A Health-Based Metric for Evaluating the Effectiveness of Noise Barrier Mitigation Associated With Transport Infrastructure Noise

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Abstract

Introduction: This study examines the use of the number of night-time sleep disturbances as a health-based metric to assess the cost effectiveness of rail noise mitigation strategies for situations, wherein high-intensity noises dominate such as freight train pass-bys and wheel squeal. Materials and Methods: Twenty residential properties adjacent to the existing and proposed rail tracks in a noise catchment area of the Epping to Thornleigh Third Track project were used as a case study. Awakening probabilities were calculated for individual’s awakening 1, 3 and 5 times a night when subjected to 10 independent freight train pass-by noise events using internal maximum sound pressure levels (L_{AFmax}). Results: Awakenings were predicted using a random intercept multivariate logistic regression model. With source mitigation in place, the majority of the residents were still predicted to be awoken at least once per night (median 88.0%), although substantial reductions in the median probabilities of awakening three and five times per night from 50.9 to 29.4% and 9.2 to 2.7%, respectively, were predicted. This resulted in a cost-effective estimate of 7.6–8.8 less people being awoken at least three times per night per A$1 million spent on noise barriers. Conclusion: The study demonstrates that an easily understood metric can be readily used to assist making decisions related to noise mitigation for large-scale transport projects.

Keywords: Annoyance, cost effectiveness, health-based metric, mitigation strategies, rail noise, sleep disturbances

Background

Sydney, the largest city in Australia, is provided with a comprehensive, convenient and accessible rail transport network for passenger and freight train movements. The rail network is an integral part of New South Wales’ (NSW) freight transportation system, and freight transported by rail is projected to grow over the next 20 years. Significant sections of the rail network in Sydney adjoin established residential communities. Studies indicate that the residential areas that are situated near rail infrastructure are likely to experience noise impacts and a loss of amenity including interference with communication, annoyance, increased motility, interference with sleep and possibly more significant health effects.

Many laboratory and field studies have been performed over the last 30 years to understand the effects of noise from road, rail and airport transport infrastructure on individuals. A number of models have been proposed to describe the impacts of noise on individuals from transportation modes. McGuire and Davie[31] have compiled a detailed overview of this research and effects of noise on sleep, including predicted results from proposed models and their perceived limitations. Studies indicate that there is a relationship between noise and the number of noise-induced awakenings and that this relationship is more noticeable for A-frequency weighted maximum sound pressure level (L_{AFmax}) events, above 70 decibels (dB).[4] The relationship between nocturnal noise exposure and health effects in populations is observable at L_{night,outside}, which is the A-weighted long-term average sound level as defined in ISO 1996-2: 1987, determined over all night periods of a year, wherein the night is 8 h (usually 23:00–07:00 local time) 40–55 dB and is increasingly harmful above L_{night,outside} 55 dB.[2]

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In terms of the impact of noise from different transportation modes, Marks et al. indicated that train noise caused more awakenings than aircraft and road noise. The study also showed that the probability of awakening increased significantly with $L_{AF_{max}}$, slope of the rise time (dB per second), noise duration and the noise-free interval between noise events. Basner et al. recently conducted a laboratory study comparing the impact of air, road and rail traffic noise on annoyance and polysomnographically assessed sleep structure in a systematic approach. The study results indicated that railway noise had a major impact on sleep in regard to the subjective feeling of annoyance and quality of sleep.

Recently, Elmenhorst et al. conducted a study of 33 participants living alongside railway tracks in the Cologne and Bonn areas of Germany. The participants were polysomnographically investigated, and the data were pooled with data from a field study on aircraft noise to directly compare the effects of railway and aircraft noise. The study found that nocturnal railway noise exposure was associated with increased awakening probabilities exceeding those for aircraft noise. The probability of awakening was found to significantly increase with elapsed sleep time, but decreased with prolonged noise events. The study also indicated that the sound pressure rise time ($L_{AF_{max}}$ rise time) of a noise event was a highly significant predictor for awakenings, and freight train noise in comparison to passenger train noise had the most impact on awakening probabilities.

Freight trains and rail vehicles generate noise from different sources while travelling on rail tracks; however, a loud tonal sound known as wheel squeal may occur, wherein small radius rail curves are encountered. Wheel squeal generally exceeds $L_{AF_{max}}$ 100 dB measured 2.5 m from the track and is typically in the 1600 and 2500 Hz one-third octave frequency bands, and it is readily distinguished from other sounds. If wheel squeal occurs in populated areas, it is one of the most significant noise impacts from rail operations. Rail track wheel squeal is a well-known occurrence in Beecroft, a suburb of northern Sydney, having first been studied in the late 1980s, and it is the subject of an ongoing investigation by Transport for NSW, wherein a trial of rail lubrication has been undertaken.

The rail line at Beecroft has recently been upgraded to increase its capacity to carry freight [the Epping to Thornleigh Third Track (ETTT) project]. The aim of the current study is to explore an appropriate health-based metric to evaluate the effectiveness of noise mitigation using the ETTT as a case study.

**CASE STUDY**

The ETTT involved construction of 6 km of new and upgraded track along the western side of the Main North Line rail corridor between Epping and Thornleigh train stations. The track is intended to provide additional capacity for slow moving northbound freight trains to travel up a steep incline in parallel with faster moving passenger trains on adjoining tracks. The project was determined to have a potentially significant impact on the environment, and the proponent was required to prepare an Environmental Impact Statement. The project was approved in 2013 with a requirement that the proponent provide an Operational Noise and Vibration Review (ONVR) to further explore noise mitigation measures to minimise the impact of the project upon the local residents.

The rail corridor between Epping and Thornleigh travels through a number of established suburban areas including the suburb of Beecroft. The rail tracks in this area are characterised by small radius track curves, and there has been a long history of freight train movements causing intrusive wheel squeal events. The ONVR divides the Epping to Thornleigh rail corridor into 10 noise catchment areas (NCAs), and NCA 6 encompasses the Beecroft rail corridor area. The eastern side of the rail corridor in NCA 6 is zoned and used for residential purposes and includes 20 residential properties within approximately 50 m from the nearest rail track. These residential properties were used in the current study because of their residential use and occupation at night time. The western side of the rail corridor is mostly comprised of commercial properties that are generally not used for residential purposes, and consequently, these properties were not considered in the study.

The number of freight train movements at night time was expected to increase from an average of nine movements on existing rail tracks before commencement of the ETTT project to a forecast peak of 21 movements following completion of the project in 2016. However, the forecast peak capacity of the rail tracks is 35 freight train movements at night time in 2026.

**MATERIALS AND METHODS**

**Noise exposure assessment**

**Operational Noise and Vibration Review**

An acoustic model was used by the proponent to calculate sound levels for day time and night time, $L_{AF_{max}}$ and $L_{Aeq}$ (period), at properties adjacent to the ETTT project to predict unmitigated noise impacts from the project. These results were compared against noise trigger levels set by the local regulatory authority to determine the need for noise mitigation at individual properties. A range of mitigation measures were considered including rail lubricators, swing-nose crossings, a technical assessment for benefits of targeting high noise locomotives, noise barriers and individual property treatments. The predictions of external sound levels ($L_{Aeq(9 h)}$ night-time 22:00–07:00 h, $L_{Aeq(15 h)}$ day-time 07:00–22:00 h and $L_{AF_{max}}$) at the façades of properties were provided in all NCAs with noise mitigation measures in place including a safety factor allowing for increases in the number of train movements over time. To calculate this safety factor, the weekly maximum capacity freight numbers (in the form of the average per day) were used in place of the forecast average freight numbers.
Wheel squeal

Although the ONVR indicated that residential noise impacts appear to be greatest during wheel squeal events associated with freight trains, the model used by the proponent to predict maximum sound levels could not assess the impact of small radius rail curves (<400 m). Consequently, the ONVR made an additional allowance for wheel squeal and estimated the number of wheel squeal events that are likely to occur. Bullen and Jiang\[16\] proposed an algorithm to detect wheel squeal events from train pass-bys, which estimated that wheel squeal events would occur in up to 50% of train pass-bys using the maximum sound pressure level descriptor. Night-time freight train movements were modelled in the ONVR with approximately 20 movements occurring each night, and hence, 10 wheel squeal events per night were deemed likely to occur in the scenario considered in this study.

Metric used by Operational Noise and Vibration Review to determine the cost effectiveness of noise barriers

The cost effectiveness, and hence reasonableness and feasibility, of noise barrier mitigation was evaluated in the ONVR with reference to a methodology advocated by Weber and Atkinson.\[17\] This method calculated the total noise benefit (measured in dB) and marginal benefit per unit area of noise barrier for residences, wherein project noise goals were expected to be exceeded. The ONVR applied a cost-effective threshold of 100 dB per A$1 million cost, wherein the benefit is the reduction in both the maximum (L_AFmax) and time average sound pressure levels for night time (L_Aeq(9h)) due to barrier installation added together and summed across all properties in each NCA. In NCA 6, the Beecroft rail corridor area, barriers with heights ranging from 0.5 m to greater than 8 m were considered with low height barriers (0.5 and 1.0 m) situated close to rail tracks for the purpose of targeting rail wheel noise. Analysis of the cost benefits established that barriers with heights of 1.0, 3.0 and 5.0 m met the overall noise and cost-benefit goals. Other noise mitigation measures were proposed, and in recognition of the particularly ‘annoying rail curve wheel squeal noise problem’ in the Beecroft rail corridor area, a proof of concept track lubrication system was installed on all tracks in July 2013 [Figures 1 and 2].

Alternate health-based metric

Researchers have advocated using awakening effects of noise events to evaluate the impacts of changes in night-time rail operation and the benefits of mitigation measures.\[18\] The current study proposes an alternate measure of the effectiveness towards total noise benefit measured in dB by using the reductions in noise-induced awakenings as the measure of benefit from reductions in noise exposure levels. This approach provides awakening probabilities at different sound levels, and these are used to compare the effects of a single event, or the number of separate freight train noise events on individuals. Only the maximum sound level is used in this approach, because it captures the magnitude of each freight train pass-by noise event, which is particularly appropriate considering the high sound levels generated by wheel squeal events. The number of pass-bys is directly used in this approach rather than attempting to indirectly capture its effect through an L_Aeq measure.

To predict awakenings, the study applied the random intercept multivariate logistic regression model (the model) devised by Elmenhorst et al. to determine the exposure–response relationship of railway noise events and the probability of sleep stage changes to awake. The model calculated awakening probabilities for the highest points on the sound event curve measured at the sleeper’s ear. The railway noise events were treated as independent events and identified as an undisturbed sleep-time window of 1 min directly preceding the start of a noise event until 90 s after the noise event began. The probabilities of awakening at least 1, 3 and 5 times each night were the primary outcome measures used to assess the mitigation effectiveness.
Assumptions used when applying awakenings predictive model

ONVR $L_{AF_{\text{max}}}$ measurements for train noise events in NCA 6 were assumed to be an accurate description of train noise experienced at each property on the eastern side of the catchment. As sound pressure levels will be lower inside dwellings compared to external sound levels, a 10 dB deduction in sound levels was used to compensate for the attenuation provided by external structures such as walls and roofs. Sound pressure levels were identified in the ONVR for the ground and upper floor levels of all properties, and the properties with a first floor were assumed to have all sleeping areas situated on this level.

The parameters used when applying the Elmenhorst model included $L_{AF_{\text{max}}}$ rise time of 3 dB per second for noise events, an intercept value of 1, duration of noise events of 58 dB per second, elapsed sleep time of 601 epochs (30 s periods assigned a sleep-stage designation), a median age of 34 years, male gender and elapsed time in the same sleep stage before the noise began of 14 epochs.

Freight train noise events were assumed to be sufficiently separated in time to cause independent chances of waking. Awakening probabilities were calculated for 10 independent train noise events at each property on the northeast side of NCA 6. Awakening probabilities were calculated for the chances that a person would wake up at least 1, 3 and 5 times at night when subjected to 10 independent freight train noise events applying the following equation:

$$Pr = \left[ R = r \right] = _nC^{r}q^{(nr)}.$$  

The probability of awakening $Pr$ or more times follows from $P_{\ge r} = P_r + P_{r+1} + P_{r+2} + \cdots + P_n$. Awakening probabilities were then related to a hypothetical household comprising of four people to provide a context for demonstrating the probable noise impacts on individuals living in properties.

RESULTS

Table 1 describes the predicted external $L_{AF_{\text{max}}}$ for the 20 properties included in the study area prior to and after the rail upgrade, both with and without proposed mitigation. Post-upgrade mitigation is predicted to result in an 8–17 dB reduction in $L_{AF_{\text{max}}}$.

Table 2 presents the predicted probability of awakening 1, 3 and 5 times per night with and without mitigation at each residence. It can be seen that even with mitigation, the vast majority of the residents are predicted to be awoken at least once per night (median 88.0%), despite there being a statistically significant reduction in the probability of being awoken. However, when comparing predictions of being awoken three and five times per night, there were substantial reductions in the median probabilities from 50.9 to 29.4% and 9.2 to 2.7%, respectively.

Assuming that four people live in each dwelling, the reduction in people being awoken at least three times per night would decrease from 39 to 23 people. The ONVR reported that the mitigation measure employed for NCA 6 would result in a total noise benefit of 106–152 dB per $1 million dollars over the study area at a total cost of A$1.8–2.1 million dollars. This was considered as cost effective, because it exceeded a threshold of 100 dB per A$1 million cost. The

| Property | Level | $L_{AF_{\text{max}}}$ prior to ETTT | $L_{AF_{\text{max}}}$ after ETTT without acoustic barriers | $L_{AF_{\text{max}}}$ after ETTT with mitigation, barriers and safety factor | Decrease |
|----------|-------|-----------------------------------|-------------------------------------------------|-------------------------------------------------|---------|
| A        | G     | 100                               | 100                                             | 91                                              | 9       |
| B        | G     | 100                               | 100                                             | 89                                              | 11      |
| C        | 1     | 101                               | 101                                             | 88                                              | 13      |
| D        | G     | 102                               | 102                                             | 88                                              | 14      |
| E        | G     | 102                               | 102                                             | 87                                              | 15      |
| F        | 1     | 104                               | 104                                             | 87                                              | 17      |
| G        | G     | 100                               | 101                                             | 86                                              | 15      |
| H        | G     | 102                               | 102                                             | 87                                              | 15      |
| I        | G     | 103                               | 103                                             | 87                                              | 16      |
| J        | G     | 104                               | 104                                             | 87                                              | 17      |
| K        | G     | 102                               | 103                                             | 90                                              | 13      |
| L        | G     | 90                                | 90                                              | 81                                              | 9       |
| M        | G     | 96                                | 96                                              | 84                                              | 12      |
| N        | 1     | 85                                | 85                                              | 77                                              | 8       |
| O        | G     | 104                               | 104                                             | 91                                              | 13      |
| P        | 1     | 104                               | 104                                             | 89                                              | 15      |
| Q        | 1     | 96                                | 96                                              | 84                                              | 12      |
| R        | G     | 101                               | 101                                             | 85                                              | 16      |
| S        | G     | 99                                | 99                                              | 84                                              | 15      |
| T        | G     | 90                                | 90                                              | 82                                              | 8       |

Source: ETTT; Operational Noise and Vibration Review.\(^{[14]}\)
comparable figure for the awakening metric of the reduction in number of the residents being awoken at least three times a night was 7.6–8.8 people per A$1 million.

**DISCUSSION**

Noise-induced sleep disturbance has been shown to cause environmental sleep disorder in individuals with resulting health effects such as insomnia, day-time fatigue and somnolence. This study proposes using the number of night-time sleep disturbances as a health-based metric to assess the cost effectiveness of rail noise mitigation strategies for situations, wherein high-intensity noises such as wheel squeal dominate. The approach is in contrast with using noise benefit estimates quantified in decibel reductions using a combination of maximum sound ($L_{A\text{max}}$) and night-time equivalent ($L_{A\text{eq}(9\,\text{h})}$) sound pressure levels. Although applying both methods leads to the same conclusion that installing noise barriers is cost effective for NCA 6, the major advantage of the proposed approach is that it presents the benefits in terms of a directly relevant health outcome that would be more easily understood by both the regulators and the public.

Freight train pass-bys are relatively short-duration events that generate elevated sound levels with special characteristics, such as low-frequency noise from engine exhausts and loud higher-frequency noise from wheel squeal, which are capable of affecting the residents living nearby. A major difference in the approaches described lies in how they account for the total number of 'high-intensity noise events' that occur over the night-time period. The noise benefit approach can only account for the number of high-intensity noise events through consideration of increases in the $L_{A\text{eq}(9\,\text{h})}$ level. The proposed alternate approach directly accounts for the number of 'high-intensity noise events' as well as their intensity, and hence, is more sensitive to this component of noise exposure. However, by ignoring other sources of noise, it may underestimate the impacts from other noise sources, although these are unlikely to cause sleep disturbance in the setting considered.

| Address | Level | Freight train noise dB | Probability (%) of awakening at least 1, 3 and 5 times each night | Freight train noise dB | Probability (%) of awakening at least 1, 3 and 5 times each night |
|---------|-------|------------------------|---------------------------------------------------------------|------------------------|---------------------------------------------------------------|
|         |       | Internal $L_{A\text{max}}$ | 1 | 3 | 5 | Internal $L_{A\text{max}}$ | 1 | 3 | 5 |
| A       | G     | 90                     | 94.8 | 49.2 | 8.5 | 81                     | 90.5 | 35.1 | 3.9 |
| B       | G     | 90                     | 94.8 | 49.2 | 8.5 | 79                     | 89.3 | 32.2 | 3.3 |
| C       | I     | 91                     | 95.2 | 50.9 | 9.2 | 78                     | 88.6 | 30.8 | 3.0 |
| D       | G     | 92                     | 95.5 | 52.5 | 10.0 | 78                     | 88.6 | 30.8 | 3.0 |
| E       | G     | 92                     | 95.5 | 52.5 | 10.0 | 77                     | 88.0 | 29.4 | 2.7 |
| F       | I     | 94                     | 96.2 | 55.9 | 11.6 | 76                     | 87.3 | 28.1 | 2.5 |
| G       | G     | 91                     | 95.2 | 50.9 | 9.2 | 77                     | 88.0 | 29.4 | 2.7 |
| H       | G     | 92                     | 95.5 | 52.5 | 10.0 | 76                     | 87.3 | 28.1 | 2.5 |
| I       | G     | 93                     | 95.9 | 54.2 | 10.8 | 77                     | 88.0 | 29.4 | 2.7 |
| J       | G     | 94                     | 96.2 | 55.9 | 11.6 | 77                     | 88.0 | 29.4 | 2.7 |
| K       | G     | 93                     | 95.9 | 54.2 | 10.8 | 80                     | 89.9 | 33.6 | 3.6 |
| L       | G     | 80                     | 89.9 | 33.6 | 3.6 | 71                     | 83.6 | 22.1 | 1.5 |
| M       | G     | 86                     | 93.1 | 42.7 | 6.1 | 74                     | 85.9 | 25.6 | 2.0 |
| N       | I     | 75                     | 86.6 | 26.8 | 2.2 | 67                     | 80.3 | 17.9 | 1.0 |
| O       | G     | 94                     | 96.2 | 55.9 | 11.6 | 81                     | 90.5 | 35.1 | 3.9 |
| P       | I     | 94                     | 96.2 | 55.9 | 11.6 | 79                     | 89.3 | 32.2 | 3.3 |
| Q       | I     | 86                     | 93.1 | 42.7 | 6.1 | 72                     | 84.4 | 23.2 | 1.7 |
| R       | G     | 91                     | 95.2 | 50.9 | 9.2 | 75                     | 86.6 | 26.8 | 2.2 |
| S       | G     | 89                     | 94.4 | 47.6 | 7.9 | 74                     | 85.9 | 25.6 | 2.0 |
| T       | G     | 80                     | 89.9 | 33.6 | 3.6 | 72                     | 84.4 | 23.2 | 1.7 |
| Median  |       | 91                     | 95.2 | 50.9 | 9.2 | 77.0                   | 88.0 | 29.4 | 2.7 |
| Mean    |       | 90.5                   | 94.3 | 48.4 | 8.6 | 76.7                   | 87.2 | 28.5 | 2.6 |
| Min     |       | 75                     | 86.6 | 26.8 | 2.2 | 67.0                   | 80.3 | 17.9 | 1.0 |
| Max     |       | 94                     | 96.2 | 55.9 | 11.6 | 81.0                   | 90.5 | 35.1 | 3.9 |
| 95% lower confidence limit | 88.6 | 93.0 | 44.5 | 7.3 | 75.1                   | 86.0 | 26.4 | 2.2 |
| 95% upper confidence limit | 92.1 | 95.5 | 52.3 | 10.0 | 78.1                   | 88.4 | 30.6 | 3.0 |

*Note: Only the highest ground or 1st floor levels are included. $L_{A\text{max}}$ levels are converted to micropascals to calculate the mean values and the confidence limits.*
The benefit of mitigation is quantified in terms of both the proportion and absolute number of people likely to be awakened by high-intensity noise events. Ideally, these benefits should be measured for the situation, wherein the residents are awakened or not during the night. However, in settings such as the one described, wherein the residents are already exposed to excessive noise, it is somewhat unrealistic to expect mitigation to achieve noise exposure levels that result in no awakenings for the majority of those exposed. Consequently, it is more appropriate to use a level such as achieving less than three awakenings per night (the level half of the residents were already expected to experience) against which to measure the cost effectiveness.\(^7\) The reported 21.5% reduction in the residents waking three or more times each night represents a substantial benefit, and when translated into absolute terms, it was estimated that 16 people would benefit per night. Whether this represents satisfactory cost effectiveness is a value judgment, but given the relatively modest cost of A$1.95 million, our study supports the implementation of the mitigation strategy as recommended by the ONVR.\(^{14}\)

In applying the suggested approach, some assumptions need to be made including that the proponent’s predictions of noise levels that the residents were exposed to, and the acoustic performance of noise barriers were accurate. The levels used in this study may underestimate the maximum sound pressure that the residents are exposed to, because the ONVR defines maximum sound pressure levels as ‘...95th percentile levels, that is, the sound level that is not exceeded by 95% of rail pass-by events’. This approach excludes the loudest 5% of measured sound pressure levels from train pass-by events such as train wheel squeal noise. Consequently, the current study may have underestimated the noise impacts upon the residents’ sleep. The current study has also not considered noise impacts from low-frequency sound emitted from locomotive engine exhausts, which are located at the top of the locomotives several metres above the ground level. This may have resulted in a further underestimation of the residents’ noise exposure, given the relatively poor acoustic performance and effectiveness of noise barriers to this sound frequency.

Individual train noise events were treated as independent events sufficiently separated in time to allow an individual to fall asleep between each event, and this obviously may not be the case should pass-bys only be separated by a short time period. However, making this assumption allowed the direct application of the Elmenhorst model, because it considers each train pass-by as a separate noise event.\(^7\) Furthermore, the habituation of the residents in NCA 6 to train noise events was not allowed in the method used by the study. It is debatable whether such an allowance should be made in any case with researchers arguing that general habituation does not occur from long-term noise exposure,\(^7\) with recent studies indicating that subcortical noise-induced arousals are unlikely to habituate.\(^{23}\)

The benefits of installing noise barriers is likely to have been underestimated, because only the residents in the first row of houses adjacent to the track have been considered. Even though the study area is set in an urban low-density residential area with free standing houses, a case could be made for including at least a second row of properties when assessing the benefits of installing mitigation measures. However, if this was to be done, then the sound attenuation due to distance and diffraction around adjacent structures would need to be considered.

**Conclusion**

This case study has demonstrated that currently available sleep disturbance models can be used to assess the effectiveness of noise mitigation measures in a setting, wherein high-intensity noise events dominate residential noise exposures. By assessing the effectiveness in terms of a direct health metric such as probabilities of awakening, more easily understood assessments of the cost effectiveness can be made.

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**Conflicts of interest**

There are no conflicts of interest.

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