In-service measurement of heavy vehicle engine brake noise

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ABSTRACT

Heavy vehicle engine compression brake noise is a major source of community annoyance due to its modulated characteristic. Traditional acoustic measurement approaches using A-weighted Sound Pressure Level have had moderate success but remained problematic. A new approach has been developed using instantaneous loudness to more accurately measure how the community hears the noise. From this an in-service test procedure and criterion has been developed to assist with potential compliance and enforcement processes. The proposed criterion was established by reviewing 170,000 roadside vehicle passbys and controlled tests using various engine silencer designs and is based on the RMS modulation of loudness in Sones. The controlled tests established the modulation scores that could reasonably be achieved with the current heavy vehicle fleet.

Keywords: truck, engine compression brake, loudness, annoyance I-INCE Classification of Subjects Number(s): 13.2.4, 21.6.6, 34, 52.3, 63.2, 72.9, 74.9

1. INTRODUCTION

Engine compression brake noise from heavy vehicles has been a long standing issue in Australia and internationally. It is generally accepted that it is the character of the noise rather than the overall noise level that leads to complaints. A defining character of the event is strong modulation due to the use of the engine as an air compressor to provide braking torque to the drive wheels. During engine braking with Jacobs Brake systems air is compressed on the upwards stroke of the piston and released at the top of the piston stroke. This is achieved by cutting fuel supply to the cylinder and managing valve timing. Each short burst of compressed air from successive cylinders produces a strongly modulated acoustic signal which is modified and filtered through the exhaust and silencer system. A key aspect to measuring the character is that the modulation depth we perceive is limited by the response of the human auditory system.

Each modulation burst of compressed air is broadband and depending on the silencer may have audible frequency content of up to 20kHz. This differs from most peoples subjective experience where it is regarded as a low frequency noise. It appears that the noise, which has a fundamental modulation frequency between 20Hz to 100Hz, creates a virtual pitch. The fundamental can vary over a large range depending on engine rpm and the number of cylinders selected by the driver depending on braking requirements. Also in most instances the concept of a fundamental modulation frequency is only notional as since the noise is from a braking event the engine rpm is generally decreasing until another gear is selected. This produces a continuously changing repetition rate where the observed modulation is from the system response to a series of pulses.

Parnell et al (1) previously summarised approaches developed to measure engine compression brake noise to set regulation and enforce compliance in Australia. The development work completed in Australia led to the National Transport Commission's (NTC) 2007 in-service test procedure (2), a regulatory impact statement (3) to summarise outcomes if enforcement was initiated and model laws being developed (4). In 2013 NTC completed a review (5) to identify any concerns Australian States and Territories had with implementing the test procedure and model laws. The New South Wales

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(NSW) Roads and Maritime Services has been working with NTC and the other States and Territories to resolve concerns identified in the review.

2. SUMMARY OF 2007 TEST PROCEDURE

The 2007 in-service test procedure defines a measurement point at 3.5 metres above the ground and 7.5 metres from the nearest trafficable lane. Measurements at this location are processed to produce an A-weighted sound pressure level time trace averaged at 200ms. This time trace is then pass band filtered using a sixth order Butterworth filter with cut off frequencies at 5Hz and 80Hz to extract the modulation from the average noise level. A time trace of the root-mean-square (RMS) of the modulation is then obtained using exponential averaging. The maximum rms during the passby event is recorded and given the descriptor modulated-RMS (mod-RMS). Hardware running this procedure has been successfully trialled in NSW at two locations where the output is used to trigger camera installations that photograph vehicles and document the mod-RMS level and send the data via a mobile telecommunications data provider to Roads and Maritime for processing.

Roads and Maritime ran a successful driver and operator education trial following vehicle detection which reduced detections of vehicles by up to 50%. Vehicle operators were able to address the issue by replacing exhaust silencers with better performing designs.

3. CONCERNS IDENTIFIED IN NTC REVIEW

NSW Roads and Maritime and other States and Territories raised concerns (5) with the test procedure based on experience with trialling the procedure and experience enforcing speed limits using similar camera technology. These included:

- Difficulties in understanding of the physical meaning of the novel mod-RMS descriptor and associated signal processing in a legal context and with non-technical audiences.
- potential for false positives and effects of ambient conditions
- influence of ground reflections on modulation measurement
- influence of ambient noise levels on measurement

4. SUMMARY OF 2014 TEST PROCEDURE

Since 2007 there has been increased awareness of psychoacoustic approaches for the measurement of diesel engine noise relevant for supporting legal processes. These have been presented in the amendment to DIN 45631 (6), *Amendment 1 - Calculation of the loudness of time-variant sound* (7). In a legal and non-technical context the use of a standard is beneficial over using a novel approach. It is also relatively easy to explain the physical meaning of the instantaneous loudness time signal produced using DIN 45631 as it is a recognised representation of what we hear using a model of the human auditory system.

In the field of psychoacoustics there are recognised measures of modulation. These commonly include roughness and fluctuation strength (8) which have calculation procedures defined and valid for classical signals with sinusoidal modulation envelopes and carrier signals. Relating roughness values of diesel engines to other noise sources using these approaches has had limited success and has resulted in further roughness research for these types of modulation envelopes (9). However for the measurement and comparison only between heavy vehicle engine brake noise these difficulties are less relevant as the same types of noise sources are being compared.

The classical roughness approach by Zwicker et al was investigated using Bruel and Kjaer Sound Quality Software, however while providing reasonable correlation with subjective testing of engine brake noise, better results were achieved using the DIN 45631 instantaneous time trace in Sones and a roughness filter to obtain mod-RMS. Using DIN 45631 to produce the time trace used in the calculation of mod-RMS also provided better correlation than using A-weighted decibels. This is described in further detail in the subsequent discussion.

A summary of how mod-RMS has been calculated from instantaneous loudness is shown in Figure 1 (11). A key difference to note is that mod-RMS is now defined as the Sone standard deviation divided by the average loudness in Sone. Previously mod-RMS was calculated from the modulation of a 200ms averaged and A-weighted sound pressure level signal.

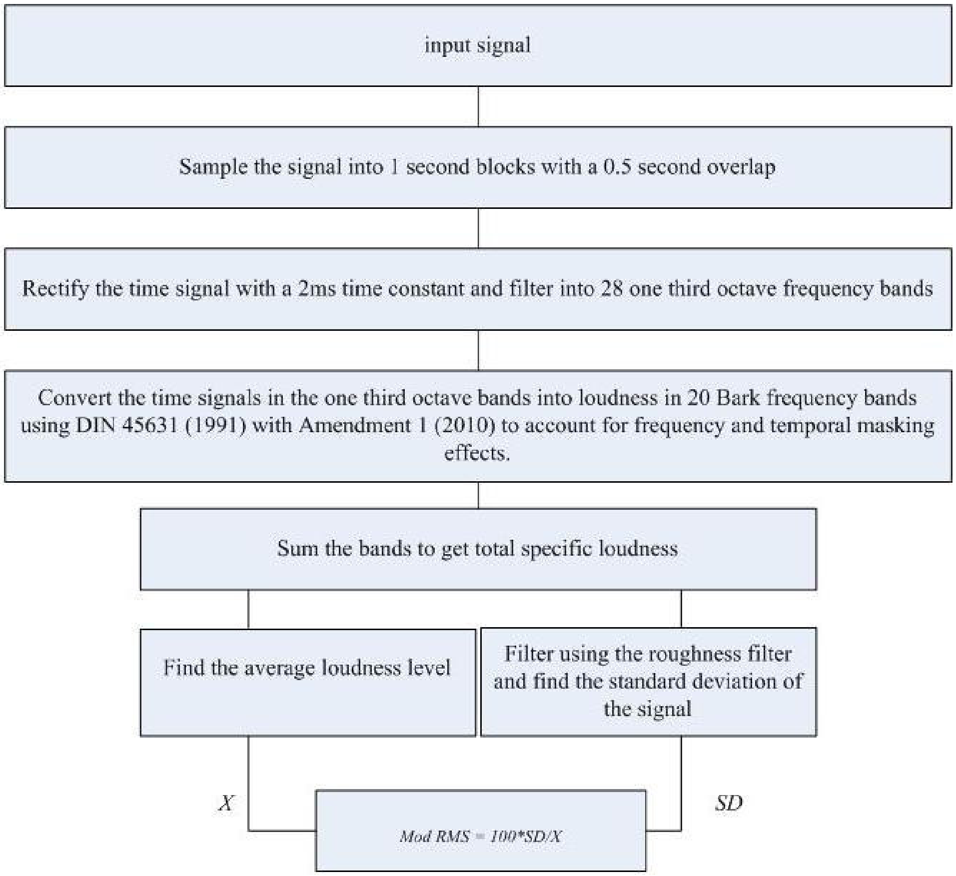

Figure 1 – Calculation procedure

5. COMPARISON WITH PERCEPTUAL STUDIES

Perceptual studies of response to engine brake noise had been completed previously during the development of the 2007 procedure. These have included the study referenced by Parnell that was completed by the University of New South Wales in 2008 and also a study completed for the NTC in 2003 (12). These studies asked the subject to grade the noise event against annoyance ratings. The test subjects were unfamiliar with psychoacoustic terms and concepts.

The study completed for NTC had a slightly different methodology than the UNSW study referenced by Parnell. The 2003 NTC study measurements were completed road side. At each measurement location, subjective gradings of the engine brake noise component were assigned to each heavy vehicle pass-by. Gradings at measurement locations in South Australia were assigned with assistance from representatives from the South Australian Environment Protection Authority (EPA) and Transport SA (TSA), whilst gradings at locations in New South Wales were assisted by representatives of the then Roads and Traffic Authority of New South Wales (RTA). The subjective gradings incorporated the components of annoyance, a clearly identifiable engine brake and the level of the noise. Each pass-by was graded on a scale of 1 to 5, with 5 being the lowest grade and 1 being the highest grade on a scale of annoyance (1 is most annoying, 5 the least).

Roads and Maritime has compared the correlation of the 2007 and 2014 procedures (Figure 2 to Figure 5) with the previous perceptual studies. When the 2007 and 2014 procedures are compared it can be seen that there is improved correlation with the perceptual studies using the revised method and better separation between annoyance categories for engine brake events.

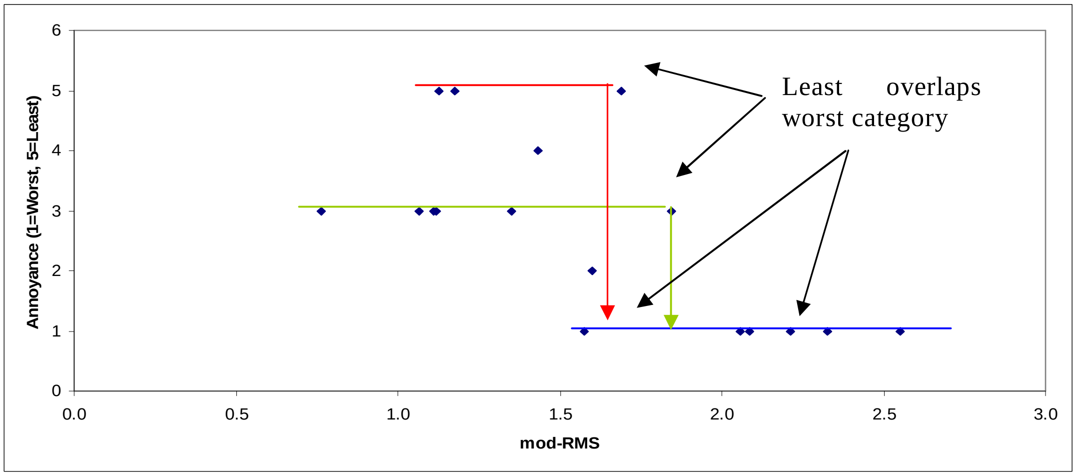

Figure 2 – NTC Study compared to 2007 procedure

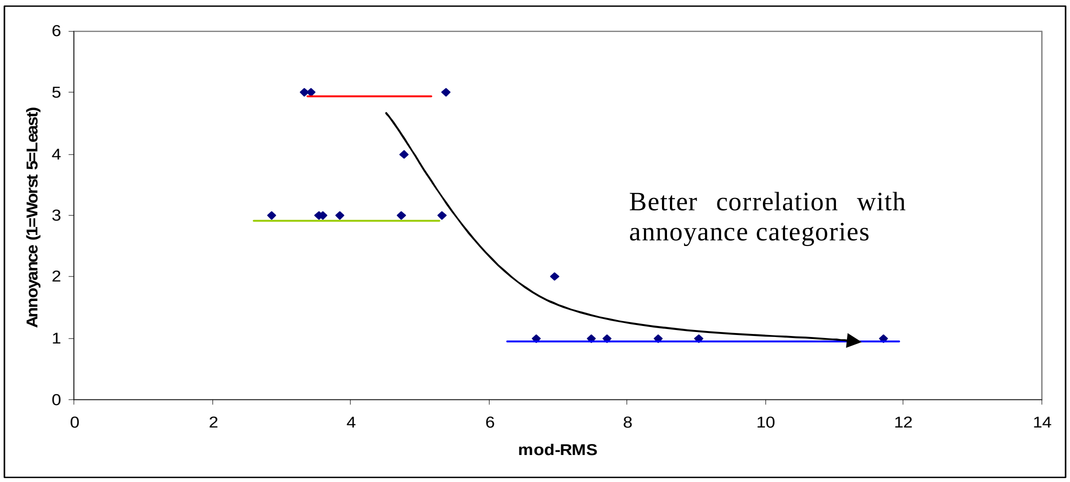

Figure 3 – NTC Study compared to 2014 procedure

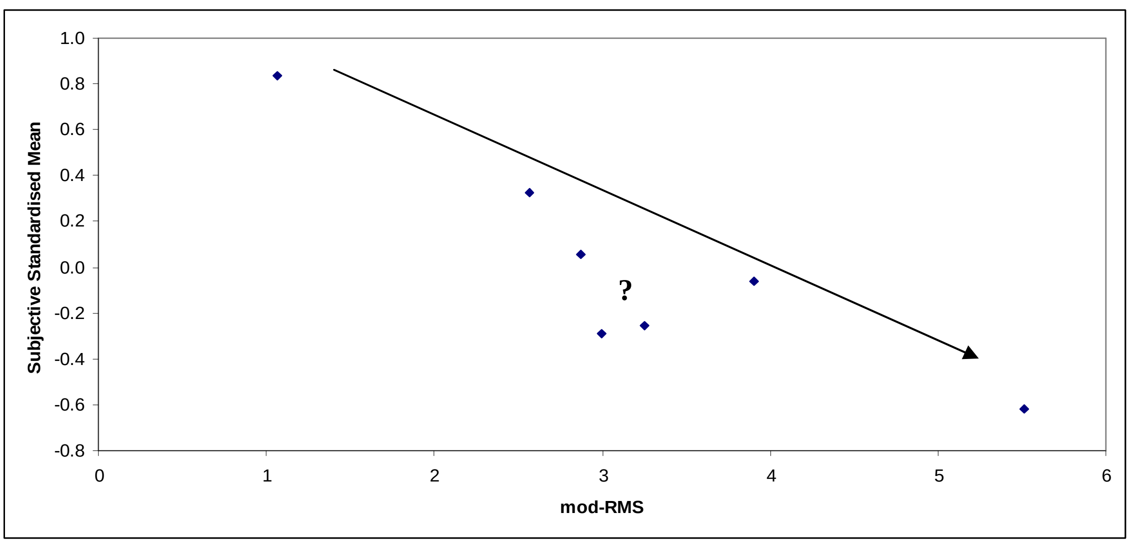

Figure 4 – UNSW Study compared to 2007 procedure

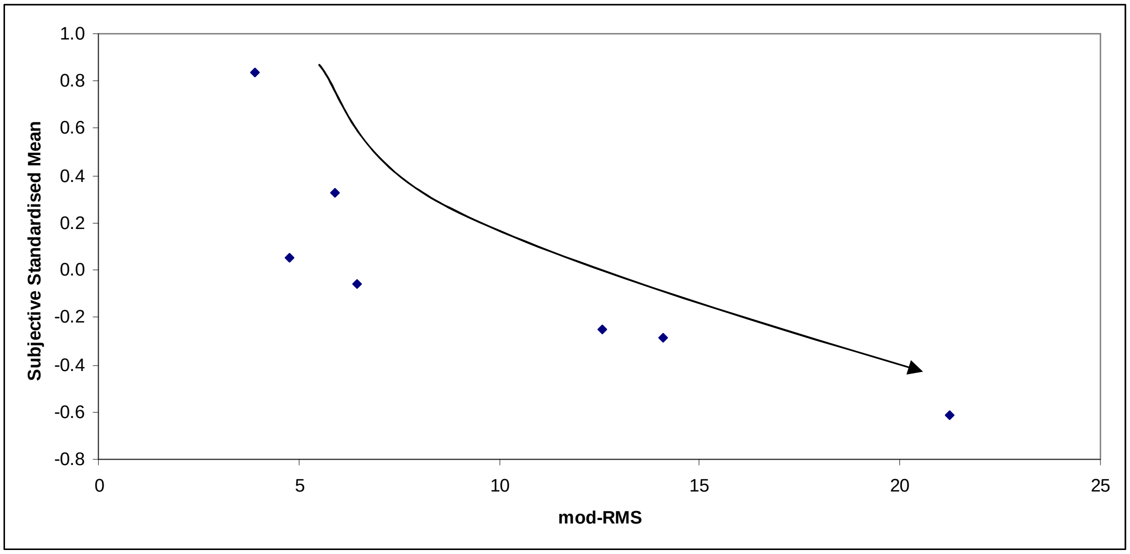

Figure 5 – UNSW Study compared to 2014 procedure

A comparison between the 2014 procedure and Zwicker roughness (Figure 6 and Figure 7) shows that slightly better correlation is achieved with the 2014 procedure. This is perhaps because engine brake noise relates more closely to temporal patterns rather than classical roughness stimulus of the auditory system.

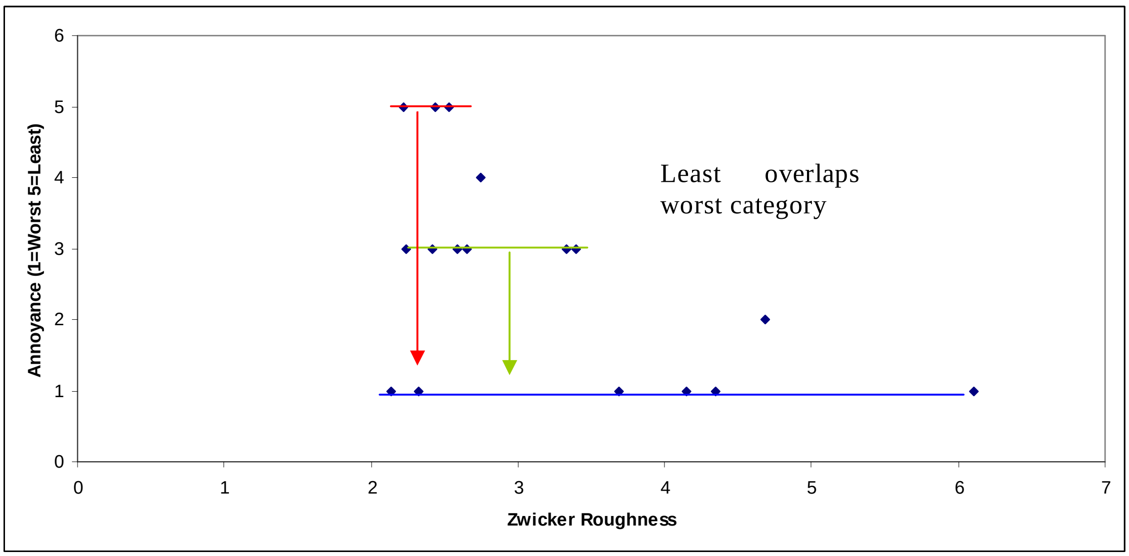

Figure 6 – NTC Study compared to Zwicker roughness (B&K)

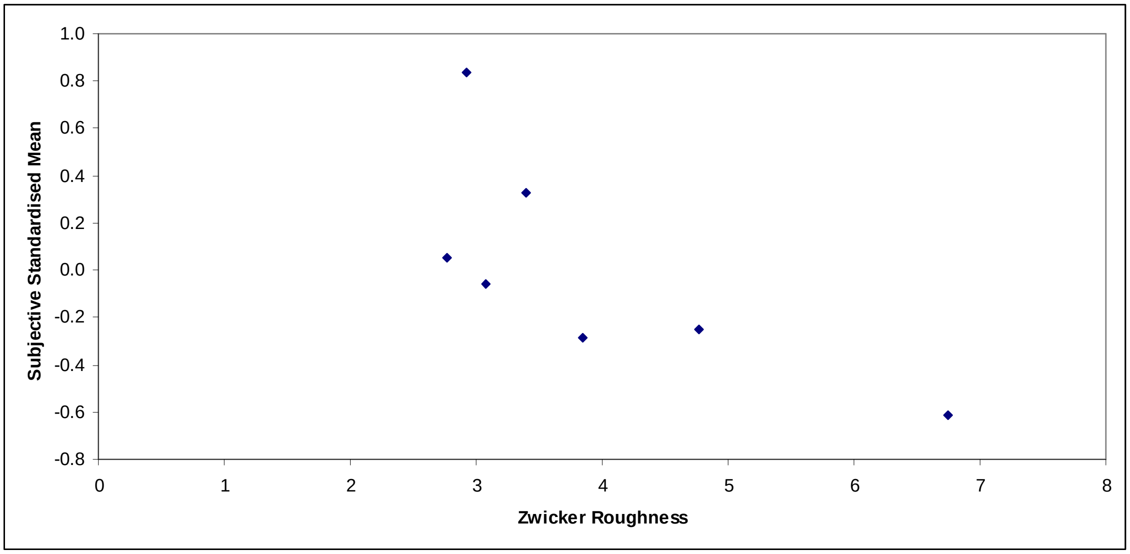

Figure 7 – UNSW Study compared to Zwicker roughness (B&K)

6. RESOLVING FALSE POSITIVES

During the trial of the 2007 procedure a number of sources of false positives were identified. How these have been resolved are discussed below.

Other noise sources such as motorbikes, particularly with twin cylinder engine configurations, are detected using the 2007 and 2014 procedure. Roads and Maritime reduced these at the automated camera installations through the use of road sensors to reject the collection of data unless a heavy vehicle exceeding 10 metres in length was present.

False positives were also identified using the 2007 procedure where there was a sudden change in noise level from the truck switching the engine brake on or off and also from some ambient noise sources, weather events or other driver behaviour. This was largely caused by the reaction of the Butterworth demodulation filter to a stepped input. The 2014 procedure addresses demodulation instead measuring the standard deviation of Sones and dividing this by the mean loudness in each time step. This limits any error to remain within the time step where there is a rapid change in noise. In addition if the average noise level changes by more than 4 Phon then the mod-RMS output in that time step is suppressed to zero.

Ambient noise such as wind and rain drops striking the microphone has the potential to create a false positive. Both the 2007 and 2014 procedures have manual verification of the event and if these noise sources are audible then the data is disregarded. Based on Roads and Maritimes experience at trial sites these are only issues during localised adverse weather. It has also been easy to identify when this occurs from the data as the amount of data being received increases dramatically and is inconsistent with standard daily detection profiles. It then requires little effort to disregard all the data during this period.

The risk of false positives due to microphone calibration drift is very small. This is because modulation measurement is highly insensitive to calibration error and changes in average noise level. This feature was one of the reasons for using modulation measurement to assess in-service heavy vehicle noise instead of more standard acoustic descriptors as the distance to the microphone and noise level change rapidly during a vehicle passby.

Exhaust directivity as with any pressure related noise measurement from a vehicle is an important consideration. Not only does noise level vary with the angle between an exhaust and the microphone, modulation can too. This is due to the broadband nature of each modulation pulse where the peak of the pulse in the instantaneous loudness time signal contains high frequency noise. Heavy vehicle exhaust outlets on trucks fitted with engine compression brakes in Australia are typically between 3.5 metres and 4.1 metres above the ground. The outlets can either be rear facing or vertical. To reduce the effects of directivity the microphone location has been shifted from 3.5 metres above the ground to a low position in the 2014 procedure so that exhausts do not point directly at the microphone. Short segments of higher modulation were also observed in the passby data a short time after vehicles with rear facing exhaust outlets pass the microphone. Since this small period of higher modulation is not representative of the truck passby, the 2014 procedure identifies a representative event maximum mod-RMS rather than the maximum. This has been defined as the upper tenth percentile of the event mod-RMS time trace. The measured event used for the statistical sampling uses a lower threshold 1 mod-RMS below the criterion value. Data below this threshold is ignored and is not assessed as part of the event. The event must also be at least 1.5 seconds long.

7. GROUND REFLECTION

The 2007 procedure set the microphone height at 3.5 metres above the ground so that it was close to the truck exhausts and also met standard noise level measurement practices (13) to minimise reflections from surfaces such as the ground. However during the trial completed by Roads and Maritime it was identified that ground reflection was still a source of error. While this error would not create a false positive it could result in low readings depending on which locations, over the 40m measurement interval either side of the microphone, the engine brake was active. This source of error was due to the time delayed ground reflection combining with the direct signal and depending on the time delay reducing the measured modulation.

The time delay also changes during the passby and goes from reinforcing the signal, which has no effect on the modulation as it is independent of level, or cancelling the signal if the delayed signal peaks fall between the direct signal peaks. A simulation using the 2007 procedure is shown in Figure 8. The effects are also similar with the 2014 procedure. The exact location where maximum cancellation occurs depends on the number of cylinders deployed in the engine braking as this alters the modulation frequency. Engine rpm also changes the modulation frequency to a lesser extent as engine brake performance limits the useful rpm range from 1200rpm to 1800rpm. Note other factors such as acoustically reactive exhaust and silencer components also create desirable internal reflections within the vehicle which reduce the measured modulation on well designed silencers. Dissipative components in the silencer also change measured modulation as they reduce high frequency content which is more audible in the temporal envelope due to shorter masking periods. These other factors are consistent properties of the vehicle design (13) and its current state of maintenance.

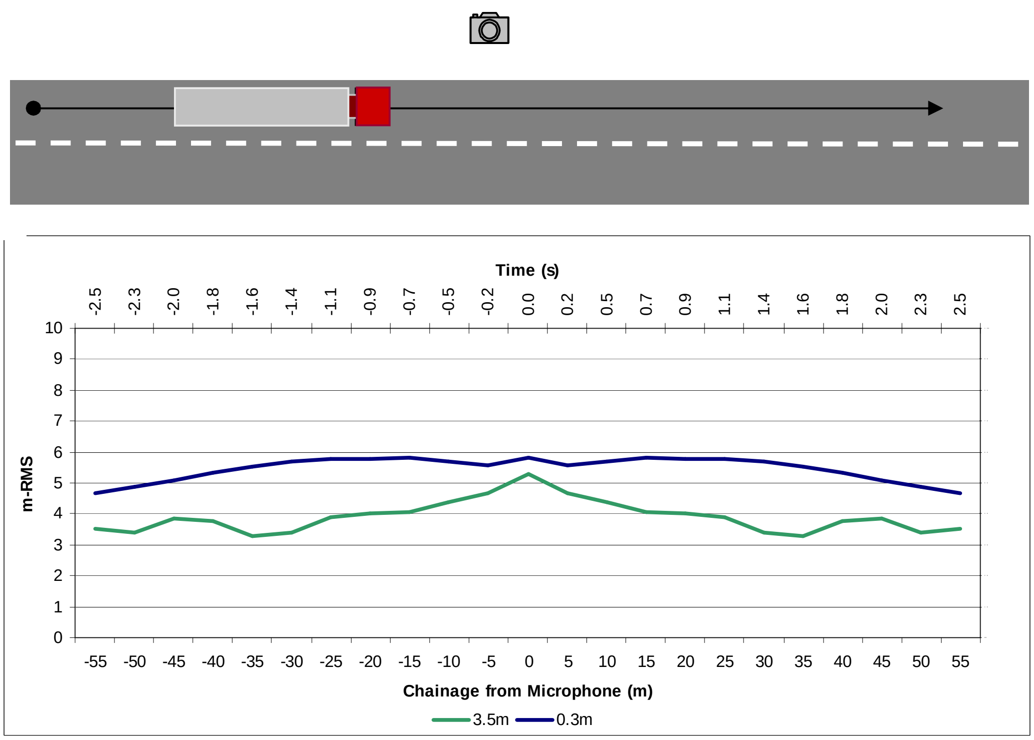

Figure 8 – Simulation of ground reflection interaction for simulated passby.

Field tests were completed in 2012 to review whether microphone height was significant using microphones placed one above the other at ground level and at 3.5 metres (Table 1). All measurements were manually verified as being from heavy vehicles. Significantly more vehicles were detected using a microphone height of 0.3 metres than 3.5 metres. The sites show a bigger difference at Mooney Mooney than Mount Ousley, NSW. This was expected as at Mount Ousley the gradients are higher and for safety reasons the speeds are slower. This ensures that all vehicles with engine brakes are using them throughout the whole measurement distance which means that they are all active directly in front of the microphone where the influence of height is less significant. However at Mooney Mooney the gradients are lower, the road straighter with speed control less critical meaning engine brakes are not on continuously and are often not engaged directly in front of the microphone.

Table 1 – Number of detections exceeding mod-RMS 3 (2007)

Location	**Microphone Height**	
	3.5m	**0.3m**
Mt Ousley	65	82
Mooney Mooney	13	49

The differences were also affected the ranking of the vehicles with the worst vehicle detected at 0.3 metres not even being detected with the 3.5 metre microphone (Table 2).

Table 2 – Ranking order at Mooney Mooney

3.5m - Ranking Order	**0.3m - Ranking Position**
1	6
2	10
3	26
4	13
5	8

Note: Ranking number 1 corresponds to the worst detected vehicle

8. BASELINE MONITORING

Baseline monitoring was previously undertaken in 2006 and 2007 in preparation for the Regulatory Impact Statement (3). This baseline monitoring and detailed measurements of a 1994 test vehicle with different silencer systems was used to identify a criterion that was achievable with Australia's existing vehicle fleet. This baseline was reviewed with additional roadside noise monitoring in 2013 to test the 2014 test procedure and to also test individual vehicles using original equipment manufacturer (OEM) fitted silencers with emission systems that were not in use in Australia in 2006.

Road side passby tests of Kenworth vehicles with Cummings engines and Jake brakes passed the criterion when fitted with OEM silencers and running Exhaust Gas Recovery (EGR) with Direct Particulate Filtration (DPF), Selective Catalytic Reduction (SCR) and without EGR or SCR fitted.

The new 2013 baseline tests were conducted at Mooney Mooney and Mount Victoria in NSW. A total of 78,000 heavy vehicles passed the two sites in the down hill direction over a three week period. The ranked distribution of events is shown in Figure 9 and Figure 10 for the two locations.

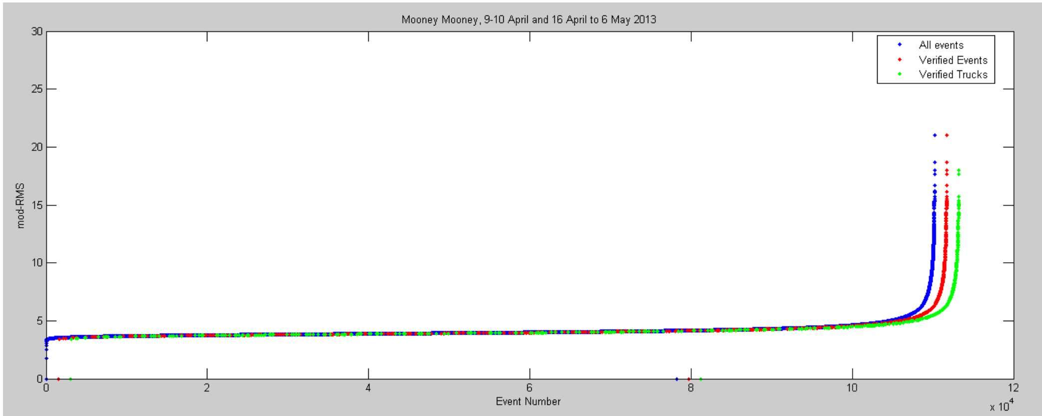

Figure 9 – Mooney Mooney Baseline 2013 – mod-RMS 2014

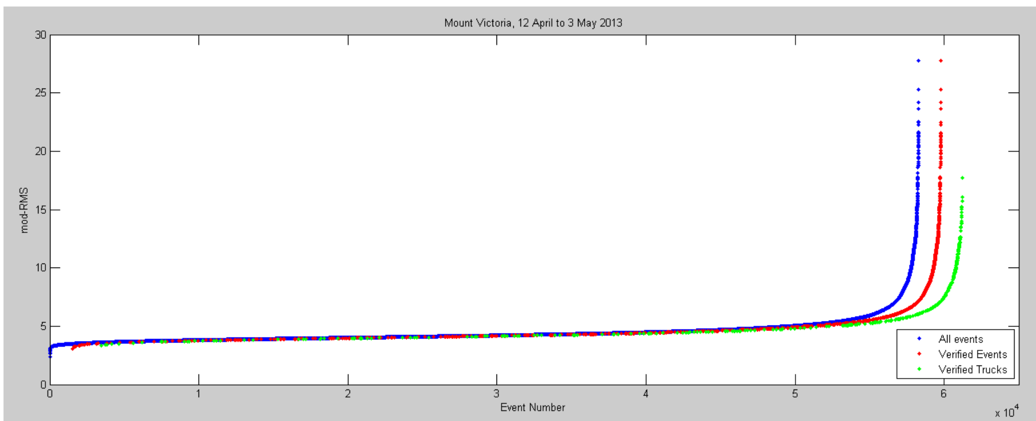

Figure 10 – Mount Ousley 2013 – mod-RMS 2014

Based on the testing with individual vehicles and the 2013 baseline data a criterion of mod-RMS 8 has been established for the 2014 test procedure. A mod-RMS value of 8 is achievable with OEM vehicles with later emission control systems such as EDR and SCR running OEM silencers and with either OEM or aftermarket silencers on older vehicles. The new criterion also results in a similar number of vehicles being identified as in the Regulatory Impact Statement which used a mod-RMS of 3 under the 2007 test procedure.

9. CONCLUSIONS

The in-service engine brake test procedure has been revised to use Zwicker instantaneous loudness obtained using DIN 45631 and the 2010 amendment for non-stationary noise sources. The instantaneous loudness time trace from the standard is then filtered to approximate sensitivity to roughness at different modulation frequencies. The approach shows improved correlation with perceptual studies of engine brake noise events. Furthermore by reference to a standard and its relationship to the human auditory system it is more easily explainable in a legal context and to non-technical audiences.

Items contributing to false positives have been identified and their influence addressed or managed.

Measurement error from ground reflection has been identified and addressed to minimise cancelling of the modulation signal.

Effects of exhaust orientation and directivity have been minimised through microphone positioning and statistical processing of the event.

REFERENCES

1. Parnell J, Dowdell B. Regulation of heavy vehicle engine brake noise in Australia. 14th International Congress on Sound and Vibration, 9-12 July 2007, Cairns, Australia

2. National Transport Commission, Australia. National in-service test procedures for engine brake noise from heavy vehicles, August 2007
3. National Transport Commission, Australia. Engine brake noise – Final proposal and regulatory impact statement. August 2007
4. National Transport Commission, Australia. Proposed model laws in relation to engine brake noise limits, August 2007
5. National Transport Commission, Australia. Review of the national in-service standard for engine brake noise. May 2013
6. Deutsches Institut für Normung. DIN 45631 Calculation of the volume level and the loudness of the Sound spectrum -Zwicker method. 1991.
7. Deutsches Institut für Normung. DIN 45631 Amendment 1: Calculation of the loudness of time-varying noise. 2010
8. Fastl H. Psychoacoustics basis of sound quality evaluation and sound engineering. 13th International Congress on Sound and Vibration, 2-6 July 2006, Vienna, Austria
9. Patsouras C, Fastl H, Psychoacoustic sensation magnitudes and sound quality ratings of upper middle class cars' idling noise. Proceedings of the International Congresses on Acoustics. Rome 2001.
10. E.Zwicker, H. Fastl: Psychoacoustics - Facts and Models. - Springer, Berlin 1990. As implemented by Bruel and Kjaer Pulse Sound Quality Software Type 7698.
11. National Transport Commission, Australia. Draft National in-service test procedures for engine brake noise from heavy vehicles, 2014
12. Sonus Pty Ltd. Engine brake noise: Development of a roadside test procedure. August 2003. Report to National Road Transport Commission, Australia.
13. Australian Standard 1055.1-1997 : Acoustics - Description and measurement of environmental noise - General procedures
14. Garcia P, Fuhrmann B. Exhaust System Sounds. 16th International Congress on Sound and Vibration, 5-9 July 2009, Krakow