Modeling road traffic noise using distributions for vehicle sound power level

Bert De Coensel[a)]
Acoustics group, Department of Information Technology, Ghent University
Sint-Pietersnieuwstraat 41, B-9000 Ghent, Belgium

A.L. Brown[b)]
Deanna Tomerini[c)]
Urban Research Program, Griffith School of Environment, Griffith University
170 Kessels Road, Nathan (Brisbane) QLD 4111, Australia

Dick Botteldooren[d)]
Acoustics group, Department of Information Technology, Ghent University
Sint-Pietersnieuwstraat 41, B-9000 Ghent, Belgium

Research evidence suggests that annoyance, sleep disturbance and other health effects of road traffic noise exposure may be related to the level and number of noise events caused by traffic as well as to energy equivalent measures of exposure. Because measurements show that the variation in noise emission between vehicles within the same category can be considerable, it is essential that the influence of vehicles that are producing significantly more (or less) noise than the average vehicle are taken into account in order to correctly predict the occurrence and strength of road traffic noise events (and in particular to calculate indicators that characterize these noise events). However, current state-of-the-art instantaneous vehicle noise emission models usually only consider a single emission law for each vehicle class. In this paper, an approach for predicting instantaneous sound levels caused by road traffic is presented, which takes into account a measured distribution of sound power levels produced by individual vehicles, for each vehicle category. The effect of this approach on estimated energy equivalent levels, percentile levels and sound event indicators is investigated for the simplified setting of a receiver along a dual-lane road carrying free flow traffic.

[a)] email: bert.decoensel@intec.ugent.be
[b)] email: lex.brown@griffith.edu.au
[c)] email: d.tomerini@griffith.edu.au
[d)] email: dick.botteldooren@intec.ugent.be

1 INTRODUCTION

As energy equivalent levels are the main indicators used in noise policy around the world (see e.g. the environmental noise directive of the European Commission[1]), road traffic noise prediction models are usually directed towards their estimation. However, energy equivalent levels say very little about the pattern of noise over time, yet it may be that this temporal pattern is of particular interest with respect to various dimensions of human health effects arising from road traffic noise. For example, sleep disturbance is a major component of the health issue of transportation noise[2,3], and the research evidence is that the physiological effect of transportation noise on human sleep may depend more on the level and number of noise events in traffic streams than on energy equivalent measures[4,5]. Next to this, it has been postulated many times in the past that the emergence of noise annoyance may also be determined, at least in part, by noise events that are noticed, distract attention and interfere with activities[6-8]. Finally, models for the prediction of road traffic noise are increasingly used for urban planning and soundscaping, where a notion of the expected strength and occurrence of noise events is essential, e.g. for estimating the efficiency of measures for masking road traffic noise.

Based on the above, it should be clear that there are several situations in which it would be of interest to be able to estimate the occurrence, both in magnitude and number, of noise events that can be expected given a particular traffic situation. Several models have been developed in the past that are suited for this purpose, as they predict the time history of the sound level caused by road traffic[9,10]. These models predict the instantaneous contribution of single vehicles to the sound level at a receiver location over time, and account for dynamic effects of vehicular traffic, such as the excess noise emission due to acceleration of vehicles near intersections. Clearly, this approach is a refinement of conventional traffic noise prediction models in which emission calculations are only based on average speeds and intensities. However, the state-of-the-art instantaneous vehicle noise emission models (e.g. the Imagine model[11]) still consider a single, prototypical emission law for each vehicle class. This is sufficient for correctly predicting energy equivalent sound levels, as these emission laws are determined on the basis of measurements on a sufficiently large number of vehicles sampled from the considered vehicle fleet.

However, roadside measurements along real traffic streams show that differences in noise emission levels (due to age, maintenance, modifications, driving style etc.) between different vehicles within a single vehicle class can be considerable, and that emission distributions for different vehicle categories largely overlap[12,13]. Maximum levels obtained by the models mentioned above may thus misrepresent reality, as for accurately predicting the occurrence and strength of noise events caused by road traffic, the influence of vehicles that are producing more/less noise than the average vehicle has to be taken into account. In Section 2 of this paper, a methodology to achieve this goal is outlined. The proposed approach uses individualized vehicle emission laws, based on maximum levels sampled from a large measurement database for cars and trucks under real operation conditions[13]. The effect of this approach on estimated energy-equivalent levels, percentile levels and sound event indicators is illustrated in Sections 3 and 4, for the simplified setting of a receiver along a dual-lane road carrying free flow traffic.

2 METHODOLOGY

The proposed approach for predicting the traffic noise level time history near roadways is similar in structure to other dynamic traffic noise prediction models[9,10], and consists of coupling a microscopic road traffic simulation model with a model for instantaneous vehicle noise emission and a point-to-point sound propagation model. A general overview of the model is shown in Fig. 1. A microscopic simulation of road traffic, in which the movement of individual vehicles is simulated, forms the basis of the proposed approach. Given a road network, vehicle fleet properties and aggregated traffic demand data, a simulation run of such a model provides the instantaneous position, speed and acceleration of each vehicle at each timestep during a predefined simulation period. Subsequently, instantaneous emission spectra for all sources are calculated using a noise emission model. Next to using prototypical vehicle emission factors to estimate the average noise emission for a vehicle given its class, speed and acceleration, the proposed approach extends existing models by taking into account a realistic distribution of vehicle noise emission levels. The latter is implemented by adding a zero-mean distribution of emission corrections to account for vehicle state and effects of driving style (see below). Finally, a point-to-point sound propagation model is used to calculate the sound level history at one or more receiver locations, potentially taking into account the geometry of the environment (buildings, barriers etc.) and the meteorological conditions.

2.1 Instantaneous vehicle noise emission model

The Imagine road traffic noise emission model[11] is used to estimate instantaneous point source sound power levels, in which two sources of noise are considered separately: rolling noise (generated by tire-road interaction and aerodynamic drag) and propulsion noise (generated by the powertrain and the exhaust). Both contributions are resp. given by the following formulae:

$$L_{W,R}(v,a) = A_R + B_R \cdot \log_{10}\left(\frac{v}{v_{ref}}\right) \tag{1}$$

$$L_{W,P}(v,a) = A_P + B_P \cdot \left(\frac{v - v_{ref}}{v_{ref}}\right) + C_P \cdot a \tag{2}$$

where v is the vehicle speed (in km/h) with v_{ref} = 70 km/h, and a is the vehicle acceleration (in m/s^2). For values of the coefficients A_R, B_R, A_P, B_P and C_P, for each 1/3-octave band and for each vehicle category, we refer to Ref. 11. Both contributions are aggregated to obtain the total instantaneous sound power level produced by a vehicle:

$$L_W^{im}(v,a) = 10 \cdot \log_{10}\left(10^{L_{W,R}(v,a)/10} + 10^{L_{W,P}(v,a)/10}\right) \tag{3}$$

To account for the distribution in sound power emitted by individual vehicles within a given category, as found in actual traffic streams, a correction ΔL_W is added to the point source sound power level calculated using the Imagine model:

$$L_W^{dist}(v,a) = L_W^{im}(v,a) + \Delta L_W \tag{4}$$

This emission model will be referred to as the "Distribution" model in the remainder of this paper, to distinguish the model from the "Imagine" model that assumes a single emission law for each vehicle class. For each vehicle that enters the simulation, a unique correction ΔL_W is sampled from a measured distribution. Such a distribution is available for each of the five vehicle categories that are considered in the Imagine model. Fig. 2 shows the distributions used in this work for two vehicle categories: cars (corresponding to Imagine Category 1) and articulated trucks (corresponding to Imagine Category 3). These distributions tend to be skewed to lower values for all vehicle categories except motorcycles. Actual counts are plotted in Fig. 2, to illustrate the sample size for each vehicle class.

2.2 Construction of correction distributions

The distributions of the sound power corrections are calculated based on the measurement data reported in Ref. 13. This study presents distributions of the noise level maxima generated during the pass-by of over 85 000 vehicles in service on urban arterials and motorways in Brisbane, Australia. Propagation effects were filtered out, and L_{AFmax} values were normalized to a distance of 15 m from the centerline of vehicle flow. In order to minimize the effect of the road surface on measurement results, all measurements were conducted near roads with an dense graded asphalt surface, and data from sites where effects of multiple lanes could have given rise to an error of more than 2 dB(A) were removed from the analysis. Consequently, the measured distributions mainly capture the effects of individual driving style and vehicle state. Distributions of L_{AFmax} measured for free-flowing traffic are available for 4 vehicle categories (cars, non-articulated and articulated trucks, motorcycles), for posted speed limits from 60 to 100 km/h.

In order to compile distributions of ΔL_W based on the distributions of L_{AFmax} reported in Ref. 13, a number of assumptions were considered. Firstly, from a visual inspection of the distributions at different speeds (free-flow conditions), it was concluded that the width and shape of the distribution does not change significantly with speed (i.e. noisy vehicles are equally noisy at different speeds). This allowed pooling the data for different speeds into a single distribution for each vehicle category, taking into account the shift in median value of L_{AFmax} for different speeds. Secondly, it was assumed that corrections are independent of frequency, because no sufficient spectral information was available which could prove otherwise. Thirdly, it was assumed that the distributions in L_{AFmax} equal the distributions in sound power level. Finally, corrections ΔL_W were normalized to a zero mean sound power. This way, energy equivalent sound levels estimated using the proposed Distribution model $L_W^{dist}(v,a)$ would equal those estimated using the Imagine emission model $L_W^{im}(v,a)$. This allows making a fair comparison between both models, in which systematic differences in noise emission between the European and Australian vehicle fleet are removed. Note that the shape and width of these distributions still characterize the Australian vehicle fleet, but a similar approach can be used elsewhere.

2.3 Implementation

The above described approach has been implemented as a simulation framework, called Noysim2, written in the Python programming language. Functionality is provided such that Noysim2 can be readily used as a plugin for Aimsun[14] and Paramics[15], both commercially available microscopic traffic simulation software packages. Noysim2 can be interfaced with any point-to-point propagation model, but functionality for using the ISO 9613 propagation model is included in the framework and is used in this paper. As an illustration, Fig. 3 shows a typical sound level time history, calculated with and without the proposed distribution of corrections. As expected, the time history calculated using the Distribution model shows a larger dynamic range.

3 CASE STUDY

3.1 Road network and simulation scenarios

The aim of the simulations performed in this case study is to investigate the influence of accounting for realistic vehicle sound power distributions on the estimation of measures that characterize sound events. For this, the simplified setting of a receiver along a straight, one-way, dual-lane road carrying free flow traffic is considered. A simulation network containing a single road segment with a length of 2200m was constructed using the Aimsun traffic simulation package. Although the current setting is relatively simple and neglects the potential effects of congestion, the presence of traffic lights etc., it may already provide some insight in the effects of using an emission distribution on estimated sound event measures. A series of scenarios was created by varying the speed limit, the traffic demand and the percentage of heavy vehicles. An overview of the parameter ranges can be found in Table 1; the total number of unique scenarios equals $2 \times 6 \times 3 = 36$. The simulation duration considered was 24 hours, with a simulation timestep of 0.4s. The actual simulations included an additional warm-up period of 5 minutes. Vehicles are loaded onto the network at the entry of the road segment, randomly distributed in time according to a negative exponential distribution.

Instantaneous vehicle noise emission spectra are calculated for all simulation scenarios using the Imagine and the Distribution emission models, based on the same traffic simulation run for both models. For the Imagine emission model, default road surface parameters are used. Subsequently, the time history of the sound level at a receiver located along the perpendicular bisector of the simulated road segment, at a distance of 15m to the centerline of the closest lane, and at a height of 2m, is calculated. The instantaneous sound level is calculated using the ISO 9613 propagation model, assuming free field propagation conditions, default meteorological conditions and a hard surface throughout the simulated area. Finally, energy-equivalent levels, percentile levels and sound event indicators are calculated based on the time history of the sound level. Due to the statistical nature of the sampling used in the Distribution model (i.e. the model randomly decides whether a vehicle is noisy or quiet), results may differ between simulation runs. Variability between simulation runs can be expected to decrease with increasing traffic volume. Therefore, a number of simulation runs are performed for the Distribution model, ranging from 10 for the lowest traffic volume to 2 for the highest traffic volume.

3.2 Results

Table 2 shows a range of acoustical measures calculated for the case study scenarios using the Distribution emission model (averaged across simulation runs), and in parentheses, the difference with the Imagine emission model. As expected, there is no significant difference between both models when it comes to predicting $L_{\text{Aeq,24h}}$, because the corrections in the Distribution model were constructed to gain a mean emission sound power equal to that of the Imagine model. The standard deviation (not shown in Table 2) in estimates of $L_{\text{Aeq,24h}}$ between simulation runs is found to be smaller than 0.7 dB(A) in all scenarios.

However, using the Distribution emission model results in estimates for the maximum sound level, L_{Amax} (calculated over the 24-hour simulation period), that are 12 to 18 dB(A) higher than those obtained using the Imagine emission model. The higher the traffic volume, the larger the difference becomes. Furthermore, it was found that the standard deviation in estimates of L_{Amax} between 24-hour simulation runs is often higher than 3 dB(A) when the Distribution model is used. This resembles the actual situation, where the maximum sound level is determined by the passage of vehicles at the extreme end of the sound emission distribution, but which are also very rare. The Distribution model is able to take into account the influence of these loud vehicles, but at the cost of the need for much longer simulation times, in order to get stable estimates. Moreover, because of the variability in estimates (and measurements) of L_{Amax}, the use of this indicator for characterizing sound events can be questioned.

When estimates of the percentile levels L_{A01} and L_{A05} that characterize the average level of sound events are considered, one finds that using the Distribution emission model results in lower values for low traffic volumes, and higher values for high traffic volumes, as compared to using the Imagine emission model. Standard deviations between runs are below 0.4 dB(A) for all scenarios. The background level, as measured by L_{A50}, is consistently estimated to be lower by 1 to 4 dB(A) when using the Distribution emission model, as compared to using the Imagine model. This is a direct consequence of the correction distributions being skewed to lower values.

Finally, two indicators for the number of sound events are considered. The first indicator, noted N_{CN}, measures the number of times that the sound level exceeds L_{A50} with at least 3 dB(A), for at least 3 seconds[16]. This indicator is adaptive, as the threshold for event detection rises with the background level. The second indicator, noted MM60, uses a fixed value of 60 dB(A) as the threshold for event detection, but only takes into account events that are separated in time by at least 3 seconds, and for which the sound level increased with at least 5 dB(A) within the 25 seconds preceding the event[13]. In Table 2, values for both indicators are given per hour.

For low traffic volumes, values for N_{CN} obtained using the Distribution model do not differ significantly from those obtained using the Imagine model. For intermediate traffic volumes, the Distribution model gives rise to slightly lower values, as sound events produced by the passby of quieter vehicles have a larger chance to be masked by the noise from louder vehicles. For high traffic volumes, the Distribution model gives rise to considerably higher values for N_{CN}. This comes as no surprise, since the use of the Distribution emission model results in a large dynamic range for the sound level. Using the Imagine model results in a quasi-constant sound level for high traffic volumes, where only the events caused by heavy vehicles emerge more than 3 dB(A) above the adaptive threshold.

For the non-adaptive event indicator MM60, values obtained using the Distribution model are consistently lower than those obtained using the Imagine model, because the quieter vehicles considered in the Distribution model do not produce sound events that exceed 60 dB(A), as could have been seen on Fig. 3 already. However, results can be expected to be rather sensitive to the arbitrary threshold level. If a level of 70 dB(A) was chosen, the result would probably be reversed, with the Distribution model producing more counts than the Imagine model.

4 CONCLUSIONS

An approach for predicting instantaneous sound levels caused by road traffic is presented in this paper. The approach extends existing models, by taking into account a distribution of sound power levels. The effect of this approach on estimated percentile levels and sound event indicators was investigated for the simplified setting of a receiver along a dual-lane road. The proposed approach was shown to result in considerably different values for percentile levels and sound event indicators, as compared to using a single emission law for each vehicle category. The Distribution model approach resulted in stable estimates of both L_{Aeq} and percentile levels, but unstable estimates of L_{Amax}. Importantly, the proposed approach provides insights into the dynamics of road traffic noise by providing a realistic temporal pattern of noise levels that can be further analyzed using sound event indicators. Two indicators for the number of events, one with and one without an adaptive threshold, were shown to be influenced in a different way by the use of a distribution emission model. Thus, the definition of the rule that is used to delimit sound events should be considered in detail when the proposed approach is used for this purpose. Future research could also focus on the spectral dependency of sound power distributions, when more detailed measurement data becomes available, and on the influence of the distribution of the speed of vehicles.

5 ACKNOWLEDGEMENTS

This study was performed within the framework of a Linkage project, supported by the Australian Research Council. Bert De Coensel is a postdoctoral fellow of the Research Foundation–Flanders; the support of this organization is also gratefully acknowledged.

6 REFERENCES

1. Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise. European Commission, Brussels, Belgium (2002).
2. B. Berglund, T. Lindvall and D.H. Schwela (eds.), *Guidelines for Community Noise*, World Health Organization, Geneva, Switzerland (1999).
3. L. Fritschi, A.L. Brown, R. Kim, D. Schwela and S. Kephalopoulos (eds.), *Burden of disease from environmental noise: quantification of healthy life years lost in Europe*, World Health Organization Regional Office for Europe, Copenhagen, Denmark (2011).
4. B. Griefahn, A. Marks and S. Robens, "Noise emitted from road, rail and air traffic and their effects on sleep", *J. Sound Vib.* **295**(1-2):129-140 (2006).
5. S. Pirrera, E. De Valck and R. Cluydts, "Nocturnal road traffic noise: a review on its assessment and consequences on sleep and health", *Environ. Int.* **36**(5):492-498 (2010).
6. M. Björkman, "Community noise annoyance: importance of noise levels and the number of noise events", *J. Sound Vib.* **151**(3):497-503 (1991).
7. T. Sato, T. Yano, M. Björkman and R. Rylander, "Road traffic noise annoyance in relation to average noise level, number of events and maximum noise level", *J. Sound Vib.* **223**(5):775-784 (1999).
8. B. De Coensel, D. Botteldooren, T. De Muer, B. Berglund, M.E. Nilsson and P. Lercher, "A model for the perception of environmental sound based on notice-events", *J. Acoust. Soc. Am.* **126**(2):656-665 (2009).
9. B. De Coensel, T. De Muer, I. Yperman and D. Botteldooren, "The influence of traffic flow dynamics on urban soundscapes", *Appl. Acoust.* **66**(2):175-194 (2005).
10. A. Can, E. Chevalier, M. Nadji and L. Leclercq, "Dynamic traffic modeling for noise impact assessment of traffic strategies", *Acta Acust. Acust.* **96**(3):482-493 (2010).
11. B. Peeters and G. van Blokland, "The noise emission model for European road traffic", Technical Report IMA55TR-060821-MP10, Deliverable 11 of the Imagine project, M+P Consulting Engineers, Vught, The Netherlands (2007).
12. G. Watts, "A preliminary study of the characteristics of noisy vehicles under cruising conditions – results of roadside measurements", *Acta Acust. Acust.* **98**(2):279-285 (2012).
13. A.L. Brown and D. Tomerini, "Distribution of the noise level maxima from the pass-by of vehicles in urban traffic streams", *Road Transp. Res.* **20**(3):50-63 (2011).
14. Aimsun is distributed by TSS-Transport Simulation Systems, http://www.aimsun.com/.
15. Paramics is distributed by Quadstone Ltd., http://www.paramics-online.com/.
16. B. De Coensel and D. Botteldooren, "The quiet rural soundscape and how to characterize it", *Acta Acust. Acust.* **92**(6):887-897 (2006).

Table 1 – Parameter values for the case study simulations.

Parameter	Values	Levels
Speed limit [km/h]	60, 100	2
Traffic demand [vehicles/h]	50, 100, 200, 500, 1000, 2000	6
Percentage of heavy vehicles [%]	5, 10, 20	3

Table 2 – Acoustical measures of the sound level time history, at a distance of 15 from the road, for all scenarios using the Distribution emission model. The difference with the Imagine model is shown in parentheses.

Speed limit	Heavy vehicles	Demand [vph]	$L_{Aeq,24h}$ [dB(A)]	L_{Amax} [dB(A)]	L_{A01} [dB(A)]	L_{A05} [dB(A)]	L_{A50} [dB(A)]	N_{CN}/h [vehicles/h]	MM60/h [vehicles/h]
60 km/h	5%	50	53.7 (+0.0)	88.4 (+13.6)	65.7 (-0.4)	58.4 (-2.4)	37.4 (-3.0)	28 (+0.64%)	37 (-27.23%)
		100	56.4 (-0.0)	89.2 (+14.2)	67.8 (+0.9)	61.9 (-2.2)	44.2 (-2.7)	50 (-2.71%)	67 (-26.33%)
		200	59.5 (-0.1)	90.9 (+14.0)	70.4 (+1.4)	65.0 (-1.1)	50.7 (-2.6)	89 (-18.65%)	121 (-25.06%)
		500	63.4 (+0.0)	92.5 (+16.6)	73.3 (+1.2)	68.4 (+0.2)	57.9 (-2.3)	123 (+1.57%)	233 (-22.41%)
		1000	66.4 (+0.0)	92.7 (+15.6)	75.6 (+1.8)	71.0 (+0.6)	62.8 (-2.3)	107 (+20.67%)	301 (-17.30%)
		2000	69.2 (+0.0)	91.9 (+14.9)	77.5 (+2.8)	73.4 (+0.6)	66.7 (-1.8)	84 (+103.18%)	295 (-5.40%)
	10%	50	54.3 (+0.0)	88.4 (+13.6)	66.2 (-0.1)	58.6 (-2.3)	37.1 (-3.2)	26 (+0.71%)	35 (-26.11%)
		100	57.2 (-0.0)	89.6 (+14.2)	68.8 (+0.8)	62.4 (-2.1)	44.6 (-2.8)	49 (-6.20%)	66 (-25.36%)
		200	60.2 (-0.1)	90.2 (+13.4)	71.5 (+0.0)	65.6 (-0.9)	51.2 (-2.5)	88 (-18.98%)	123 (-23.96%)
		500	64.2 (+0.0)	91.2 (+14.2)	74.5 (+0.9)	69.3 (+0.1)	58.5 (-2.3)	117 (-4.48%)	231 (-20.84%)
		1000	67.1 (+0.1)	92.7 (+15.6)	76.5 (+2.1)	72.0 (-0.0)	63.3 (-2.2)	106 (+6.51%)	293 (-14.86%)
		2000	69.9 (+0.0)	93.4 (+15.9)	78.4 (+3.2)	74.4 (+0.3)	67.3 (-1.7)	91 (+84.88%)	291 (-3.76%)
	20%	50	55.4 (+0.1)	89.2 (+12.6)	67.4 (-0.0)	59.3 (-2.2)	37.6 (-3.3)	25 (+1.65%)	35 (-25.52%)
		100	58.5 (+0.1)	90.5 (+14.0)	70.4 (-0.7)	63.4 (-1.8)	45.6 (-2.9)	50 (-7.49%)	67 (-24.86%)
		200	61.3 (-0.0)	91.1 (+14.4)	72.9 (-0.2)	66.6 (-0.7)	51.9 (-2.5)	84 (-21.06%)	119 (-23.05%)
		500	65.2 (-0.0)	91.7 (+14.7)	75.7 (+1.5)	70.6 (-0.7)	59.3 (-2.3)	110 (-10.88%)	228 (-19.64%)
		1000	68.1 (+0.0)	92.3 (+14.8)	77.7 (+2.8)	73.4 (-0.3)	64.1 (-2.2)	110 (-8.24%)	284 (-14.94%)
		2000	71.1 (+0.1)	93.8 (+15.9)	79.9 (+3.8)	75.8 (+0.7)	68.3 (-1.6)	99 (+40.29%)	292 (-12.62%)
100 km/h	5%	50	58.2 (-0.0)	92.9 (+12.7)	70.8 (-1.5)	61.9 (-2.2)	37.6 (-3.6)	27 (-0.11%)	47 (-8.36%)
		100	61.0 (-0.0)	95.2 (+15.0)	73.0 (-0.2)	66.2 (-2.4)	45.9 (-3.0)	52 (-2.83%)	86 (-8.35%)
		200	64.1 (-0.1)	97.1 (+16.6)	75.4 (+1.1)	69.9 (-2.0)	53.3 (-2.7)	93 (-14.50%)	157 (-8.83%)
		500	68.0 (+0.0)	98.0 (+16.6)	78.3 (+2.1)	73.5 (-0.4)	61.2 (-2.3)	132 (+2.19%)	301 (-13.06%)
		1000	71.1 (+0.0)	98.5 (+16.4)	80.4 (+2.4)	75.9 (+0.3)	66.5 (-2.4)	118 (+14.94%)	420 (-18.34%)
		2000	73.9 (+0.1)	98.2 (+15.8)	82.5 (+3.2)	78.2 (+0.8)	71.0 (-2.2)	83 (+229.03%)	470 (-18.99%)
	10%	50	58.5 (-0.0)	93.3 (+13.2)	71.0 (-1.4)	61.9 (-2.1)	36.9 (-3.8)	26 (+0.85%)	44 (-7.85%)
		100	61.5 (-0.0)	95.2 (+15.0)	73.5 (-0.1)	66.5 (-2.4)	46.3 (-2.9)	52 (-2.89%)	85 (-8.06%)
		200	64.3 (-0.1)	96.7 (+15.3)	75.8 (+1.1)	70.1 (-2.0)	53.2 (-2.8)	89 (-15.50%)	153 (-8.84%)
		500	68.4 (+0.0)	98.2 (+16.0)	78.8 (+1.3)	73.9 (-0.3)	61.5 (-2.3)	130 (-0.64%)	301 (-12.71%)
		1000	71.4 (+0.0)	98.8 (+16.7)	80.9 (+2.0)	76.4 (+0.2)	66.8 (-2.4)	118 (+14.40%)	410 (-16.41%)
		2000	74.3 (+0.1)	100.8 (+18.4)	83.0 (+3.1)	78.8 (+0.6)	71.4 (-2.2)	85 (+199.78%)	464 (-16.39%)
	20%	50	59.2 (+0.1)	94.4 (+14.5)	71.5 (-1.2)	62.4 (-2.2)	36.8 (-4.1)	25 (+0.94%)	44 (-8.16%)
		100	62.1 (-0.0)	95.1 (+14.5)	74.2 (+0.1)	66.9 (-2.4)	46.4 (-3.1)	49 (-3.31%)	82 (-7.58%)
		200	65.2 (-0.1)	96.8 (+15.4)	76.9 (-0.0)	70.8 (-1.7)	54.1 (-2.8)	88 (-17.22%)	154 (-9.24%)
		500	69.1 (+0.0)	99.1 (+17.1)	79.8 (+1.2)	74.7 (-0.3)	62.0 (-2.3)	124 (-7.51%)	293 (-12.67%)
		1000	72.1 (+0.1)	98.4 (+16.1)	81.8 (+2.4)	77.3 (-0.1)	67.4 (-2.3)	118 (+12.54%)	403 (-16.45%)
		2000	75.0 (+0.1)	100.0 (+17.3)	83.9 (+3.5)	79.7 (+0.5)	71.9 (-2.1)	90 (+145.75%)	453 (-15.84%)

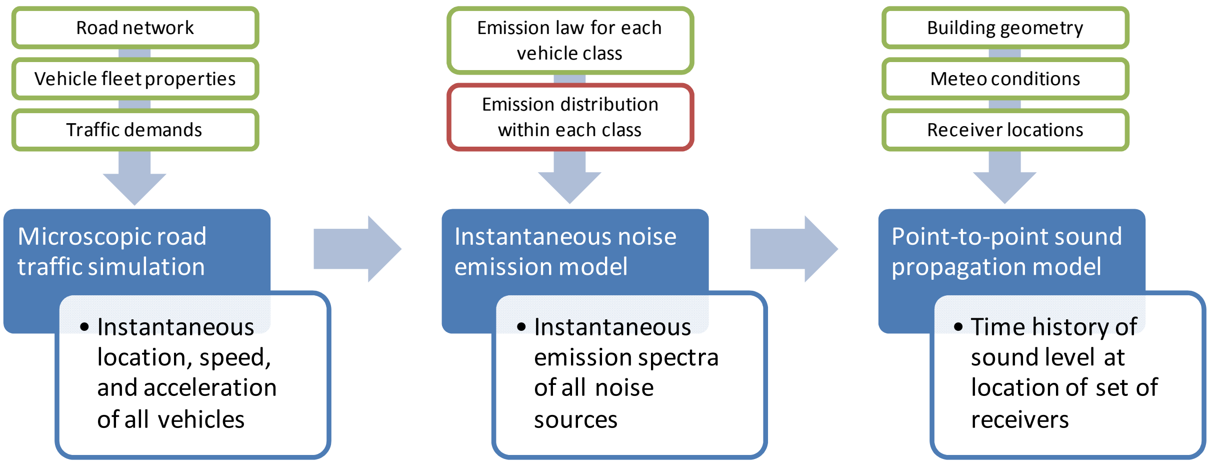

Fig. 1 – Overview of the proposed methodology. The top row boxes show the inputs, the middle row boxes show the models applied, and the bottom row boxes show the outputs.

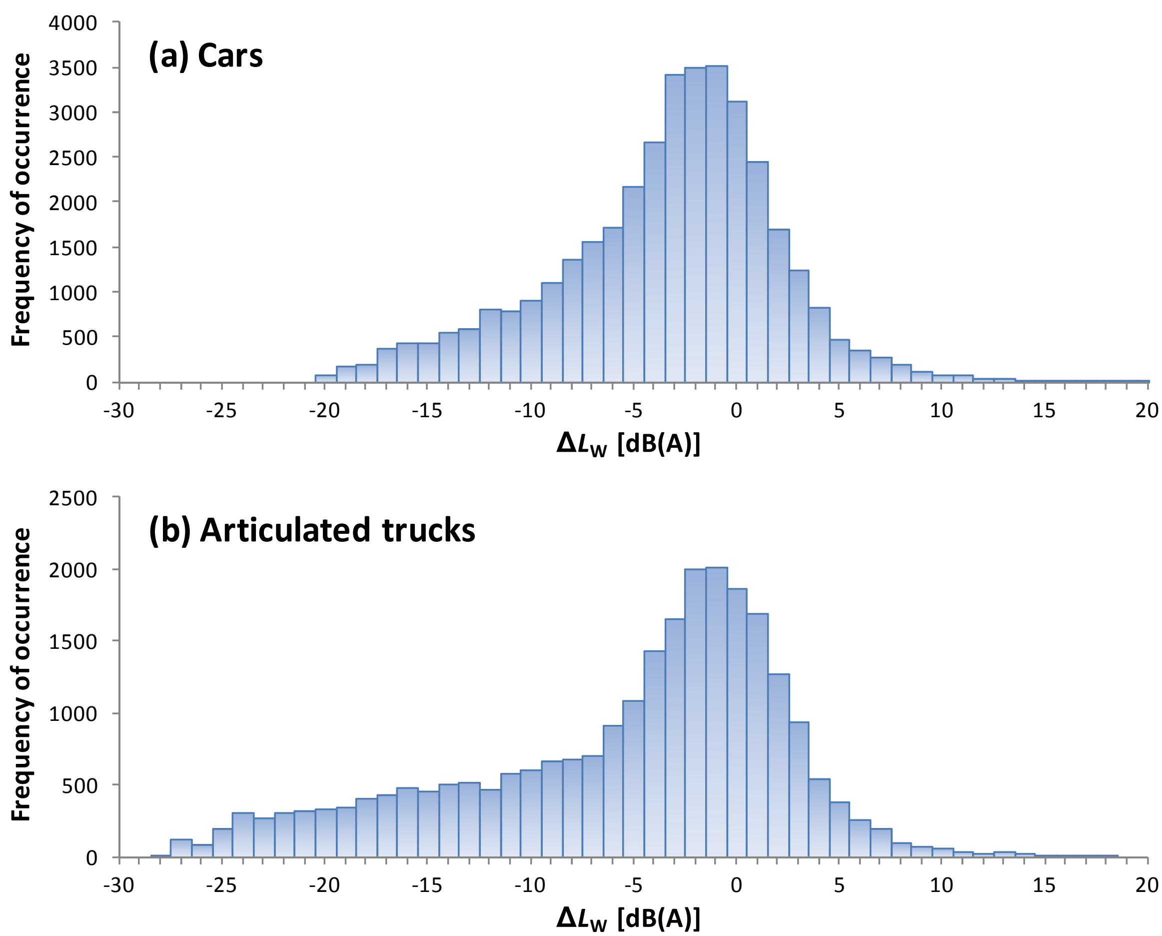

Fig. 2 – Frequency of occurrence of the sound power level, relative to the values provided by the Imagine noise emission model, emitted by cars (top panel) and articulated trucks (bottom panel). Data is based on measurements performed in Australia in 2009.

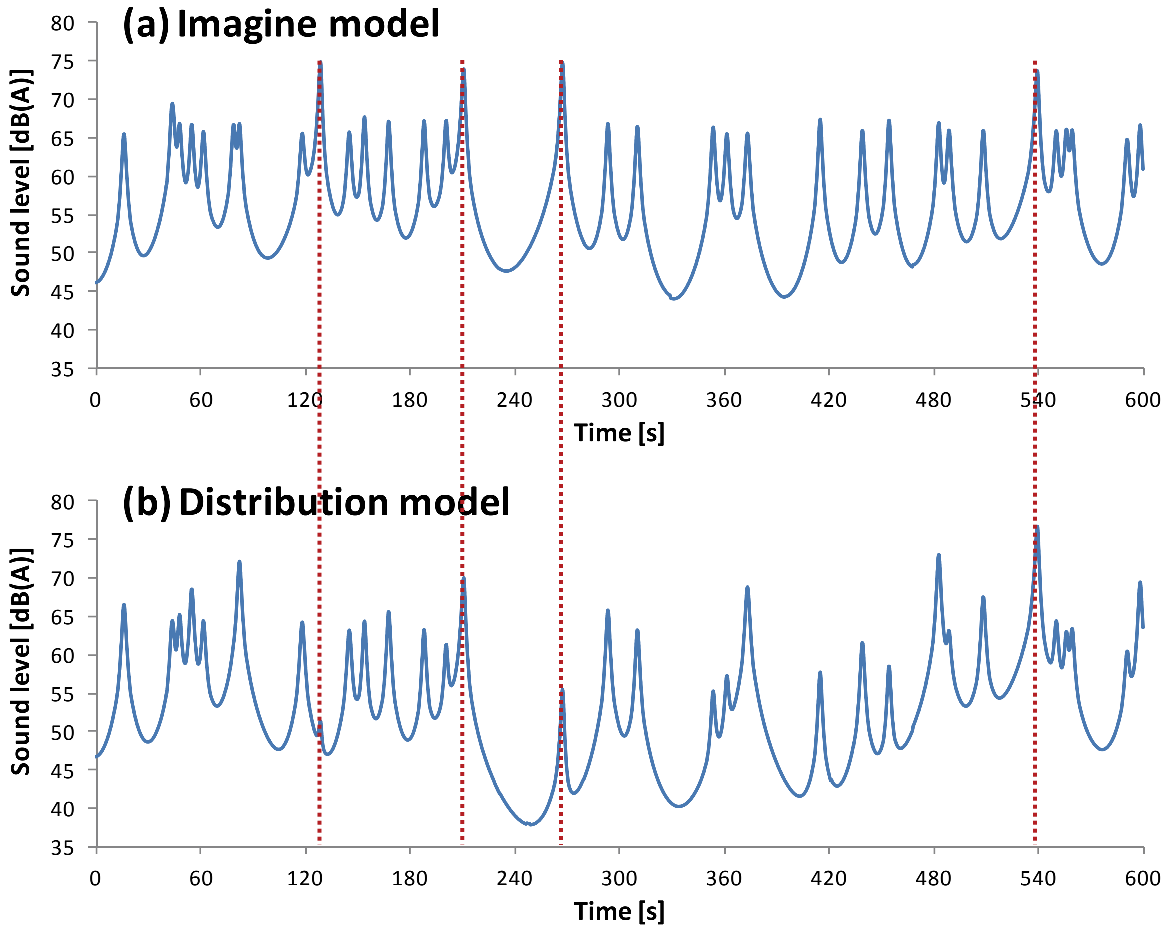

Fig. 3 – Time history of the sound level at a distance of 15m from a two-lane road with a speed limit of 60 km/h, and a traffic intensity of 200 vehicles/h, of which 10% heavy vehicles, calculated using both the Imagine and Distribution emission models. The same traffic simulation was used for both curves; the red dashed lines match the passby of a heavy vehicle.