Comparison of rail noise prediction methodologies for elevated rail designs

Arvind Deivasigamani[1] and Adrian White[1]

[1]Acoustics, WSP | Parsons Brinckerhoff, Melbourne, Australia

ABSTRACT
In this paper, some of the well-known rail prediction methodologies, such as Kilde Rep 130, Nord2000 and the United States' FTA (Federal Transit Administration) methodologies are compared using a simple elevated rail model. An overview of the relevance and applicability of these source models for an elevated rail design is provided. For each of the above mentioned methodologies, simple single point receiver results for an at-grade and an elevated rail design are presented. Further, a test-case representing a real-world scenario is also studied using these different methodologies. The results indicate a significant variation in predicted noise levels across the methodologies. Kilde Rep 130 is found to be conservative, and predicts minimum shielding from the bridge structure. On the other hand, Nord2000 implements source directivity, thereby predicting larger shielding effects from the base bridge and barrier structures. FTA methodology provides a flexibility to use a more simplistic ISO 9613 propagation model, which reduces computational time. While the accuracy of these methodologies can be only determined by comprehensive field measurements, the paper provides an insight into the effectiveness of these methodologies when carrying out predictive modelling of rail operational noise for an elevated rail design.

1. INTRODUCTION
There are several rail noise prediction methodologies used around the world. Some of them include Schall 03 method (a German standard), Japan Narrow-Gauge Railway method based on ASJ 2008, and Calculation of Railway Noise (CRN, a UK standard). There are no known legislative requirements or standards in Australia that prescribes to use one particular prediction methodology. However, rail noise predictions have been commonly carried out using the Kilde Rep 130 methodology in Australia. However, this Nordic methodology has been twice superseded. With the advent of new, or redevelopment of, infrastructure with elevated designs, it is important to study the applicability of existing rail noise prediction methodologies. The comparative study described in this body of work is limited to only Kilde Rep 130, Nord 2000 and the FTA-ISO methodologies.

Kilde, a Norwegian organization, started a project in 1980 for the Norwegian Ministry of the Environment to develop a prediction methodology for railway noise. After several revisions, the final Kilde Report 67 was released in 1983/1984 (Ringheim, 1984). Kilde Report 130 contains the background material with relevant equations for this method. The Kilde prediction method, developed in 1984, was developed to carry out manual calculations only and did not include the development of any computer model. This model was intentionally made simplistic for architects and planners, without previous knowledge of acoustics, to easily comprehend (Ringheim, 1984).

In 1996, this Kilde method was superseded with the Nordic Prediction Method for Trains, NMT96. This method had extensive source and propagation modelling parameters to be developed as a computer model. This method was relatively soon superseded in 2000 by the new Nordic Prediction Method, Nord 2000. This method utilized the source data from NMT 96, but however modified the source model to represent train noise sources more accurately. The propagation model was also significantly revised to account for several environmental conditions such as ground surface roughness, wind speeds and temperature gradients. The propagation model was developed to be uniform across the Nordic road and industrial noise calculations (Jonasson and Storeheier, 2001).

The Nordic Methods used for railway noise assessments are a package of source and propagation models, implemented together for any scenario modelled. This can often be considered as a limitation as the advantages of a source model from one method cannot be combined with advantages of a propagation model from another method. In this regard, acoustic consultants often explore opportunities to separate the source and propagation models, and conduct assessments using two different standards. One option in this regard for rail noise prediction is to use the Train Noise and Vibration Impact Assessment method, developed by the Federal Transport Administration (FTA), USA. The source model described in this method is simple to be computed manually, similar to Kilde. However, once the source levels are determined independently, the equivalent continuous sound level (L_{eq}) levels can be modelled as a line emission source, with the propagation algorithm implemented in accordance with ISO 9613-2 which is a widely accepted propagation model for industrial noise sources. This approach can overcome some of the limitations associated with other propagation models. However, this simple line source method does not allow for calculation of L_{max} levels in accordance with FTA.

The above mentioned methodologies are well established and documented for general assessments. De Lisle and Burgemeister (2014) have compared differences in shielding, ground effects, directivity and basic propagation between Kilde and Nord 2000 for at-grade rail design. However, there are currently no known detailed studies to understand the applicability of these methodologies for elevated rail designs. The objective of this paper is to understand the following:

- Differences in the source models among methodologies
- Advantages and limitations associated with Kilde, Nord 2000 and simple line source models
- Applicability of these models for elevated rail designs

2. SOURCE MODEL COMPARISON

Elevated rail designs often incorporate bridges and track-side barriers. These track-side barriers are generally found to be effective due to their close proximity to the train source (Morgan and Peeling, 2012). However, different methodologies follow different source models and hence the results heavily depend on the modelling method. Table 1 summarises the key differences in the source models among Kilde Rep 130, Nord 2000 and FTA method.

Table 1: Basic source model parameters

Parameter	Kilde	FTA	Nord 2000
Source heights	0.5m above rail head	2.44m (8 ft) for diesel locomotives 0.6m (2 ft) for electric trains	Standard split heights: Electric - 0.01m, 0.35m, 0.7m Locomotives - 0.01m, 0.35m, 0.7m, 2.5m
Source spectra	Not available - single overall source level	Not available - single overall source level	Source level modelled in 1/3 octave bands (25Hz-10KHz)
Speed coefficients	23.5 for L_{eq}; 30.5 for L_{max}	20 for commuter rail cars; 0 for DMU; -10 for passenger diesel	Varies for every 1/3 octave band
Reference speed	80 kmph	80.5 kmph (50 mph)	100 kmph

Source heights mentioned in Table 1 are standard reference heights above the rail head. When more detailed information on source heights are available, Nord 2000 allows these heights to be varied. While the source heights can be modelled differently for Kilde and FTA, it would be generally regarded as a deviation from the prescribed methodology. Nord 2000 also has the ability to vary the frequency content between the split heights (for example, low frequency noise between 20 - 250 Hz to be modelled as engine source, 2.5m above ground).

None of the above mentioned methodologies have Australian train noise source data in their libraries. Therefore, field measurements are vital to calibrate sources. When using Nord 2000, speed coefficients must also be determined for every 1/3 octave band. Alternatively, speed coefficients of a similar Norwegian train type present in the library may be used as an approximation. Appendix A presents a comparison of speed coefficients of a Norwegian train with speed coefficients of Melbourne metro trains (which were derived from field measurements).

While Kilde and Nord 2000 allow for L_{max} calculations, a simple line source model does not. When FTA-ISO source-propagation method is implemented, L_{max} can only be modelled as a moving point source, which is not representative of the actual L_{max} source from a train of finite length. Therefore, L_{max} levels cannot be accurately calculated using this method. L_{max} levels are challenging to precisely model and, in reality, may be triggered by localised discontinuities/defects in tracks. However, Kilde and Nord 2000 models do not precisely address this potentially controlling factor within their methodologies either.

3. METHODOLOGY

In order to understand the key differences between the methodologies, the following 3D model scenarios are developed using SoundPLAN 7.3:

- At-grade rail source with realistic terrain (no buildings)
- Elevated rail source on bridge with realistic terrain (no buildings)
- At-grade rail source with realistic terrain and buildings
- Elevated rail source on bridge with realistic terrain and buildings

The calculation settings used are 1000m search radius, reflection order 2 and tolerance 0.1 dB. The bridge width is modelled to be 2.7m from track center with a 1m high edge wall on either side. The bridge height varies between 8 - 11 m from the digital ground model. The ground effects used for the assessment are ground factor 0.5 (Kilde and FTA-ISO), ground resistivity 5000kNs/m^4 and roughness class 0 (Nord 2000). Note that ground effects are calculated using different equations in Kilde and Nord 2000. A sensitivity study is essential to quantify these effects clearly, and this would form a part of future work.

Each of the above mentioned scenarios are modelled using Kilde, FTA-ISO and Nord 2000 methodologies. The source levels (LAeq, 16hr) were initially calibrated to 73 dB(A) at 15m from a straight rail source and flat hard ground. These calibrated line sources are then used in each of the modelling scenarios. The 3D model developed in SoundPLAN for an elevated scenario is shown in Figure 1. Note that single point receivers are placed along a street, away from the rail corridor (at approximately 80^0 from corridor), to understand the noise propagation along the study area at specific distances. A mix of 244 EMU, 36 DMU and 12 freight trains were modelled for all scenarios (to represent a typical suburban rail corridor). The source heights were modelled as per Table 1 (with 2.5m for freight in Kilde and FTA). The source spectra for the trains used in Nord 2000 model is presented in Figure 2.

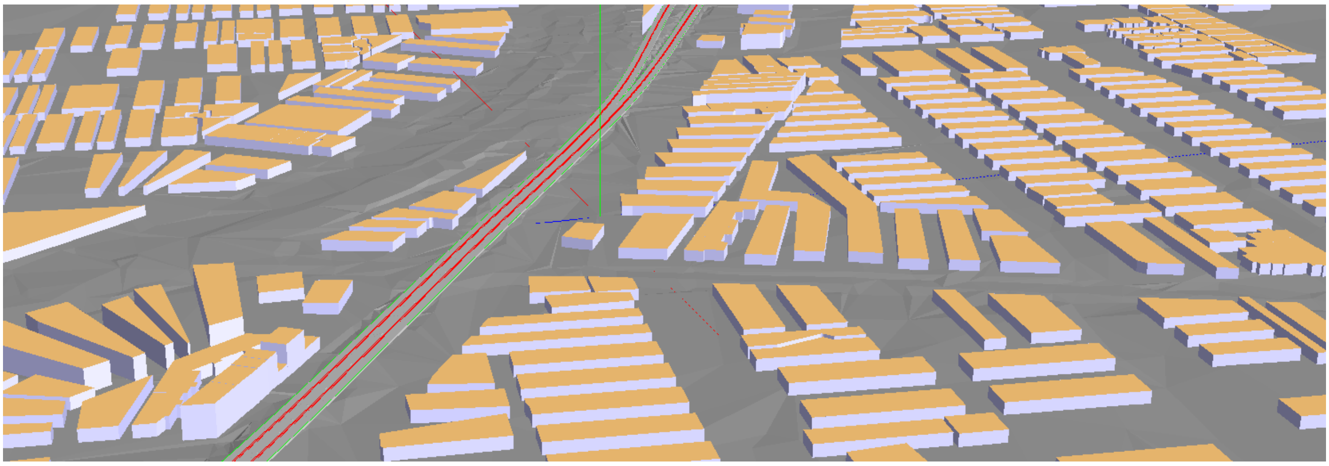

Figure 1: 3D model of at-grade and elevated scenarios

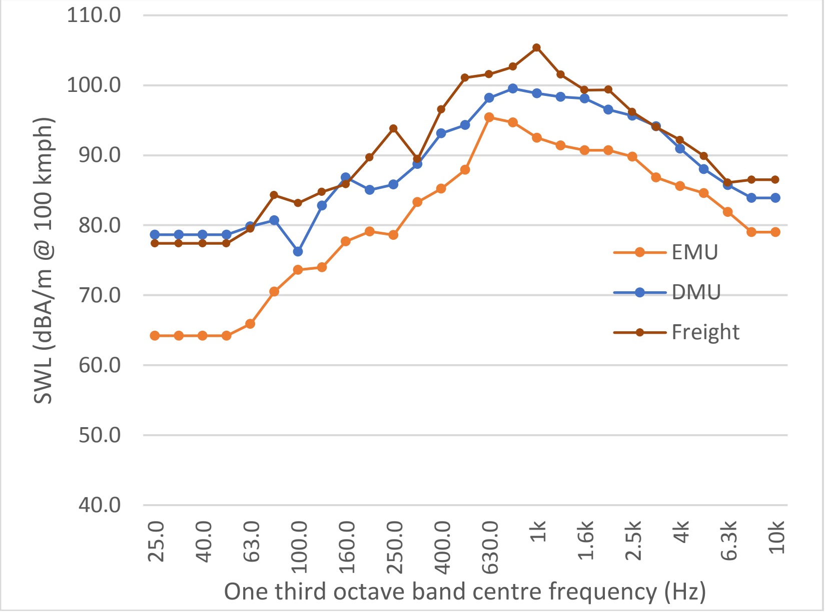

Figure 2: Source spectra used for Nord 2000

4. RESULTS AND DISCUSSION

In order to compare the rail noise algorithms detailed above, a combination of grid noise maps (1.5m above ground), cross section maps and single point receiver results are used. These are described in the following sections.

4.1 Elevated vs. At-Grade (with no buildings)

Simple SoundPLAN models are created with a relatively flat terrain and straight rail sources (elevated and at-grade). The grid noise maps are then subtracted ((elevated) - (at-grade)) for each methodology to understand the noise level difference predicted between the two scenarios. These results are presented in Figure 3. Note that buildings are not included in the model to avoid any localised shielding effects around buildings.

Figure 3 indicates that there is a significant difference across the rail noise methodologies considered. For all the scenarios, the results indicate that the elevated scenario would reduce the noise levels closer to the rail corridor. However, when Kilde is implemented, the elevated scenario is found to increase the noise levels (compared to the at-grade scenario) as the distance between the source and receiver increases. In an at-grade scenario, the source is located closer to the ground, resulting in greater absorption and shielding in comparison to an elevated scenario. However, the shielding from the bridge structure and side walls should also aid the elevated rail design in reducing noise levels. Given that there are no buildings in the model to induce shielding effects, the exact reason for obtaining higher noise levels further away from source is unclear. This observation may be attributed to the fact that Kilde is not valid for larger propagation distances (>300m).

The ISO 9613-2 propagation indicates that the noise levels for an elevated scenario would be lower closer to the source. However, at larger propagation distances, the level difference is found to be relatively small (0-3 dB), with the elevated scenario predicting slightly lower noise levels. This could be attributed to the fact that as distance between source and receiver increases, the path difference for propagation also reduces, resulting in minimal noise reduction.

Nord 2000 source and propagation model, on the other hand, indicates that the noise levels would be significantly reduced for an elevated scenario in comparison to an at-grade scenario. This is due to the fact that Nord 2000 provides high losses for shielding from the bridge and side walls. Also, Nord 2000 implements rail-specific source directivity, while Kilde and ISO use omni-directional sources. Therefore, when Nord 2000 is implemented, noise levels below the bridges are significantly lower. These aspects are discussed further in the following sections.

One aspect which is not investigated in this paper is the effect of track-side barriers on the results. It will be useful to understand how parallel barriers are treated in SoundPLAN across the methodologies. In this paper, barriers are modelled to represent a realistic case as track-side barriers are usually designed for architectural, visual amenity and noise protection reasons. The study of barrier effects would form part of the future work.

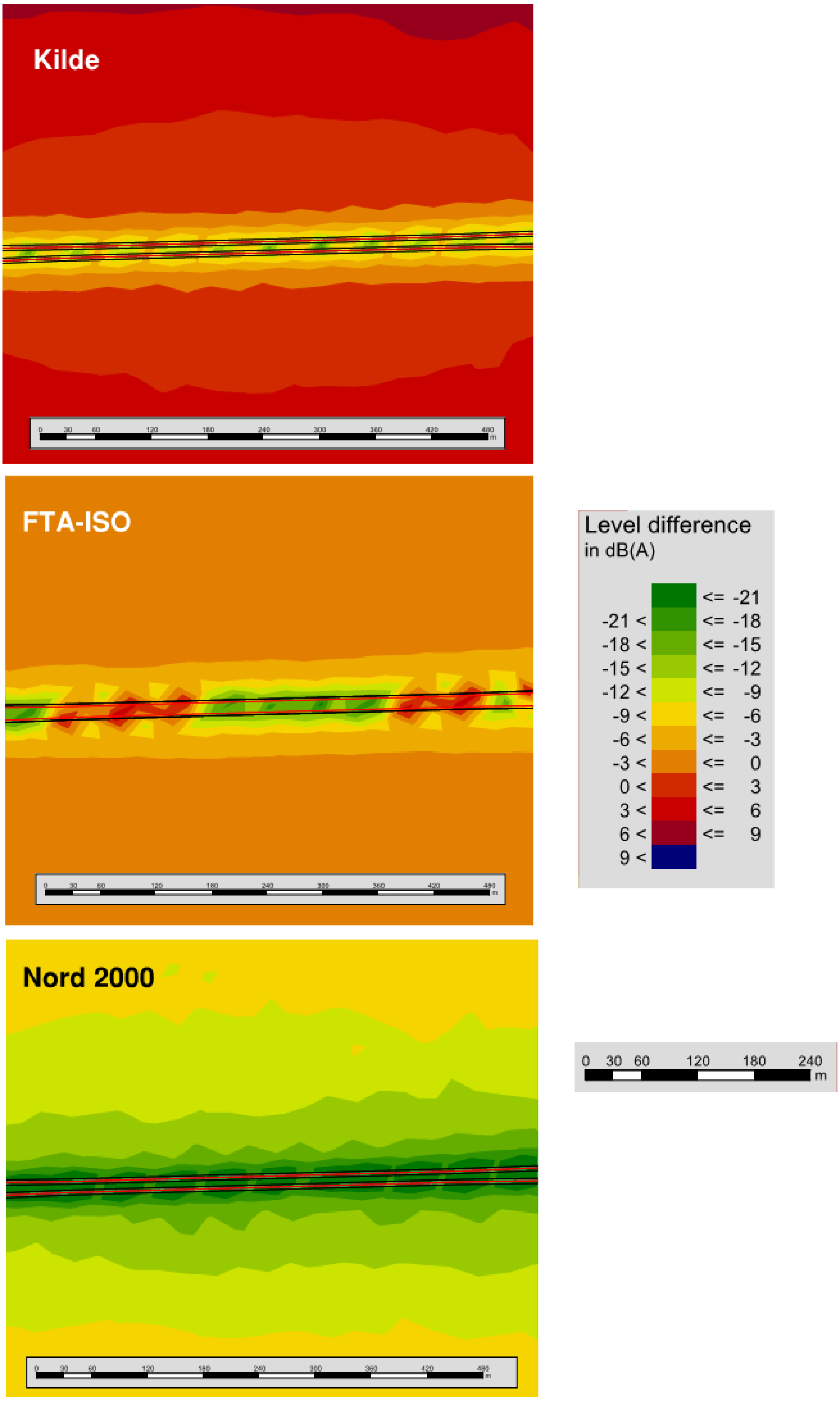

Figure 3: Grid noise map comparisons across rail standards ((L_{Aeq} elevated)-(L_{Aeq} at-grade))

4.2 Elevated vs. At-Grade (with buildings)

A 3D model with buildings, as indicated in Section 3, is created in SoundPLAN to compare Kilde, FTA-ISO and Nord 2000. The results are discussed in the following sections. Buildings were set to the same DGM as used in no-buildings scenarios.

4.2.1 Single Point Receiver Results

Single Point Receiver (SPR) results for the at-grade scenario are presented in Figure 4(a). The results indicate that the propagation losses are similar across the three methodologies. These sources, when elevated, however result in significant variation across the methodologies (Figure 4(b)).

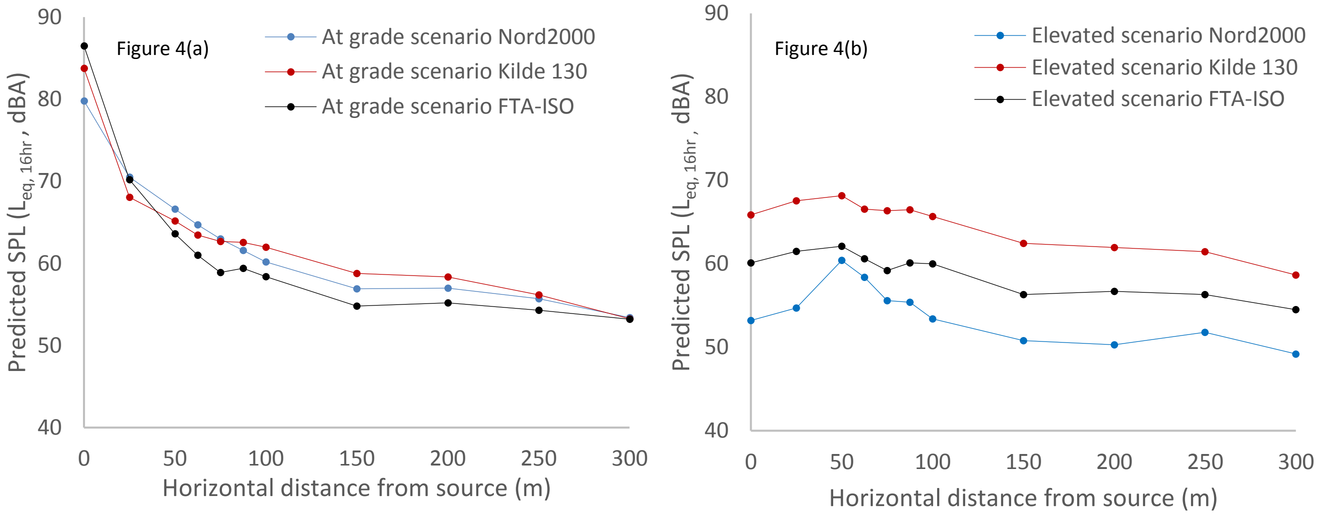

Figure 4: SPR $L_{eq,\ 16hr}$ results for at-grade and elevated scenarios

The results show that at distances greater than 50m, Kilde predicts higher noise levels, especially for the elevated scenario. The difference between Kilde and Nord is greater than 10 dB for the elevated scenario, while it is within 3 dB for the at-grade scenario. FTA-ISO method provides a 'middle ground', predicting noise levels higher than Nord 2000, but lower than Kilde. Also, higher shielding losses from the bridge and side wall can be observed in Nord 2000 (for distances less than 50m).

Figure 5 compares the Nord 2000 and Kilde L_{max} propagation for the at-grade and elevated scenarios. Kilde predicts higher noise levels for the elevated scenario in comparison with Nord 2000.

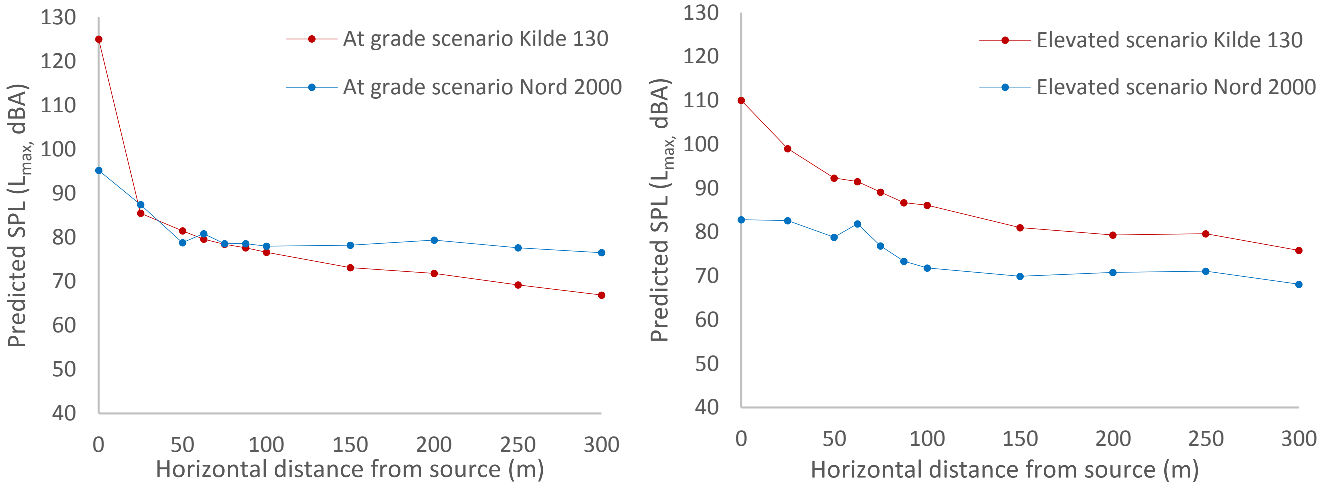

Figure 5: L_{max} results comparison between Kilde and Nord 2000

In Nord 2000, the receiver distance and the train length are compared to predict the L_{max} source levels. These source levels are then distributed along the train at finite positions. This implies that when the receiver is close to the train, only parts of the train would contribute towards L_{max}. The train modelled here is a 1200m long freight train, and hence Nord 2000 assumes only part of the train contribute towards L_{max}.

Kilde assumes the engine as a point source, and the whole train (wagons) as a finite line source. For long freight trains, the locomotive engine noise generally dominates, and hence the propagation and algorithms are significantly different to Nord 2000. Therefore, calibration of L_{max} levels are generally not trivial in Nord 2000 models.

4.2.2 Cross-Section Map

Figure 6 indicates a cross-section map comparison between Kilde and Nord 2000 for the elevated scenario. From the figure, it is evident that Nord 2000 uses source directivity in the vertical plane, and hence predicts significantly lower noise levels below the bridge. On the other hand, Kilde is observed to be conservative, using an omni-directional source and minimal shielding losses.

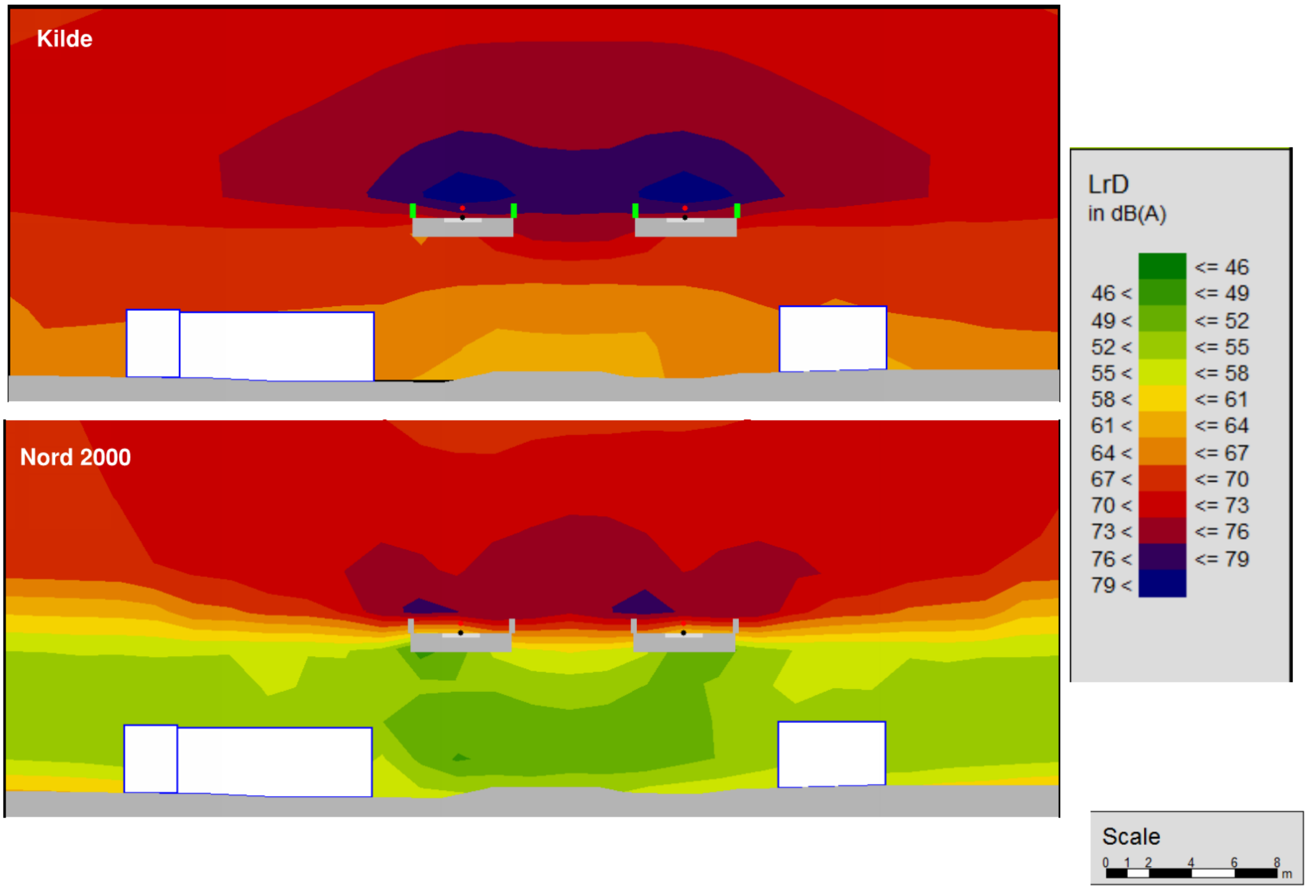

Figure 6: Cross-section map ($L_{Aeq,\ 16\ hr}$) comparison between Kilde and Nord 2000

4.2.3 Grid Noise Map

Figure 7 compares grid noise maps for the elevated scenario. The results indicate that there is a significant difference in predicted noise levels across the methodologies. Nord 2000 offers higher shielding loss and more complex terrain and building interactions. These results align well with findings detailed in De Lisle and Burgemeister (2014). On the other hand, Kilde offers very minimal shielding loss, resulting in higher noise level predictions. The ISO propagation predicts noise levels in-between Kilde and Nord 2000. Note that the noise levels were comparable across the methodologies for an at-grade scenario (Figure 4(a)). However, when the rail is elevated, it is clearly seen that predictions significantly differ, hence requiring detailed study and validation before concluding on any predicted impacts associated with the elevated design.

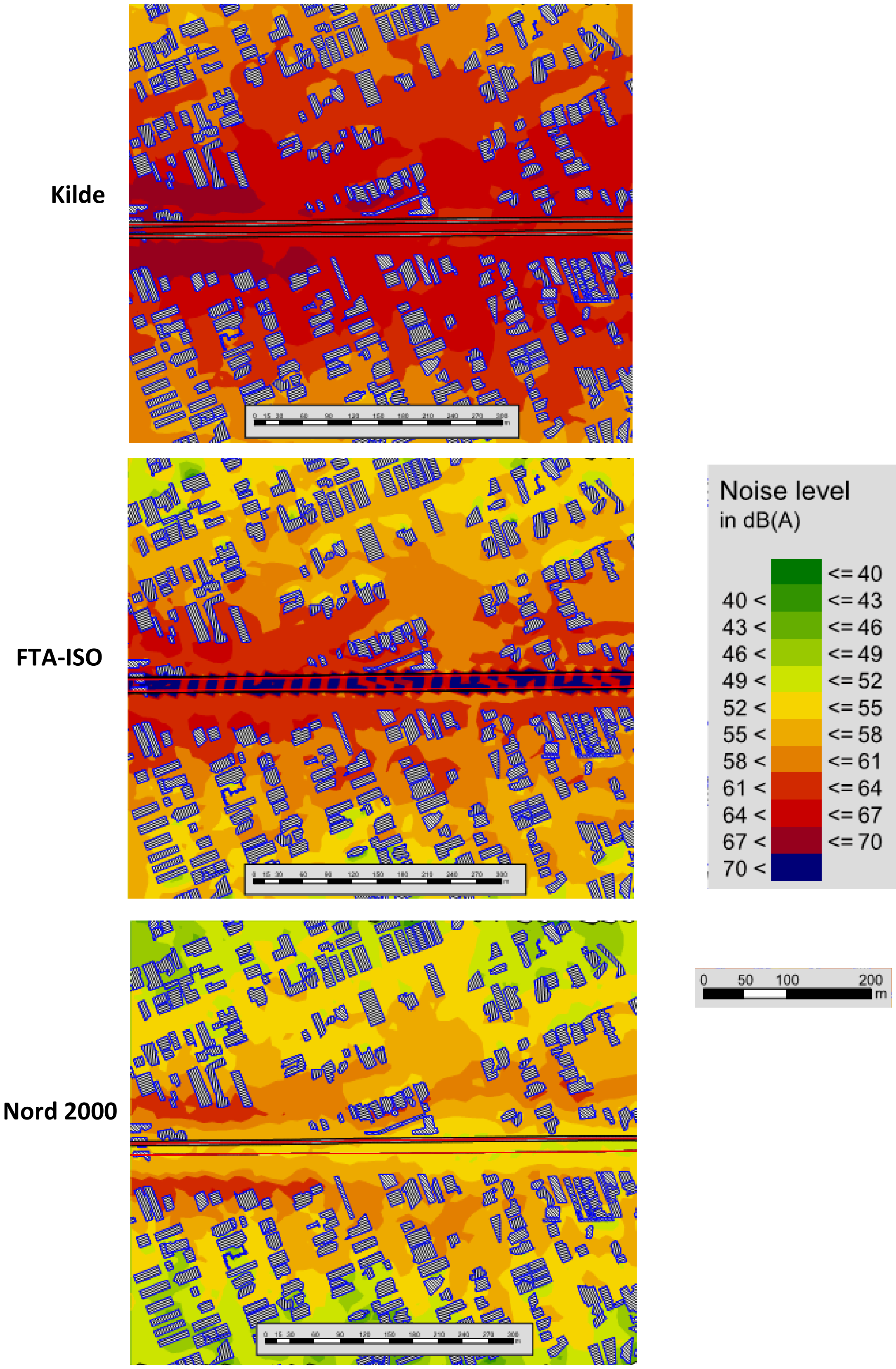

Figure 7: Grid Noise Map ($L_{Aeq,\,16\,hr}$) for elevated scenario based on real-world terrain and buildings

5. CONCLUSION

Significant differences are observed in the results of the three methodologies investigated in this work. Therefore, when designing noise control measures such as noise barriers, the height of these barriers would significantly vary, depending on the methodology implemented in the predictive modelling.

Elevated rail systems generally adopt track-side barriers as a noise control measure. When optimising these barrier heights, it is important to model the source levels, source heights and directivity as realistically as possible. In this regard, Nord 2000 provides the most detailed algorithm with flexibility to alter a wide range of parameters. However, it is generally not feasible to determine all these parameters accurately by on-field measurements within a short time span. Also, the computing times are significantly higher for Nord 2000. On the other hand, when adopting Kilde, the simplistic and conservative nature of the model may result in significantly high/tall barriers.

Using independent source and propagation models may be advantageous when a particular source or propagation model is tested to be inappropriate (for example, not calibrating) for a scenario. Also, using a simple propagation model such as ISO9613-2 significantly reduces computing times in comparison with Nord 2000. However, implementation of L_{max} predictions may not be possible when adopting this approach.

Determining the accuracy of any rail methodology would involve validation with significant field measurements. However, the authors are of the opinion that any rail methodology, prior to implementation, has to be studied in detail to assess its applicability, advantages and limitations. In this way, the predictive model would yield in more realistic results and more appropriate design of noise control measures.

6. FUTURE WORK

This paper provides a comparison between few prediction methodologies, but does not provide conclusive evidences to determine the most accurate modeling methodology. In order to further understand the differences between the models, the following studies are recommended:

- Effect of barriers on predicted results – The results presented in this paper for elevated design incorporate track side barriers as these are often implemented on projects as a noise control measure. A parametric study on barrier heights and their impact on results shall be conducted to understand the implementation of these models for elevated rail designs.
- Effect of ground absorption – Kilde and Nord 2000 treat ground absorption differently. In this regard, a parametric study on ground absorption properties would aid in understanding the influence of absorption settings on the predicted results
- Field measurements and validation – While different methodologies may provide different results, predictive modelling and comprehensive field measurements (post-construction) are critical to determine the accuracy of any model.

The authors are currently undertaking further modelling to understand the fundamental differences across the available modelling methodologies, and their applicability for elevated rail designs.

APPENDIX A: Speed Coefficient determination for Nord 2000

In order to determine the speed coefficients in accordance with Nord 2000, SELs of 50 Melbourne Metro trains (combination of Siemens, Comeng and X'Trapolis; measured at 5 different locations along the corridor) were measured along with their speeds. These values were distance corrected in accordance with Nordic prediction method (Ringheim, 1996; Jonasson and Storeheier, 2001), and then used to determine speed coefficients (a) by linear regression. The source level follows Equation 1:

$$L_{W,1m} = a.\,log\left(\frac{v}{100}\right) + b \tag{1}$$

where a - speed coefficient; v - velocity (km/h) and b is sound power level (dB) per meter length of train at 100 km/h. These speed coefficients are compared with the speed coefficients of an electric Nordic train (SL-X60) in Figure 8. The figure indicates that the coefficients correlate well at certain frequencies, while having significant deviations at other frequencies (especially low frequencies). During regression analysis, it was observed that the measured values have high scatter, and hence the speed coefficients are a crude approximation. This deviation may be attributed to rail roughness which was not quantified during measurements. Also, trains measured between 70 to 80 km/h may not correlate well with trains measured at 100 km/hr. It is therefore envisaged that significant number of train-pass-bys (>300) have to be considered under known rail conditions to accurately determine these constants.

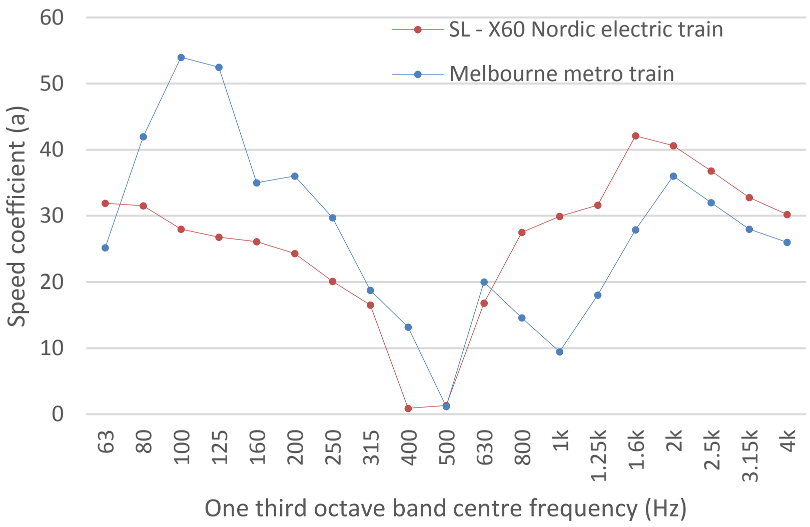

Figure 8: Speed coefficient comparison

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