The Clem7 Motorway Tunnel: Mechanical and Electrical Plant Acoustic Design and Performance

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ABSTRACT

The 4.8 kilometre Clem7 tunnel passes underneath the Brisbane river, providing a direct connection between the northern and southern Brisbane suburbs. During the design and construction phases of the project, various acoustic design issues were addressed. These included airborne noise emissions from the electrical and mechanical plant servicing the Clem7 tunnel. Computational acoustic model predictions of plant noise emissions from the ventilation building outlets, and the various tunnel portals were completed using specialist acoustic software. This paper presents an overview of the key acoustic design issues associated with the mechanical and electrical plant noise sources for the Clem7 tunnel. The modelling methodology and acoustic control solutions that were adopted are described, and the outcomes of the acoustic monitoring during the commissioning phase are presented.

INTRODUCTION

The Clem7 commenced operations in March 2010 and is one of the largest infrastructure projects ever to be completed in Queensland. To assist in providing an appropriate acoustic environment external to the tunnel infrastructure once operations commenced, various elements of the project were the subject of specific acoustic investigation during the detailed design phase.

This paper describes the methodology, key issues and outcomes of the acoustic analysis of airborne noise emissions from the electrical and mechanical plant servicing the Clem7 tunnel.

THE CLEM7 TUNNEL

Key Features of the Tunnel

The Clem7 Tunnel connects north and south-bound traffic under Brisbane. The Clem7 comprises dual twin lane tunnels approximately 4.8 km in length that transport traffic from Ipswich Road and the Pacific Motorway (M3) in Woolloongabba to Lutwyche Road and the Inner City Bypass at Bowen Hills and vice versa. An on/off ramp connection is also provided at Shafston Avenue, Kangaroo Point. Figure one identifies the location and alignment of the Clem7 Tunnel.

The tunnel ventilation system utilises a series of axial and jet fans to regulate air flows through the tunnels and thereby to exhaust in-tunnel air via the ventilation outlets. The ventilation outlets are situated at Bowen Hills and Woolloongabba.

Jet fans are the primary means of controlling the speed and quantity of air flowing through the tunnel and tunnel portals. This control of air is required to maintain the ventilation system operations within the project constraints.

Axial fans located within the ventilation outlet buildings are used to control the air movement from the tunnels and out of the ventilation outlets.

Plant Noise Emission Sources

The key potential mechanical and electrical plant noise sources identified for acoustic assessment at the design phase were as follows:

Ventilation Building Noise:

- Emissions from Ventilation Release Point
- Emissions from Exhaust Air Release Point
- Noise transmission through ventilation building (roof and walls)

Noise Emitted from Tunnel Portals:

- Noise emissions from underground electrical substations
- Jet Fans
- Noise transferred to driven tunnel from ventilation outlet buildings

Additional sources that were considered in the acoustic design for the mechanical and electrical plant, that are not included in this paper, are noise emissions from the external electrical substation, cable tunnel and the ventilation inlet duct.

Significant Acoustic Design Issues

At the project outset, some key acoustic design issues were identified as follows:

(i) The highly reverberant nature of the concrete tunnel walls and concrete road surface, particularly given the concave profile of the main bored tunnel sections.

(ii) Construction of the Shafston off-ramp in a deep cut (>25 m deep), with vertical concrete walls having a potential for significant reverberation.

(iii) The close proximity of dense residential development in to the tunnel portals and the northern ventilation station in particular.

Figure 1: Location and alignment of the Clem7 Tunnel

These design issues were addressed in the acoustic modelling and resulted in the integration of appropriate acoustic mitigation solutions into the mechanical and electrical design.

ACOUSTIC CRITERIA AND GOALS

The acoustic assessment primarily addressed the potential for external noise impacts. These goals were derived on the basis of existing background noise levels, in accordance with the requirements of the planning approval for the project. These requirements were defined in the Coordinator-General's Report on the Clem7 project (Queensland Government, 2005). The specific acoustic criteria for the ventilation system were defined as follows:

‘(e) The ventilation system must be designed and operated to achieve the goals as set out in Table 7 at the commencement of operation of the Project.’

Table 1. Operational Noise Goals – Ventilation System

Source	Values
Ventilation System Noise (via outlets, portals, fan stations)	*The overall A-weighted sound pressure level component from ventilation plant, assessed as an $L_{Amax,adj}$ level with tonality penalty adjustments determined in accordance with AS1055.1, should not exceed the Average Background Noise Level, as defined in AS1055.2, at a noise sensitive location at any time of the day or night*

In addition, as a design goal, the acoustic analysis also considered whether a contractual requirement to achieve NR 85 was expected to be achieved in and around the various in-tunnel mechanical and electrical plant areas.

To allow determination of the numeric value of the noise limits at sensitive receptors in the vicinity of the project, extensive background noise monitoring was completed at a total of 11 positions. The background noise monitoring programme included octave band frequency analysis.

Determination of existing background noise frequency data was considered to be an important aspect of the noise monitoring, to assist in the determination of any tonal impacts from the ventilation system during the operational phase of the project.

ACOUSTIC MODELLING METHODOLOGY

Overview

The environmental acoustic modelling was completed using the computational software Cadna/A (Version 3.5) developed by DataKustik. The model was utilised to predict the combined impacts associated with airborne noise emissions from the various mechanical and electrical plant noise sources on nearby sensitive receptors.

Additional in-tunnel modelling was completed using the software package Odeon. The in-tunnel and ventilation station modelling results from Odeon were input to the Cadnaa/A model for the purposes of the environmental modelling of the axial and jet fan noise sources.

The modelling assumptions and data inputs are discussed in the following sections in more detail.

Cadna/A

Cadna/A is a recognised modelling packaged designed to account for the influences of three dimensional terrain, ground type and air absorption in addition to source characteristics, shielding and/or reflections from buildings and barriers, distance attenuation and meteorological influences to predict noise impacts at receptor locations.

The Cclem7 mechanical and electrical plant noise sources were input to the model as either point sources, area sources, or vertical area sources depending on their geometric characteristics, location and the expected emission profile into the surrounding area.

Figures 2 and 4 present 3D isometric representations of the northern and southern (Shafston Avenue) model domains, including the buildings, sources, and sensitive receptors considered. Rendered 3D images of the areas considered are shown in Figures 3 and 5.

All building structures were modelled as solid façades (absorption coefficients of 0.44 across all spectra), with two reflections calculated from each noise source. For some of the road portal on/off ramps concrete retaining walls were to be provided either side of the roadway. This feature was identified as having a significant potential to increase reflected noise. Therefore, these structures were included as solid reflective barriers (absorption coefficients of 0.02 across all spectra) and higher orders of reflections were modelled.

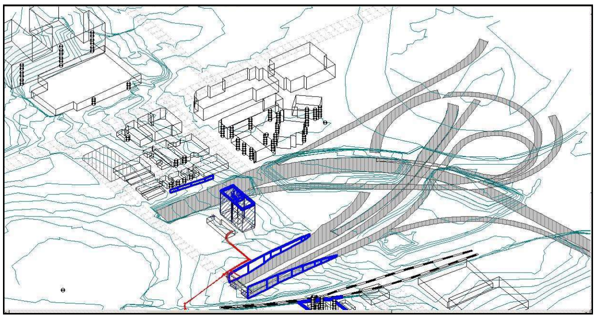

Figure 2. Cadna/A representation – northern model domain

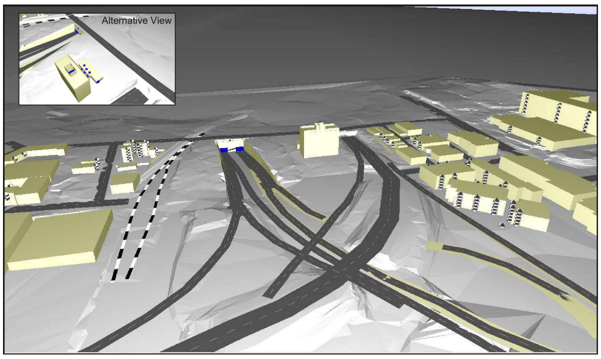

Figure 3. Cadna/A 3-d image – northern model domain

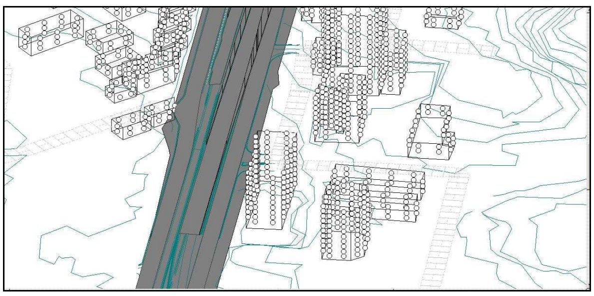

Figure 4. Cadna/A representation – southern model domain

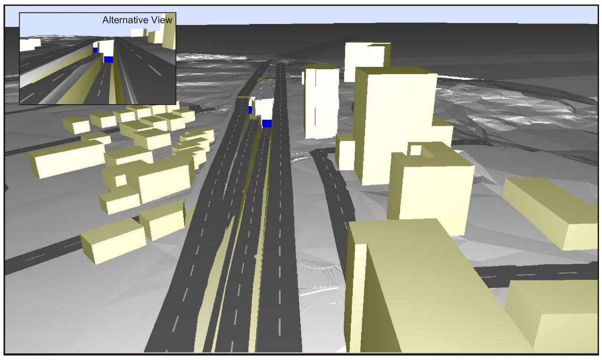

Figure 5. Cadna/A 3d image – southern model domain

Noise modelling was completed for worst case meteorological conditions during daytime periods, and for evening/night-time periods as follows;

Daytime:

- Temperature: 20 ºC
- Humidity: 50 %
- Wind speed: 3 m/s
- Stability Class D

Night-Time/Evening:

- Temperature: 20 ºC
- Humidity: 50 %
- Wind speed: 3 m/s
- Stability Class F (atmospheric inversion).

The modelling considered a total of four wind directions (northerly, easterly, southerly and westerly) for each of the meteorological scenarios. This provided for a worst-case down-wind assessment scenario for each receptor.

Odeon

Estimates of the combined source noise levels at the tunnel portals (from roof mounted jet fans and the VSO axial fans) were modelled using the Odeon model. This is a specialised room acoustics modelling package distributed by Brüel & Kjær. This model was also utilised to predict the attenuation of ventilation noise sources from the point of release within the confines of the tunnel to the tunnel portal.

For the purposes of the modelling, a typical bored tunnel cross section drawing was imported into the Odeon model. The cross sectional extrusion tool within the Odeon model was then utilised to generate a section of driven tunnel of an appropriate length (> 400 m) for the purposes of completing the acoustic modelling of the internal environment.

The modelling assumed that the roof top jet fans were aligned, and all axial fan ventilation sources were directed toward the nearest portal. This represents a conservative approach in predicting the emissions from the portal. All jet fans, underground substations and axial fan noise sources located within 400 m of a tunnel portal were considered as having a potential to influence portal noise levels.

Additional data was then incorporated into the Odeon model, including fixtures expected to be placed within the tunnel and the surface finishes. As noted earlier, a key design issue with a concave tunnel, is the potential for significant reflection of emitted noise. The absorption provided by internal surfaces is a primary factor in determining the reverberation time.

In the case of the Clem7, as with many transport tunnels, the primary structural elements are constructed from concrete. This includes the tunnel walls and the road surface itself. Therefore, limited absorption is provided by the key surface materials as demonstrated by the absorption data input to the Odeon model (refer to Table 2.).

Table 2. Absorption Coefficients (α) for Key Materials

	Frequency Band (Hz)							
Surface type:	63	125	250	500	1k	2k	4k	8k
Road (Rough Concrete)	0.02	0.02	0.03	0.03	0.03	0.04	0.07	0.07
Tunnel Walls (Smooth Concrete)	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02

Using the extruded tunnel model, the surface absorption coefficients and other data input to the model, reverberant noise fields were predicted in Odeon.

To provide verification that the reverberation times (RT) calculated in the Odeon model were representative of the expected values in a real world situation, comparison was made with data for a concave, concrete rail tunnel and the results of testing in a concrete underpass structure. The concrete underpass had a square profile, hence was not expected to provide a directly comparable RT dataset. The resultant RT values from these sources are presented in Table 3.

Table 3. Reverberation Times (RT, seconds)

	Frequency Band (Hz)							
	63	125	250	500	1k	2k	4k	8k
Odeon - predicted	9.5	9.2	7.7	6.8	5.4	4.1	2.4	1.2
Concave road tunnel - measured	-	-	8.0	4.0	3.6	2.7	1.9	1.0
Square underpass - measured	3.2	4.1	5.1	5.3	3.8	2.6	1.3	0.7

The comparison of RT data in Table 3 indicates that the Odeon predictions provide for a longer RT for each octave band frequency, hence provides for a conservative analysis of the influence of reverberation on overall noise levels.

During the commissioning phase acoustic testing, RT values were measured in the driven tunnel sections of the Clem7. Unfortunately, due to the high background noise level in the tunnel at the time of the tests, determination of the RT for all frequency bands was compromised. However, the available data indicated an RT value ranging from 2.5 to 8.7 seconds for specific octave bands.

INITIAL ACOUSTIC MODELLING

Initial acoustic modelling was completed that included estimated source noise levels for the various items of plant and equipment. These data were provided by the mechanical and electrical design team at United Group Limited.

The total estimated sound power levels for the ventilation station outlets (main exhaust and emergency smoke exhaust) are provided in Table 4.

Table 4. Sound Power Levels: Axial and Jet Fans (dB_{Lin})

	Frequency Band (Hz)								
Source:	63	125	250	500	1k	2k	4k	8k	Total
Ventil-ation exhaust	130	130	132	134	133	133	131	126	137.4
Smoke exhaust	113	113	116	133	135	134	129	121	137.4

The results of the initial modelling were used as an input to the design and plant selection process. This initial modelling also provided an indication of the required insertion losses for inlet and outlet silencers for the ventilation station axial fans.

RESULTS OF INITIAL ACOUSTIC MODELLING

Axial Fans

For the northern VSO, the results of the noise modelling predicted exceedence of the assessment criteria for day and night periods by up to 25 dB for worst-case meteorological conditions. Iterative modelling was then completed to determine a suitable silencer insertion loss for the northern VSO for achieving appropriate noise levels at the surrounding receptors. A slightly more stringent noise criteria than required in the Coordinator General's report was also adopted for this analysis, based on the minimum measured background noise levels.

The resultant recommended minimum insertion loss for the northern VSO is as shown in Table 5.

Table 5. Calculated Minimum Insertion Loss - Northern (dB)

	Frequency Band (Hz)							
Source:	63	125	250	500	1k	2k	4k	8k
Ventilation	1	13	16	31	36	37	33	21
Exhaust	1	13	16	31	36	37	33	21

For the southern VSO the results of the noise modelling confirmed exceedance of the specified criteria by up to 39 dB for worst-case meteorological conditions. On that basis, the minimum silencer insertion losses were calculated as shown in Table 6.

Table 6. Calculated Minimum Insertion Loss - Southern (dB)

	Frequency Band (Hz)							
Source:	63	125	250	500	1k	2k	4k	8k
Ventilation	0	12	20	34	42	44	39	28
Exhaust	0	12	20	34	42	44	39	28

The calculated minimum insertion losses were utilised in the development of the acoustic control solutions for the axial fans in the ventilation station outlets.

Discussions with the silencer manufacturer (Sound Control Pty Ltd) indicated that, for the size and length of attenuators proposed, insertion losses of up to 20 dB at 63 Hz, and 27 dB at 125 Hz were achievable. Although these low frequency attenuations were in excess of the calculated reductions determined on the basis of the 'A' weighted environmental criteria, it was recommended that a degree of low frequency attenuation should be adopted in the silencer design to minimise the potential for low frequency noise impacts.

Jet Fans

Portal noise for the northern modelling domain was predicted to be well within the assessment criteria, hence no mitigation was identified as being required.

For the southern portal at Shafston Avenue, as noted previously there are significant constraints imposed by the proximity of residential receptors and the acoustic reflections caused by the portal emerging in deep cut. In view of this, and in consideration of the likely ventilation requirements, it was determined that during night-time operations jet fans closest to the portal openings would not be operational. Adoption of this mitigation approach resulted in predicted compliance with the adopted criteria for all sensitive receptors in the vicinity of the Shafston portal.

Noise Rating (NR) Levels

The model predictions were also analysed to determine the expected Noise Rating (NR) levels in close proximity to key noise sources. Cumulative predictions were considered in this analysis, to ensure the noise contributions from all plant with potential to affect the overall noise levels were considered.

Whilst the majority of areas were predicted to comply with the NR85 requirement, some small areas were identified as potentially non-compliant. On this basis, consideration was given to selecting lower noise plant that would assist in achieving the required noise reduction.

Additional Mitigation Recommendations

The initial modelling of the jet fan noise identified that although compliance was predicted, there was only a small margin of certainty provided for in the case of the Shafston portal. Therefore, wherever possible, selection of absorptive surface materials was advised as a design recommendation. Areas where this recommendation was particularly relevant were portals emerging in cut, as in the case of Shafston Avenue. The use of architectural panels with some ability to provide absorption and scatter of incident noise was recommended to be adopted for portals in cut.

In the case of the concave tunnel, architectural panels were also to be provided for a section of the walls (approximately 2 m in height). The recommendations from the acoustic design were considered in the material selection, and a more absorptive fibre cement type panel was selected in place of the non-perforated metal sheeting that was originally one of the design options.

RESULTS OF VERIFICATION MODELLING

Subsequently, following manufacturing of the selected plant and equipment, manufacturer's test data for the axial and jet fan units to be installed was provided. At this stage of the project, test data was also available for the insertion losses for both the inlet and outlet attenuators for the ventilation station axial fans. Further modelling was completed using the test data for the as constructed plant and equipment to confirm that compliance was still predicted to be achieved for the ventilation stations, tunnel jet fans and other mechanical and electrical plant and equipment. The same modelling methodology was adopted as for the initial predictions.

The axial and jet fan test data for the as installed plant is presented in Table 7. Due to differing ventilation requirements, the Northern Ventilation Outlet (NVO) axial fan specifications differ from the Southern Ventilation Outlet (SVO). Two types of jet fan were to be installed, again due to differing ventilation requirements in certain sections of the tunnel.

Table 7. Sound Power Levels: Axial and Jet Fans (dB_{Lin})

	Frequency Band (Hz)								
Source:	63	125	250	500	1k	2k	4k	8k	Total
NVO Exhaust Fan	112	113	118	115	114	110	107	106	122
SVO Exhaust Fan	112	113	118	115	114	110	107	106	122
NVO Vent Fan	112	109	115	116	117	114	111	107	123
SVO Vent Fan	114	112	118	117	117	115	113	109	124
30 kW Jet Fan	97	98	103	96	97	93	89	85	106
45 kW Jet Fan	91	95	99	93	93	93	88	81	103

The silencer insertion loss data input to the model for the axial fans for each of the ventilation stations (northern and southern) is presented in Table 8.

Table 8. Silencer Insertion Losses (dB)

	Frequency Band (Hz)							
Source:	63	125	250	500	1k	2k	4k	8k
NVO Exhaust Fan Outlet Silencer	13	27	35	43	54	36	22	14
SVO Exhaust Fan Outlet Silencer	13	27	35	43	54	36	22	14
NVO Vent Fan Outlet Silencer	13	27	35	43	54	36	22	14
SVO Vent Fan Outlet Silencer	16	32	43	48	61	43	24	18
Inlet Fan Silencer (Type 1)	4.7	10.2	13.7	19.5	24.8	16.3	12.2	10.8
Inlet Fan Silencer (Type 2)	6.1	11.8	16.0	22.4	28.9	20.1	14.5	12.6

Comparison of the tested insertion loss (Table 8) with the minimum insertion losses identified from the acoustic modelling (Table 6) indicates some differences. The manufactured silencers performed better at 500 Hz and below and had a poorer performance at 1 kHz and above.

Revised modelling was completed on the basis of the manufacturer's data to determine the predicted receptor noise levels using the new source noise data and silencer attenuations. This modelling confirmed that full compliance with the airborne environmental noise requirements from the two ventilation station outlets (northern and southern) continued to be predicted under typical and worst-case meteorological conditions. Therefore, additional attenuation measures were not considered necessary for the ventilation station outlets.

COMMISSIONING TESTS

Introduction

During the commissioning phase of the project compliance testing was completed. The purpose of the testing was to verify the acoustic performance of the ventilation system and associated plant under a range of operating conditions.

Source Noise Testing - Axial Fans and NR Levels

The source noise testing at the commissioning phase served two purposes. Firstly, the data could be used to verify the actual source noise levels achieved in situ for the various items of plant and equipment. Secondly, this phase of the testing allowed for measurement of compliance with the NR85 requirement for in-tunnel environment.

The source noise testing followed the methodologies defined in ISO 3744:1994, Acoustics – Determination of Sound Power Levels of Noise Sources sing Sound Pressure (ISO, 1994) and ISO 13350:1999, Industrial Fans – Performance Testing of Jet Fans (ISO, 1999). The NR tests were completed in accordance with Australian Standard 1469-1983, Acoustics – Method for the determination of noise rating numbers (AS, 1983).

Overall, the test results confirmed that measured source noise levels for the various items of plant and equipment conformed closely to the manufacturer's design specifications. The NR results confirmed full compliance with NR85 requirement in the mainline tunnels.

Ambient External Noise Verification Testing

The ambient monitoring verification testing was completed during night time periods expected to represent the quietest periods, to allow determination of the expected contribution of VSO and portal fan noise to the local environment. Despite timing the testing to coincide with these periods, for a number of the tests, as would be expected in an urbanised area, local noise sources were significant at times. This resulted in background noise levels being affected by local noise sources for some of the test positions. Further, given the acoustic design for the project was based on achieving stringent noise limits, the potential to measure the noise levels significantly above existing background was not expected.

Overall, the observations and measurements made during the ambient noise testing confirmed that noise emissions from the VSOs was barely audible or inaudible at all measurement positions for a range of worst case and normal operational scenarios. No significant change in background L_{A90} noise levels were observed for all monitoring positions.

In the case of the portal noise emissions from jet fans, for the southern and northern tunnel mainline portals, the noise emissions were barely audible or not audible at all monitoring positions. No significant change in background L_{A90} noise levels were observed for all monitoring positions.

CONCLUSIONS

This project has highlighted some of the key issues associated with acoustic modelling for concave, concrete tunnel structures and associated mechanical and electrical plant and infrastructure.

The adopted modelling methodology provided a valuable input to the design of the project, and allowed verification of key acoustic design parameters at the initial and detailed design stage of the project.

The verification testing completed following commencement of operations of the Clem7 motorway has confirmed that the acoustic goals set for the project are being met at the nearest sensitive receptors.

In addition, the modelling methodology allowed prediction of in-tunnel noise levels thus facilitating calculation of occupational exposure levels and NR values. The verification monitoring confirmed full compliance with NR85 requirement in the mainline tunnels, and close correspondence between the modelled and the measured NR values.

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