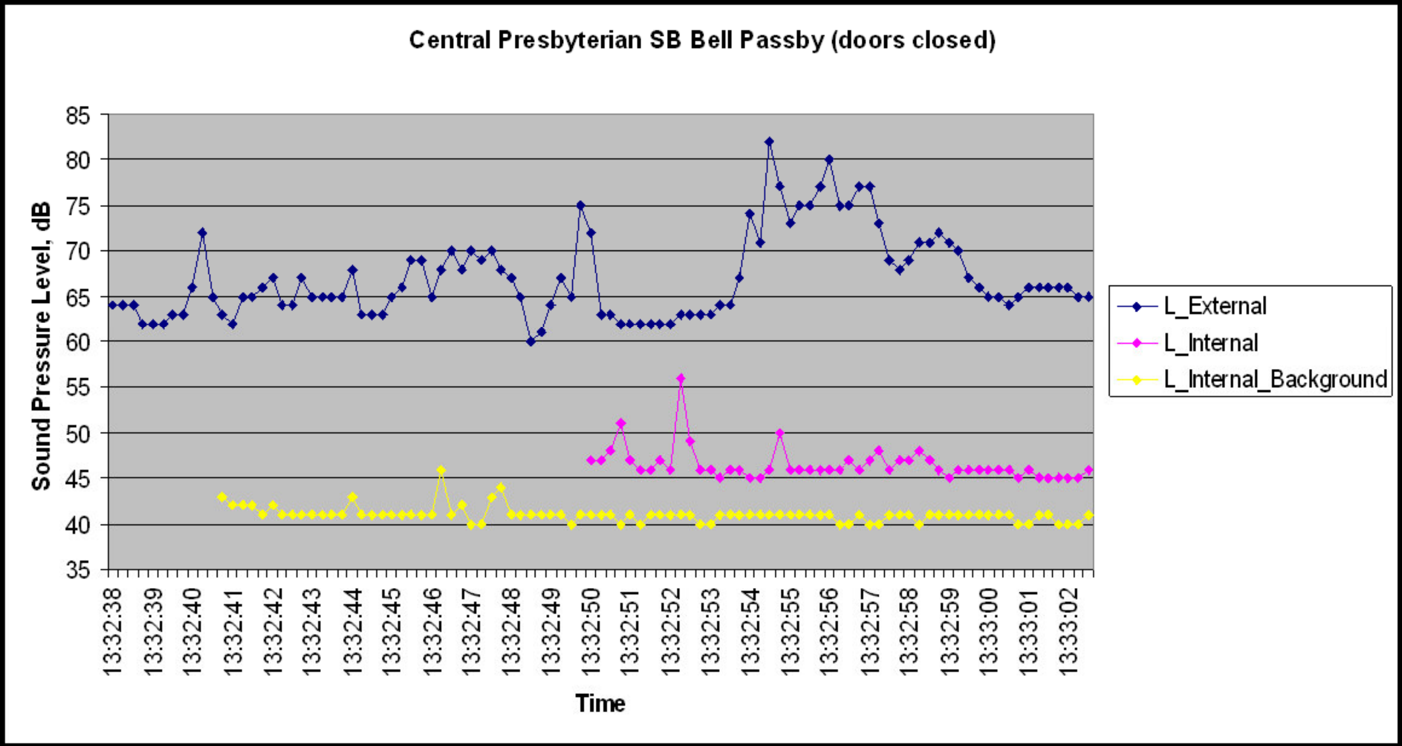
Results from Central Pres. SB Bell Passby, Doors Closed



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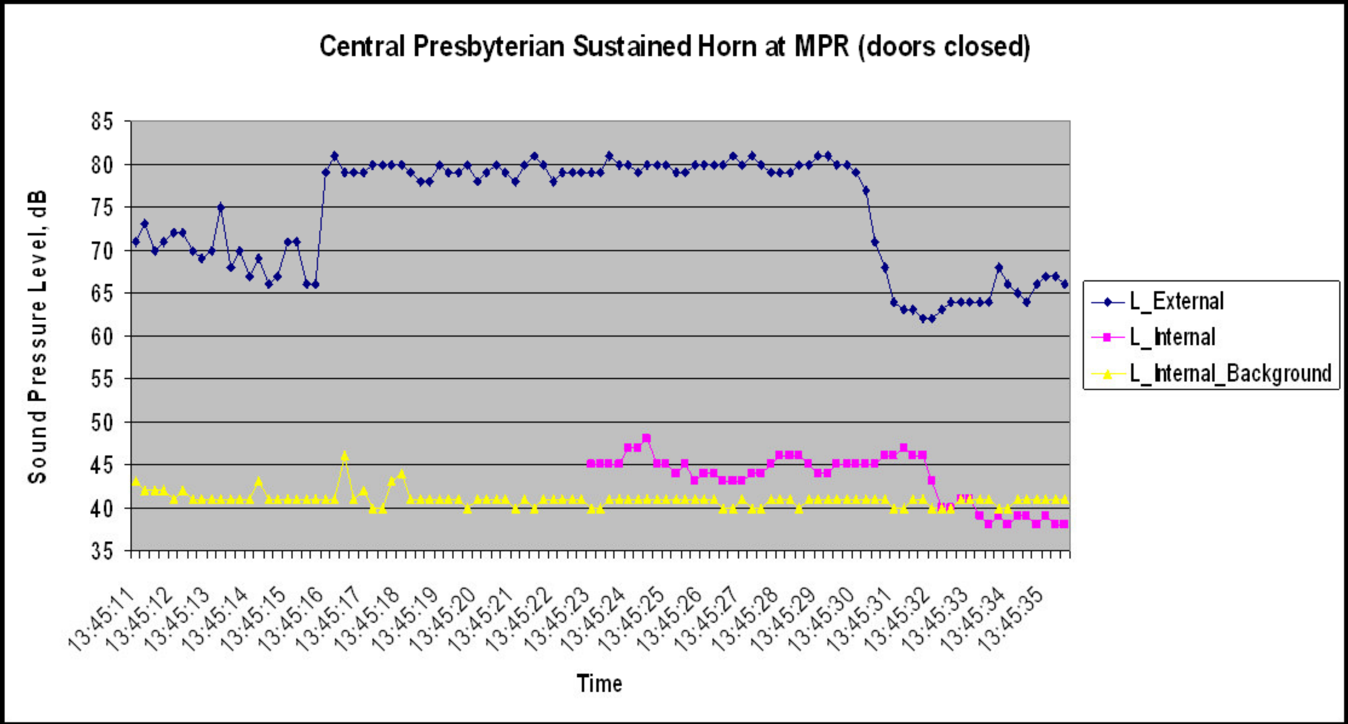
Results from Central Pres. Sustained Horn at MPR, Doors Closed



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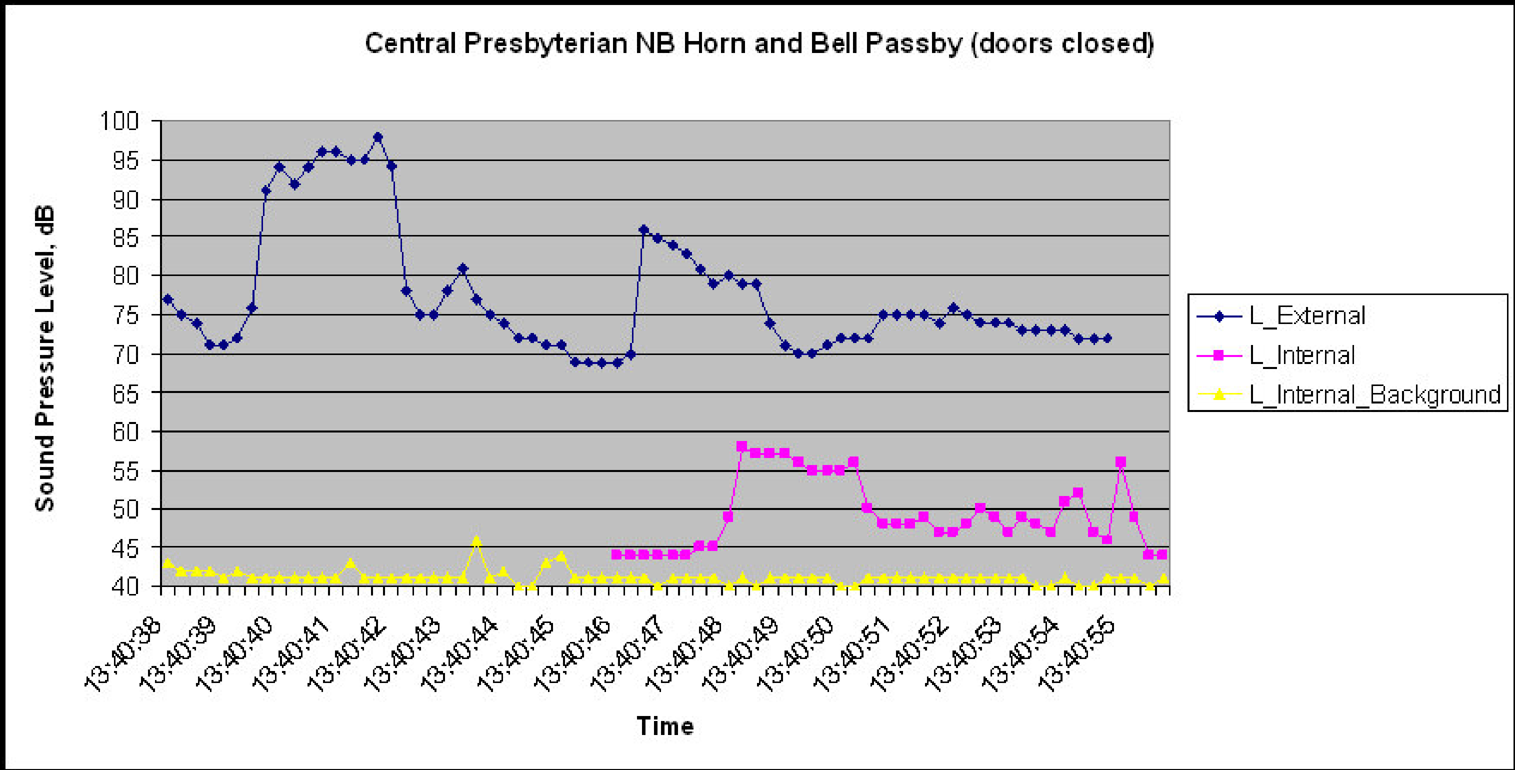
Results from Central Pres. NB Horn and Bell Passby, Doors Closed



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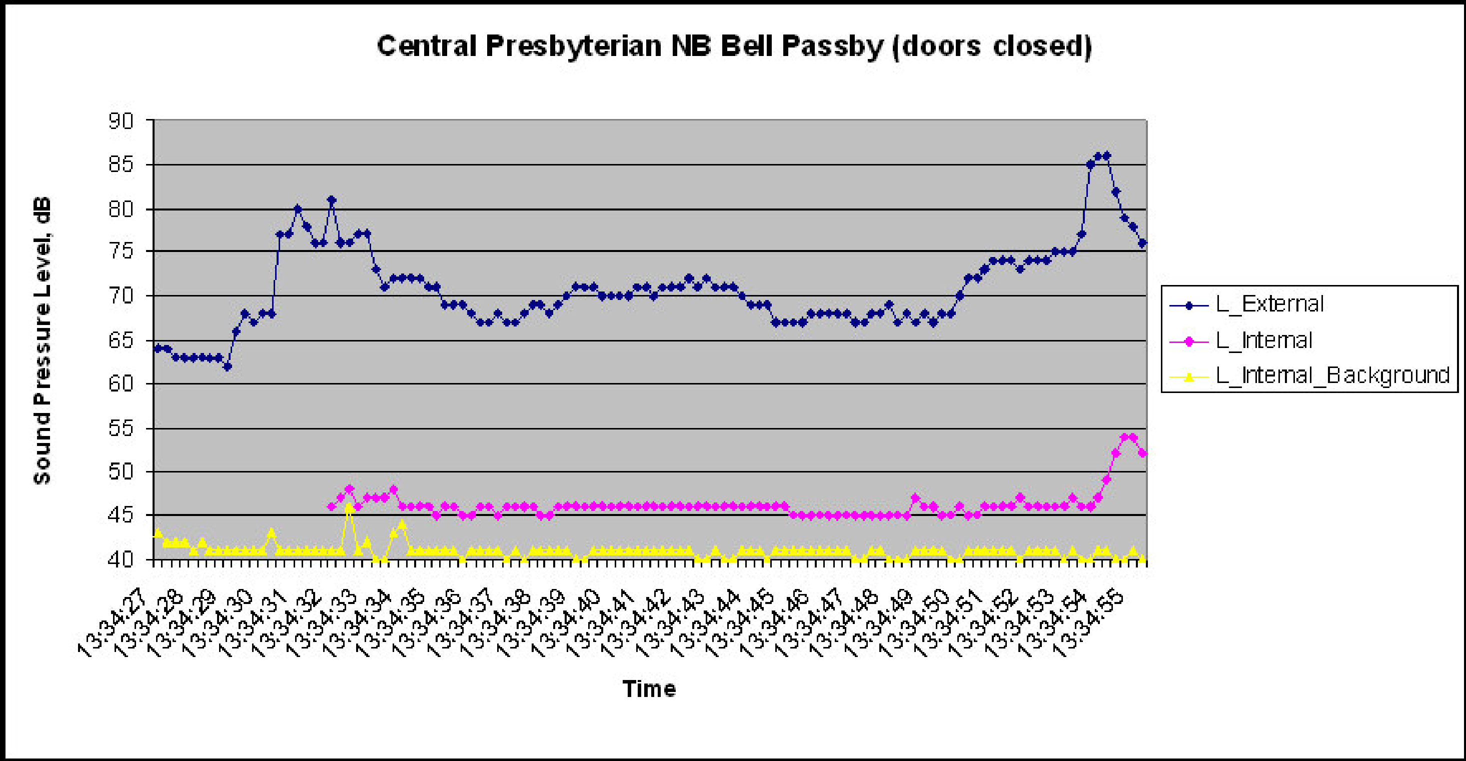
Results from Central Pres. NB Bell Passby, Doors Closed



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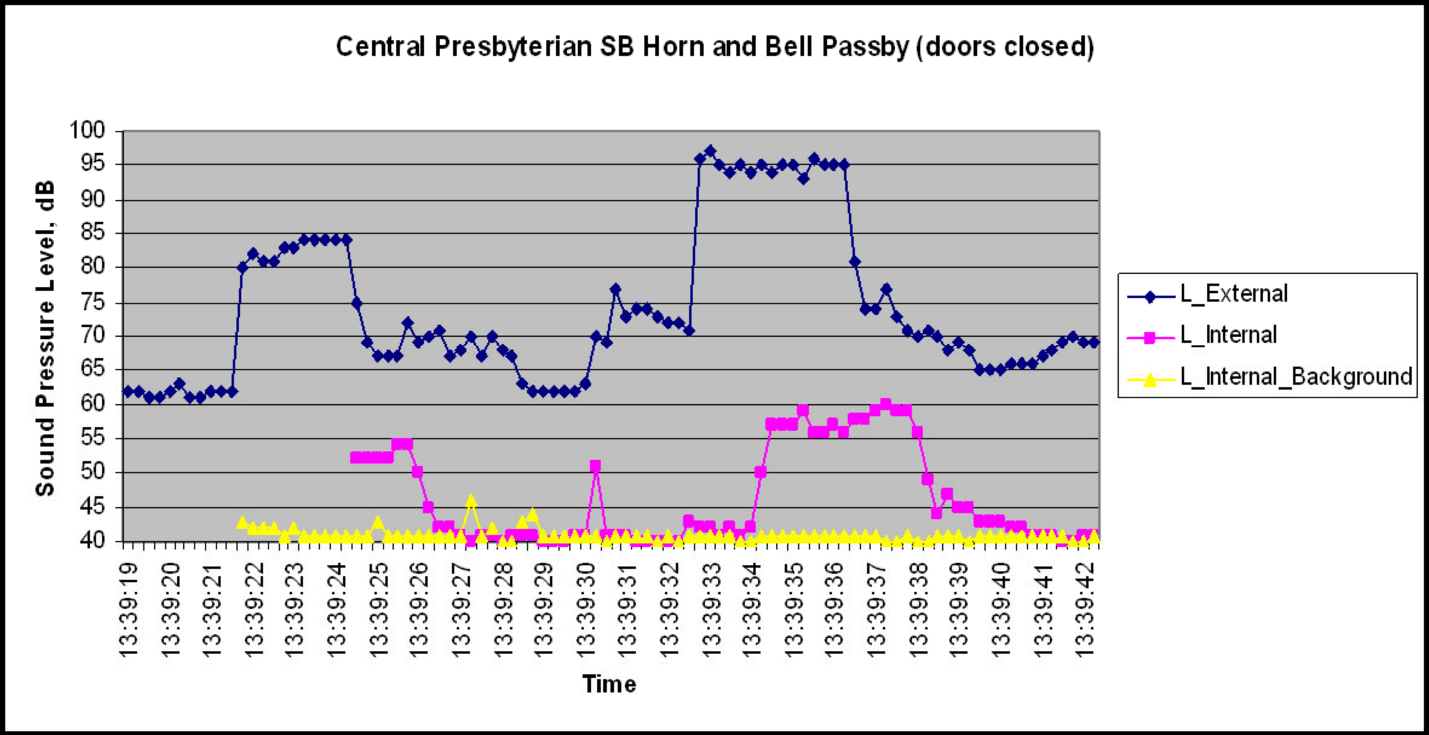
Results from Central Pres. SB Horn and Bell Passby, Doors Closed



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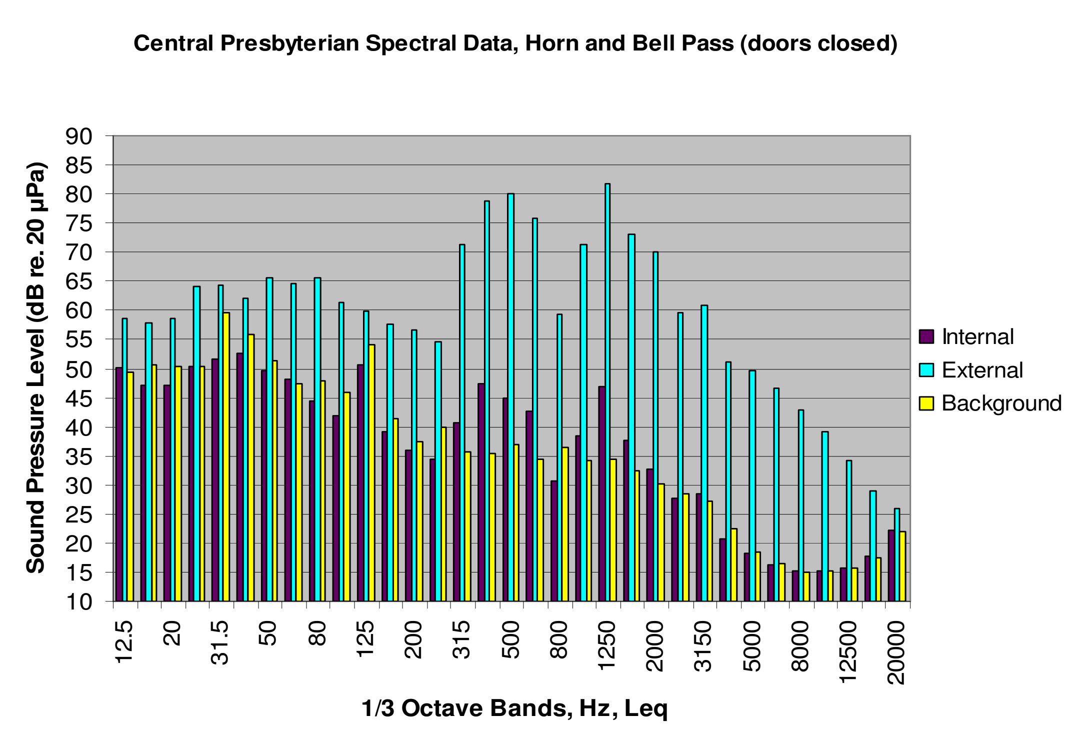
Results from Central Pres, Horns and Bells, Octave Band Analysis and Comparison



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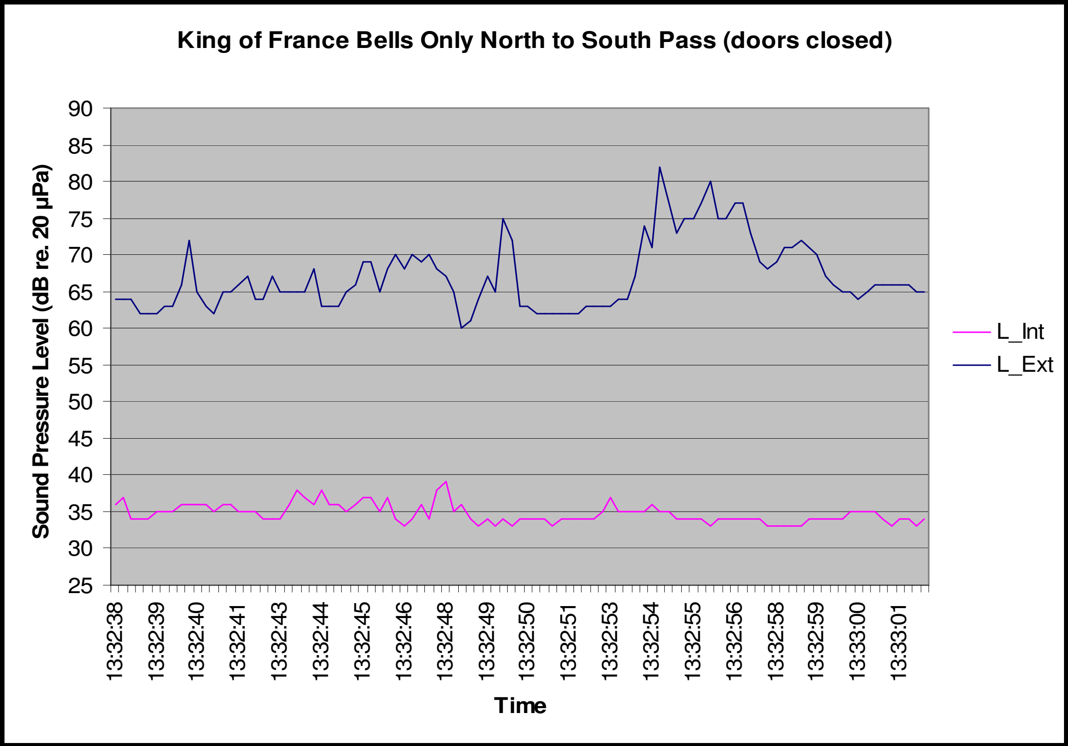
Results from Louis King of France, Bells Only, Doors Closed



HDR

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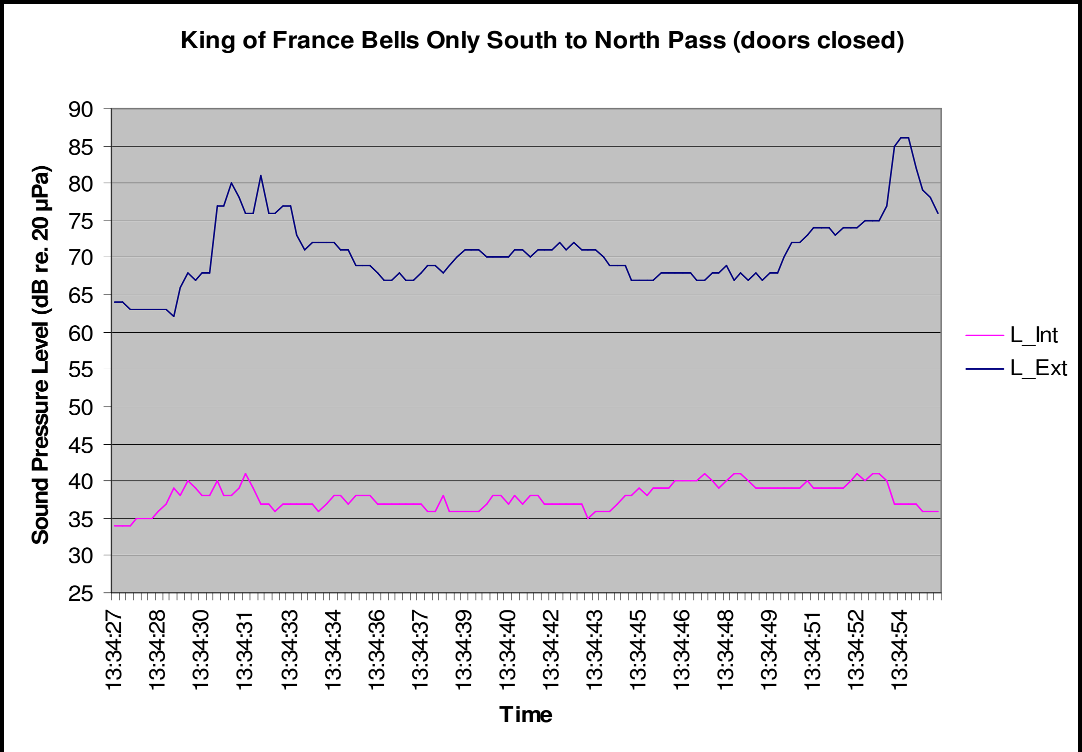
Results from Louis King of France, Bells Only, Doors Closed



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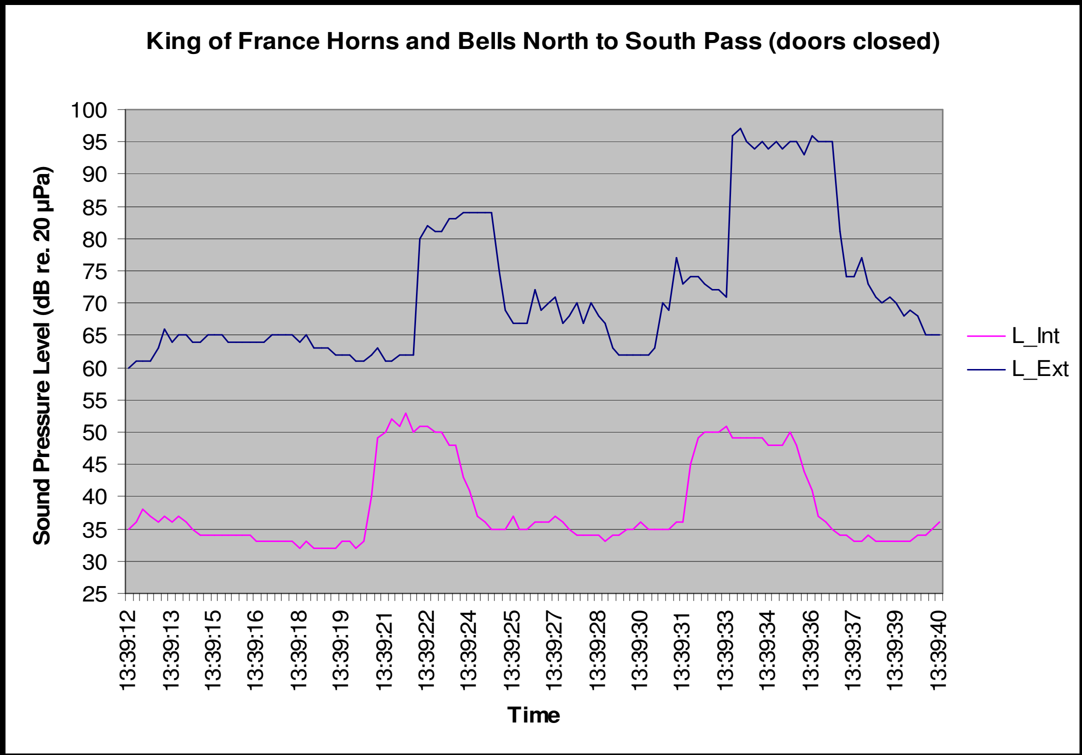
Results from Louis King of France, Horns and Bells, Doors Closed



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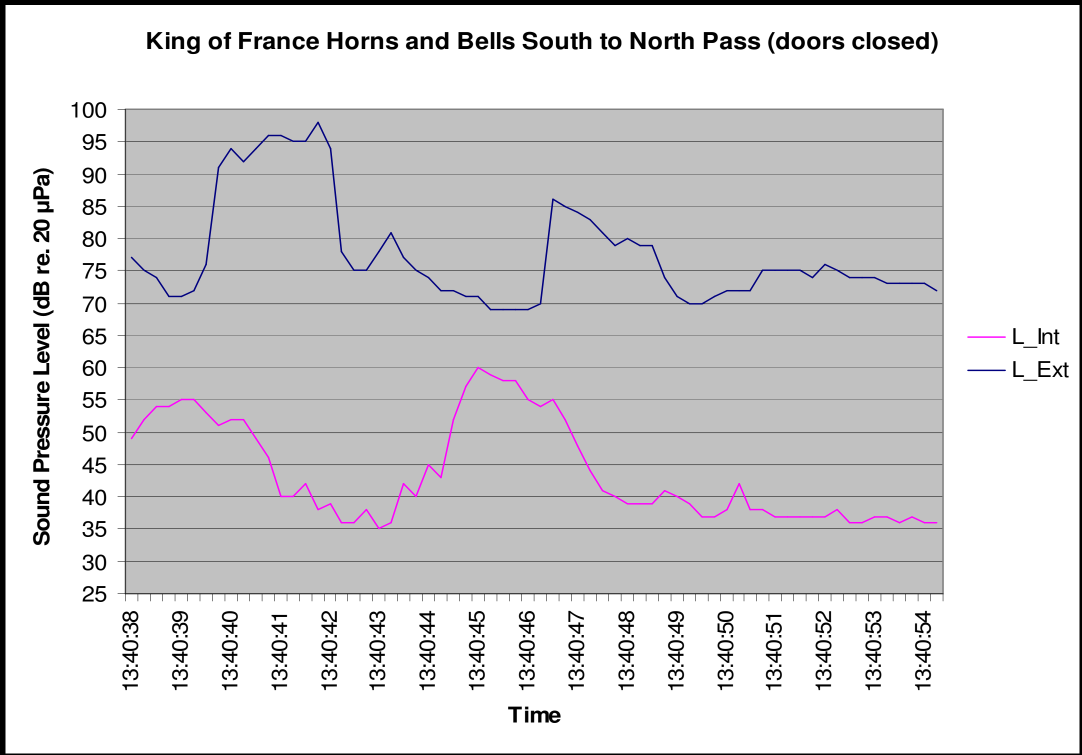
Results from Louis King of France, Horns and Bells, Doors Closed



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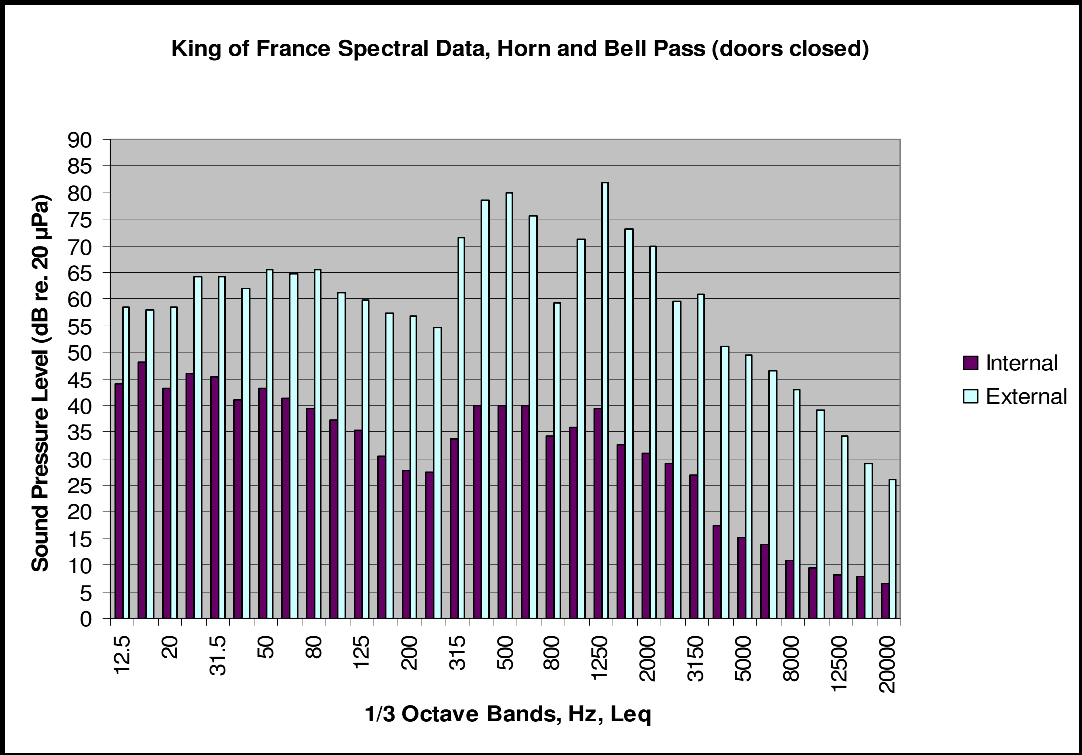
Results from Louis King of France, Horns and Bells, Spectral Comparison, Doors Closed



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Memo

To:	Kathryn O'Brien		
From:	Tim Casey and Elliott B. Dick	Project:	Central Corridor Light Rail Transit
cc:	Oscar Gonzalez		
Date:	March 23, 2009	Job No:	65891

Re: Light Rail Horn and Bell Simulation at MPR Studios H, I and P

BACKGROUND

The building which houses *Minnesota Public Radio* (MPR) is located in downtown St. Paul, along the *Central Corridor Light Rail Transit* (CCLRT) route on Cedar Street. Some noise-sensitive interior spaces at MPR may be affected by the introduction of Light Rail Transit on Cedar Street.

Studio P

Studio P was assessed in the LRV horn and bell simulation. Studio P is a recording studio with one exterior wall adjacent to Cedar Street. There are two windows inside of the studio. The window located on the exterior wall, adjacent to Cedar Street, is a tall rectangular studio window which is double paned with an airspace for isolation from exterior noise sources. The semi-circular internal is a similar construction, and looks out on the atrium and office spaces.

Studios H and I

Studios H and I were also assessed in the LRV horn and bell simulation. Studios H and I are smaller spaces equipped for editing and vocal recording. The studios share a common exterior wall adjacent to 9th Street. Each editing suite contained one quarter-circle shaped window located on the exterior wall, adjacent to 9th Street. Each of the exterior windows are double paned with an airspace for isolation from exterior noise sources.

LRV Horn and Bell Use

Metro Transit has adopted standard operating procedures for the sounding of bells and horns on the Hiawatha Light Rail line. Bells are sounded when entering and leaving an LRT station platform. High horns are sounded in emergency situations when operators believe a loud warning is required to alert persons outside the LRV to a hazard. The high horns (2 short blasts) are also sounded when two trains pass each other at a grade crossing. Low horns are typically used only at the Franklin yard and shops as part of LRV operations and maintenance occurring there.

MEASUREMENT METHOD

On February 23, 2009 HDR Engineering conducted a simulation of LRT horn and bell use on Cedar Street in downtown St. Paul. The HDR simulation and measurement was lead by Tim Casey and Elliott Dick, both with HDR, and assisted by a team of three other attendants. Kathryn O'Brien of the Central Corridor Project Office, and Tony Baxter of ESI, were also present to observe the measurements.

The LRV horn and bell mock-up have been described in previous memoranda. The levels of the bells, low horn, and high horn, were each measured and adjusted to match the standard specified levels currently used on *Hiawatha Light Rail Transit* (HLRT). The following table shows the current LRV horn and bell noise level standards according to Metro Transit standard operating procedures, and the .

Table 1

Metro Transit LRV Horn and Bell Noise Levels

	Measurement Distance	Target Level	Simulated Level
Bells	50 ft	79 dBA	69 dBA
Low-Horn	100 ft	90 dBA	84 dBA
High-Horn	100 ft	95 dBA	92 dBA

Previous simulations were able to attain the HLRT specified levels. For this simulation session, all signals fell short despite all attempts to adjustment the settings. The simulated levels shown above represent the maximum levels that the simulation rig was capable of producing. The measured spectra of the simulated signal are shown in Attachment C, provided by ESI from their instrumentation.

LRV horn and bell noise was measured by HDR staff during a series of simulated pass-bys of a Metro Transit vehicle operating horns and bells. Measurements of the simulated horns and bells occurred at Studio P, Studio H and Studio I.

Data collected during measurements allows HDR to assess the anticipated affect of the LRV horns and bells within these interior spaces. HDR compared the interior noise levels without LRT horns or bells against the noise levels in churches with LRT horns, and the levels with LRT bells. Attachment A of this memorandum contains details of the measurement instrumentation and procedures.

The time histories were examined to differentiate levels during LRV horns or bells sounds, versus during pauses between LRV sounds. Sounds of LRV horns and bells, at each measurement location, are compared to the measured natural ambient sound of the location (in the absence of simulated LRV horn and bell noise).

MEASUREMENT RESULTS

Results of HDR horn and bell simulation for Studios H, I, and P found that horns are audible inside all studios; bells, as calibrated for this simulation session, are not audible in Studio H or I, and were not observed in Studio P despite being measurable in Studio P. Figure 1 displays data collected during this exercise. These data indicate the following in regard to Studio P:

- The sound level of the simulated LRV bells during a northbound passby is 1 dBA above the interior ambient noise floor of Studio P.
- The sound level of the simulated LRV bells during a northbound passby is 2 to 6 dB above the ambient interior noise floor in the 500 Hz, 1 kHz and 2 kHz octave-bands.
- The sound level of the simulated LRV horns stationary in front of Studio P is up to 7 dBA above the interior ambient noise of Studio P.
- The sound level of the simulated LRV horns stationary in front of Studio P is 14 to 22 dB above the ambient interior noise floor in the 500 Hz, 1 kHz and 2 kHz octave-bands.
- The simulated horns and bells mainly affect the 500 Hz, 1 kHz and 2 kHz octave-bands.

Figure 1

Results in Studio P

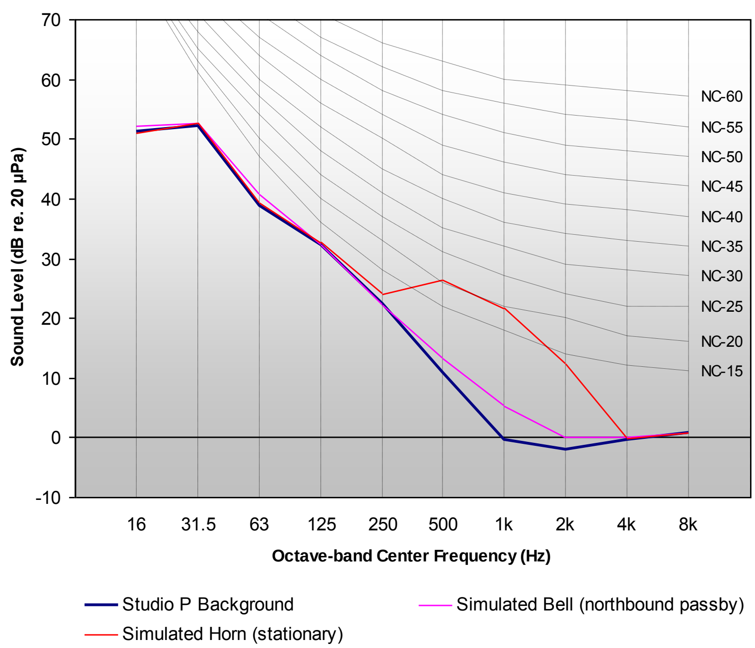


Figure 2 displays data collected during the LRV horn and bell simulation in Studio H. The data in Figure 2 indicates the following in regard to Studio H:

- The sound levels of the simulated LRV bells alone were neither audible nor measurable in Studio H.
- The sound level of the simulated LRV horns stationary on Cedar Street is up to 3 dBA above the interior ambient noise of Studio H.
- The sound level of the simulated LRV horns stationary in front of Studio H is 1 to 10 dB above the ambient interior noise floor in the 250 Hz, 500 Hz and 1 kHz octave-bands.
- The simulated horns mainly affect the 500 Hz octave-bands in Studio H.

Figure 2

Results in Studio H

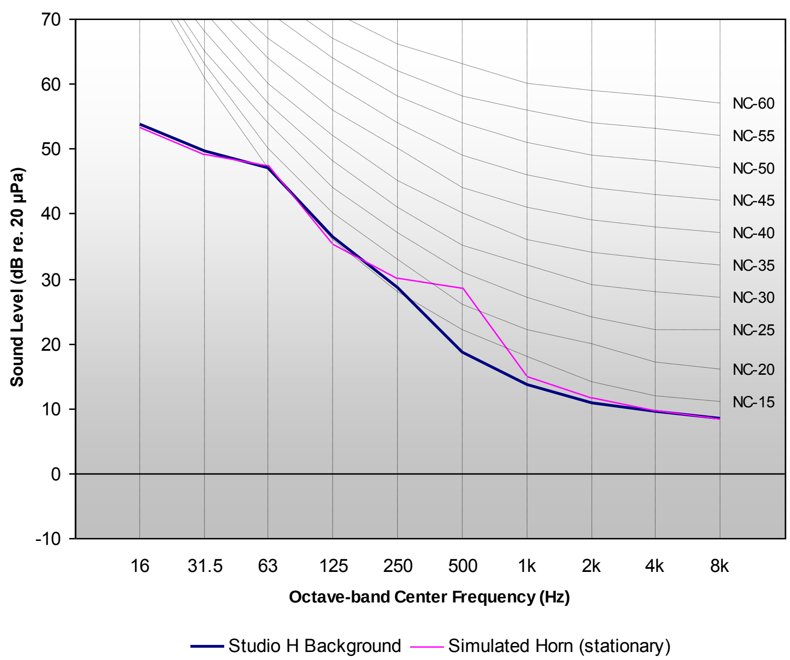


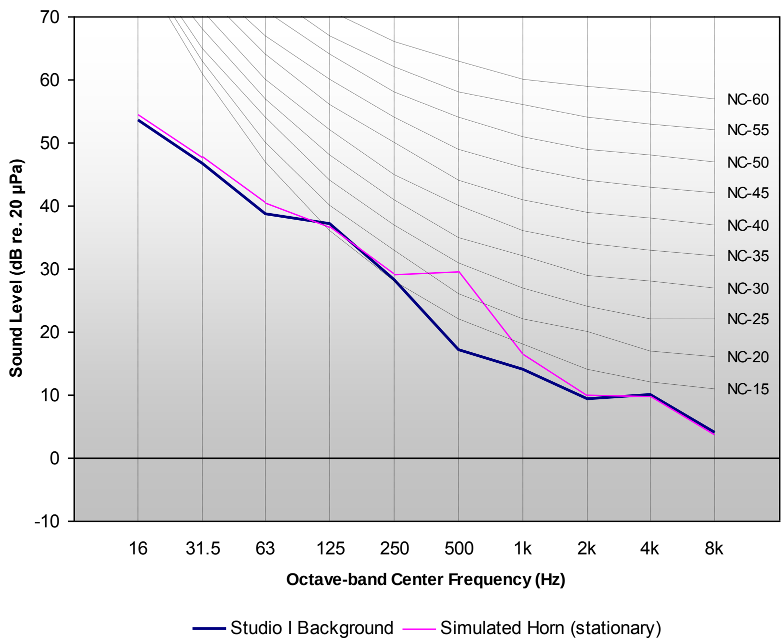
Figure 3 displays data collected during the LRV horn and bell simulation in Studio I. The data in Figure 3 indicates the following in regard to Studio I:

- The sound levels of the simulated LRV bells alone were neither audible nor measurable in Studio I.

- The sound level of the simulated LRV horns stationary on Cedar Street is up to 4 dBA above the interior ambient noise of Studio I.
- The sound level of the simulated LRV horns stationary in front of Studio I is 3 to 13 dB above the ambient interior noise floor in the 500 Hz and 1 kHz octave-bands.
- The simulated horns mainly affect the 500 Hz octave-bands in Studio I.

Figure 3

Results in Studio I



CRITICAL ANALYSIS

Simulated LRV horns were present in all studios at a level that may interfere with audio recording and production activities. HDR understands that Metropolitan Council is committing to administrative mitigation measures for the LRV horns. The remaining question is whether LRV bells require mitigation in these studios.

Studio P

The fact that the simulated LRV bells were measurable in Studio P is due in no small part to the very low ambient noise level in the room. Based on the difference in previously measured HLRT bell levels and the lower simulated bell levels, it is reasonable to expect that the HLRT bell levels would be even higher than measured during this simulation.

HDR recommends Metropolitan Council to commit to structural mitigation for Studio P, such as window and wall improvements. The LRV bell information measured during this simulation, combined with the OITL measurement results and previous measurements of the HLRT vehicle bell measurements, should be sufficient to determine the magnitude of structural mitigation.

Studios H and I

Simulated LRV bells were not measurable in studios H and I. The simulated LRV bells were simulated at a level lower than the HLRT bell calibration specifications. We cannot say whether increasing the bell level from the simulated level will approach or exceed the background noise levels of Studios H and I. Therefore this simulation can not predict whether future LRV bells will interfere with audio recording and production activities in these studios.

A meaningful estimation of the future bell levels in Studios H and I is not achievable with the information obtained in Studio P. A number of factors contribute to this. In comparison to Studio P, the exterior walls of Studios H and I are further from the LRT alignment, which would result in lower bell levels. The exterior windows of Studios H and I have a larger surface area than those in Studio P, which would result in higher bell levels. And the ambient room noise levels of Studios H and I are higher than that of Studio P, so any bell noise in Studios H and I would need to be higher, at least, than the simulated bell level in Studio P to be detectable.

HDR recommends Metropolitan Council to commit to reassessing Studios H and I after construction of the CCLRT, if MPR finds the bell levels to interfere with audio recording and production activities in these studios.

ATTATCHMENT A – INSTRUMENTATION AND SETUP

Ambient levels in Studios P, H and I are very quiet. To avoid microphone self-noise as interference in the measurement of sound levels, the self-noise of the low-noise microphones was less than 10 dBA (re. 20 μPa) to ensure adequate signal-to-noise when the signal is the ambient sound level of the studio. HDR also used Larson Davis 824 (LD824) analyzers.

Table A.1

Equipment for Interior Studio Locations

Microphone	Brüel & Kjær Type 4955 low noise free-field microphone
Measurement Equipment	Larson Davis Type 824 analyzer
Accessories	Brüel & Kjær Nexus conditioning amplifier

The measurement systems include the capability to measure the time-average sound level (L_{eq}), simultaneously over one or more prescribed periods of time. The sound levels were measured in 1/3 octave bands, whole octave bands, and overall A-weighted levels. Each measurement was stored as a separate file. Data acquired by the sound level meters was stored in the meters, and later downloaded for post-measurement analysis of data.

The overall measurement duration is determined by a run/stop programmed by the operator. Each run was pre-programmed to allow for minimal operator created noise, therefore each run including ambient background measurements and LRV passby events were performed in unoccupied spaces, with operators in adjacent rooms documenting noise events.

Instrumentation Setup

HDR positioned the microphone between 3 ft and 5 ft above the ground, mounted on stable tripod. The interior free-field microphone was oriented to face the incident noise (the window) in all studio measurements, where the orientation vector is normal to the microphone diaphragm. Microphone positions in each studio were consistent for ambient measurements and LRV simulation measurements.

Instrumentation Calibration

HDR instrumentation is calibrated on an annual basis by an independent laboratory using standards traceable to the National Institute of Standards and Technology. Rented equipment is likewise calibrated annually. Calibration certificates of HDR equipment and rented equipment are available to the client upon request.

The sound measurement equipment is adjusted to a reference level traceable to the National Institute of Standards and Technology, using a battery-operated precision microphone calibrator meeting ANSI S1.40 and IEC 60942, Class 1 Sound Calibrators. Sound measurement equipment is calibrated and adjusted in HDR's office prior to transportation to the measurement site. Calibration checks are performed in the field before the first measurement and after completion of the series of measurements.

ATTATCHMENT B – ADDITIONAL EVENTS

During LRV simulation measurement additional noise events, not associated with bell or horn noise, were also captured.

An event observed in the Studio P data, a transit bus passed on Cedar, idled at the corner for greater than one minute, and then proceeded travel. This is shown in Figure B.1, and the data indicate the following in regard to Studio P:

- The sound level of buses traveling on Cedar Street is 4 to 7 dBA above the ambient interior noise floor.
- The sound level of buses idling on Cedar Street is 1 dBA above the ambient interior noise floor.

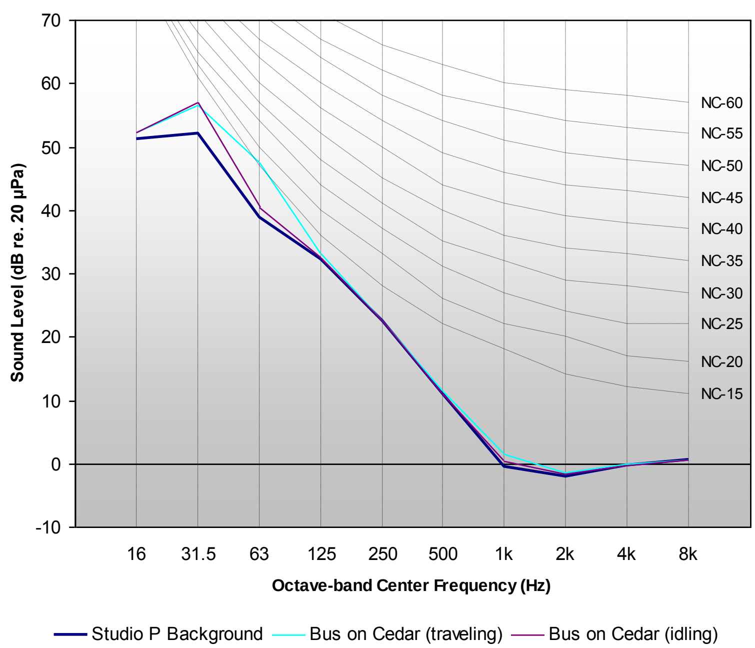


Figure B.1

The time-history of the Studio H showed an intermittent noise. Its duration was less than one second, and repeated in 8 to 30 second intervals – possibly a clicking from the studio equipment. These events were found to be similar in frequency content, and all the distinct events of this type were averaged. This is shown in Figure B.2, and the data indicate the following in regard to the unknown clicking:

- The sound level of the unknown clicking is 1 dBA above the ambient interior noise floor.
- The sound level of the unknown clicking increases the ambient interior noise floor by 5 dB or more between the 500 Hz and 4 kHz octave-bands.

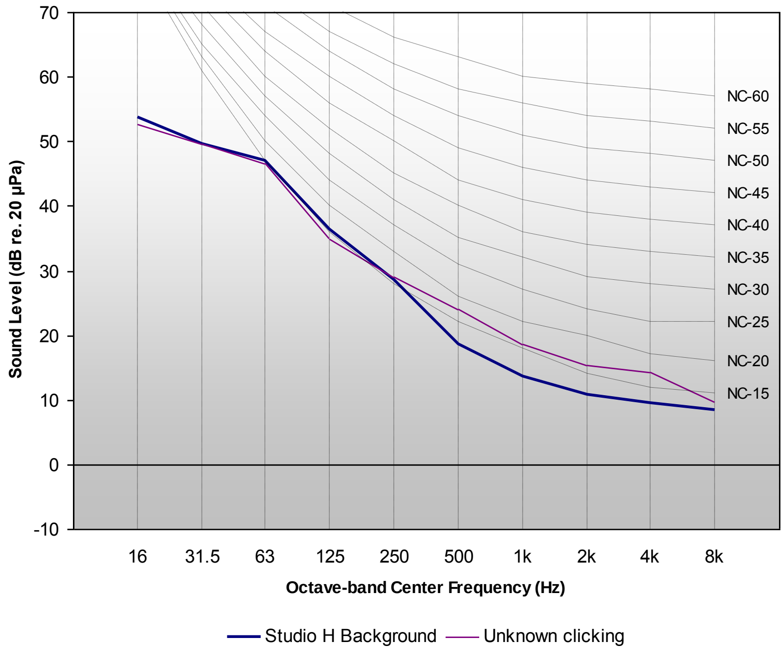

70
60
50
40
30
20
10
0
-10
Sound Level (dB re. 20 µPa)
NC-60
NC-55
NC-50
NC-45
NC-40
NC-35
NC-30
NC-25
NC-20
NC-15
16
31.5
63
125
250
500
1k
2k
4k
8k
Octave-band Center Frequency (Hz)
Studio H Background
Unknown clicking

Figure B.2

ATTATCHMENT C –BELL AND HORN LEVEL CALIBRATION RESULTS

Noise Control Test

ESI Engineering, Inc. 7831 Glenroy Rd/Ste 340 Minneapolis, MN 55439 Tel:(952) 831-4646

Project No: P1629
Project: MPR - CCLRT
Location: St Paul, Minnesota
Engineer: Bret Peterson

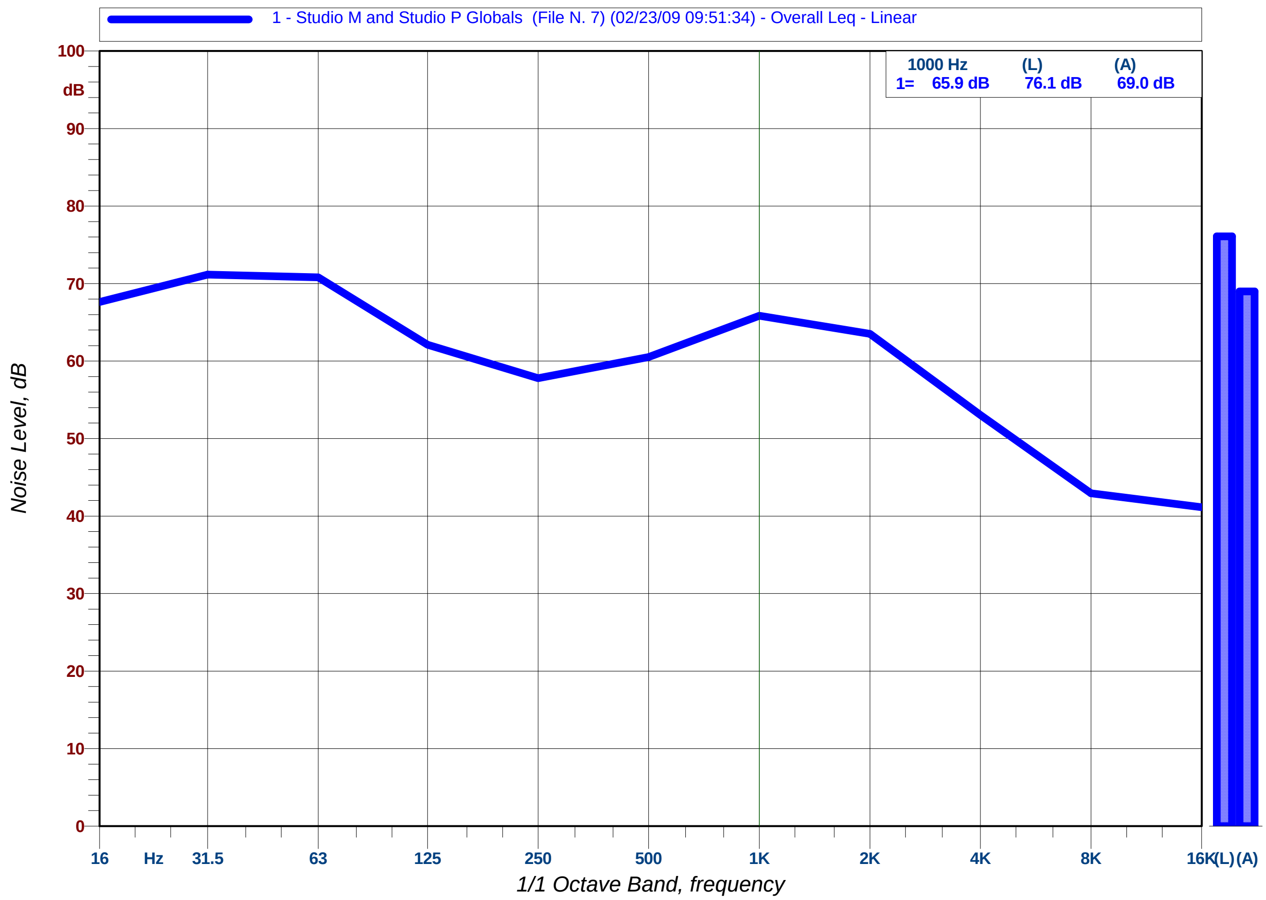
Instrumentation: Larson Davis 824 SLM s/n 824A0852
Calibrator: Larson Davis Cal-200 s/n 2386
Last Calibration: 24 September 2008 10:12

Location: MPR
Date: 2/23/2009

Temperature: deg. F
Wind Speed / Dir.: indoors
Humidity:

Test Conditions:
- Bells at 50 feet

RunTime: 20.6



Tabulated Data:

Overall Leq: 69.0 dBA
LMax: 75.1 dBA

Hz	dB	Hz	dB	Hz	dB	Hz	dB	Hz	dB
16 Hz	67.6 dB	63 Hz	70.8 dB	250 Hz	57.8 dB	1000 Hz	65.9 dB	4000 Hz	53.0 dB
31.5 Hz	71.1 dB	125 Hz	62.1 dB	500 Hz	60.5 dB	2000 Hz	63.5 dB	8000 Hz	43.0 dB

Figure 1

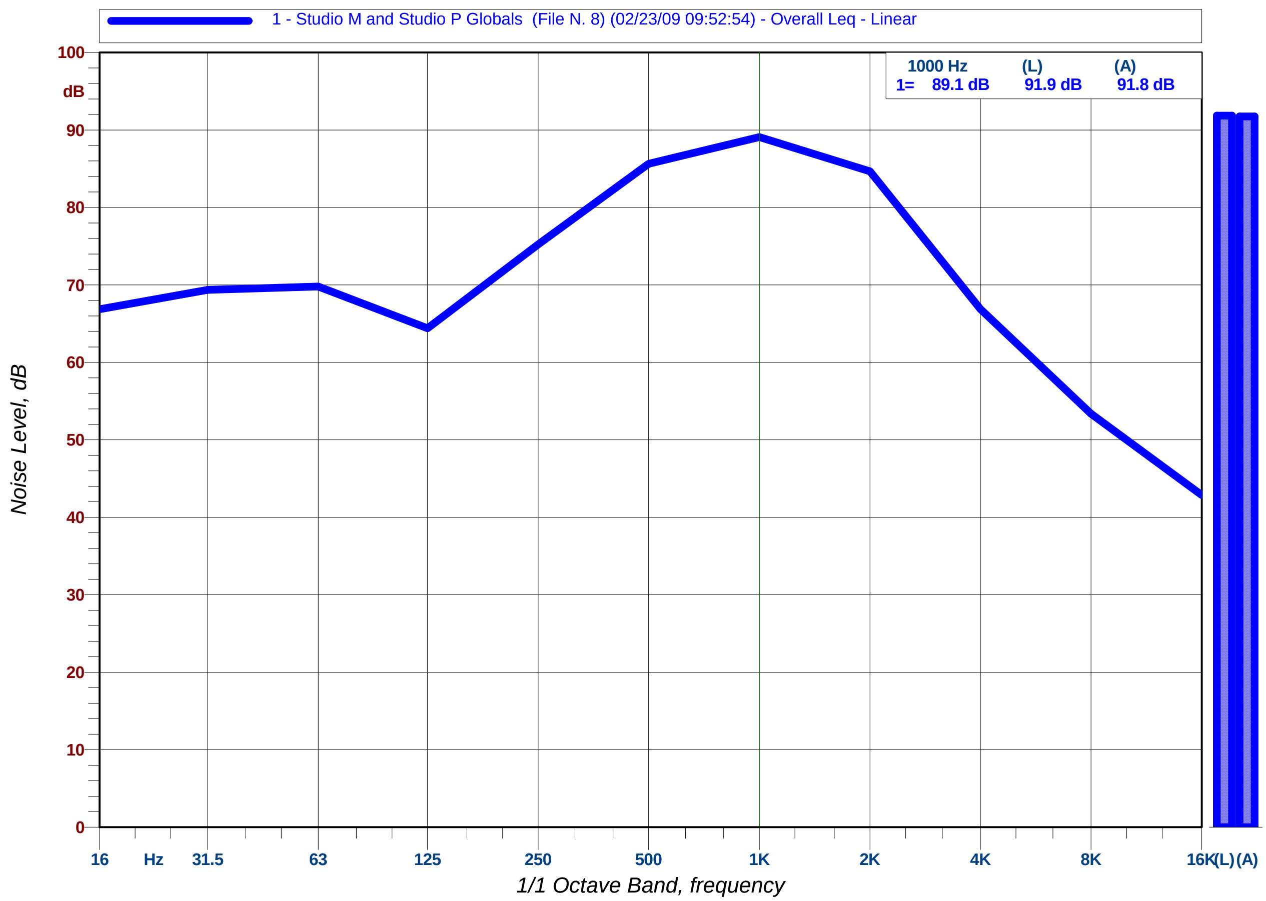
Project No:	P1629	**Instrumentation:**	Larson Davis 824 SLM s/n 824A0852
Project:	MPR - CCLRT	**Calibrator:**	Larson Davis Cal-200 s/n 2386
Location:	St Paul, Minnesota	**Last Calibration:**	24 September 2008 10:12
Engineer:	Bret Peterson		

Location: MPR
Date: 2/23/2009

Temperature: deg. F
Wind Speed / Dir.: indoors
Humidity:

Test Conditions:
- High Horn at 100 feet

RunTime: 21.1



Tabulated Data:

Overall Leq: 91.8 dBA
LMax: 95.4 dBA

Hz	dB	Hz	dB	Hz	dB	Hz	dB	Hz	dB
16 Hz	66.8 dB	63 Hz	69.8 dB	250 Hz	75.2 dB	1000 Hz	89.1 dB	4000 Hz	66.9 dB
31.5 Hz	69.3 dB	125 Hz	64.4 dB	500 Hz	85.6 dB	2000 Hz	84.7 dB	8000 Hz	53.4 dB

Figure 2

Noise Control Test

ESI Engineering, Inc. 7831 Glenroy Rd/Ste 340 Minneapolis, MN 55439 Tel:(952) 831-4646

Project No: P1629
Project: MPR - CCLRT
Location: St Paul, Minnesota
Engineer: Bret Peterson

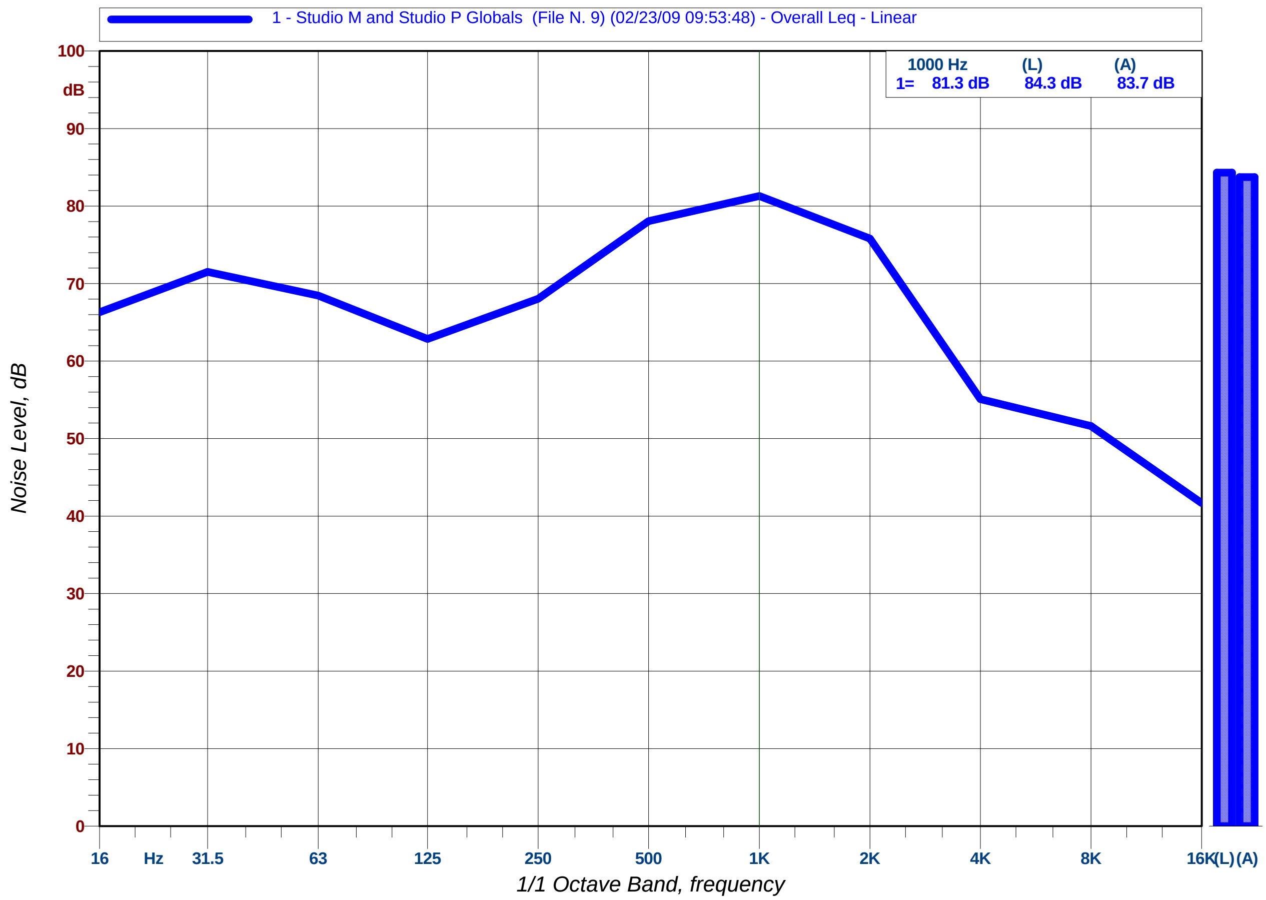
Instrumentation: Larson Davis 824 SLM s/n 824A0852
Calibrator: Larson Davis Cal-200 s/n 2386
Last Calibration: 24 September 2008 10:12

Location: MPR
Date: 2/23/2009

Temperature: deg. F
Wind Speed / Dir.: indoors
Humidity:

Test Conditions:
- Low Horn at 100 feet

RunTime: 20.6



Tabulated Data:

Overall Leq: 83.7 dBA
LMax: 85.8 dBA

Hz	dB	Hz	dB	Hz	dB	Hz	dB	Hz	dB
16 Hz	66.3 dB	63 Hz	68.4 dB	250 Hz	68.0 dB	1000 Hz	81.3 dB	4000 Hz	55.1 dB
31.5 Hz	71.5 dB	125 Hz	62.8 dB	500 Hz	78.0 dB	2000 Hz	75.8 dB	8000 Hz	51.6 dB

Figure 3

HDR | ONE COMPANY *Many Solutions*℠

Memo

To:	Kathryn O'Brien		
From:	Elliott B. Dick and Tim Casey	Project:	Central Corridor Light Rail Transit
cc:			
Date:	March 30, 2009	Job No:	65891

Re: Sound Insulation Testing at MPR Studio MMW and Studio P

SUMMARY

On February 23, 2009, HDR conducted a test of the sound insulation from exterior noise in two studios at the Minnesota Public Radio (MPR) building in downtown St. Paul. The studios were the *Maud Moon Weyerhaeuser Studio* (Studio MMW) and the *Atrium Studio* (Studio P). Both studios face Cedar Street, the proposed alignment for future *Central Corridor Light Rail Transit* (CCLRT). These tests measured the Outdoor to Indoor Transmission Loss (OITL) of the large window in Studio MMW and the exterior window and wall in Studio P. In layman's terms, transmission loss refers to the amount of noise a wall or window blocks. HDR performed the tests in accordance with ASTM Standard E 966 - 04. Transmission loss is usually measured under ideal, laboratory conditions. The intent of the ASTM standard is that OITL tests be performed under typical field conditions. Recording studios, by design, are not typical field conditions. Recording studios are ordinarily designed to have better-than-average acoustical isolation from outdoor noise and controlled reverberant characteristics.

Noise reduction refers to the overall amount of outdoor noise that is blocked, and does not enter a receiving room. Noise reduction is expressed as sound pressure, in decibels. Noise reduction is dependant upon the size of the partition, the size and reverberation characteristics of the receiving room. Transmission loss is an acoustical characteristic that is independent of the existing environment; the size and characteristics of the partition and receiving room are not factored into the transmission loss. It represents the noise reduction characteristics of a partition under reference conditions. The ASTM standard provides several different methods to perform the measurements and process the monitoring data. This memo provides a detailed discussion of the measurement and data processing methods used in this test, to assist a qualified acoustical consultant understand the salient aspects of the testing methodology, and to interpret the results.

Test results characterize the acoustical performance of the existing window in Studio MMW, and window and wall in Studio P. The results are intended for use in the design of noise mitigation measures at MPR, along with information on the level of CCLRT noise intrusion into the studios, and the target level of mitigation.

TECHNICAL DISCUSSION

The acoustical tests were planned in accordance with the ASTM *Standard Guide for Field Measurements of Airborne Sound Insulation of Building Facades and Facade Elements*, Designation: E 966 - 04, employing the specific methods identified therein of a fixed (loudspeaker) source and flush outdoor microphone positions. The measurement was planned by Elliott Dick of HDR, and reviewed by Tim Casey of HDR, and Tony Baxter and Kay Hatlestad of ESI. A consensus plan was reached between HDR and ESI.

Participants in the testing included Elliott Dick of HDR to supervise the setup and execution of the tests, Roger Anderson and Derrick Anderson of Acoustics and Noise Control (ANC) to operate the instrumentation, and Gina Ramirez and Kent Peterson of HDR to position microphones and the sound source. Support was also provided by MPR staff for the sound source, and Metropolitan Council personnel for lift operation.

Measurement results are reported as OILR(θ) and apparent OITL(θ), where θ identifies the angle of incident sound – the angle of the noise source onto the face of the facade. The *Outdoor-indoor level reduction* (OILR) is the reduction, in 1/3 octave bands, from outside into the specific receiving room in question. This will be the most informative metric to determine the current level of sound isolation of these studios.

The OILR metric cannot be used to compare the performance of the facade element against other materials (i.e. to select a material with higher transmission loss). To compare materials against each other, the *Apparent outdoor-indoor transmission loss* (apparent OITL or aOITL) is the outdoor-indoor level reduction, in 1/3 octave bands, normalized to a common specimen size and receiving room absorption. Normalization occurs to enable this measurement to be compared with other measurements that don't have the same size specimen, or an identical receiving room. The *Outdoor-indoor transmission loss* (OITL) is the same as apparent OITL, in 1/3 octave bands, but requires additional flanking investigations.

TEST SITE

The Minnesota Public Radio building is located on the east side of Cedar Street, north of Seventh Street in downtown St. Paul. The building has several additions, each of different vintages. The original building was a two-story bank. One renovation added two stories atop the original bank and houses the two studios addressed by the OITL tests. The most recent renovation (2006) included an atrium and a new building to the north of the original bank.

Studio MMW

Studio MMW is a large shoebox-shaped recording studio. The walls are reportedly double wall construction to mechanically decouple the inside and outside walls, with one wall on the floating slab of the studio and held in place with resilient sway-bracing. One of the long-dimension walls is the exterior wall adjacent to Cedar Street. The floor covering is wood parquet, and the wall finishes were a mix of materials providing acoustical absorption, diffusion; the non-treated walls were covered with gypsum wall board. There was a large window between the studio and its control room. The ceiling had wood-slat diffusers with acoustically absorptive material laid on top, visually estimated to extend three feet below the finished ceiling. These diffusers occupied approximately one-third to one-half the area of the ceiling, though the ceiling surface was continuous behind the diffusers. The studio contained equipment and cabinets stored at the end north end of the room, an isolation booth in the northwest quadrant of the room, a piano in the middle of the floor, and around the perimeter of the room chairs, tables and freestanding absorber panels were stored.

There is a semicircular window in the exterior wall of Studio MMW, made up of two quarter-circle windows. This window faces Cedar St. and is made up of a flat, possibly laminate, exterior window pane and an interior assembly of clear half-cylinders placed over the windows. This half-cylinder surface is intended to increase the window isolation by adding mass and an airspace, and additionally to prevent reflections (echoes) by eliminating the flat window surface, according to studio personnel. The half-cylinders are approximately two to three feet in diameter, and made of a thick, clear plastic material, possibly ½ to 1 inch thick, according to a visual inspection. There are grilles at the top and bottom of the confined airspace, reportedly with an absorptive cavity. During the outdoor microphone setup, several potential sound leaks were observed on the window trim, in the form of gaps without caulk, and holes due to rust.

The window in Studio MMW is the apparent sound path with the least isolation from the outside into Studio MMW. Based on observations and anecdotes about the window and the wall, we assume that the wall will insulate much more sound than the window and the surface area of the window will be the dominant source of transmitted outside sound into the studio. Further, an attempt to test the wall itself would be influenced by interference from flanking sound from the window. To determine the magnitude of the interference requires additional "flanking testing", but in this case, such "flanking testing" would involve a significant and unrealistic effort to isolate the window sound transmission from the wall, or vice versa. Therefore *the facade element under test in Studio MMW is the window*, which will yield *apparent OITL* results.

Studio P

Studio P is smaller than Studio MMW, and is located above the Northwest corner of the original bank building. It contains similar materials as Studio MMW, though without the slat/absorber assembly on the ceiling. Likewise, it contained similar furnishings and equipment, including a piano but no free standing isolation booth. There was a carpet placed in the middle of the wood floor.

Studio P has two windows: a tall, narrow window that looks out onto Cedar Street, and a quarter-circle window looking out into the new atrium. The windows in Studio P are acoustically designed for use in recording studios, with a thick airspace between the panes of glass and absorption around the airspace perimeter.

HDR cannot make the same assumption about the window in Studio P as we did in Studio MMW. Observations in Studio P indicate that for some sounds, the small exterior window is the dominant sound path from outside to inside. However, the interior levels of exterior sound sources are relatively low, and we can assume that the larger surface area of the wall will contribute transmitted sound to the interior measurement. If we attempted to test the window on its own, the level of interference from the wall surface is unknown. Additionally, it would be difficult to measure the incident sound on such a small window, using several microphones and windscreens, that wouldn't interfere with the incident sound. Therefore, *the facade element under test in Studio P is the composite facade wall*, comprised of both the wall portion and the window portion, and the test will yield *apparent OITL* results, where the window is an apparent flanking path around the isolation of the composite wall.

METHOD

The ASTM Standard E966 specifies several combinations of methods to measure façade insulation. Of these methods, the flush microphone method was employed, and the fixed (loudspeaker) source. This allowed simultaneous measurements inside and outside without overly-complex microphone mounting, and with a test source that could be positioned to specific angles and a higher output level than achievable with passing traffic.

The OITL measured at a single angle is not comparable to the laboratory test method (ASTM Standard E90) where a random-incidence noise is produced on the "outside" of the wall. To achieve a result that can be compared with laboratory tests, random-incidence noise was approximated by measuring at multiple angles of incidence. The three angles 34°, 60° and 80° represent equal areas of a hemisphere, allowing a simple average of the squared sound pressure.

Fixed-Source Setup

The fixed (loudspeaker) source was provided by MPR and consisted of a subwoofer, 2-way loudspeaker, amplifiers, and a signal generator. The source level was set to just below clipping level.

To achieve the 34°, 60° and 80° angles of incidence, Table 1 shows distances used to locate the source. The height was determined by the difference of the vertical offset from the ground elevation.

Table 1

Source Location Relative to Facade Element Center

Angle of Incidence	34°	60°	80°
Diagonal distance	20.0 ft	25.0 ft	30.0 ft
Perpendicular distance to facade face (out)	16.6 ft	12.5 ft	5.2 ft
Vertical offset from element center (down)	11.2 ft	18.8 ft	14.7 ft
Horizontal offset from element center (sideways)	0.0 ft	10.8 ft	25.6 ft

Microphone Setup

Exterior microphones for the facade element under test were installed at 5 simultaneous locations, in the flush microphone positions. The microphone diaphragms were oriented perpendicular to the facade surface (the preamplifier bodies and the normal vector of the microphone diaphragms were oriented parallel to the window surface). Five microphone windscreens were modified (trimmed) so the microphone and preamplifier could be taped to the facade element under test, positioned so the microphone diaphragms were entirely within 5/8” of the facade surface but not touching the surface.

Interior microphones for the facade element under test were at 3 simultaneous locations, mounted on microphone stands and booms. The interior low-noise free-field microphones were oriented to face the facade element under test. In both Studio MMW and Studio P, there was an anticipated excess of absorption (the absorption exceeded the recommended in most bands, according to §7.4.1 in ASTM E966-04), which inhibits the diffuse sound field in the room. Lack of a diffuse sound field will limit comparisons of the normalized apparent OITL test results to other published material data. Comparisons are still valid with some margin to account for this. However, the absorption measurement does not affect the non-normalized level reduction, which is the metric of most interest.

Studio MMW Microphones

Exterior microphones for the Studio MMW window were spaced approximately 30” apart. Logistic limitations prohibited a broader spacing of the microphones (the cherry-picker bucket couldn’t reach any higher). Figure 1 shows microphone locations and orientations on the Studio MMW window.

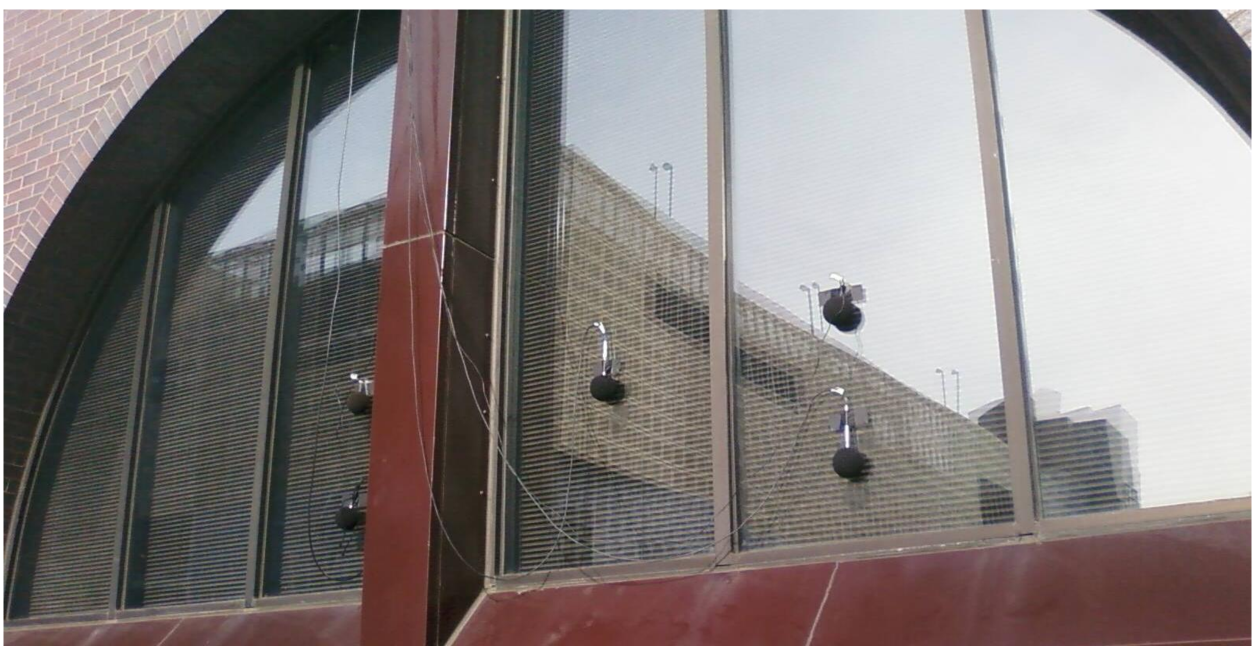


Figure 1 – Studio MMW exterior microphone locations

Interior microphones for Studio MMW were mounted approximately 7 feet above the ground, and spaced approximately 12-15 feet apart. All three microphones were located in front of the window, between 5 and 20 feet away from the window. These locations are a slight deviation from the standard in that they represent an average of the area in front of the window, rather than an average of the area of the entire room. However, the microphones were placed in front of the window as a "worst case" for non-normalized level reduction, which is the metric of most interest.

Studio P Microphones

Two of the microphones were placed on the window portion of the composite facade. As with the Studio MMW window, logistic limitations prohibited a broader spacing of the microphones (the cherry-picker's reach was limited). Figure 2 shows microphone locations and orientations on the Studio P facade.

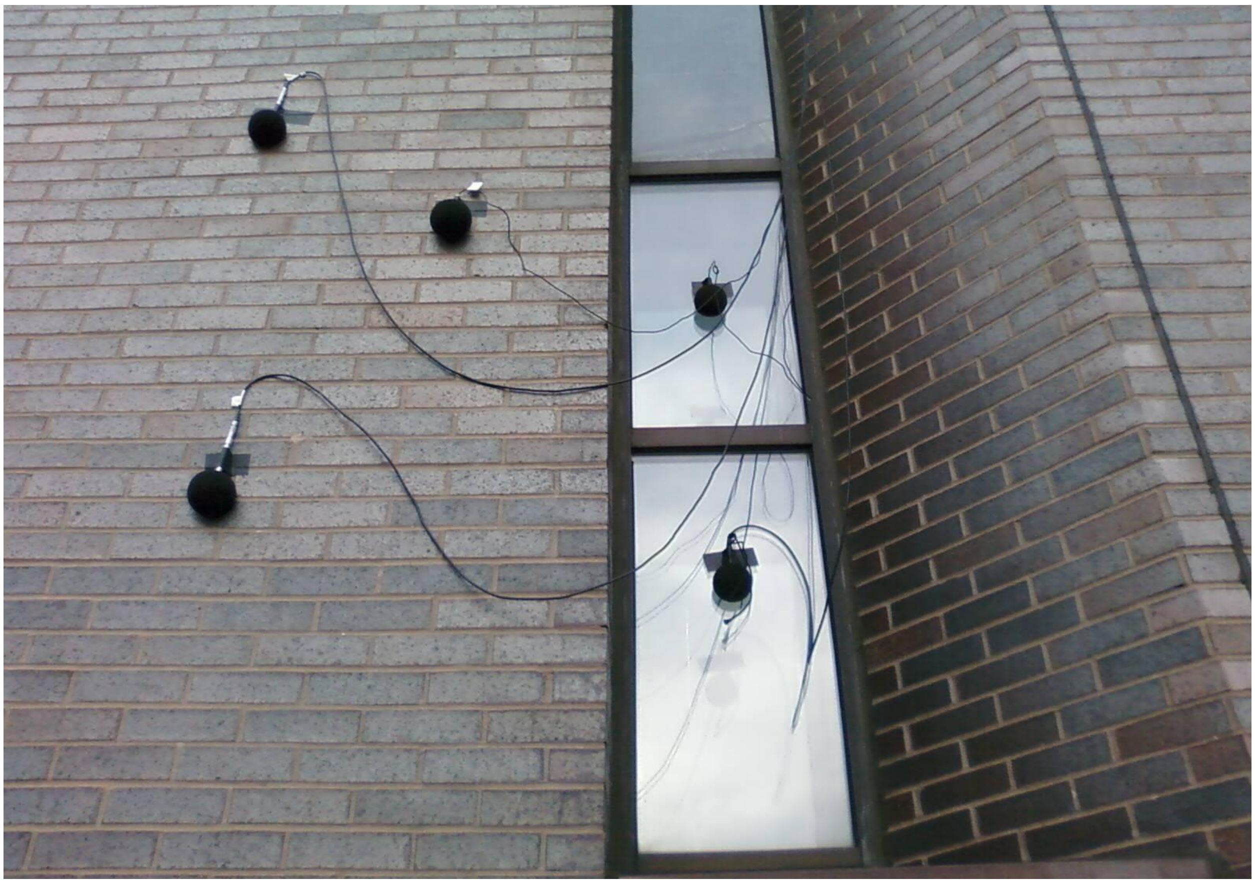


Figure 2 – Studio P exterior microphone locations

Interior microphones for Studio P were mounted between 5 and 7 feet above the ground, and spaced approximately 6 to 10 feet apart. All three microphones were positioned at least 3 feet from any surface. The three microphones represent a spatial average of the whole room.

Instrumentation

To measure at all interior and exterior locations simultaneously, multichannel analyzers were operated by Roger Anderson of Acoustics and Noise Control (ANC). The analyzers consisted of two Sinus Soundbooks, provided by ANC, and one Larson-Davis 824, provided by ESI. The five exterior microphones were provided by ANC, and the three interior microphones consisted of two Brüel & Kjær low-noise microphones rented by HDR, and one G.R.A.S. low-noise microphone rented by ESI.

Prior to measurements, ANC checked all channels to confirm that they were properly recording 1/3 octave-band spectral data. Upon processing the measurements, ANC discovered one channel for the exterior microphones did not record spectral data. Therefore data from only 4 microphone locations are available for processing.

Calibration

The sound measurement equipment is adjusted to a reference level traceable to the *National Institute of Standards and Technology* (NIST), using a battery-operated precision microphone calibrator meeting ANSI S1.40 and IEC 60942, Class 1 Sound Calibrators, provided by ESI. Sound measurement equipment was calibrated and adjusted on-site before the first measurement and checked after completion of the series of measurements.

HDR-provided rental instrumentation was laboratory-calibrated within a year of the test date. Calibration certificates of HDR-provided rental instrumentation are available to the client upon request.

Measurement and Post-processing

The measurement ran continuously during setup, operation, and moving of the sound source from one angle of incidence through the third angle of incidence. These very long measurements were post-processed to isolate the periods when the test source was on, simultaneously within the inside and outside measurement results, to average the level of the test source. These long measurements were further post-processed to isolate an average background noise level in close proximity to the test source events.

Background Correction

The individual microphones were each adjusted for the background noise at their own location. The background noise adjustment was applied according to ASTM Standard E966-04 §10.1. No adjustment is required for background levels 5 dB to 10 dB below the measured level of the test source. Formula 12 in ASTM Standard E966-04 was used for background levels 5 dB to 10 dB below the measured level of the test source.

The ASTM Standard E966-04 states, “the background level should be at least 5 dB below the level [of the measured test source],” but does not require such, and does not specify how to handle such situations. Therefore, this method adopts the instructions from ASTM Standard E336-07, or the version of this method for field tests between two adjacent rooms, and ASTM Standard E90-04, the laboratory version of this test method. These both specify subtracting 2 dB from the measured test source level, and identify this band as an “estimate of the lower limit”. In other words the actual isolation may be higher than the stated value, but it couldn’t be measured any higher than the stated value.

Calculation

The OILR calculation for the Flush Microphone Method and a Fixed (Loudspeaker) Source in each 1/3 octave band for a particular angle of incidence θ is:

$$OILR(\theta) = L_{flush} - L_{in}(\theta) - 6 \text{ dB}$$

Where L_{flush} is the average level of the flush measurements in dB, and $L_{in}(\theta)$ is the average level of the indoor measurements in dB.

The apparent OITL calculation for the same method in each 1/3 octave band is:

$$aOITL(\theta) = OILR(\theta) + 10 \log(S \cos(\theta) / A_2) + 6 \text{ dB}$$

Where S is the surface area of the test façade element, and A_2 is the room absorption; both in the same units (square meters or square feet/sabines).

A measurement at a single angle of incidence is not comparable with laboratory tests, which are tested with random-incidence sound fields. To approximate the random incidence sound isolation of the facade elements, the source measurements of the three angles were averaged, and the indoor measurements of the three angles were also averaged. Then the OILR and apparent OITL calculations were performed on these averages.

The OITL calculation required the measurement of the room absorption in each 1/3 octave band. The absorption in Studio MMW was calculated from the room decay rate, measured according to ASTM standard E2235 (per §7.4.2.1 of ASTM E966-04). The analyzer outputs broadband pink noise (equal energy per octave) into a powered loudspeaker. The pink noise built to a steady-state within the room, and then the analyzer cut off the signal and measured the decay within the room. Measurements were at three different combinations of microphone and sound source locations. Each location combination consisted of three repeated measurements. The analyzer provided an average reverberation time of all nine measurements, (RT60 or the number of seconds that it takes to decay 60 dB).

The absorption in Studio P was estimated by building a simple computer model of the room, using standard material absorption coefficients. This produced absorption values for the 100 Hz to 10 kHz one-third octave bands. Absorption values for the 20 Hz to 80 Hz on-third octave bands were entered conservatively high.

The 95% uncertainty was calculated for each test. The uncertainty values are due to the outdoor and indoor measurements only, not the room absorption measurements. Therefore the uncertainty is applicable to the OILR(θ), but the uncertainty to the OITL(θ) could be greater.

STUDIO MMW RESULTS

Results of the OILR(θ) and OITL(θ) calculations for Studio MMW are shown in the following tables and figures.

Table 2 – MMW results at 34°

Freq. (Hz)	OILR(34°) (dB)	OITL(34°) (dB)	Notes
20	12.9	10.5	[2]
25	14.8	15.1	[2]
31.5	20.5	17.2	[2] [3]
40	28.8	24.7	[2] [3]
50	33.3	28.9	[2] [3]
63	39.3	34.5	[1] [3]
80	42.7	37.0	[1] [3]
100	46.6	41.0	[1] [3]
125	45.1	39.1	[3]
160	51.4	45.1	[3]
200	51.6	45.7	[3]
250	47.8	41.2	[3]
315	51.1	44.0	[3]
400	54.7	47.8	[3]
500	59.1	52.0	[3]
630	60.6	53.4	[3]
800	63.4	56.0	[3]
1000	70.6	63.4	[1] [3]
1250	71.8	65.0	[1] [3]
1600	73.7	69.7	[2] [3]
2000	68.2	61.0	[1] [3]
2500	61.7	54.3	[3]
3150	63.6	56.1	[3]
4000	66.2	58.5	[1] [3]
5000	67.9	60.3	[2] [3]
6300	72.6	65.0	[2] [3]
8000	76.7	69.5	[2] [3]
10000	75.1	69.8	[2] [3]

Table 3 – MMW results at 60°

Freq. (Hz)	OILR(60°) (dB)	OITL(60°) (dB)	Notes
20	12.1	3.0	[2]
25	15.4	9.0	[2]
31.5	17.6	7.4	[2] [3]
40	29.4	18.5	[1] [3]
50	33.6	22.4	[3]
63	37.3	25.8	[3]
80	37.5	25.0	[3]
100	40.3	27.9	[3]
125	44.9	32.0	[3]
160	49.6	36.5	[3]
200	49.2	36.5	[3]
250	48.4	35.1	[3]
315	52.2	38.3	[3]
400	52.0	38.4	[3]
500	53.2	39.3	[3]
630	55.0	41.0	[1] [3]
800	55.6	41.4	[1] [3]
1000	55.0	40.9	[1] [3]
1250	58.0	44.4	[1] [3]
1600	54.2	43.4	[1] [3]
2000	51.8	37.8	[2] [3]
2500	55.0	40.8	[2] [3]
3150	52.2	37.9	[1] [3]
4000	51.2	36.7	[2] [3]
5000	48.8	34.4	[1] [3]
6300	41.3	26.9	[1] [3]
8000	38.3	24.3	[1] [3]
10000	40.7	28.6	[1] [3]

Note 1: One or more microphone locations were measured with less than 5 dB signal-to-noise, therefore the value may be an estimate of the lower limit.

Note 2: All microphone locations were measured with less than 5 dB signal-to-noise, therefore the value is an estimate of the lower limit.

Note 3: Absorption in this band exceeded the maximum recommended for the room volume according to §7.4.1 in ASTM E966-04.

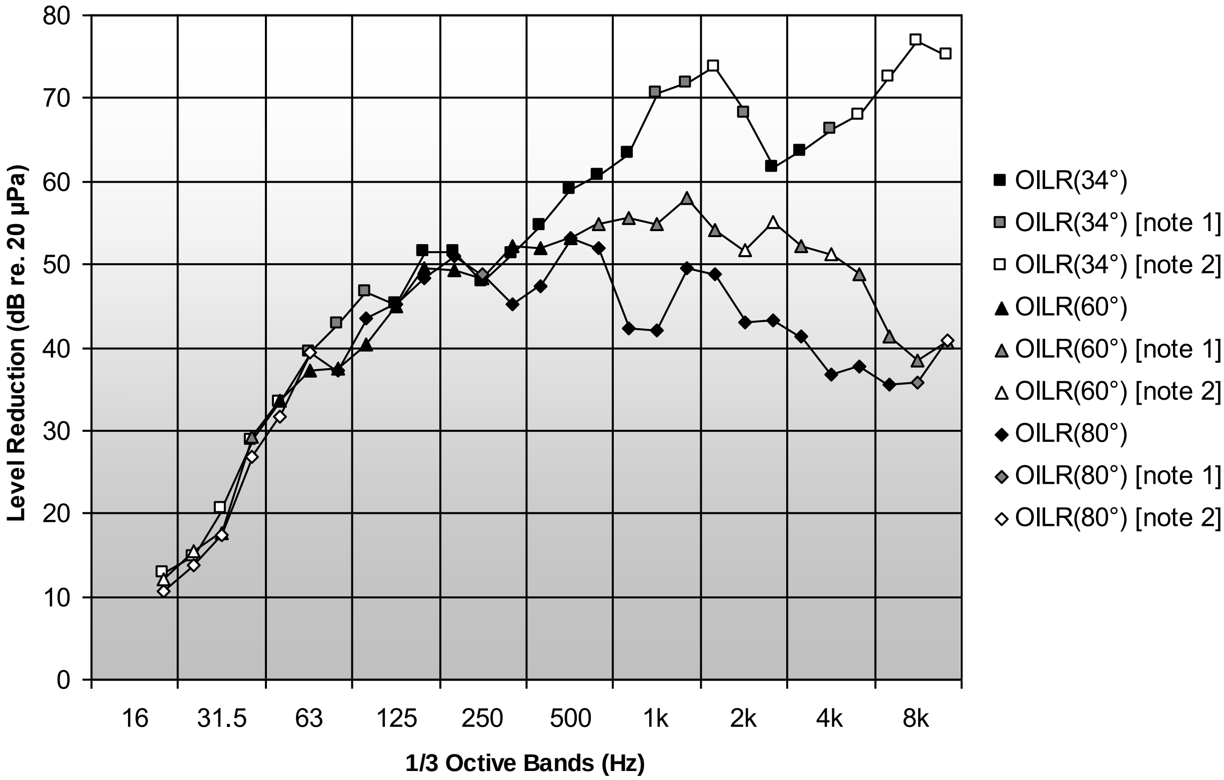
Table 4 – MMW results at 80°

Freq. (Hz)	OILR(80°) (dB)	OITL(80°) (dB)	Notes
20	10.7	6.2	[2]
25	13.7	11.9	[2]
31.5	17.4	11.8	[2] [3]
40	26.9	20.6	[2] [3]
50	31.7	25.0	[2] [3]
63	39.3	32.3	[2] [3]
80	37.2	29.3	[3]
100	43.5	35.7	[3]
125	45.1	36.9	[3]
160	48.5	39.9	[3]
200	51.1	43.0	[3]
250	48.8	40.1	[1] [3]
315	45.3	35.9	[3]
400	47.5	38.4	[3]
500	53.2	43.9	[3]
630	51.9	42.5	[3]
800	42.4	32.8	[3]
1000	41.9	32.5	[3]
1250	49.5	40.4	[3]
1600	48.9	42.7	[3]
2000	43.0	33.6	[3]
2500	43.2	33.7	[3]
3150	41.3	31.6	[3]
4000	36.7	26.8	[3]
5000	37.6	27.9	[3]
6300	35.4	25.6	[3]
8000	35.8	26.4	[1] [3]
10000	40.8	33.3	[2] [3]

Table 5 – MMW random-incidence estimation

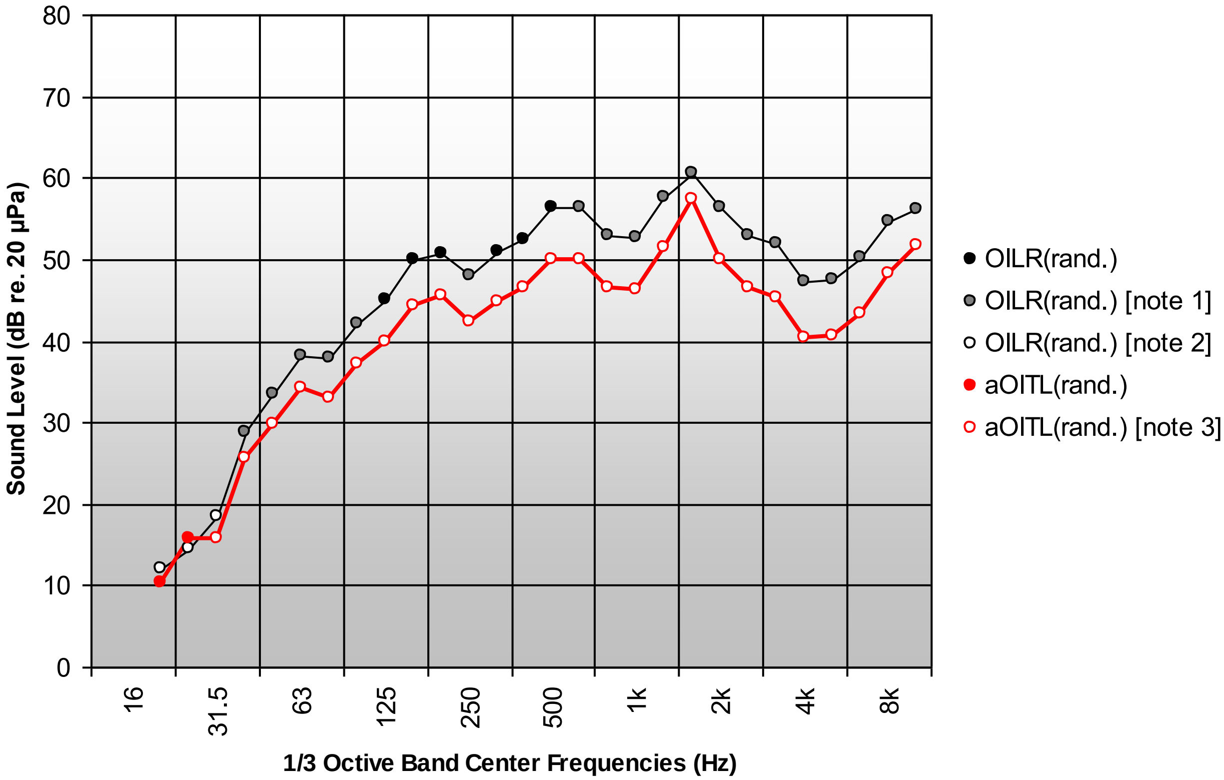
Freq. (Hz)	OILR(rand.) (dB)	OITL(rand.) (dB)	Notes
20	12.0	10.4	[2]
25	14.6	15.7	[2]
31.5	18.4	15.8	[2] [3]
40	28.8	25.6	[1] [3]
50	33.5	29.9	[1] [3]
63	38.1	34.2	[1] [3]
80	37.8	32.9	[1] [3]
100	42.1	37.3	[1] [3]
125	45.0	39.8	[3]
160	49.9	44.4	[3]
200	50.7	45.5	[3]
250	48.0	42.3	[1] [3]
315	51.0	44.7	[3]
400	52.5	46.4	[3]
500	56.3	50.0	[3]
630	56.4	50.1	[1] [3]
800	53.0	46.4	[1] [3]
1000	52.6	46.2	[1] [3]
1250	57.5	51.5	[1] [3]
1600	60.5	57.3	[1] [3]
2000	56.3	49.9	[1] [3]
2500	53.0	46.5	[1] [3]
3150	52.0	45.3	[1] [3]
4000	47.3	40.4	[1] [3]
5000	47.5	40.7	[1] [3]
6300	50.2	43.4	[1] [3]
8000	54.6	48.1	[1] [3]
10000	56.1	51.7	[1] [3]

Note 1: One or more microphone locations were measured with less than 5 dB signal-to-noise, therefore the value may be an estimate of the lower limit.
Note 2: All microphone locations were measured with less than 5 dB signal-to-noise, therefore the value is an estimate of the lower limit.
Note 3: Absorption in this band exceeded the maximum recommended for the room volume according to §7.4.1 in ASTM E966-04.



Note 1: One or more microphone locations were measured with less than 5 dB signal-to-noise, therefore the value may be an estimate of the lower limit.
Note 2: All microphone locations was measured with less than 5 dB signal-to-noise, therefore the value is an estimate of the lower limit.

Figure 3 – Studio MMW level reduction at three angles



Note 1: One or more microphone locations were measured with less than 5 dB signal-to-noise, therefore the value may be an estimate of the lower limit.
Note 2: All microphone locations were measured with less than 5 dB signal-to-noise, therefore the value is an estimate of the lower limit.
Note 3: Absorption in this band exceeded the maximum recommended for the room volume according to §7.4.1 in ASTM E966-04.

Figure 4 – Studio MMW random-incidence estimation

Table 6 – 95% Uncertainty in Studio P due to OILR

Freq. Band (Hz)	source at 34° (dB)	source at 60° (dB)	source at 80° (dB)	combined uncertainty (dB)	ASTM E966 Recommended (dB)
20	± 9.5	± 9.0	± 8.2	± 4.8	
25	± 9.2	± 7.7	± 5.9	± 4.1	
31.5	± 3.6	± 4.5	± 7.8	± 3.0	
40	± 4.0	± 5.2	± 3.3	± 2.3	
50	± 2.8	± 3.6	± 2.1	± 1.7	
63	± 3.8	± 2.5	± 4.4	± 2.3	
80	± 5.7	± 8.4	± 12.1	± 5.2	± 4.0
100	± 2.6	± 3.0	± 6.9	± 2.9	± 4.0
125	± 4.2	± 2.9	± 4.9	± 2.5	± 4.0
160	± 3.8	± 3.1	± 3.2	± 2.0	± 4.0
200	± 5.9	± 8.2	± 3.6	± 3.5	± 4.0
250	± 4.3	± 4.9	± 2.3	± 2.3	± 3.0
315	± 2.7	± 3.3	± 6.7	± 2.7	± 3.0
400	± 5.6	± 4.3	± 4.3	± 2.6	± 3.0
500	± 4.6	± 5.2	± 8.1	± 3.5	± 3.0
630	± 6.4	± 4.8	± 10.3	± 4.2	± 2.0
800	± 4.0	± 1.9	± 14.4	± 4.8	± 2.0
1000	± 7.0	± 2.5	± 15.5	± 5.6	± 2.0
1250	± 6.5	± 5.5	± 10.5	± 4.5	± 2.0
1600	± 3.3	± 5.0	± 4.3	± 2.6	± 2.0
2000	± 5.8	± 3.7	± 4.6	± 2.7	± 2.0
2500	± 5.3	± 4.9	± 8.8	± 3.8	± 2.0
3150	± 8.4	± 5.6	± 11.1	± 5.1	± 2.0
4000	± 3.1	± 5.5	± 18.5	± 6.3	± 2.0
5000	± 5.0	± 7.6	± 17.9	± 6.6	± 2.0
6300	± 3.6	± 8.0	± 17.2	± 6.2	± 2.0
8000	± 6.0	± 6.5	± 20.8	± 7.4	± 2.0
10000	± 8.5	± 8.2	± 20.4	± 7.8	± 2.0

STUDIO P RESULTS

Results of the OILR(θ) and OITL(θ) calculations for Studio P are shown in the following tables and figures.

Table 7 – P results at 34°

Freq. (Hz)	OILR(34°) (dB)	OITL(34°) (dB)	Notes
20	17.0	8.2	[2] [4]
25	16.2	7.4	[2] [4]
31.5	18.8	10.1	[2] [4]
40	32.4	23.6	[2] [4]
50	35.1	26.3	[2] [4]
63	36.4	27.6	[4]
80	35.1	26.3	[4]
100	44.7	36.7	[1] [3]
125	47.3	39.3	[1] [3]
160	51.0	42.1	[2] [3]
200	55.9	46.2	[2] [3]
250	57.4	46.9	[2] [3]
315	61.5	50.2	[1] [3]
400	64.6	52.8	[3]
500	66.1	53.6	[3]
630	67.7	55.2	[2] [3]
800	70.4	57.9	[2] [3]
1000	72.5	60.0	[2] [3]
1250	75.5	63.4	[2] [3]
1600	71.3	59.2	[2] [3]
2000	68.6	56.8	[2] [3]
2500	71.1	59.3	[2] [3]
3150	67.0	55.2	[2] [3]
4000	66.4	54.6	[2] [3]
5000	65.1	53.3	[2] [3]
6300	61.1	49.3	[2] [3]
8000	59.9	47.8	[2] [3]
10000	58.3	46.2	[2] [3]

Table 8 – P results at 60°

Freq. (Hz)	OILR(60°) (dB)	OITL(60°) (dB)	Notes
20	19.2	17.2	[2] [4]
25	24.2	22.2	[2] [4]
31.5	19.1	17.1	[2] [4]
40	32.5	30.5	[2] [4]
50	37.4	35.4	[2] [4]
63	36.4	34.4	[4]
80	36.1	34.1	[4]
100	47.2	46.0	[1] [3]
125	46.8	45.6	[2] [3]
160	50.9	48.7	[2] [3]
200	58.8	55.8	[1] [3]
250	59.4	55.6	[3]
315	63.0	58.5	[1] [3]
400	60.5	55.5	[3]
500	61.4	55.8	[3]
630	72.2	66.5	[2] [3]
800	72.7	67.0	[2] [3]
1000	70.6	65.0	[2] [3]
1250	73.8	68.5	[1] [3]
1600	73.4	68.0	[2] [3]
2000	73.7	68.7	[2] [3]
2500	74.6	69.6	[2] [3]
3150	73.2	68.2	[2] [3]
4000	71.5	66.5	[2] [3]
5000	68.8	63.8	[2] [3]
6300	63.3	58.3	[2] [3]
8000	62.7	57.4	[2] [3]
10000	62.8	57.5	[2] [3]

Note 1: One or more microphone locations were measured with less than 5 dB signal-to-noise, therefore the value may be an estimate of the lower limit.

Note 2: All microphone locations were measured with less than 5 dB signal-to-noise, therefore the value is an estimate of the lower limit.

Note 3: Absorption in this band exceeded the maximum recommended for the room volume according to §7.4.1 in ASTM E966-04.

Table 9 – P results at 80°

Freq. (Hz)	OILR(80°) (dB)	OITL(80°) (dB)	Notes
20	17.2	13.0	[2] [4]
25	15.8	11.6	[2] [4]
31.5	18.1	13.9	[2] [4]
40	33.4	29.2	[2] [4]
50	36.7	32.5	[1] [4]
63	36.0	31.8	[4]
80	35.8	31.6	[4]
100	45.4	42.0	[1] [3]
125	49.8	46.3	[1] [3]
160	53.3	49.0	[2] [3]
200	57.7	52.6	[3]
250	59.0	53.0	[3]
315	64.8	58.2	[3]
400	64.0	56.8	[3]
500	67.5	59.6	[3]
630	67.2	59.3	[3]
800	67.7	59.8	[3]
1000	68.1	60.3	[1] [3]
1250	69.3	61.8	[3]
1600	72.9	65.4	[3]
2000	72.0	64.8	[3]
2500	74.8	67.6	[1] [3]
3150	74.5	67.3	[2] [3]
4000	72.6	65.3	[2] [3]
5000	72.6	65.4	[2] [3]
6300	74.0	66.8	[2] [3]
8000	77.4	69.9	[2] [3]
10000	75.1	67.6	[2] [3]

Table 10 – P random-incidence estimation

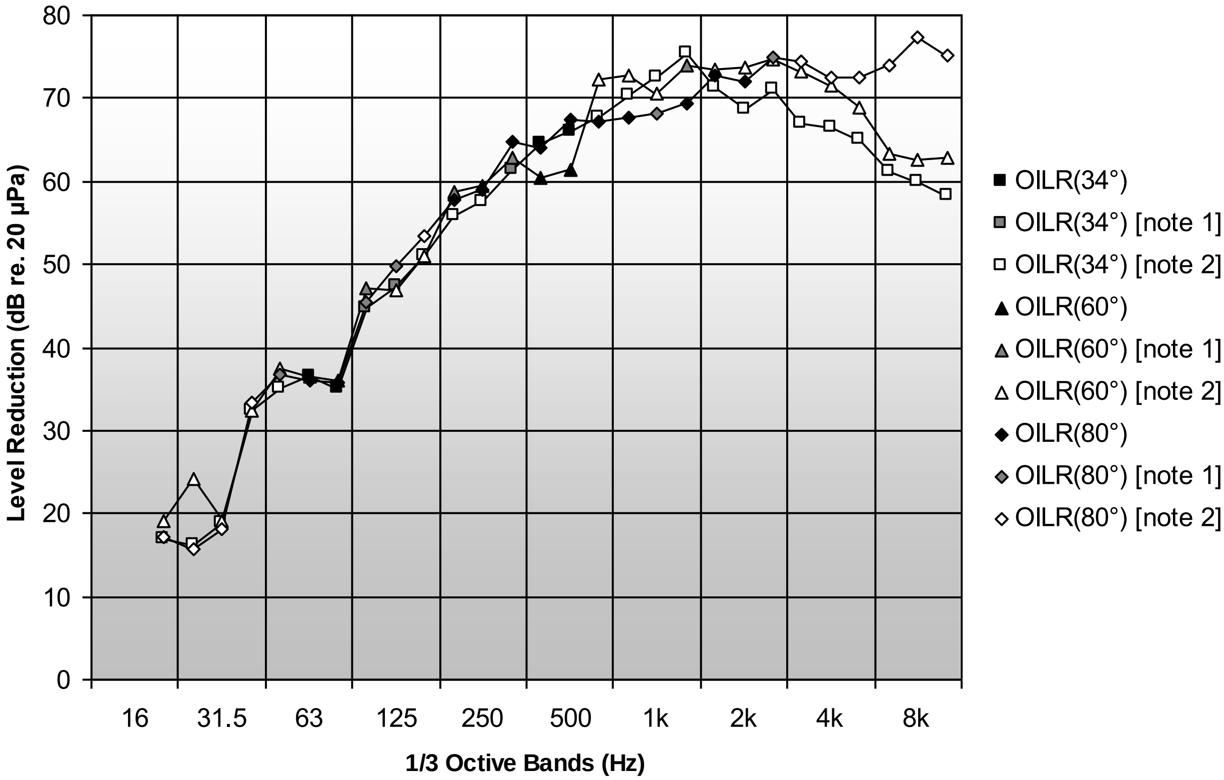
Freq. (Hz)	OILR(rand.) (dB)	OITL(rand.) (dB)	Notes
20	18.0	16.8	[2] [4]
25	20.8	19.6	[2] [4]
31.5	18.7	17.5	[2] [4]
40	32.8	31.6	[2] [4]
50	36.6	35.4	[1] [4]
63	36.2	35.0	[4]
80	35.6	34.4	[4]
100	45.7	45.3	[1] [3]
125	48.4	48.0	[1] [3]
160	52.0	50.7	[2] [3]
200	57.8	55.6	[1] [3]
250	58.9	56.0	[1] [3]
315	63.6	60.0	[1] [3]
400	63.5	59.3	[3]
500	65.3	60.5	[3]
630	67.8	63.0	[1] [3]
800	68.9	64.1	[1] [3]
1000	68.8	64.0	[1] [3]
1250	71.1	66.6	[1] [3]
1600	72.8	68.3	[1] [3]
2000	72.0	67.8	[1] [3]
2500	74.4	70.2	[1] [3]
3150	72.9	68.7	[2] [3]
4000	71.0	66.8	[2] [3]
5000	70.0	65.8	[2] [3]
6300	69.8	65.6	[2] [3]
8000	72.8	68.3	[2] [3]
10000	70.6	66.1	[2] [3]

Note 1: One or more microphone locations were measured with less than 5 dB signal-to-noise, therefore the value may be an estimate of the lower limit.

Note 2: All microphone locations were measured with less than 5 dB signal-to-noise, therefore the value is an estimate of the lower limit.

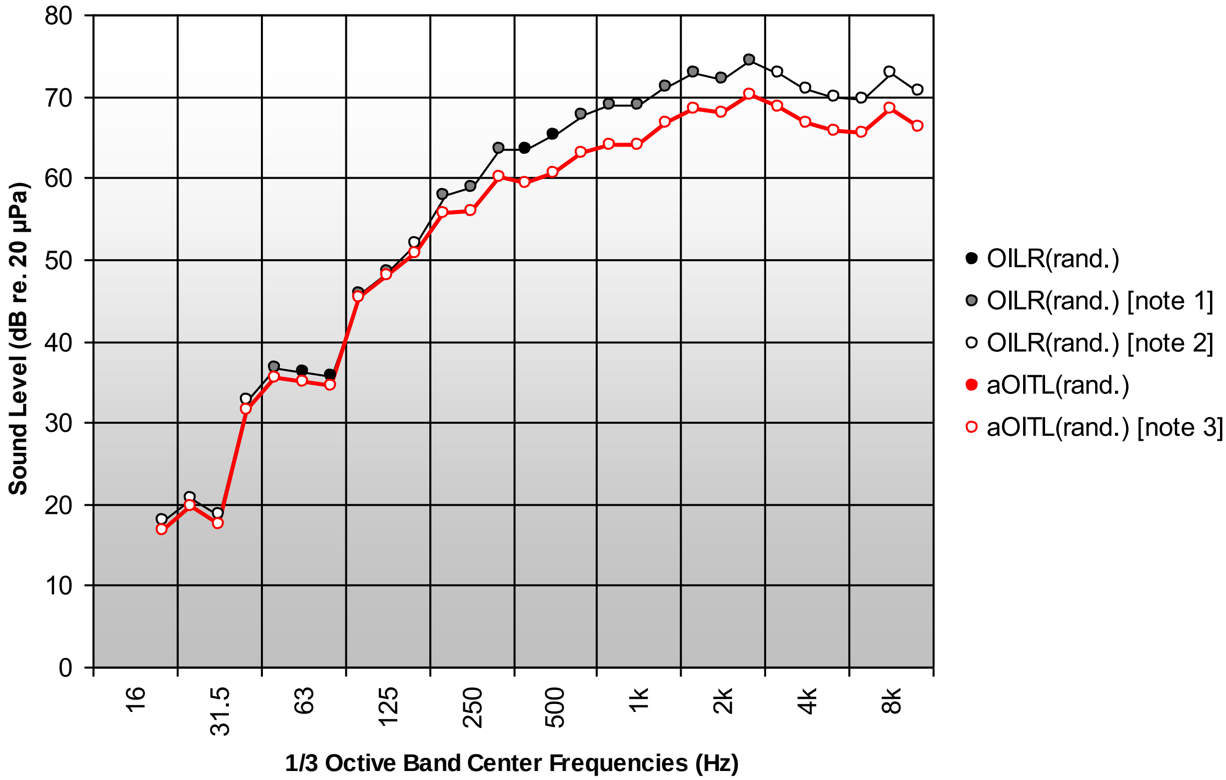
Note 3: Estimated absorption in this band exceeded the maximum recommended for the room volume according to §7.4.1 in ASTM E966-04.

Note 4: Absorption in this band was set conservatively high, and exceeded the maximum recommended for the room volume.



Note 1: One or more microphone locations were measured with less than 5 dB signal-to-noise, therefore the value may be an estimate of the lower limit.
Note 2: All microphone locations were measured with less than 5 dB signal-to-noise, therefore the value is an estimate of the lower limit.

Figure 5 – Studio P level reduction at three angles



Note 1: One or more microphone locations were measured with less than 5 dB signal-to-noise, therefore the value may be an estimate of the lower limit.
Note 2: All microphone locations were measured with less than 5 dB signal-to-noise, therefore the value is an estimate of the lower limit.
Note 3: Estimated absorption in this band exceeded the maximum recommended for the room volume according to §7.4.1 in ASTM E966-04.

Figure 6 – Studio P random-incidence estimation

Table 11 – 95% Uncertainty in Studio P due to OILR

Freq. Band (Hz)	source at 34° (dB)	source at 60° (dB)	source at 80° (dB)	combined uncertainty (dB)	ASTM E966 Recommended (dB)
20	± 1.1	± 0.8	± 1.0	± 0.6	
25	± 6.1	± 5.1	± 5.6	± 3.0	
31.5	± 14.1	± 13.2	± 13.1	± 7.2	
40	± 3.6	± 3.6	± 4.3	± 2.2	
50	± 5.3	± 7.2	± 9.4	± 4.1	
63	± 8.4	± 5.5	± 7.7	± 4.1	
80	± 8.2	± 6.6	± 9.3	± 4.5	± 4.0
100	± 4.2	± 4.0	± 5.1	± 2.8	± 4.0
125	± 7.4	± 5.8	± 8.8	± 4.4	± 4.0
160	± 3.0	± 3.5	± 5.9	± 2.7	± 4.0
200	± 4.8	± 7.2	± 6.9	± 3.6	± 4.0
250	± 8.2	± 7.9	± 9.4	± 4.7	± 3.0
315	± 7.8	± 5.8	± 6.5	± 4.2	± 3.0
400	± 8.2	± 5.3	± 9.4	± 4.7	± 3.0
500	± 7.2	± 5.1	± 5.4	± 3.8	± 3.0
630	± 7.3	± 7.3	± 4.7	± 4.1	± 2.0
800	± 6.1	± 9.5	± 7.4	± 4.8	± 2.0
1000	± 10.0	± 7.9	± 10.3	± 5.5	± 2.0
1250	± 10.5	± 9.0	± 5.2	± 5.2	± 2.0
1600	± 10.5	± 6.8	± 6.1	± 4.9	± 2.0
2000	± 11.2	± 9.9	± 10.8	± 6.5	± 2.0
2500	± 12.4	± 9.7	± 6.5	± 6.3	± 2.0
3150	± 13.2	± 9.5	± 6.1	± 6.3	± 2.0
4000	± 14.4	± 9.5	± 7.0	± 6.9	± 2.0
5000	± 14.9	± 10.9	± 8.1	± 7.4	± 2.0
6300	± 15.4	± 9.8	± 6.4	± 7.2	± 2.0
8000	± 13.3	± 9.2	± 5.9	± 6.5	± 2.0
10000	± 12.8	± 9.4	± 7.7	± 6.8	± 2.0

DISCUSSION

Single-number Ratings

The *Outdoor-indoor transmission class* (OITC) and the *Field OITC* (FOITC) is a single-number rating based on the 1/3 octave band OITL results, calculated according to ASTM standard E1332. This is the A-weighted noise reduction of a standardized traffic noise spectrum, based on "typical" highway, railroad, and aircraft takeoff traffic.

The *Sound transmission class* (STC) and the *Field sound transmission class* (FSTC) is a single-number rating based on the 1/3 octave band OITL results, calculated according to ASTM standard E413. This is based on subjective impressions of speech transmission through walls, and so not generally applicable to facade walls – FOITC is preferred – but is nonetheless frequently calculated for facade assemblies.

These ratings are not useful for the studios' mitigation designs. Single-number metrics such as FOITC and FSTC are useful for general categorization of walls, but they are limited in their utility. Their respective governing standards state outright that these ratings are not appropriate for sound sources with different spectrum shapes than their respective bases, and they are intended to be used as a device to rank against other assemblies.

Uncertainty Values

Much of the ASTM standard is aimed at maximizing the repeatability and reproducibility of the measurement for a particular facade construction. Reproducibility is the ability to test the same facade construction at different locations, by different personnel, or with different equipment. An overriding limitation to repeatability of measurements where the walls have nominally alike constructions but are in different buildings is variations in construction and quality, and flanking paths which differ from building-to-building.

Repeatability is the ability to test one particular facade construction and get the same results from test to test. This is of particular interest to these facade elements under test. The repeatability of these measurements are predicated on a diffuse sound field in the receiving room – that is a sound field which, in theory, measures the same level at any point throughout the room. Increase the level of absorption in a room to reduce the ideal of a diffuse sound field.

Note that a diffuse sound field, sometimes referred to as a random-incidence sound field, is a physical/mathematical concept, and is not necessarily referring to the diffusion of reflected sound from room surfaces such as in studios or auditoria. The diffuse sound field also refers to a field free from boundary effects – measurements aren't allowed near room surfaces where boundary effects influence the measured level.

These receiving rooms (the studios) are far from a laboratory reverberation chamber and exceed their respective recommended absorption for field tests in nearly every band. This results in a sound field which varies at different locations in the room. The sound level will be higher nearer the source, and decrease as distance increases. This is exactly what one would expect in a studio environment. It also means that the measurement microphones closest to the exterior wall will measure a higher level than the microphones further than the wall. The standard deviation of these receiving-room measurements is greater than desired due to the amount of absorption in the room.

This inherent property of the studio environment inflated the 95% uncertainty by necessity. So a large portion of the uncertainty values represent the excess absorption in the room, combined with the fact that the minimum number of microphone locations was used, and not more. These uncertainty values could have been reduced by reducing absorption, specifically by removing furniture and wall materials until only hard surfaces remained.

Estimates of Lower Limits

Many bands exhibited poor signal-to-noise ratio. In the lowest bands (20 Hz to 40 Hz) this is simply due to the low output of the noise source. In the higher bands (nearly always 4 kHz and up, but sometimes 1 kHz and up) this is due to the high performance in these bands of the facade elements under test. This means that the sound insulation performance may actually be better than tested.

The following information is provided to help more fully understand the limits of the data and the performance of the partitions under study. The outside incident noise levels are shown in Table 12 below (corrected for exterior background levels). As long as the outside sources, such as LRV noise, do not exceed these incident noise levels, the measured lower limit OILR can be used to effectively reduce such noise.

CONCLUSION

This information provides a quantitative understanding of the existing isolation from outdoor noise into Studio MMW and Studio P at Minnesota Public Radio. The data are essential to the design of modifications to the studios to create greater acoustical isolation from airborne noise generated by Central Corridor LRT.

There are limitations to the data, which have been thoroughly described in this memorandum. However, qualified acousticians who are well-versed in the OITL measurement standard and other relevant acoustical concepts will be able to interpret this information and use it appropriately to design modifications to studios MMW and P at MPR.

Table 12 – Exterior Incident Noise Levels

Freq. (Hz)	Studio MMW (dB)	Studio P (dB)
20	62.1	64.5
25	64.9	69.8
31.5	66.0	68.6
40	73.0	71.1
50	83.0	77.9
63	84.5	85.5
80	89.7	86.9
100	85.8	86.2
125	85.3	84.8
160	84.2	84.5
200	87.6	87.0
250	87.1	86.9
315	86.1	85.7
400	85.9	85.7
500	86.5	86.2
630	84.3	84.7
800	80.5	79.7
1000	78.0	76.0
1250	80.8	79.4
1600	80.4	78.1
2000	76.0	76.8
2500	74.3	76.3
3150	72.5	72.4
4000	70.4	70.3
5000	69.5	69.8
6300	70.1	69.8
8000	73.9	73.1
10000	71.7	71.1

HDR | ONE COMPANY *Many Solutions*[SM]

Memo

To:	Kathryn O'Brien		
From:	Tim Casey Elliott B. Dick	Project:	Central Corridor LRT
cc:			
Date:	May 1, 2009	Job No:	65891

Re: Background Noise Measurements on Feb. 11, 2009, in MPR Studios MMW and P

TASK OVERVIEW

Previous memoranda have described Studio MMW and Studio P located at Minnesota Public Radio's building in Downtown St. Paul. On Febuary 11, Tim Casey and Elliott Dick of HDR Inc., with Tony Baxter of ESI, measured a 4-hour average of each studio. Additionally, Tony Baxter, with Tim Casey observing, performed a spatial average of each studio. These measurements are to gain a further understanding of the ambient background noise environment within these studios.

The measurements were performed with Larson-Davis 824 Sound Analyzers, one owned by HDR and the other owned by ESI. Low-noise microphones and conditioning amplifiers were rented from Brüel and Kjær. Timers were used to measure an unoccupied ambient room noise level.

FOUR-HOUR MEASUREMENT SUMMARY

The L_{eq} is the average energy-equivalent sound level in A-weighted decibels (dBA) over a measurement interval. In any measurement interval, the instantaneous sound pressure level can vary. This is a level average, obtained by averaging the sound pressure. It is often considered the equivalent level, if the level were constant over the measurement interval. The average equivalent sound levels were measured with the standardized A-weighting characteristic.

Sound level measurements are integrated with a certain time constant, which determines the sensitivity of the measurement; specifically whether events that are less than 1 second long will affect the instantaneous sound level. The sound level meters were set to use the standardized fast exponential time averaging constant. As noted above, instantaneous sound pressure level varies within a measurement interval. The L_{max} is the highest fast-averaged sound level occurring within a measurement interval in A-weighted decibels (dBA), and the L_{min} is the lowest fast-averaged sound level occurring within a measurement interval in A-weighted decibels (dBA). The L_{peak} is the highest instantaneous level that the sound wave achieves – much higher than the instantaneous fast-averaged level. The following table shows the L_{eq}, L_{min}, L_{max}, and L_{peak}.

4-hour Measurement A-weighted Levels

	L_{eq}	L_{min}	L_{max}	L_{peak}
Studio M	18.0	15.4	47.3	69.5
Studio P	19.7	15.9	36.2	56.9

The following table shows statistical/centile noise descriptors that represent the fast-averaged sound level exceeded during the stated percent of a measurement interval in A-weighted decibels (dBA). For example, the $L_{50\%}$ is the sound level exceeded 50% of the time (the median sound level during the measurement interval). The $L_{10\%}$ is the level exceeded 10% of the time during the interval, and is often higher where intermittent sounds occur during the measurement interval.

4-hour Measurement A-weighted Centile Levels

	$L_{1\%}$	$L_{5\%}$	$L_{10\%}$	$L_{50\%}$	$L_{90\%}$	$L_{99\%}$
Studio M	21.5	19.4	18.7	17.5	16.7	16.1
Studio P	22.7	21.1	20.6	19.4	18.3	17.6

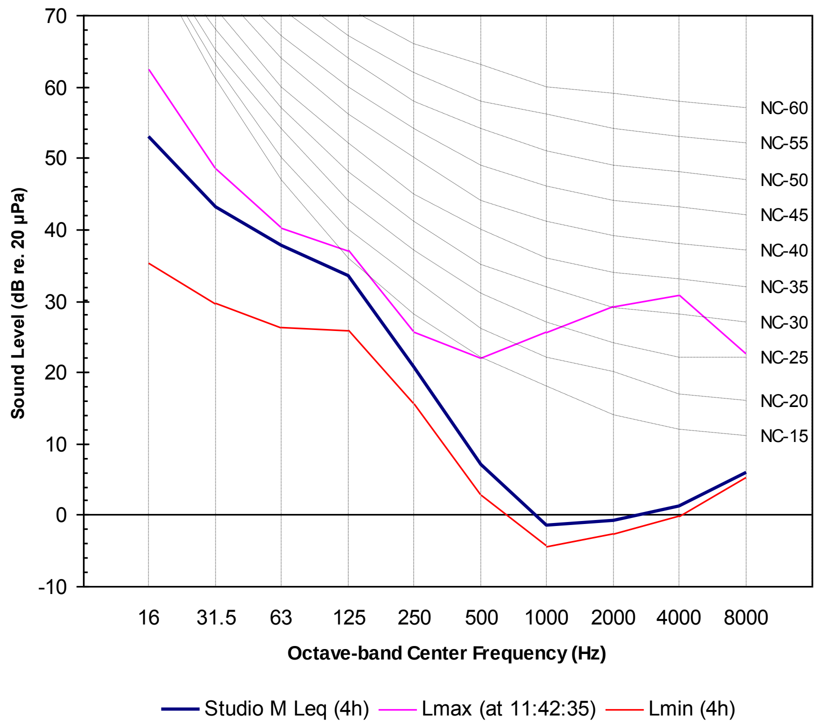
RESULT GRAPHS

The following pages show results of the 4-hour measurements and the comparison of the 4-hour averages versus the spatial average. The graph for Studio P, from the 1 kHz band and above, the curves resemble typical curves of instrumentation noise (the electrical noise that the instrumentation inherently produces), and is close in value to the manufacturer's stated microphone thermal noise for those bands. This resemblance suggests that the actual noise floor of the room is at least 10 dB lower, but even this highly sensitive instrumentation is not capable of measuring the background noise level of this room. The same may be said about the graphs for Studio MMW, although to a lesser extent than for Studio P. This suggests that Studio MMW may have an actual background noise level within 10 dB of the measured level in some of the bands from 1 kHz and up.

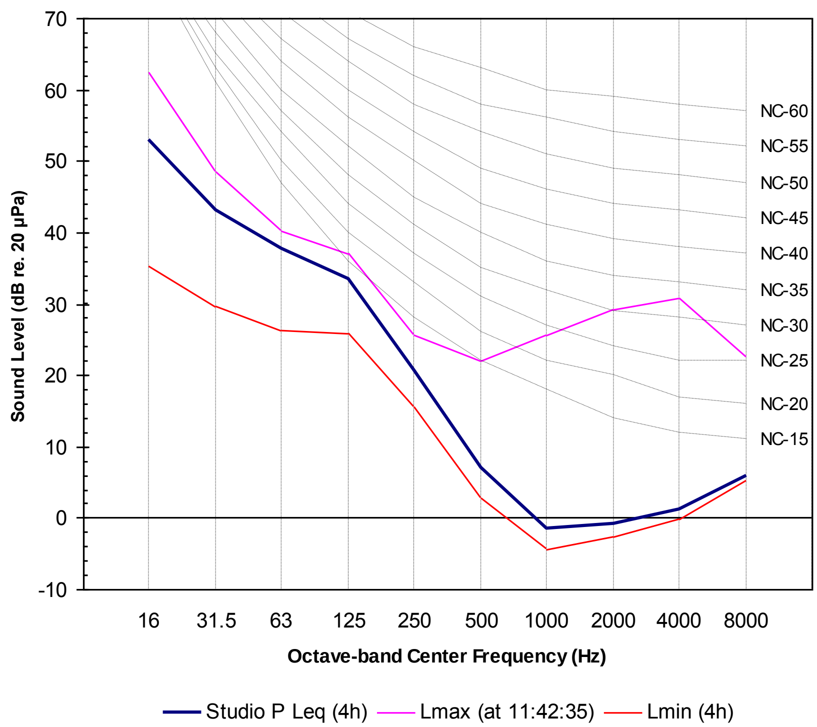
Note that the spatial average measurements used +20 dB gain setting on the analyzer, whereas the 4-hour measurements did not. This may account for some of the difference in the higher frequencies. By adding 20 dB gain to the analyzer, the analyzer should be able to measure 20 dB lower than normal. However, the microphone's thermal noise prevented measuring a full 20 dB lower, so only 2 dB to 4 dB was realized. Due to these reasons, the small differences above 1 kHz should be considered inconsequential.

Additional details of the 4-hour measurements are available, including additional metrics and hourly summaries in Studio MMW.

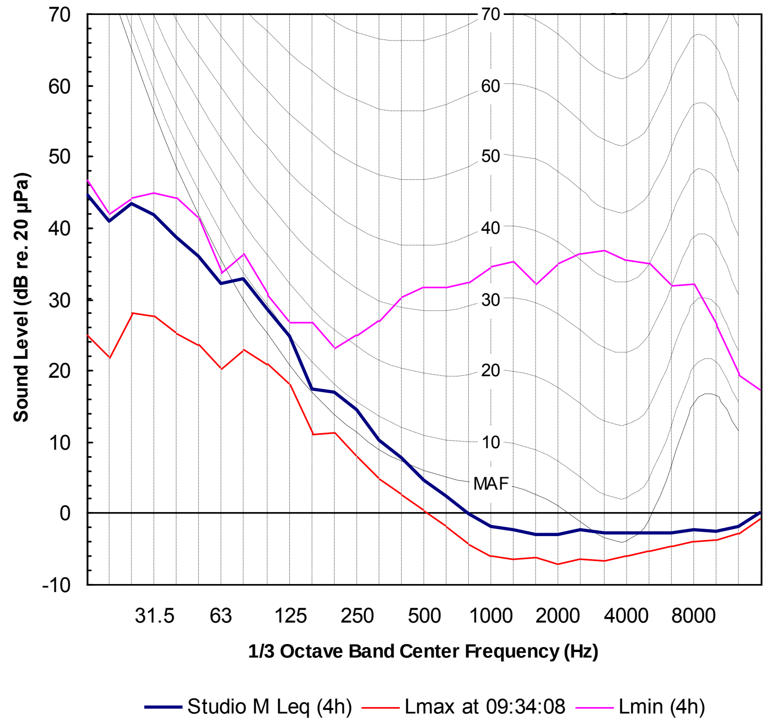
Whole Octave Results in Studio MMW against Noise-Criteria Curves



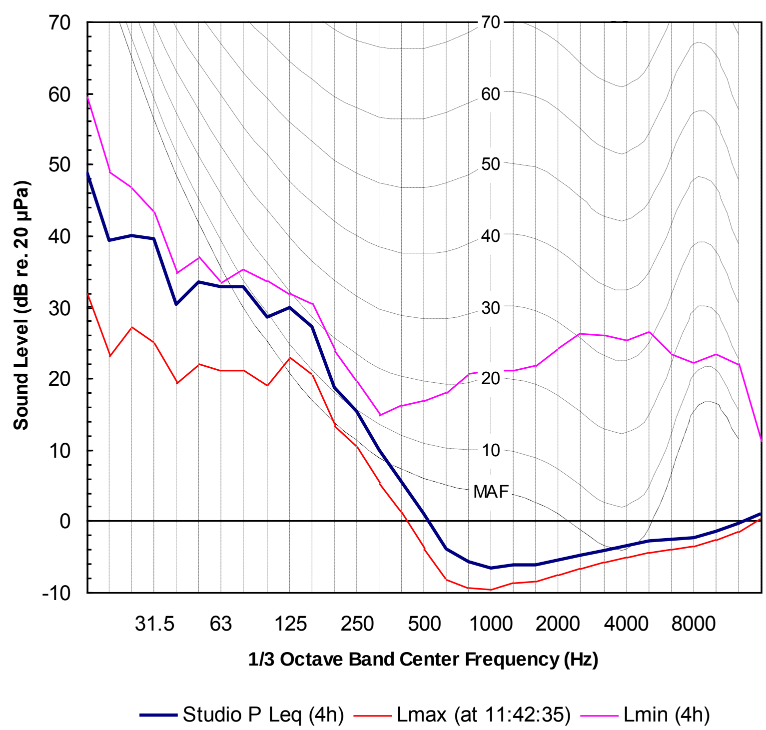
Whole Octave Results in Studio P against Noise-Criteria Curves



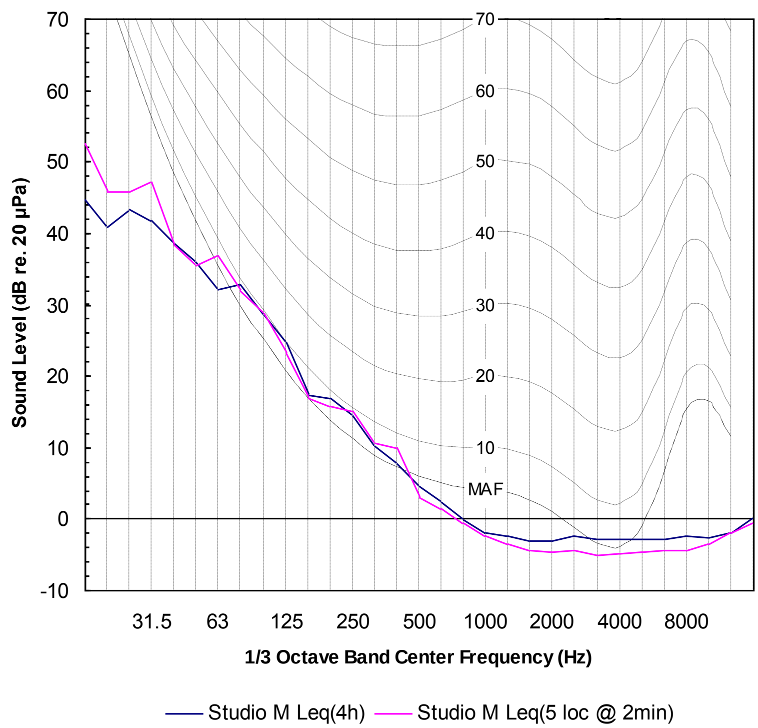
One Third Octave Results in Studio MMW against Equal-Loudness Contours



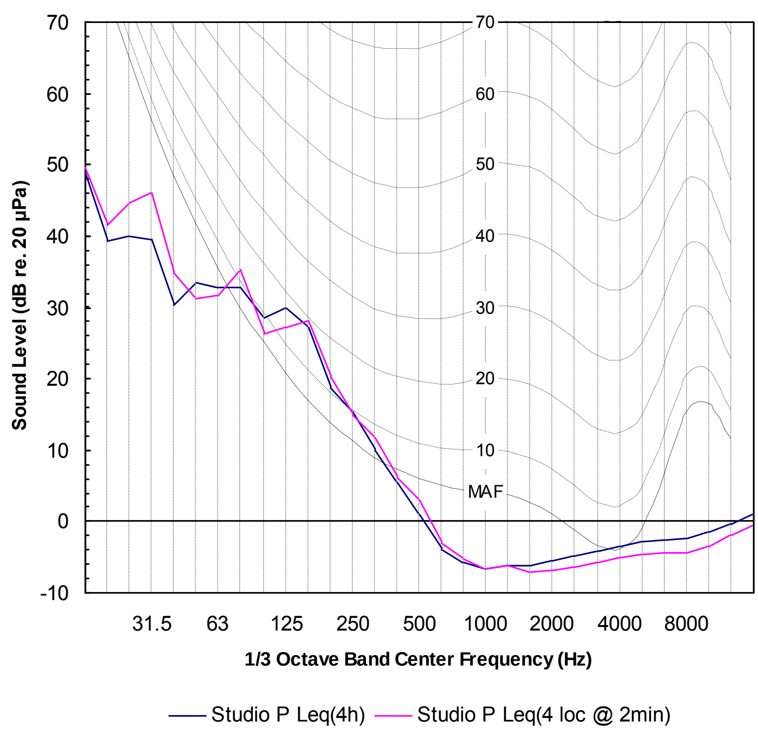
One-Third Octave Results in Studio P against Equal-Loudness Contours



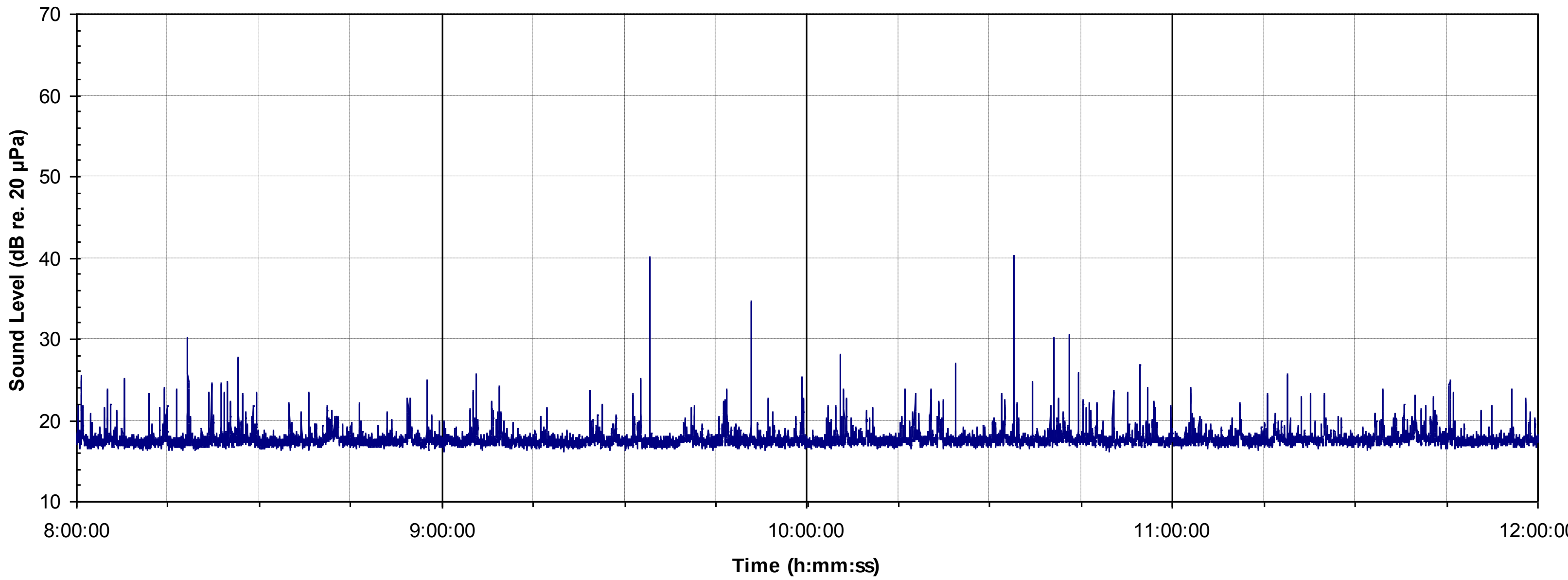
Four-Hour Average versus Spatial Average Comparison in Studio MMW



Four-Hour Average versus Spatial Average Comparison in Studio P



A-weighted 4-hour Time History/Profile in Studio MMW



A-weighted 4-hour Time History/Profile in Studio P