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Tyre/Road Noise Contribution From Heavy Vehicles

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Definitions, Acronyms, and Abbreviations

AADT	Annual Averaged Daily Traffic (in vehicles per day)
CPX	Close-proximity Measurement (of noise level)
CRTN	Calculation of Road Traffic Noise (a noise model)
Cruise-by	A vehicle pass-by where the vehicle is neither accelerating nor decelerating
Coast-by	A vehicle pass-by where the vehicle's engine is off and gearbox is in neutral
DAC	Dense Asphaltic Concrete
DGA	Dense-Graded Asphalt
Drive-by	A vehicle pass-by where the vehicle is accelerating (engine under increased load)
EPA	Epoxy-Modified Open-Graded Porous Asphalt
EU	European Union
HCV	Heavy Commercial Vehicle (EEM classification)
%HCV	Percentage Heavy Commercial Vehicles (of a stated traffic volume; incl. HCV & MCV)
Heavies	Colloquial term for the combination of the MCV and HCV classes
LCV	Light Commercial Vehicle (EEM classification)
$L_{Aeq(t)}$	A-weighted energy equivalent sound pressure level over time period, *t*
L_{AFmax}	A-weighted maximum sound pressure level with 'fast' time averaging
L_{WA}	A-weighted sound power level
Macrotexture	Road surface texture at wavelengths between 0.5 mm and 50.0 mm
Microtexture	Road surface texture at wavelengths of less than 0.5 mm
MCV	Medium Commercial Vehicle (EEM classification)
MPD	Mean Profile Depth (of the road surface, measured in mm)
NZ	New Zealand
NZTA	Waka Kotahi NZ Transport Agency
OGPA	Open-Graded Porous Asphalt
ONRC	One Network Road Classification
PC	Passenger Car (EEM classification)
Powertrain	The engine and transmission components, including gearbox and axles
TPG	Twente Proving Ground (Netherlands)
RAMM	Road Assessment and Maintenance Management (software and database)
rpm	Revolutions per minute
SPB	Statistical Pass-by (measurement of noise level)
SRTT	Standard Reference Test Tyre
TMS	Traffic Monitoring System
Truck	In the context of this report, a vehicle within either of the MCV or HCV classifications
Ute	Utility Vehicle (a pickup truck)

1 Introduction

In an effort to reduce road traffic noise "at source", Waka Kotahi NZ Transport Agency ("the Agency") is conducting research into how the road surface affects road traffic noise. This report describes a study into the noise emission of heavy vehicles, with a focus on the tyre/road interaction.

1.1 Heavy Vehicle Tyre/Road Noise

At highway speeds, it is generally accepted that road traffic noise is dominated by the tyre/road interaction. This has been well-established for light vehicles [Sandberg & Ejsmont, 2002], which make up the majority of the traffic on most NZ roads, meaning that the acoustic properties of the road surface directly affect the overall noise level.

For heavy vehicles, the other contributing noise sources, such as engine and exhaust noise, may remain significant above 50 km/h. Consequently, the road surface is expected to play less of a role in defining the overall noise emission of a heavy vehicle, compared with that for a light vehicle. Finding the sensitivity of the overall road traffic noise level to the tyre/road noise contribution from heavy vehicles is a central research aim of this report.

Knowing this sensitivity will allow the Agency to correctly prioritise work that will have a material impact on road traffic noise, and avoid costly work that would not.

1.2 Measurement of Tyre/Road Noise

Measuring heavy vehicle tyre/road noise is not straightforward. There are several standardised methods for measurement of tyre/road noise generally, but neither of the two methods currently employed in NZ are demonstrably representative of heavy vehicles, for different reasons.

The statistical pass-by (SPB) method [ISO 11819-1:1997] uses an aggregation of the maximum noise levels (L_{AFmax}) of regular vehicles passing a stationary sound level meter (SLM) to quantify the influence of the road surface on the noise emission. The standard claims that differences between the aggregated noise levels determined at different locations are solely the effect of the road surface, but this is clearly not the case, as the SLM cannot distinguish between tyre and engine noise, for example.

The CPX method [ISO 11819-2:2017] uses a microphone in close proximity (CPX) to a reference test tyre to measure an equivalent sound pressure level (L_{Aeq}) as the tyre rolls along the road surface. There is a "P1" reference test tyre intended to represent passenger car tyre/road noise generation and an "H1" reference test tyre intended to represent heavy vehicle tyre/road noise generation. The CPX method does provide an uncontaminated measurement of the tyre/road interaction itself, and is capable of producing noise data over a long distance of road, as opposed to SPB's single location. However, for the results to be representative of heavy vehicles, the H1 reference test tyre used must also behave in a representative fashion. It has not yet been demonstrated that the H1 reference test tyre, which is a van tyre, is representative of the tyres fitted to NZ's heavy vehicle fleet.

This study aims to identify a short-list of methodologies that will allow representative measurement of the tyre/road noise emission of heavy vehicles, suitable for use in road surface research.

1.3 CPX Measurement

The CPX approach offers substantial benefits over the SPB approach in many respects, but in particular the resolution and speed with which it is able to acquire good quality tyre/road noise emission data. NZTA own a CPX noise trailer [Chiles & Bull, 2018], which is the preferred instrument for measuring tyre/road noise for light vehicles (via the P1 passenger car reference tyre). In future the trailer may be used to determine compliance of low-noise road surfaces against performance-based criteria, for example. The trailer has previously been used to run both the P1 and H1 tyres over a variety of chipseal and asphalt surfaces [Jackett, 2018; Jackett, 2019] for the purposes of research.

This study will consider whether the CPX trailer can provide an indication of the heavy vehicle noise performance of a road surface, and if so, how this could be practically achieved.

1.4 Scope

This is a desktop-based study, and is largely focused on extracting information relevant to New Zealand heavy vehicle noise from published literature from overseas heavy vehicle noise studies, supplemented by quantitative analyses of available traffic, CPX, and SPB data from NZ and overseas. It aims to:

- Determine the hierarchy of noise generation mechanisms for heavy vehicles over the speed range 50 km/h to 100 km/hr.
- Propose heavy vehicle classifications appropriate for the NZ fleet to improve/expand on the ISO 11819-1 classifications (which are ambiguous and unrepresentative of NZ vehicles).
- Quantify the potential for road surface optimisations to reduce heavy vehicle traffic noise, and road traffic noise overall.
- Propose a short list of methods for measurement of the tyre/road noise emission of heavy vehicles, suitable for the optimisation or assessment of road surfaces.
- Propose a short list of methods to evaluate the contribution of the road surface to wayside noise levels, suitable for determining road surface correction factors for heavy vehicles.

The original scope included field trials to validate that literature on the relative contribution of heavy vehicle noise emission sources could be applied in NZ across a representative range of speeds. Due to the Covid-19 pandemic this field work had to be deferred, so is not covered in the current version of this report.

Throughout this study there has been a strong focus to avoid adopting existing assumptions into this analysis that might be incorrect, outdated, or suboptimal for New Zealand heavy vehicles. For example, while CRTN is commonly and successfully used in NZ, it does not have a depth of recent data or detail behind it, so has not been used for any part of this study. This project takes a 'first-principles' approach to gather data for and construct a model that allows an unbiased and trustworthy analysis that is the state-of-the-art in NZ.

1.5 Investigation Structure

1. The contribution of tyre/road noise to overall heavy vehicle noise is investigated.
2. A model for calculating the tyre/road noise contribution from heavy vehicles is selected.
3. Heavy vehicle traffic volumes are determined for different NZ traffic conditions (such as speed, road classification, and time of day) from NZ telemetry data, and the contribution of heavy vehicles to the overall road traffic noise level is determined.
4. The selected noise model is used to investigate the relationship between the road surface and the overall road traffic noise level, for light and heavy vehicles.
5. Methods for measuring the influence of road surfaces on heavy vehicle noise are suggested, to complement the theoretical investigation.

2 Hierarchy of Noise Generation Mechanisms

2.1 Noise Generation Mechanisms

The mechanisms that cause a moving vehicle to generate noise are generally common to both light and heavy vehicles, but their magnitude of influence often differs. Figure 2-1 shows the main mechanisms that contribute to noise emission from heavy vehicles.

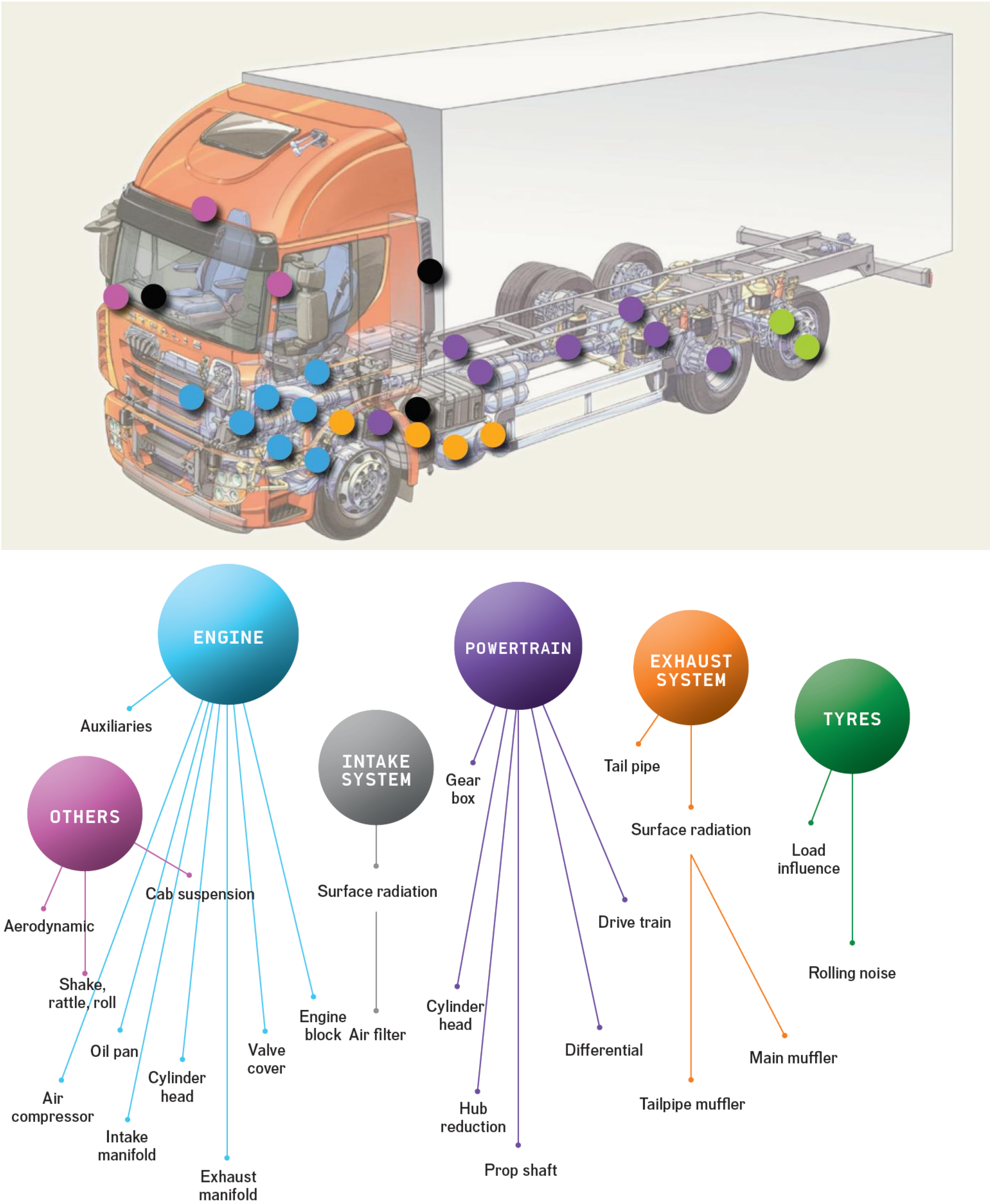

Figure 2-1: Heavy vehicle noise-generation mechanisms by location in the vehicle
Image credit: European Automobile Manufacturers Association [ACEA, 2012]

Although often labelled differently, there is general agreement within the literature on what the key noise-generating mechanisms for heavy vehicles are. Their exact order of importance is not universally agreed (and also depends on vehicle speed) but is generally held to approximate the following, from most to least important at highway speeds:

1. Tyre/Road Noise
2. Engine Noise
3. Exhaust Noise
4. Transmission Noise
5. Aerodynamic Noise
6. Other Noise Sources

2.1.1 Tyre/Road Noise

The tyre/road interaction is the dominant source of noise for most modern cars at all road driving speeds, and it is also very significant for heavy vehicles at 50 km/h and above. As the tyre rolls along the road there are a number of different ways it generates noise, which can be grouped into broad categories as in Table 2-1.

Table 2-1: Tyre/road noise generation mechanisms (adapted from Sandberg & Ejsmont, 2002)

Mechanism	Role	Phenomena
Impact	Generation	Deformation of the tyre and tread blocks as they come into (and leave) contact with the road surface texture
Adhesion	Generation	Stick/slip or stick/snap behaviours caused by the friction between the tread blocks and road surface
Air displacement	Generation	Pumping and displacement of air by the rolling tyre, and resonances in the tyre cavities
The horn effect	Amplification	Multiple reflections within the 'horn' shaped voids in front and behind a tyre (between tread and road)
Acoustic impedance	Absorption	Voids in porous surfaces act to absorb sound

For light vehicle tyres, the impact mechanisms arguably dominate. For heavy vehicle tyres the other mechanisms also appear to play important roles.

2.1.2 Engine Noise

Truck engines are typically required to deliver vastly more torque than car engines, and as a result they are much larger and generate more noise. They are also more likely to be diesel powered.

Engine noise comes from the engine cylinder block, air intakes, forced induction systems, exhaust manifold, cooling fans, and various other components.

2.1.3 Exhaust Noise

Exhaust gases run through a pipe from the exhaust manifold to an outlet somewhere on the exterior of the truck, and en route may pass through mufflers, catalytic converters, recirculators, and filters. The exhaust outlet may be near road level or in the form of a stack above the cab. Overseas studies have indicated that noisy stacks have become quite rare: less than 10% of HCVs in the US [NCHRP 635, 2009] and about 1% of HCVs in Europe [Peeters & van Blokland, 2007].

2.1.4 Transmission Noise

The function of the transmission is to carry power from the engine to the tyres, so it is dominated by rotating components: the clutch, gearbox, propeller shaft, differentials, universal joints, axles, and bearings. Geared components may generate tonal sounds. These components are also prone to component wear or debris ingress causing friction-related noise. But in general, transmission noise is expected to be less significant than the preceding sources.

2.1.5 Aerodynamic Noise

Aerodynamic noise arises from the movement of air around the truck body, trailer, wheels, and auxiliaries. Aerodynamic noise also arises from air movement through radiators and inlets. It is not an important noise source on modern vehicles, which have been designed for reduced cabin noise [Sandberg & Ejsmont, 2002] and, particularly in the case of trucks, fuel efficiency. Aerodynamic noise from trucks is insignificant at under 100 km/h compared to other noise sources, and originates primarily from the wheel arches [Peeters & van Blokland, 2007], meaning it is not easily separated from tyre/road noise.

2.1.6 Other sources

There are various other possible noise sources on trucks, such as wheel and cab suspension movements, couplings, flapping canvas sides or tie-down straps, loose fittings or cargo, chains, and so on. These may be significant on a vehicle-by-vehicle basis, but are not significant in terms of their contribution to the overall road traffic noise.

2.2 Review and Analysis of International Data

The international literature is strong on quantifying the various mechanisms that contribute to light vehicle noise but has been observed to be much weaker concerning heavy vehicles [Sandberg & Ejsmont, 2002]. In the 20 years since that observation was made several in-depth studies into truck noise have taken place, but quantification of contributing sound sources is still rare. This review of the literature finds that there is not yet agreement on even the hierarchy of mechanisms.

The following publications contribute useful information on the quantification of noise-generating mechanisms of heavy vehicles. Where possible, raw or summary data has been extracted from the documents for a targeted analysis.

2.2.1 Tyre/Road Noise Reference Book, 2002

Sandberg & Ejsmont's (2002) reference book is the definitive work on tyre/road noise. It includes information about quantifying truck tyre/road noise with respect to other sources, which is summarised below.

- Power unit noise depends mainly on the engine rpm and the load (which in cruise conditions are managed by gear selection). Tyre/road noise is a function of vehicle speed, the tyre, and the road surface. Therefore, at some speed there is a cross-over from power unit noise to tyre/road noise being more dominant. Sandberg & Ejsmont place this cross-over at 15-25 km/h for cruising cars and 30-35 km/h for cruising trucks.
- Cross-over speeds are dependent on engine loading. Trucks can have greatly increased power unit noise under acceleration or deceleration (or on a gradient) compared to cruise conditions.
- Low speed acceleration tests on Scania G93 and Volvo F12 trucks in 1991 showed an increase of 10 dB under maximum power compared to cruise power. Cruise noise levels were nearly identical at about 25 km/h and about 40 km/h. The implication is that tyre/road noise was not dominant at these low speeds and that engine and transmission noise were independent of speed within the speed range 25 to 40 km/h.

- Drive-by, cruise-by, and coast-by measurements of the same trucks indicated that tyre/road noise exceeded power noise at speeds of 70 km/h and 90 km/h, and that these two sources were probably about equal at 50 km/h. Repeating the measurements with 'low noise' specification trucks (power noise reduced by 3 dB, according to the manufacturer) indicated that tyre/road noise then exceeded power noise at 50 km/h. At 30 km/h engine noise dominated in all cases.
- In terms of the variation in overall vehicle noise emission, car noise is noted to be sensitive to the road surface and doesn't vary much from car-to-car, whereas truck noise is fairly insensitive to the road surface and varies greatly from truck-to-truck, depending particularly on their tyres.

2.2.2 NordTyre Project, 2018

The NordTyre Project's primary aim was to evaluate the efficacy of new tyre noise labelling requirements; in doing so it established evidence on the tyre/road contribution to traffic noise emission in the Nordic countries [NordFoU, 2018].

Coast-by testing at 70 km/h produced indicative wayside noise levels for tyre/road interaction for 30 different C3 (heavy vehicle) tyres[1], over 4 different road surfaces. The selection of European, North American, and Asian heavy vehicle tyres is likely to be broadly representative of those used in NZ. Although there is no direct equivalency between the road surfaces used and NZ road surfaces, two of the test surfaces have similar characteristics to NZ surfaces grade 4 chipseal and EPA7 (see Appendix A). A dense asphalt road surface used was much smoother than a typical NZ dense asphalt.

- Coast-by testing showed a 4-5 dB reduction from the fine chipseal-equivalent to the EPA7-equivalent surface, indicating that truck rolling noise can be sensitive to surface type.
- The dense asphalt surface coast-by noise levels were midway between the fine chipseal and porous asphalt coast-by levels, despite having the lowest texture of the three (MPD_{dense} = 0.3 mm compared to MPD_{porous} = 0.6 mm and $MPD_{fine\ chip}$ = 1.1 mm). This reflects the NZ experience [Dravitzki & Kvatch, 2007] that *heavy* vehicle tyres benefit from some degree of surface porosity or airflow, even at the expense of higher macrotexture, but only up to a point.
- Drive axle tyres[2] were about 1.5 dB noisier than steer or trailer tyres on fine chipseal, whereas on the smoother asphalt surfaces (dense and porous) the drive axle tyres were 4 dB noisier.
- The results did not quantify rolling noise in comparison to propulsion noise.

2.2.3 NCHRP Report 635, 2009

This in-depth study [NCHRP 635, 2009] investigated the use of beam-forming (microphone array) techniques to locate and quantify heavy truck noise sources, primarily aiming to measure vertical noise distribution to update noise modelling algorithms.

- A survey of 59 heavy trucks travelling at high speed showed that most have one strong emission height at about 0.2 metres above the ground. Four trucks (7%) showed a strong emission at stack height (around 3.7 metres), and in only two cases did this exceed the ground level noise emission.

Drive-by, cruise-by, and coast-by measurements with five test vehicles were performed over a dense asphalt surface. We have collated this data (Table 2-2) to allow a fresh analysis relevant to the current study.

[1] EU regulation (EC) 661/2009 defines tyre classifications C1 for passenger car tyres, C2 for light commercial vehicle tyres, and C3 for heavy vehicles tyres.
[2] C3 tyres are often designed and fitted for a particular purpose on heavy vehicles: steering, drive, or trailer.

Table 2-2: Collated truck pass-by data from NCHRP Report 635

International Truck and Engine Corporation Model Number	NZ EEM Class (axles)	Engine Speed (rpm)	L_{Amax} at 7.6 m (dB)			Derived difference between power & rolling Approximate (dB)
			Stationary (0 km/h)	Cruise-By (80 km/h)	Coast Down[3] (80 km/h)	
4400	MCV (2)	1400	73.7	83.6	80.9	-0.6
9200i	HCV I (3)	1500	78.6	83.0	81.4	-3.5
9200i (modified exhaust)	HCV I (3)	1600	79.6	89.6	80.0	9.1
5900i	HCV I (3)	1400	76.2	84.7	81.8	-0.2
5900i and trailer	HCVII (5)	1400	76.2	87.2	86.9	-11.5

- With reference to Table 2-2, the coast-down noise level is typically 2 - 3 dB below the cruise-by level. This project has analysed the data further. Assuming coast-down is dominated by rolling noise, the power noise has been calculated as the additional noise required to achieve the cruise-by level. The derived difference" column then shows the approximate relationship between power noise and rolling noise – negative values implying that rolling noise is higher than power noise at 80 km/h. The HCV I with modified exhaust is completely dominated by power noise, the HCV II is dominated by rolling noise, and the remaining three trucks have power and rolling components at a similar level.

- With reference to Table 2-2, for the same "cruising speed" rpm, the cruise-by noise level is typically about 10 dB higher than the stationary noise level. Following the analysis above, this difference cannot all be due to rolling noise. It appears that the stationary truck measurements are not representative of the actual contribution of power noise, probably due to the lack of engine load and transmission noise.

- From the imagery of NCHRP Report 635 it is clear that the beam-forming results have insufficient resolution to separate out closely-spaced noise sources, such as engine noise from front tyre noise. It is therefore unlikely that an acoustic camera would be able to provide a validation of the noise source hierarchy on NZ roads.

- NCHRP Report 635 concludes that tyre/road noise is the dominant source at 80 km/h, followed by powertrain noise, and with some exhaust stack noise in a minority of vehicles, but does not quantify the contributions.

2.2.4 HARMONOISE, IMAGINE, and CNOSSOS-EU, 2001-2015

HARMONOISE was a collaborative European project from 2001-05 to develop a new Europe-wide noise model for road and rail [HARMONOISE, 2005]. IMAGINE (2003-06) expanded that to aircraft and industrial noise sources, and developed a noise source database[4] for road noise [IMAGINE,

[3] The definition of "coast down" appears to differ between runs: for the majority it is off-throttle and in neutral, but for the 4400 it appears to be off-throttle but in-gear. Also note that this differs from European definitions for "coast-by", which typically means killing the engine altogether.

[4] Unfortunately, the project websites that hosted the documents from both these multi-million-euro projects are now inoperative. We have been able to find some reports and papers published elsewhere, and have received some reports directly from the authors. We have made the EU project teams aware of this.

2006]. The HARMONOISE model and the IMAGINE source data were later (2010-2015) incorporated into a standard European noise model, CNOSSOS-EU [Directive 2015/996].

- All three projects model individual vehicle noise emission in sound power as a combination of "rolling noise" (tyre/road, aerodynamic) and "propulsion noise" (engine, intake, exhaust, transmission) components, which are both functions of vehicle speed [Nota et al, 2005; de Graff, 2008]. The overall sound power of the vehicle is the sum of those components.
- The CNOSSOS-EU vehicle classifications align closely to NZ EEM vehicle classifications PC, MCV, and HCV I & II (see Table 3-1).
- HARMONISE was considered to over-estimate truck propulsion noise, which was reduced in IMAGINE [Peeters & van Blokland, 2007] based on better availability of truck data [de Graff, 2008]. The IMAGINE data was translated into the form required by CNOSSOS-EU, but introduced errors in the process [Peeters & van Blokland, 2018]. We observe that recent proposed updates to CNOSSOS-EU [Kok & van Beek, 2019] to resolve the errors lead to additional reductions to the propulsion noise component relative to rolling noise. It is not known whether the Kok & van Beek (2019) revisions will be officially adopted by the EU, but review for this project finds that they are appropriate and have been incorporated into this analysis.
- The IMAGINE truck data derives from a great number of experiments across EU member states, including anechoic chamber tests of engine components, pull-away tests, roadside pass-by testing, and controlled single vehicle testing. The CNOSSOS-EU model represents a composite of all these measurement sources and describes an 'average' vehicle, normalised to reference conditions (a dry virtual DGA/SMA surface[5] and no gradient or acceleration).

We have constructed the CNOSSOS-EU vehicle model from the data in Directive 2015/996 and the proposed updates [Kok & van Beek, 2019]. Figure 2-2 shows how the rolling and propulsion components of the three vehicle classes change with vehicle speed.

[5] It is not known how this surface relates to NZ surfaces. We assume that it approximates a 50:50 ratio of NZ AC-10 and SMA-10 surfaces, while noting that a ± 2 dB error would not materially affect any conclusions.

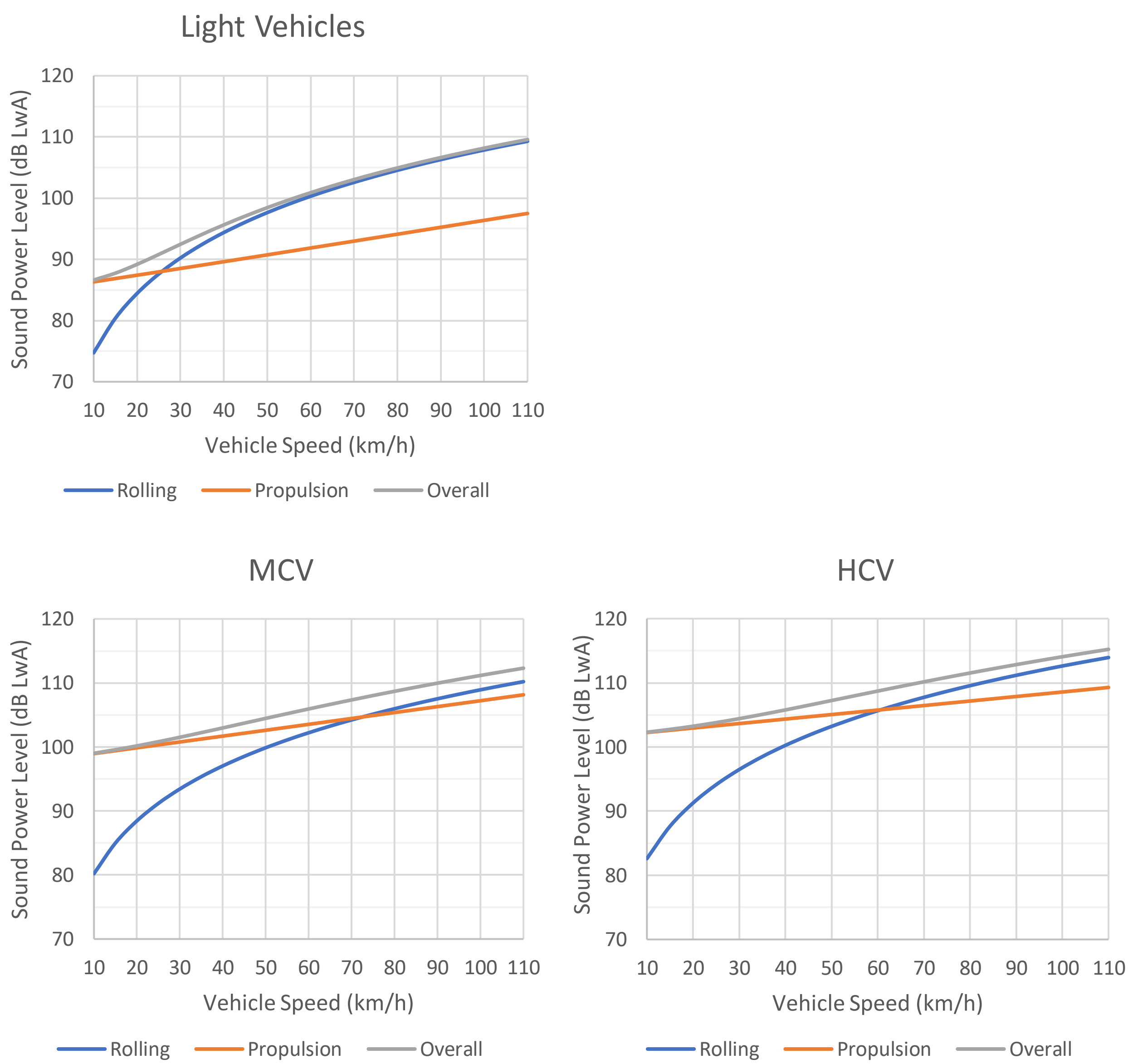

Figure 2-2: The CNOSSOS-EU model of vehicle noise, including proposed updates, for light vehicles , MCVs , and HCVs .

- Under reference conditions, the crossover speed for MCVs is about 70 km/h, but propulsion noise and rolling noise both contribute significantly over the range 50 km/h to 110 km/h.
- Under reference conditions, the crossover speed for HCVs is about 60 km/h, and by 90 km/h most of the overall noise emission is due to rolling noise.
- Corrections to the reference conditions can be made for gradient, acceleration, temperature, and road surface[5] [Directive 2015/996; Kok & van Beek, 2019]. However, the provided road surface corrections are not appropriate for NZ application (see section 4.1.1).

2.2.5 European Validation of HARMONOISE-IMAGINE, 2005-2008

- Trow & Shilton [2005] performed an uncertainty analysis of the HARMONOISE model, showing that Monte Carlo techniques were able to determine the sensitivity of the model output to the input data, but did not include road surface type or review the relative contributions of rolling and propulsion noise.
- Czyzewski & Ejsmont [2008] contended that for heavy vehicles the IMAGINE coefficients overstated the contribution of propulsion noise, citing pass-by measurements from two HCVs

(seemingly the same data as discussed in section 2.2.1). We have compared this data to CNOSSOS-EU predictions (as published) and there appears to be general agreement with the model once an A-weighting has been applied.

2.2.6 Australian Pass-by Studies of Heavy Vehicles, 2010 & 2011

No studies have been performed to evaluate the European noise models for NZ use, but two Australian measurement-based studies have been conducted.

- Naish [2010] performed attended SPB measurements on over 2,000 vehicles, including 600 trucks, across five different types of road surface (4 asphalts, 1 chipseal) on high speed roads (80 – 110 km/h). The data aligns well with HARMONOISE for the HCV II class, but was higher than either of the models predicted for cars and MCVs, and was not compared to IMAGINE.
- Brown & Tomerini [2011] used a rule-based automated SPB methodology to capture noise data from 32,000 trucks on DGA surfaces, with speed limits from 60 km/h to 100 km/h. The levels were 2 dB to 6 dB lower than Naish [2010] and align well with the IMAGINE model across all vehicle types at most speeds.

2.2.7 Australian Truck Traction Noise Study, 2019

A recent Australian study [Peng et al, 2019] into noise on gradients has calculated A-weighted speed coefficients for 6-axle trucks (HCV II) for five noise models[6], which we have used to reconstruct the rolling, propulsion, and overall noise relationships for this heavy vehicle subclass in cruise conditions. Figure 2-3 compares the predictions for the overall A-weighted sound power level of a 6-axle truck under approximately reference conditions. Figure 2-4 shows the rolling and propulsion noise components of four of the models (ASJ-RTN has only a rolling noise component).

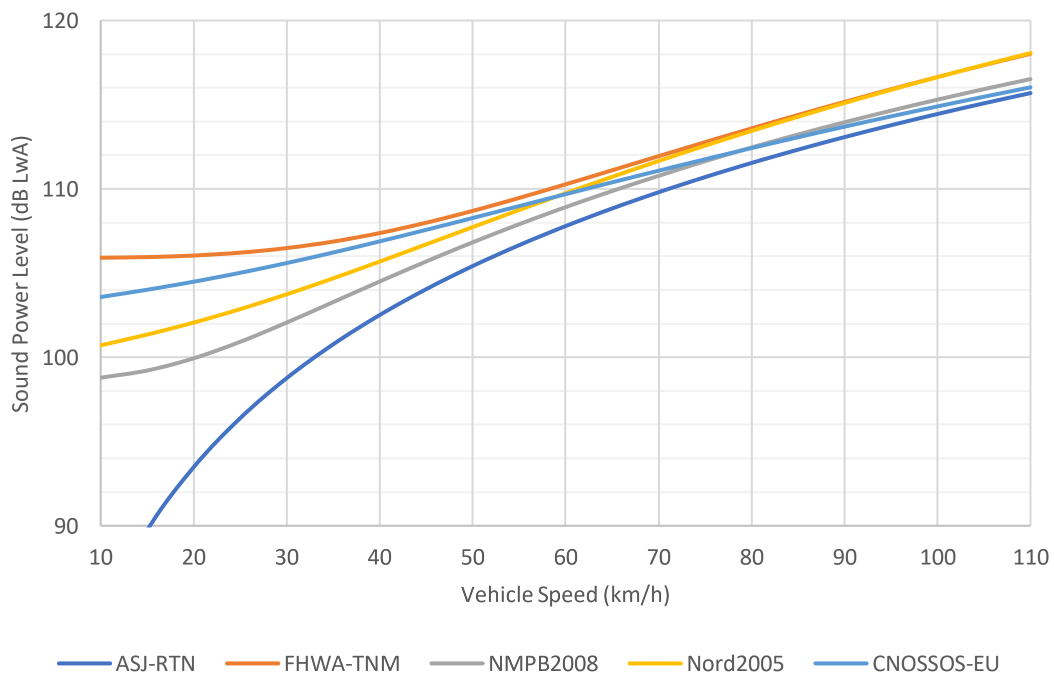

Figure 2-3: Overall sound power of a 6-axle truck on SMA14 according to five noise models

[6] ASJ-RTN: Acoustical Society of Japan Road Traffic Noise model
FHWA-TNM: Federal Highway Administration (US) Traffic Noise Model
NMPB2008: Nouvelle Méthode de Prévision du Bruit routier 2008 (French)
Nord2005: Nordic Noise Prediction Method 2005
CNOSSOS-EU: Common Noise Assessment Methods in Europe noise model (without proposed revisions)

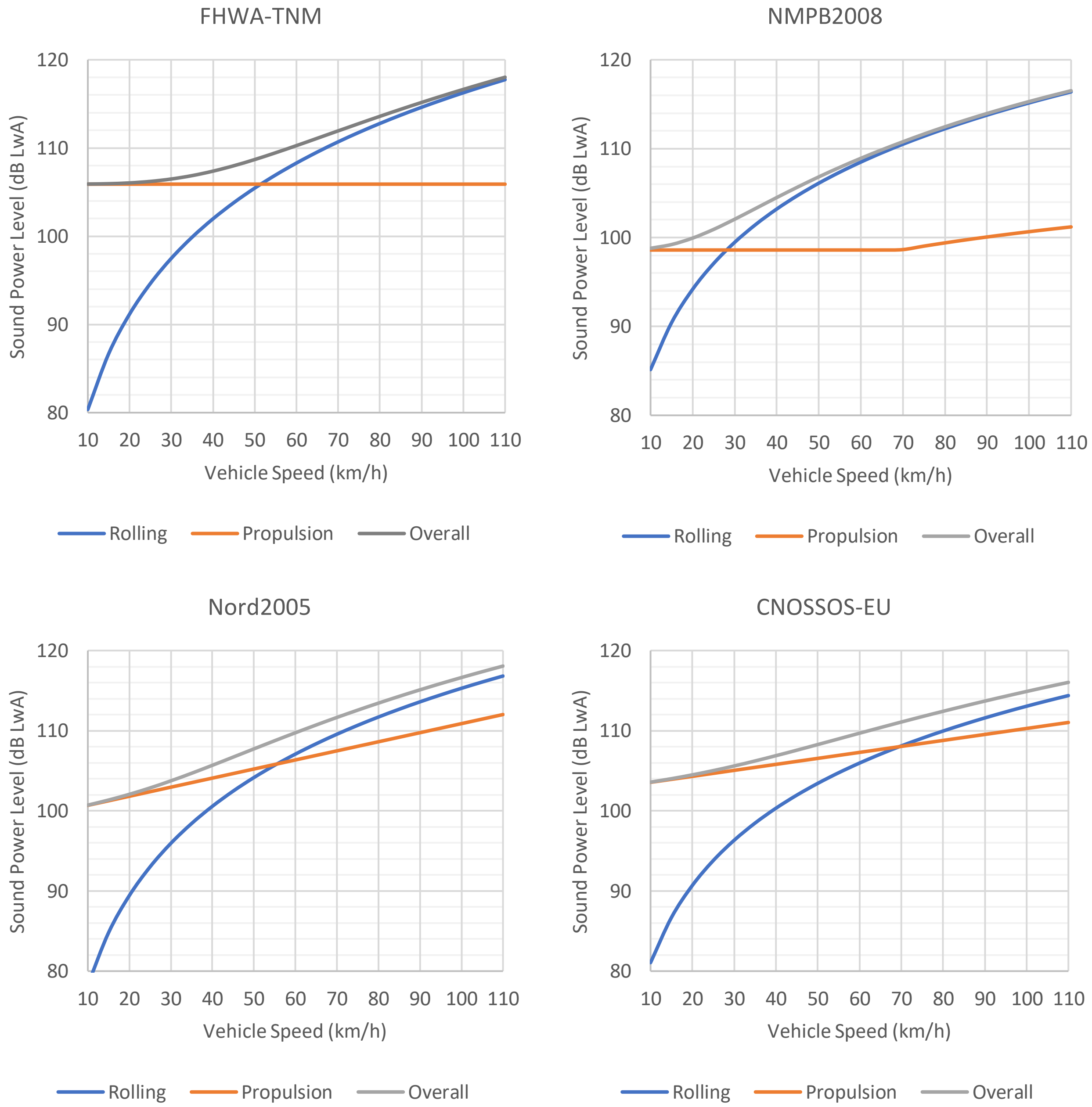

Figure 2-4: Rolling and Propulsion noise for a 6-axle HCV according to 4 different noise models

- It is clear that there is no consensus to be found on the relative influence of tyre/road and powertrain sources at highway speeds. The crossover speed ranges between 30 km/h and 70 km/h. At 90 km/h three models are completely defined by rolling noise, but in Nord2005 and CNOSSOS-EU (sans revisions) the propulsion noise still affects the overall level.

- Despite arising from dramatically different rolling and propulsion components, the overall emission of all five models is within 2 dB at high speed (Figure 2-3). This may be indicative of the overall noise level being relatively straightforward to measure (and therefore model), while propulsion and rolling subcomponents are more challenging to isolate (section 5.2).

2.3 Quantification of the Truck Tyre/Road Noise Contribution

The conclusion from section 2.2 is that the most useful data for quantifying the truck tyre/road contribution comes from noise models. While themselves based on noise measurements, models provide continuous quantitative relationships between vehicle class, speed, and noise generation mechanism, which is what is required for the current analysis.

For this project, relationships of rolling and propulsion noise to truck speed have been extracted for seven different noise models in total (sections 2.2.4 and 2.2.7). No two models agree on the split between rolling and propulsion components, however all agree on the overall noise level within a range of about 2 dB at highway speeds (section 2.2.7). The CNOSSOS-EU noise source emission model, including the proposed revisions [Kok & van Beek, 2019], has been chosen as the basis for further analysis for the following reasons:

- It appears to have the most comprehensive recent set of MCV and HCV measurements behind it (though many of the reports and datasets are no longer available[4]).
- It is consistent with the American 80 km/h pass-by measurements [NCHRP 635, 2009] that were re-analysed to extract rolling and propulsion components in section 2.2.3, whilst most other models are not consistent with those measurements.
- The CNOSSOS-EU (née IMAGINE) predictions of overall noise level were validated by an Australian pass-by survey of 32,000 trucks (section 2.2.6).
- The IMAGINE predictions had been suspected of over-estimating propulsion noise (section 2.2.5) but CNOSSOS-EU predictions appear to be consistent with European pass-by data (sections 2.2.1 and 2.2.5).
- It is the standardised prediction method for the EU strategic noise mapping and as such has undergone significant international scrutiny.
- It uses vehicle classifications that align well with a NZ application, is well documented in English, and the required data are generally available.

Nonetheless, we recommend that further research and measurements are performed to validate the truck vehicle source model in NZ.

3 NZ Heavy Vehicle Data

The Agency's Traffic Monitoring System (TMS) includes data from about 80 continuous telemetry monitoring stations on NZ state highways and many shorter-term surveys [NZTA, 2011]. A dataset from TMS data over the five years 2010-2014 has been formed that includes the vehicle classification, axle layout, and speed of every vehicle pass, which is then used to investigate NZ heavy vehicle movement patterns and to determine a suitable relationship between NZ vehicle classifications and the ISO 11819-1 classifications.

3.1 Heavy Vehicle Classification Schemes

The NZTA 2011 Vehicle Classification Scheme [NZTA, 2011] provides 14 detailed classifications of motor vehicle, which may be mapped to the six broad vehicle classes of the Economic Evaluation Manual (EEM) [NZTA, 2018] (formerly known as the "PEM classes") [7]. The previous Transit NZ 1999 ("TNZ99") scheme is also in current usage, which can be found in [Petrie et al, 2005]. Table 3-1 provides the relationship between these three NZ classification schemes.

Table 3-1: Relationship between EEM, NZTA 2011, and TNZ 1999 vehicle classes

EEM Class	EEM Class description	NZTA 2011 Axel [sic] Class[7]	TNZ 1999 Class
Passenger Car (PC)	Cars and station wagons with wheelbase < 3.2 m	2	1
Light Commercial Vehicle (LCV)	Vans, utes, light trucks up to 3.5 t gross laden weight. Mainly single rear tyres but some small trucks with dual rear tyres	2	1
Medium Commercial Vehicle (MCV)	Two axle heavy trucks without a trailer, over 3.5 t gross laden weight	4	3
Heavy Commercial Vehicle I (HCV I)	Rigid trucks with or without a trailer, or articulated vehicles with three or four axles in total	5,6,7	4,5,6,7
Heavy Commercial Vehicle II (HCV II)	Trucks and trailers and articulated vehicles with or without trailers with five or more axles in total	8,9,10,11,12,13,14	8,9,10,11,12,13,14
Buses	Buses, excluding minibuses	4,5	3,4 (implicit)

There is no clear separation between PC and LCV classes in the NZTA 11 and TNZ99 classification schemes. A nominal wheelbase threshold placed at 3.0 metres can be used if required.

[7] There is disagreement between sources [NZTA, 2011] and [RAMM, 2012] for how classes 1 to 3 should map to the EEM class, but this has not affected the current analysis, which uses data classified by TNZ99.

We have constructed the working dataset from TMS data for the five years 2010-2014 because more recent data uses a mix of classification schemes and a very different survey philosophy (fewer sites, longer surveys). The resulting dataset covers an average of 500 unique monitoring sites per year, and about 700 unique sites in total, providing good nationwide coverage of state highways (Figure 3-1), with the exception of the Auckland region. The dataset contains 170 million individual vehicle passes, which means that even the least common vehicle classes are well represented. Whilst this set does not use the most recent TMS data, it has been confirmed as still representative of the recent traffic mix by comparison with 2018 data (which reverted to the TNZ99 classification system).

Figure 3-1: Distribution of traffic monitoring sites around NZ

3.2 Statistical Pass-by Noise Measurement

Recent NZ studies incorporating Statistical Pass-by (SPB) road traffic noise measurements [Jackett, 2018; Jackett, 2019] noted that the vehicle classification described in the SPB standard [ISO 11819-1:1997] was insufficient to ensure consistent application of the standard, and suggested that a NZ-specific interpretation of classifications based on NZ traffic data would resolve this.

In April 2020, the ISO working group responsible for ISO 11819-1 circulated a committee draft for review [ISO/CD 11819-1, 2020], which appears to resolve many of the previous issues. Most significantly, annex A of the standard, in new normative text:

- explicitly breaks down the heavy vehicle category into two well-defined sub-categories: HD – heavy vehicles having two axles; and HM – heavy vehicles having multiple axles;
- acknowledges that the ISO classification may not apply well to some countries and that when it is not possible to comply with the given definitions, a separate classification may be required;
- states that future versions of the draft will include illustrations of vehicles that would, or would not, fall into each class.

Table 3-2 suggests what we consider to be an optimal mapping from the ISO 11819-1 and ISO/CD 11819-1:2020 vehicle classes to the NZ vehicle classes. It is not precisely one-to-one, so further explanation of each class and the reasoning behind the suggested mapping follows. In the table, [*wb<3*] and [*wb>3*] indicate that filtering of TMS wheelbase data would be required to distinguish vehicles subclasses: less-than and greater-than 3 metres, respectively.

Note that this is not a recommendation for expanding the current system for modelling road traffic noise (e.g. CRTN uses AADT and %HCV – effectively a 2-classification system). This investigation is intended to clarify how vehicles should be identified and classified during SPB measurement.

Table 3-2: Recommendation for NZ interpretation of ISO 11819-1 vehicle classes

ISO 11819-1 Vehicle Classification	Recommended NZ Classification (c.f. EEM)	NZTA 2011 Class	TNZ 1999 Class	Differences between recommended NZ EEM classification and ISO 11819-1 classification
Light Vehicle (P)	Passenger Car (PC)	2 [wb>2.1, wb<3]	1 [wb>2.1, wb<3]	Completely equivalent if vehicle exclusions are followed
Dual-axle Heavy Vehicle (HD)	Medium Commercial Vehicle (MCV) *	4	3	EEM MCV includes dual-axle trucks down to 3.5 t instead of 8 t
Multi-axle Heavy Vehicle (HM)	Heavy Commercial Vehicle (HCV I & II) *	5-14	4-14	EEM HCV I & II includes up to 9 axles instead of up to 8 axles
--	Light Commercial Vehicle (LCV)	2 [wb>3]	1 [wb>3]	New optional LCV class to reflect high NZ usage of utes

* Including the EEM "Buses" classification, as appropriate by axle count (2 or 3)

3.2.1 Light vehicles (P)

The new definition [ISO/CD 11819-1, 2020] includes passenger cars and "crossover SUVs" having four or five seats. It does not include utes, very small cars (K category), vehicles with off-road tyres, or cars with loud exhausts.

This definition is consistent with a reasonable interpretation of the existing 1997 version of the standard and matches the selection process used in the Agency's Road Surface Noise Research Programme to date.

The P classification is a good fit for the EEM "Passenger Car" class, represented by NZTA 2011 class 2 and TNZ99 class 1, after filtering for wheelbase < 3.0 metres.

3.2.2 Dual-axle heavy vehicles (HD)

Also referred to by the new standard as "medium heavy vehicles", this includes medium-sized trucks and buses of at least 8 tonnes (gross vehicle mass) having two axles but only using two or four tyres on the driving axle (usually C2-class tyres[1]).

The EEM Medium Commercial Vehicle (MCV) class is also defined by two axles with a wheelbase of greater than 3.2 metres, but the minimum gross vehicle mass is 3.5 tonnes. To adopt the EEM MCV classification as equivalent to ISO HD classification would therefore be to include lighter vehicles in the HD measurements.

However, in practice when classifying vehicles during measurements in the field, many vehicles within the ISO HD classification will be difficult to distinguish from trucks lighter than 8 tonnes when seen in isolation and at highway speeds (e.g. Figure 3-2).

Figure 3-2: Two-axle trucks, 10 tonne on the left and 5 tonne on the right (shown to scale). Image credit: isuzu.co.nz

While some uncertainty is bound to occur wherever the arbitrary vehicle mass threshold is placed, a review of online vehicle specification sheets indicates that the EEM's 3.5-tonne threshold sits conveniently between ute-like/van-like vehicle shapes and truck-like vehicle shapes, which are easily distinguished in the field. Furthermore, general classification of NZ traffic is based on axle count and wheelbase, and there is no ability to distinguish the heavier from the lighter two-axle trucks within NZ traffic data. Finally, placing the threshold at 3.5-tonne follows closer to international precedent in road noise management [Directive 2015/996; Brown & Tomerini, 2011].

For ease of application in the field and to achieve harmonisation of definitions within NZ, our view is that the EEM MCV class definition should be adopted in preference to the ISO 11819-1 HD definition. Some EEM "Buses" may fall into this category, depending on axle count. Light trucks should still be excluded from the SPB measurement where their wheelbase is not clearly longer than 3.2 metres (i.e. if they are not obviously longer than a large ute).

3.2.3 Multi-axle Heavy Vehicles (HM)

Represented by full-size trucks having three or more axles, but not more than eight axles, and avoiding vehicles fitted with off-road tyres (e.g. quarry trucks).

TMS data indicate that less than 2% of traffic within the combined EEM HCV I and HCV II classes have greater than eight axles, and no vehicles have 10 or more axles. Excluding 9-axle vehicles would significantly complicate the fieldwork and traffic analysis. In the expectation that the noise emission of 8-axle and 9-axle trucks is to all effects indistinguishable, and given the tiny proportion of these vehicles on NZ roads, we recommend including 9-axle trucks in the multi-axle heavy vehicle definition.

The ISO HM classification is therefore a good fit for the combined EEM HCV I and HCV II classes, which are represented by NZTA 2011 classes 5-14, and TNZ99 class 4-14. Some EEM "Buses" may also fall into this category, depending on axle count.

3.2.4 Exclusions

Notable exclusions from the standard are long wheelbase vehicles that might fit in the EEM "Light Commercial Vehicle" category, such as utes, vans, and light trucks (less than 8 tonnes). These are popular vehicle classes in NZ, compared with Europe, and are still rising in popularity [Chaston, 2019]. Especially on some rural roads, this class can make up a considerable proportion of passing traffic. We suggest that ute and van pass-bys may still be captured during SPB measurements and coded under an additional "LCV" category, for informational purposes.

As discussed in section 3.2.2, our recommendation is for 2-axle light trucks that are obviously larger than a ute to form part of the dual-axle heavy class, HD.

3.3 Heavy Vehicle Movements

In road traffic noise modelling in NZ, the daily traffic flow is usually described by just two parameters, the Annual Averaged Daily Traffic volume (AADT) and the percentage of this that is made up of the MCV and HCV heavy vehicle classifications (%HCV). Heavy vehicle movements are particularly important in determining night-time noise effects on receivers near state highways [NZTA, 2014]. Future revisions of road traffic noise guidance or modelling methodology are likely to incorporate more detail on night-time noise, so the following section investigates how the NZ traffic mix changes over the day and between road classifications.

3.3.1 Time of day

Average hourly traffic data have been extracted from the TMS dataset and recoded into the EEM classification following Table 3-1. The *vehicle_config* field (a depiction of the axle configuration) has been used to expand the EEM Passenger Car classification into approximate sub-classifications of motorbikes[8] (wheelbase < 2.1 m), cars, and LCVs (wheelbase > 3.0 m).

The average hourly volumes for each vehicle classification are shown in Figure 3-3, normalised to an AADT of 10,000 for ease of interpretation. Note that the car curve (orange) and all traffic curve (black-dashed) use the right-hand vertical axis for scaling reasons, and are 10-times higher than they appear in relationship to the other curves.

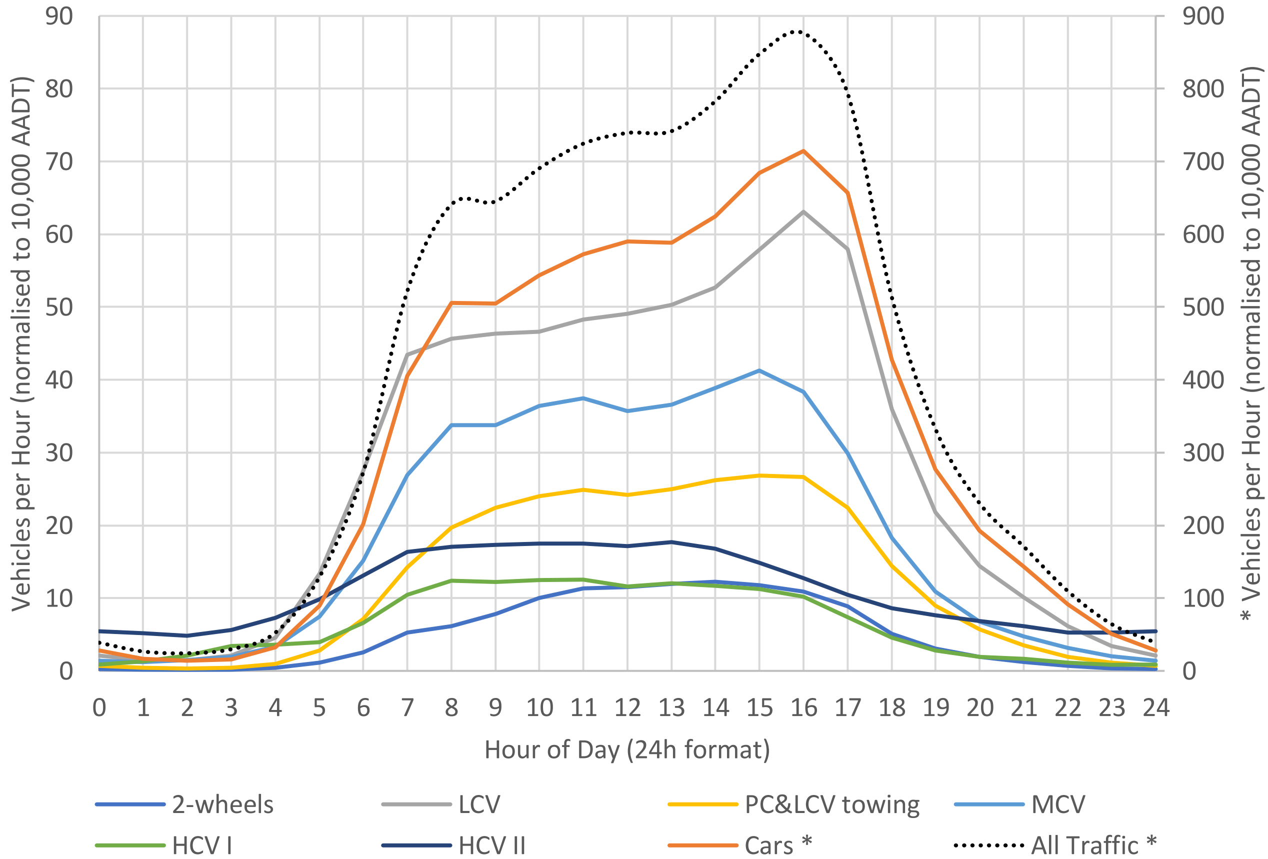

*Figure 3-3: Hourly volume of each vehicle classification over 24 hours, normalised to AADT of 10,000. The "Car * " (orange) and "All Traffic * " (black) volumes only are read from the right-hand axis, which is 10-times higher than the left axis.*

A day-night pattern applying to all classifications is immediately apparent, though the HCV II volume is less dependent on time of day than the other classifications.

[8] Pneumatic tube counters are generally not effective at detecting bicycles

Figure 3-4 shows how the traffic mix varies proportionally over the course of a day (motorbikes and light vehicles with trailers have been removed). A black dotted curve represents %HCV, which includes MCV and HCV I & II classes.

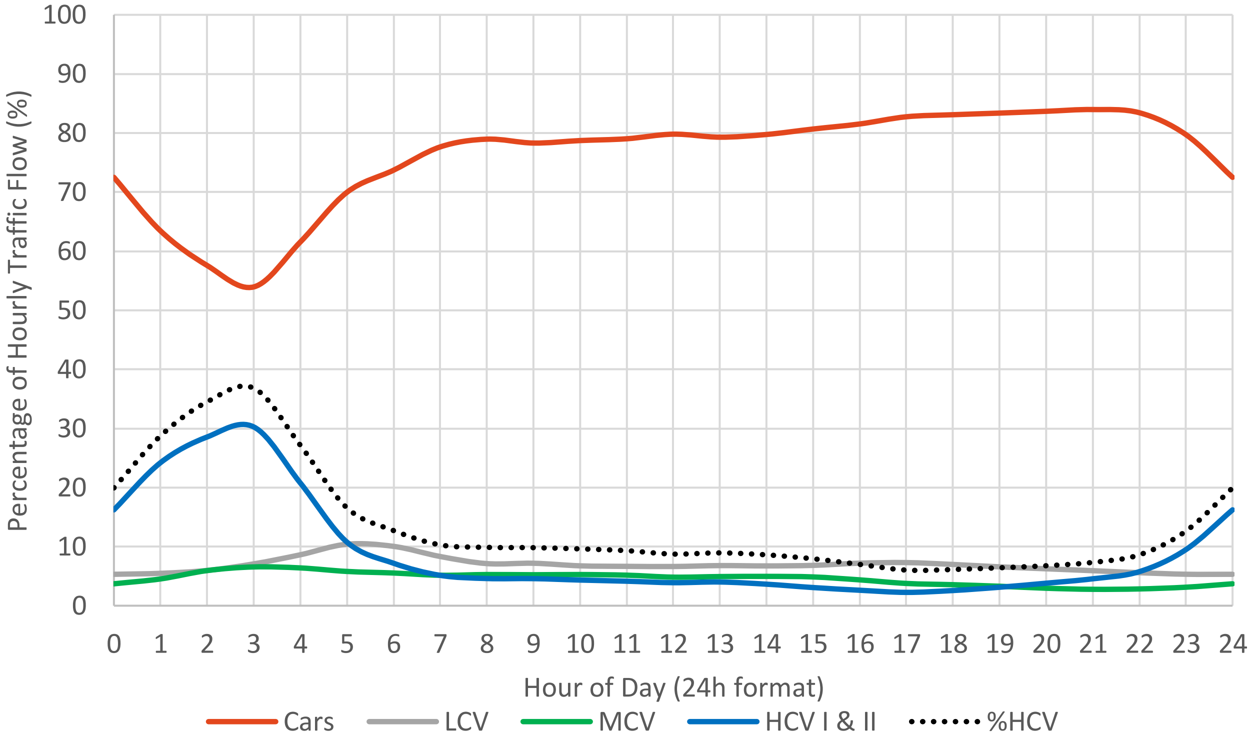

Figure 3-4: Average change in traffic mix over 24 hours

Across all the traffic monitoring stations the average %HCV over the full day is 9%, but in the early hours it gets as high as 37% of the total traffic flow. Within the %HCV metric, the variation is driven by the HCV I and HCV II classifications, while the MCV classification remains consistent at about 5% of the total traffic flow, mostly independent of time of day.

Incidentally, during the daylight hours, when SPB measurements typically occur, the average number of vehicles in the MCV and HCV categories is likely to be similar.

3.3.2 Road classification

To investigate how traffic patterns vary by location and usage of the road network, traffic monitoring sites have been grouped by their One Network Road Classification (ONRC), and %HCV calculated for each. Strategic roads not only have the highest overall traffic volumes (not shown), but also the highest proportion of heavy vehicles during the night time hours (Figure 3-5). Primary Collector roads also reach nearly 50% HCV traffic overnight, on average. During the day all ONRCs had similar %HCV on average, but it is known that this can vary greatly on a road-by-road basis within a given ONRC class.

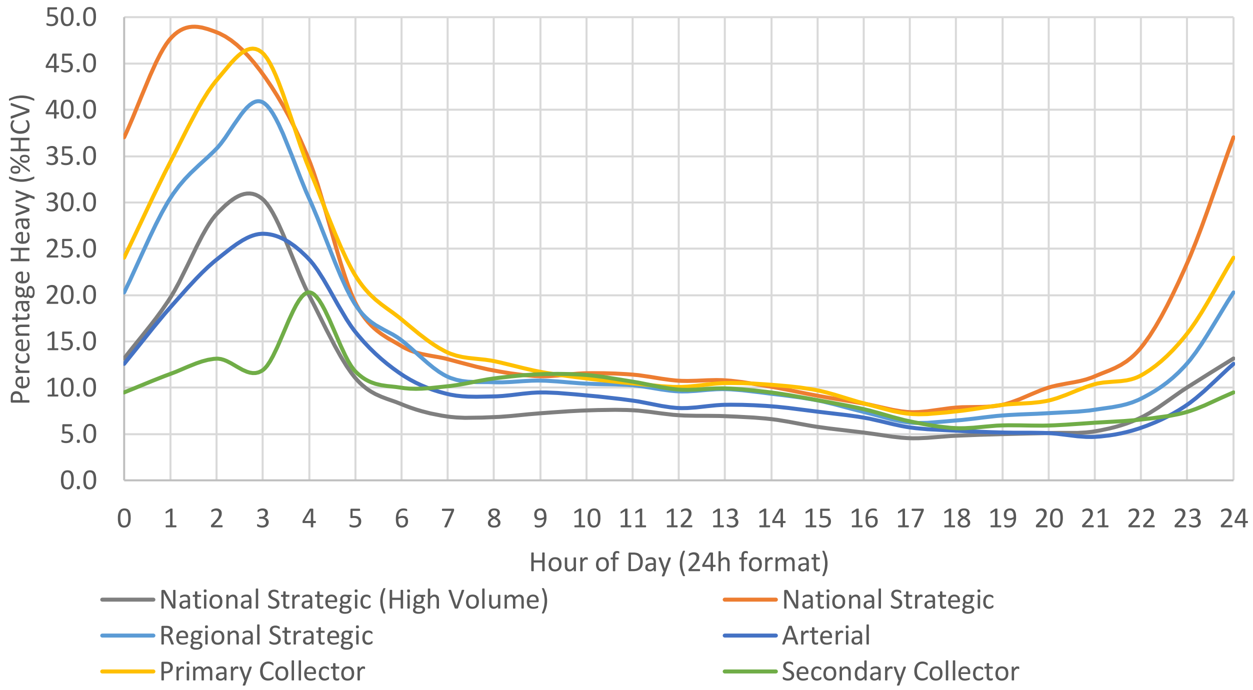

Figure 3-5: Percentage heavy (%HCV) by ONRC and time of day

3.3.3 Speed

The average vehicle speeds for each vehicle classification by hour-of-day have been calculated for each ONRC, with each representing a different mix of straights, curves, speed limits, and weather conditions depending on the details of the survey sites. Figure 3-6 shows average speeds for Primary Collector roads (high proportion of heavy traffic and close proximity to residences) and Figure 3-7 shows National Strategic roads (the ONRC with the highest proportion of heavy traffic). The other ONRCs, not shown, follow a similar pattern, generally laying somewhere between these two examples.

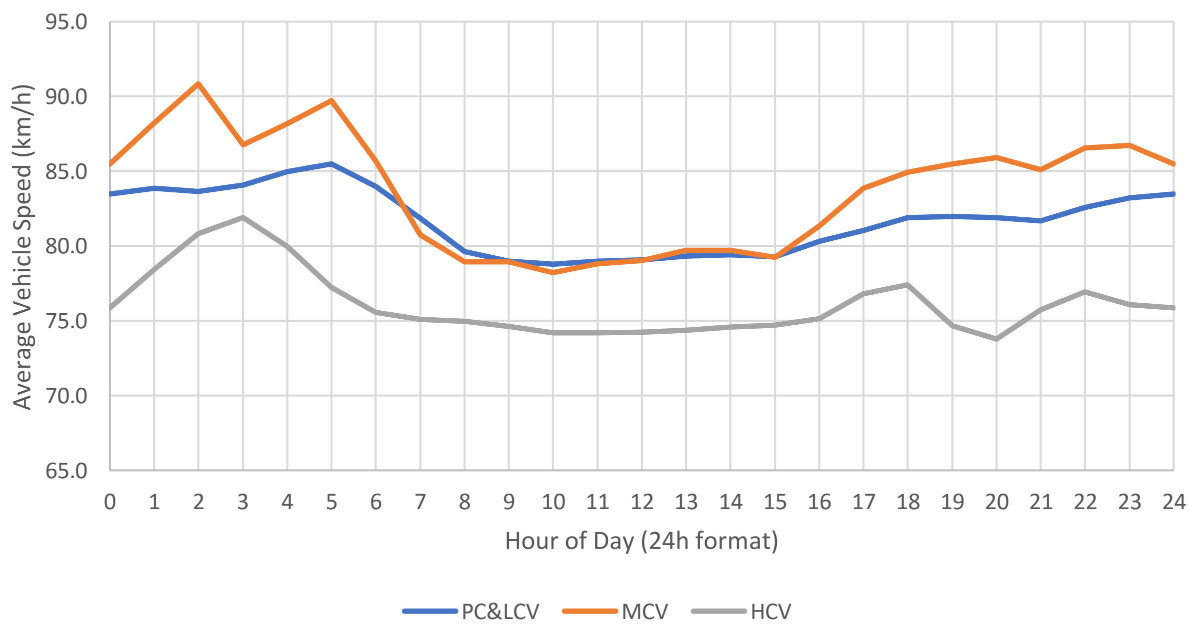

Figure 3-6: Average vehicle speed for Primary Collector roads by hour of day

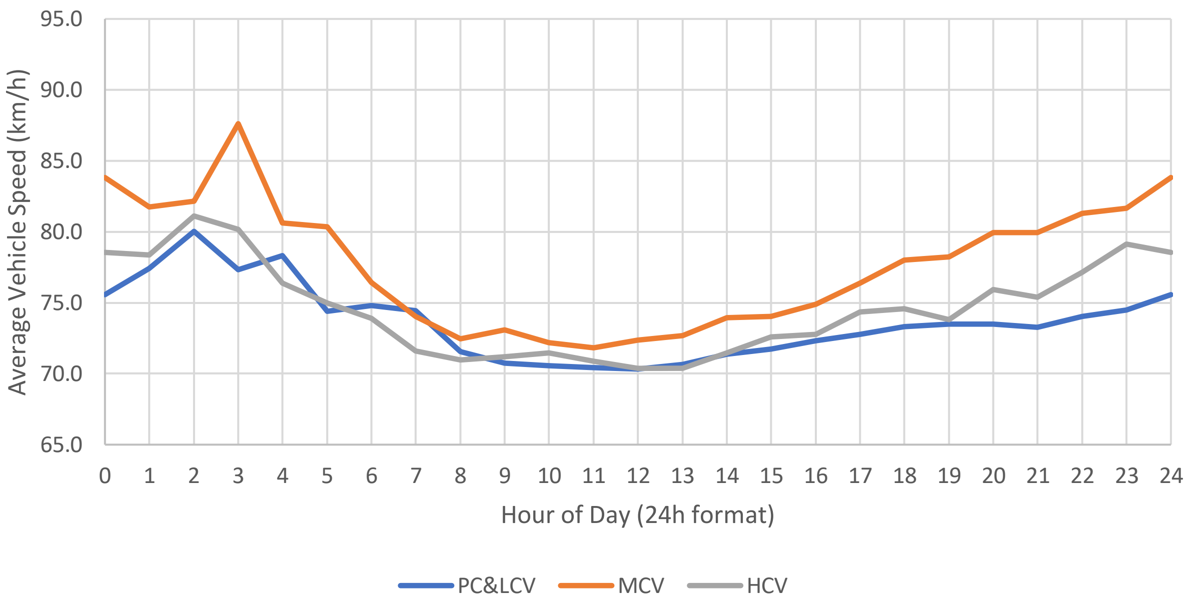

Figure 3-7: Average vehicle speed for National Strategic roads by hour of day

The MCV class consistently shows the highest average speed across all ONRCs. The HCV class typically has a similar average speed to that of the PC&LCV class (though in the case of Primary Collectors (Figure 3-6) it is 5 km/h slower). This is unexpected, but closer investigation reveals that on straight 100 km/h roads the HCVs are indeed somewhat slower (Table 3-3). None-the-less, both versions of the SPB standard [ISO 11819-1:1997; ISO/CD 11819-1, 2020] assume that MCV and HCV vehicles will be at least 10 km/h slower than passenger cars on “medium speed category” roads, which is not what the TMS data indicate occurs in NZ.

All ONRC and vehicle classifications indicated higher average speeds during night time hours compared to the day: PC by 7%, MCV by 14% and HCV by 12%.

The average speeds from all straight road sections within the TMS dataset are provided by vehicle classification in Table 3-3.

Table 3-3: Average speeds by vehicle class on straight sections of NZ state highways

Alignment	Speed Limit (km/h)	Average vehicle speed (km/h)		
		PC&LCV	MCV	HCV
Straight	100	91.9	90.2	84.6
Straight	50	47.7	47.5	46.6

4 Heavy Vehicle Tyre/Road Noise

This chapter combines elements of the CNOSSOS-EU vehicle source model identified in chapter 2 with the NZ traffic data discussed in chapter 3 to examine the effect of truck tyre/road noise on the overall noise level.

4.1 Vehicle Noise Emission

The balance between propulsion and rolling noise has been assumed to follow the CNOSSOS-EU model (section 2.2.4) including the updated coefficients of Kok & van Beek [2019].

4.1.1 Road Surface Contribution on Vehicle Noise Emission

The effect of the road surface is central to the calculation of road vehicle noise emission, but there are no surface corrections available from any source that can be confidently applied for NZ surfaces as a correction to the rolling noise component.

CNOSSOS-EU [Directive (EU) 2015/996] provides default corrections for common surface types in the Netherlands, but the surfaces are poorly specified in the Directive, and cannot be readily applied even within Europe [Lédée et al, 2016]. Further, we believe that the method CNOSSOS-EU uses to apply surface corrections for porous surfaces leads to a significant over-estimation of their effect.

The existing NZ road surface corrections [NZTA, 2014] were derived from wayside measurements performed at 50 km/h [Dravitzki & Kvatch, 2007], where propulsion noise is expected to be significant, and it is not possible to decouple the relative influences of rolling and propulsion noise.

The European Project ROSANNE (2013-2016) included the characterisation of road surfaces for noise, and Deliverable D2.5 was specifically about relating CPX road noise measurements to the CNOSSOS-EU model. The report [ROSANNE D2.5, 2016] concludes that in general the CPX method provides a feasible link to populating CNOSSOS-EU input datasets for light vehicles, but states that there is an issue with “how representative the [H1] test tyre [is] of heavy truck rolling emission” when it comes to populating heavy vehicle data. The same conclusion has been reached in NZ in respect of CPX with the H1 tyre [Jackett, 2018].

Instead of applying corrections that are of dubious quality or relevance, a sensitivity analysis on the road surface correction term has been performed (sections 4.3.3 and 4.3.4).

4.1.2 Validation for the NZ fleet

To verify that the CNOSSOS-EU overall noise emission is broadly representative of each NZ vehicle classification in relative terms, the CNOSSOS-EU light vehicle sound power in dB L_{WA} is subtracted from the MCV and HCV sound powers, respectively, for each speed (Figure 4-1), and compared with available NZ-specific data in the form of individual SPB measurements[9]. It is not a perfect test: in general the difference in sound power levels may be somewhat greater than the equivalent difference in SPB levels for HCVs because of the long duration of the pass-by. However, it is the best test available, and should identify whether or not the CNOSSOS-EU overall levels approximate the NZ levels in relative terms.

[9] NZ data must be in the form of wayside measurements of the overall noise level of both cars and trucks, travelling at the same or very similar specified speeds, on the same section of specified road surface. Further, the road surface should be as similar in character to the CNOSSOS virtual reference road surface of 50/50 DGA-11/SMA-11 as possible, so should be from (mostly) non-porous surfaces with relatively low macrotexture. This discounts OGPA and most chipseals, leaving only DGA, SMA, grade 4 to 6 chipseals, and most slurries).

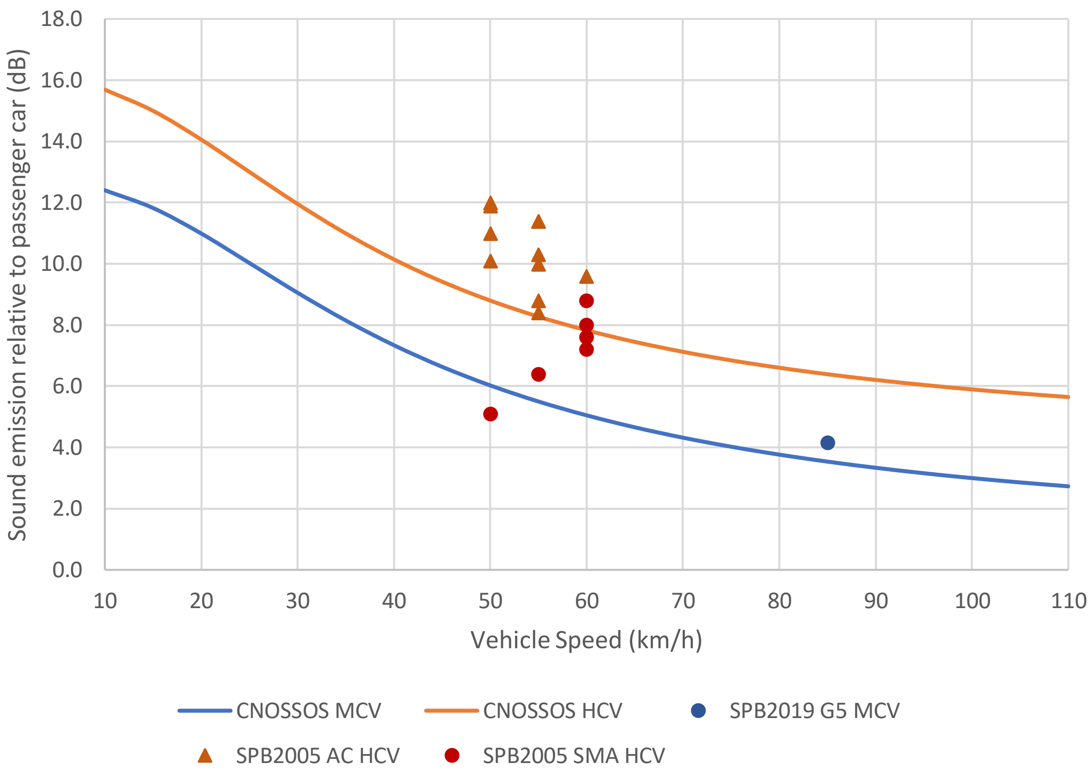

Figure 4-1: Vehicle noise emission of MCVs and HCVs relative to cars

NZTA Report 326 [Dravitzki & Kvatch, 2007] includes SPB data for cars and HCVs on several road surfaces, including 11 examples of AC-10 and 6 examples of SMA-10 and SMA-11. These surfaces are nominally equivalent[5] to the CNOSSOS-EU reference surfaces and are plotted in Figure 4-1 at speeds from 50 to 60 km/h in orange, for comparison with the orange CNOSSOS-EU HCV curve. Within this narrow speed range the SMA surfaces (red circles) fell on or below the CNOSSOS-EU HCV curve, while the AC-10 surfaces (orange triangles) were generally above it. On average, the agreement seems to be very good. The large range in the NZ measurement data is a reminder that the models only deal with the 'average' emission over a great number of vehicles and surface examples, and the variation about that mean can be large.

More recent SPB data [Jackett, 2019] was gathered on OGPA and chipseal surfaces at 80-100 km/h and while it did not include AC or SMA surfaces, it did include one grade 5 chipseal surface, which is fairly similar in acoustic characteristics to European SMA-11 (similar texture, similar chipsize, non-porous; see Appendix A). A value is only available for MCVs at 85 km/h, and this is plotted as a blue dot in Figure 4-1 and fits reasonably well to the CNOSSOS-EU MCV curve.

Whilst only covering a fraction of the speed range, the comparison to NZ SPB data is quite good, and supports using the CNOSSOS-EU overall vehicle emission levels as they stand.

4.2 Traffic Noise Emission

The individual vehicle sources (chapter 2) can be summed to predict the noise emission of a stream of traffic as a line source. For the purpose of this project, the CNOSSOS-EU method [Directive (EU) 2015/996] is adapted to determine an A-weighted sound power per metre, $L_{WA,line,m}$ in dB (re. 10^{-12} W/m), for each vehicle classification, m, as in equation 4.1:

$$L_{\mathrm{WA,line,m}} = L_{\mathrm{WA,veh,m}}(v_m) + 10\, log_{10}\left(\frac{Q_{\mathrm{m}}}{1000\ v_{\mathrm{m}}}\right) \qquad (4.1)$$

Where $L_{WA,veh,m}(v_m)$is the individual vehicle sound power emission of vehicle class m travelling at average speed v_m, and Q_m is the traffic volume of that class in vehicles per hour. By way of explanation, the divisor v_m indicates the inverse relationship between vehicle-passing-time and sound energy; the relationship between vehicle speed and sound power is covered by the vehicle noise emission term $L_{WA,veh,m}(v_m)$.

The vehicle rolling and propulsion noise emission data from chapter 2 have therefore been linked, via equation 4.1, to the TMS dataset, from which the vehicle classifications, volumes, and speeds can be drawn.

4.3 Analysis of Noise Level Data

For each ONRC classification (section 3.3.2) the average relative traffic volumes for each vehicle classification (normalised to 10,000 AADT) and their average speeds (section 3.3.3) are calculated. For each hour of the day the vehicle rolling and propulsion noise emissions for each class are predicted by the CNOSSOS-EU model based on the average vehicle speed and the reference surface. The traffic noise emission is predicted (as sound power per metre of road) from the overall vehicle noise emission for each class and the volume and average speed of vehicles of that class, as described in section 4.2. The predicted overall noise emission of the road by hour of the day is the incoherent combination of levels from the three vehicle classifications.

4.3.1 Influence of road classification

National Strategic Highways carry the highest overall proportion of HCVs of all the ONRC classes, and as noted in section 3.3.2, show the least decline in HCV volumes overnight. Figure 3-7 showed that vehicle speeds were on average 10 km/h faster during the night time than during the middle of the day on this road classification.

Figure 4-2 shows how this might translate into the noise emission of a National Strategic Highway. The volume of passenger cars and light commercial vehicle traffic dominates the noise emission during the daytime, and drives the evening peak around 5pm, but thereafter the noise emission drops off into the evening. Meanwhile, the much more constant volume of HCV traffic, coupled with the increase in speeds at night time and the sharp fall in PC&LCV numbers means that between 23:00 and 05:00 it is HCVs that drive the overall noise emission from the highway. MCVs do not appear to contribute significantly to the overall noise emission on this road classification.

Note that the vertical scale on the following graphs is an A-weighted sound power per metre of road (dB L_{WA} / m), but that the same relationships *between* curves also apply to sound pressure levels close to the roadside, such as from an $L_{Aeq(1h)}$ measurement.

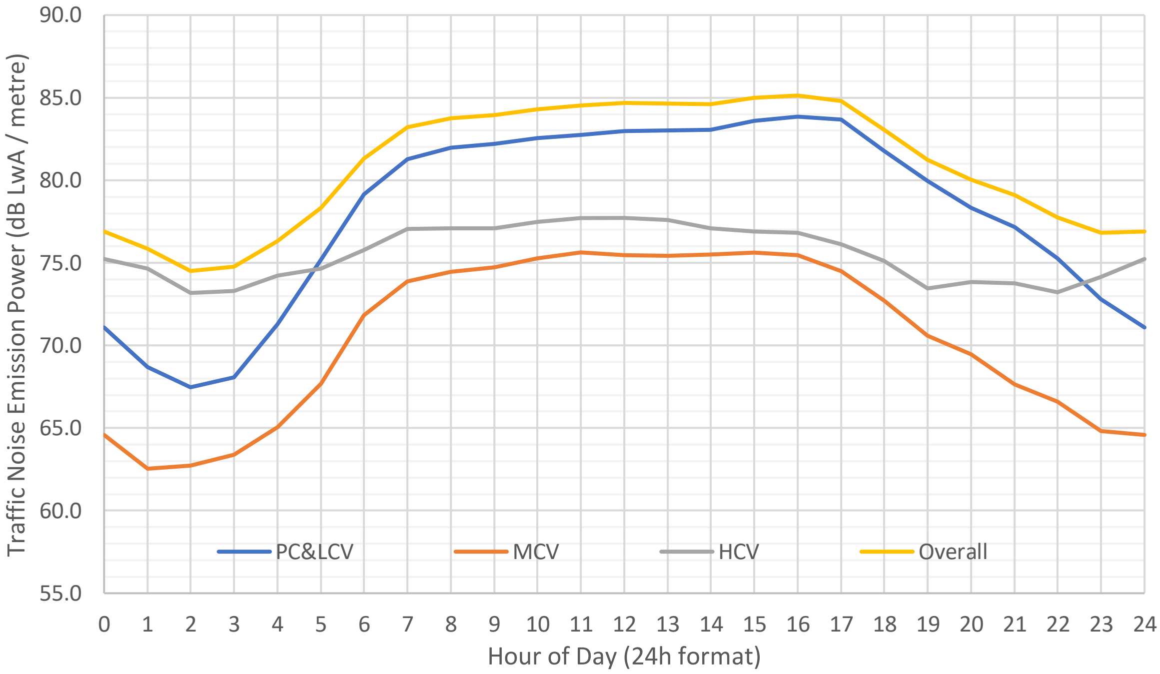

Figure 4-2: Traffic Noise Emission for the "National Strategic" ONRC road classification

While the National Strategic road shows the strongest HCV influence, the other Strategic classifications show similar behaviour, with HCV traffic contributing more sound power than MCV traffic at all hours, and more than PC&LCV at night.

The Arterial classification (Figure 4-3), similar to the Primary and Secondary collectors, is dominated by PC&LCV traffic for most of the 24-hour period. Only between about 00:00 and 04:00 is HCV traffic on even terms with the PC&LCV noise emission. Whilst MCVs match the HCV contribution during the day, they play little part in the overall noise emission of the road.

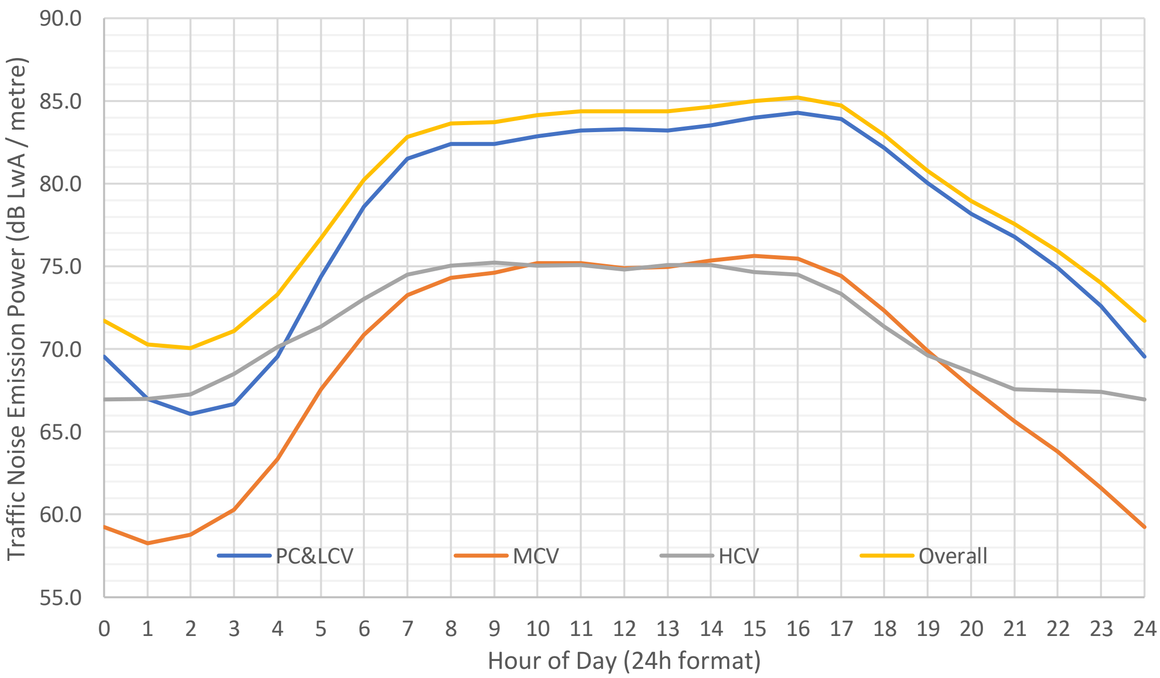

Figure 4-3: Traffic Noise Emission for the "Arterial" ONRC road classification

The road classification is important in describing when HCVs may be significant in the overall noise emission level of the road, whereas MCV traffic was of much lower importance to the overall emission for all road classifications. Note that this is not to say that MCV or HCV traffic is insignificant when it is not the dominant sound power source, because passing MCVs and HCVs may still produce the peak noise events (L_{AFmax}) on any given stretch of road at any time of the day.

4.3.2 Influence of traffic speed

To illustrate the influence of speed, on the left hand side of Figure 4-4 are the noise emission curves for the average Secondary Collector (average speed of 85 km/h for cars and MCVs and 80 km/h for HCVs), and on the right is the same classification but with the speed reduced to 50 km/h for all vehicle classes.

PC&LCV traffic emission is reduced by about 5 dB at 50 km/h (-7 dB from vehicle rolling noise reduction, but +2 dB from vehicles taking longer to pass by at 50 km/h). The overall MCV and HCV traffic emissions reduce by only about 2 dB each, despite their individual rolling noise emissions decreasing by 6 dB, because at 50 km/h the propulsion noise now dominates overall (Figure 2-2). Noise emissions from the 50 km/h traffic is therefore more sensitive to variations between individual heavy vehicles or heavy vehicle volumes than the 85 km/h traffic, and the spectra would also represent that. A difference in wayside noise level of about 4 dB $L_{Aeq(24h)}$ would be expected between these speeds.

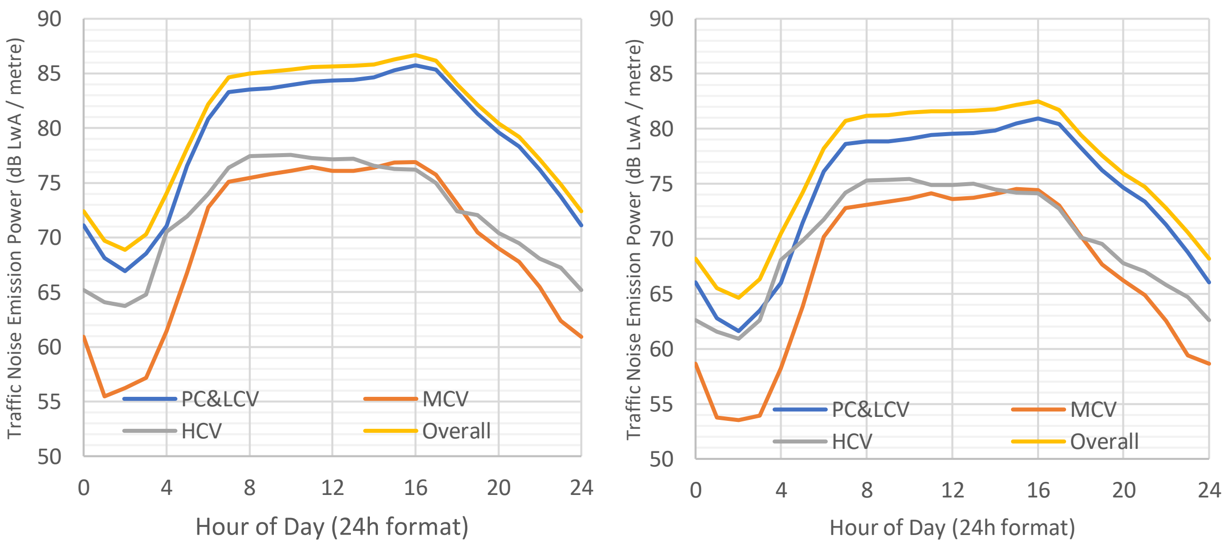

Figure 4-4: A Secondary Collector with average speed 85 km/h (left) and 50 km/h (right)

Speed reductions are rarely used as an instrument for noise mitigation, but this example illustrates that at lower speeds, the ability of the road surface to influence overall truck noise is diminished, as would be the effectiveness of "quiet tyre" regulations (for trucks). "Quiet engine" regulations would become more effective.

4.3.3 Sensitivity of $L_{Aeq(24h)}$ to the road surface correction

The core aim of this study is to quantify the benefit (or cost) of changes to the road surface for heavy vehicles in terms of the overall road traffic noise level. In the absence of usable road surface corrections (section 4.1.1), sensitivity of the overall road traffic noise emission with respect to the road surface correction term itself has been analysed.

The baseline traffic data for this analysis uses the average of the normalised traffic volumes across all ONRCs so that no single road classification dominates. An additional 24-hour speed profile for each vehicle class has been extracted from only those TMS sites located on straight sections of highway with 100 km/h speed limits. This was not necessary for 50 km/h zones because all vehicle classes travel at very near the same speed in those speed zones (Table 3-3). The traffic data were used as an input to the CNOSSOS-EU vehicle and traffic noise methods, and baseline hourly sound power levels for the two speed zones were calculated.

Pseudo surface corrections of + 3 dB and – 3 dB were used to perturb the model for noisier and quieter surfaces, respectively[10]. This was propagated through the model for the three scenarios below, and the output compared to the baseline to quantify their sensitivity to a ± 3 dB surface change:

1. An increase/decrease of the surface correction affecting passenger cars only.
2. An increase/decrease of the surface correction affecting heavy vehicles only (MCV & HCV).
3. An increase/decrease of the surface correction affecting all vehicles equally.

The hourly sensitivity results (in dB L_{WA}) have been combined to approximate the effect of each simulated surface intervention on the overall 24-hour wayside level noise level ($L_{Aeq(24h)}$), and these are presented in Table 4-1 for the two speed zones[11].

Table 4-1: Sensitivity of the $L_{Aeq(24h)}$ level to changes in the road surface for cars, heavy vehicles, and both

Speed Limit (km/h)	Effect on wayside noise level in dB $L_{Aeq(24h)}$ from a change to road surface correction by ± 3 dB					
	Surface + 3 dB for:			Surface - 3 dB for:		
	Cars	Heavy vehicles	Both	Cars	Heavy vehicles	Both
50	1.8	0.6	2.2	-1.3	-0.3	-1.7
100	2.3	0.6	2.7	-1.9	-0.3	-2.4

The effect of the ± 3 dB road surface correction change on the resulting wayside $L_{Aeq(24h)}$ level depends greatly on whether it affects passenger cars or just heavy vehicles. The wayside level is insensitive to changes affecting only heavy vehicle rolling noise, whether those are positive or negative changes, and this applies across both speed limits. Conversely, a ± 3 dB change to the surface correction that only affects cars leads to an approximate ± 2 dB effect on $L_{Aeq(24h)}$; a much better "rate of return". A ± 3 dB road surface correction that affects the rolling noise of both classifications equally achieves in the region of a 2.5 dB change to $L_{Aeq(24h)}$ at 100 km/h, and 2 dB at 50 km/h, driven by the passenger car rolling noise emission.

This result is consistent with findings from earlier chapters: heavy traffic makes up approximately 10% of the daily traffic volume, and although they are individually noisier than cars, the noise is only partially generated at the road surface where a surface intervention might be effective.

If the wayside A-weighted 24-hour equivalent noise level, $L_{Aeq(24h)}$, is the only parameter of interest, then it is clear that surface interventions affecting only truck tyres will not provide any noticeable benefit (a -3 dB investment leads to a -0.3 dB return, an efficiency of about 7% in terms of acoustic energy). The analysis suggests that surfaces designed to benefit car tyre/road noise that also

[10] The arbitrary magnitude of 3 dB was chosen because it represents a decent step (a doubling/halving of sound power and an audible change) whilst still being a conservative estimate of what might be practically achieved by moving from the reference surface to say a coarse chipseal (+ 3 dB) or to an OGPA (- 3 dB).
[11] Greater sensitivity to increases in rolling noise compared to the same sized reductions is typical for acoustic applications, and relates to the logarithmic combination of multiple sources at comparable levels. A related detail is that multiple reductions, when combined, can be greater than the sum of their parts.

provide an incidental benefit to heavies can be effective (up to 74% efficiency, by energy), but this is almost entirely due to the benefit realised by cars.

4.3.4 Sensitivity to road surface correction by hour of day

Continuing the analysis methodology of the previous section (4.3.3), the effect of a ± 3 dB change in road surface correction on the overall road noise emission level has been determined hour-by-hour for 100 km/h and 50 km/h speed zones.

In Figure 4-5, the top half of each graph shows the effect of a + 3 dB change to the car surface correction (dotted), the heavy vehicle surface correction (dashed), and both (solid). The bottom half of the graph shows the effect of a - 3 dB change (i.e. moving to a quieter road surface).

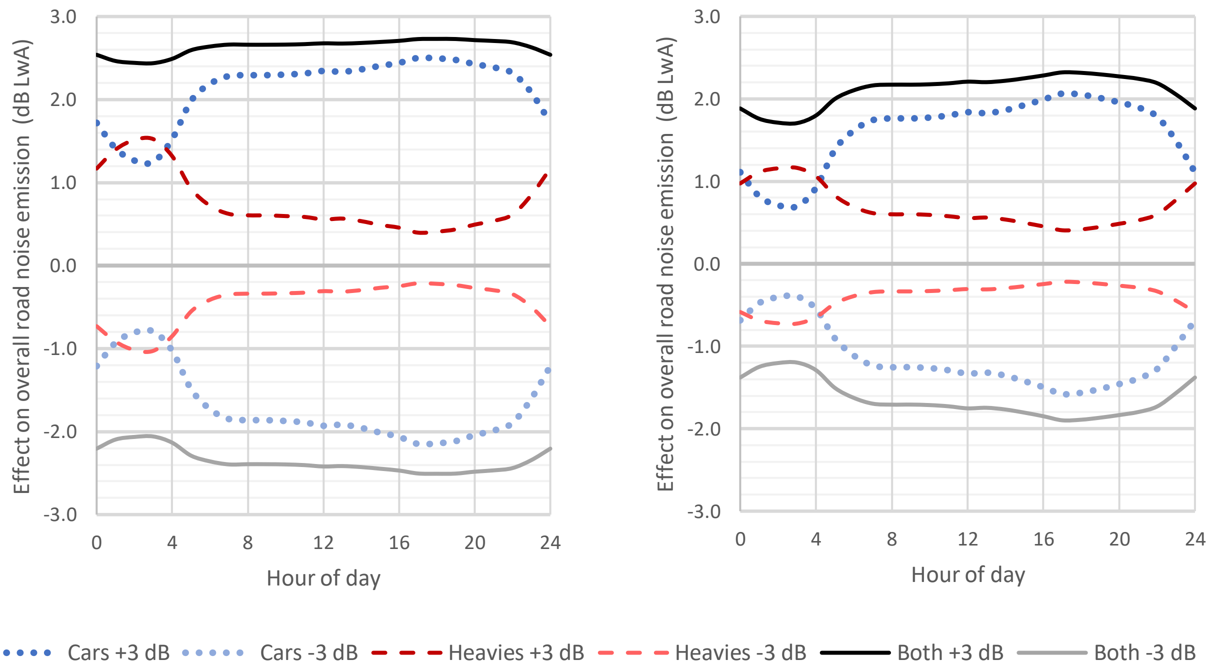

Figure 4-5: Sensitivity of overall noise emission to a ± 3 dB change in road surface correction for roads with 100 km/h (left) and 50 km/h (right) speed limits

First, consider a +3 dB surface correction for the 100 km/h road (the top half of the left graph in Figure 4-5). The black line shows the overall increase in road noise emission due to a surface that affects car and truck rolling noise equally. The blue dotted line indicates that for most of the day it is the surface's effect on car rolling noise that drives this increase. But from about 23:00 to 05:00 the surface's effect on truck rolling noise is also important – just as important as the surface's effect on car rolling noise.

The same general statement holds for a surface correction reduction of 3 dB, and 50 km/h hour roads are different only in that the surface correction has less influence on the emission overall.

These results generally echo those of section 4.3.3, in that the overall acoustic performance of a surface is almost entirely determined by how car tyres, rather than truck tyres, respond to it. However, during the night-time period, the performance of the surface with respect to truck tyres is just as influential on the overall traffic noise level as its performance with respect to cars.

5 Measurement Methodologies

There is currently demand in NZ for methods to:

1. measure the tyre/road noise emission of heavy vehicles, suitable for the optimisation or assessment of road surfaces; and
2. evaluate the contribution of the road surface to wayside noise levels, suitable for determining road surface correction factors for heavy vehicles.

In general, the first requirement will need tyre/road noise to be isolated, while the second could use either isolated tyre/road noise measurements or overall pass-by noise. This chapter provides shortlists for both types of measurement.

5.1 Accuracy Requirements

The accuracy requirements for a measurement will depend on the application, and should be understood before deciding on the measurement methodology.

However, the sensitivity of the $L_{Aeq(24h)}$ wayside noise level to the road surface correction is very low for heavy vehicles (in the order of ± 0.5 dB for a ± 3 dB change, see section 4.3.3), and this may be relevant in identifying the appropriate measurement methodology. For other applications, such as night time noise or low frequency noise, or on other roads, the sensitivity may be greater (section 4.3.4).

5.2 Measuring the Tyre/road Noise Emission of Heavy Vehicles

This method needs to be able to isolate the contribution of tyre/road noise from the overall noise of a moving truck. This is not a trivial task, and requires either highly specialised instrumentation or a well-controlled experimental design.

5.2.1 CPX trailer with H1 tyre

CPX noise measurements are made using microphones mounted just a few centimetres from a rolling test tyre's contact patch, and are very effective at isolating tyre/road noise from most other sound sources of the vehicle and environment.

The H1 test tyre, an Avon AV4 van tyre, was selected by the ISO 11819-2:2017 technical committee as the best candidate to represent the behaviour of both C2 and C3[1] truck tyres. However, previous CPX surveys with this tyre in NZ did not find a statistically significant correlation to wayside truck levels at highway speeds [Jackett, 2019] and stated that the H1 should not be used to populate corrections if a correlation could not be established. European research [ROSANNE D.25, 2016] also found a poor correlation (r^2 = 0.52), and expressed concern that the AV4 test tyre may poorly represent heavy truck rolling noise emission.

Current knowledge of the (current) H1 tyre specification suggests that it would not be a reliable method to determine the tyre/road noise emission of heavy vehicles on NZ roads.

5.2.2 On-board CPX

The Agency currently operates a trailer-based CPX system, but CPX systems can also be mounted directly "on-board" motor vehicles [ISO 11819-2:2017], and one has been used this way in NZ previously [Lester et al, 2017], on a passenger car. On-board sound pressure (OBSP) or on-board sound intensity (OBSI) systems are possible, and in either case require a special mounting rig to maintain precise positioning of the microphones near the tyre/road contact area. OBSP and OBSI each have their advantages, but the instrumentation requirements for OBSI are more onerous.

Either OBSP or OBSI would be a viable method of isolating and measuring tyre/road noise. A significant advantage over a trailer-based system is that actual heavy vehicle tyres could be used under representative loadings. However, representative test vehicles and tyres would need to be selected with care, and consideration given to how the method could be made reproducible in the absence of an officially specified test tyre. The system will also suffer from the same drawback of all CPX-based systems, which is a low-frequency limit of about 250 Hz due to system geometry.

A NZ implementation of OBSP might be able to use much of the existing CPX trailer instrumentation setup, but would require the purchase or construction of a mounting rig (or rigs) suitable for use on MCVs and HCVs. The accuracy, repeatability, and reliability of the measurement system would need to be determined and any safety issues from the rig considered.

5.2.3 CPX trailer with P1 tyre

This novel method would estimate the heavy vehicle tyre/road noise emission through a calculation involving CPX trailer P1-tyre measurements (usually for representing cars) and additional information already known about the road surface, for example its texture and surfacing material.

The method is based on one proposed by Sandberg & Ejsmont (2002), who provide equations that derive passenger car tyre/road noise (as SPB levels) from the non-acoustic parameters of road surface texture, porosity, thickness, and age. Heavy vehicle tyre/road noise is subsequently derived from the passenger car noise, with a further correction for texture only. The heavy vehicle calculation was validated against SPB(heavy) measurements on over 50 heavy vehicles and 100 cars over 13 different surfaces, achieving residual standard deviations of below 1 dB ($r^2 = 0.95$), which appears to far exceed the ability of CPX(H1) to estimate wayside truck levels ($r^2 = 0.52$) [ROSANNE D.25, 2016].

The method proposed here would substitute measured CPX(P1) levels for the passenger car calculation, and could therefore be used to predict either the wayside level from heavy vehicles (via the strong CPX(P1) to SPB(cars) correlation, $r^2 = 0.94$ [Jackett, 2019]) or a pseudo-CPX heavy vehicle tyre/road emission. Detailed macrotexture data is available from RAMM for NZ state highways, and may eventually be measured by the Agency's CPX trailer itself. Surface porosity and thickness data, if required, are not readily available for NZ roads.

Once established, this method is efficient in terms of the effort required to survey a given route for both passenger car and heavy vehicle tyre/road noise. The accuracy will rely on the quality of the CPX(P1)-to-HCV-noise relationship, and its ongoing validity. There will always be a risk that erroneous characterisations will be calculated for surfaces that do not fit the established relationship, and this would need to be evaluated against the accuracy requirements (section 5.1).

The method will also require the initial collection of measurements by an independent method in order to establish the correlations in NZ conditions, and this could be a considerable effort.

5.2.4 Coast-by

Coast-by measurements [ISO 13325:2019] are controlled pass-by measurements where the engine is switched off (in some cases put into a low idle) and the gearbox is put into neutral, with the aim of reducing engine, exhaust, and transmission noise emission as much as possible. The remaining noise is attributed to 'rolling noise', which in the case of trucks travelling between 50 km/h and 100 km/h is almost entirely due to the tyre/road interaction (section 2.1). The sound pressure measurement is made with a sound level meter or data acquisition system at the wayside, similar to SPB measurements[12], though the possibility exists to measure a sound exposure level from passing trucks rather than just L_{AFmax}, to capture the longer pass-by duration.

This method has the advantage of not requiring complex instrumentation, while still being a well-controlled experiment that isolates tyre/road noise effectively [Czyzewski & Ejsmont ,2008], and provides a wayside noise level directly rather than via the abstraction of an on-board or CPX level.

[12] ISO 11819-1:1997 states that SPB itself isolates the influence of the road surface, but this is incorrect.

Only a few passes are necessary to achieve good accuracy [Dravitzki & Kvatch, 2007], but it is time consuming to perform and is representative of just a short section of one lane. Safety needs to be managed before operating a truck with its engine switched off on public roads. Test vehicle and tyres would need to be selected with some care.

Coast-by measurements would be the most effective method for validating vehicle source models or other measurement techniques, because it provides a wayside sound pressure level directly, and can be combined with cruise-by (constant rpm) and drive-by (accelerating) measurements to quantify both the rolling and propulsion components. However, the complexity of securing an appropriate test site makes it impractical to do on a regular basis in NZ.

5.2.5 Tyre/Road dominated cruise-by

To mitigate some practical limitations of coast-by testing (section 5.2.4), it may be possible to identify a heavy vehicle make and model and operation modes such that the noise emission at high speed is intentionally dominated by tyre/road noise. This may be achievable through a combination of (comparatively) loud tyres, many axles, a high pass-by speed (e.g. 90 km/h), a quiet engine and exhaust design, low rpm via selection of a high gear, a skilled driver, and perhaps additional factors[13]. The aim would not be to remove propulsion noise entirely, as in coast-by, but to reduce it sufficiently far below the rolling noise component that the overall wayside noise level is representative of the rolling noise component, and therefore sensitive to the road surface.

Because the heavy vehicle would effectively be operating in a 'normal' driving condition, it is anticipated that the safety requirements would be greatly reduced.

In other respects this method would be equivalent to the coast-by method, with the exception that back-to-back comparisons of cruise-by and coast-by would no longer be representative.

5.2.6 Microphone Arrays

Large roadside arrays of microphones can be used to determine both the magnitude and the direction of incidence of pass-by noise, using either beam-forming or holography [Li, 2018]. Arrays have been used to successfully distinguish onboard noise sources from each other spatially [Li, 2018], including for trucks [NCHRP 842, 2017], but also present a number of technical limitations. Viewed from wayside, the engine noise, aerodynamic noise, and tyre/road noise of a passing truck all originate predominantly from the front wheel well [NCHRP 635, 2009], and thus are not easily distinguished spatially even under ideal measurement conditions. Additionally, beam-forming and holography are challenged by pass-by measurements, because of the rapidly changing source angle and distance, the low frequency source, and the Doppler effect [NCHRP 635, 2009].

This technique appears inappropriate as the primary method of measurement, but could be a useful supporting tool if used in a more qualitative fashion.

5.3 Measuring the Overall Noise Emission of Heavy Vehicles

Measuring the overall noise emission of passing heavy vehicles is more straightforward, and consequently fewer methods have been proposed.

5.3.1 Statistical Pass-By

SPB [ISO 11819-1:1997] is the method that has traditionally been used internationally and in NZ [Dravitzki & Kvatch, 2007] for determining the pass-by noise level of different vehicle classifications, and is still being specified even in applications that require separate propulsion and rolling noise components [Lédée et al, 2016]. The key advantages of the method are that it is simple to employ

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[13] An additional modification, or alternative, would be to use post-processing to focus the analysis time-window on the final axles of the trailer and exclude the front of the truck where the engine noise is strongest. This would require synchronous video capture and add some complexity.

and its noise levels are generated by the actual vehicle fleet, so are inherently more representative of wayside noise levels than most other methods.

Its main disadvantages are having to identify sites appropriate for the method (straight, flat roads with wide flat berms, far from intersections and reflecting surfaces) and the time it takes to accumulate sufficient valid heavy vehicle pass-bys on some roads.

The standard SPB metric is based on the average of many L_{AFmax} measurements, but with additional effort the process could be modified to include sound exposure level over some defined duration, and octave or 1/3-octave band levels.

5.3.2 Controlled Pass-By

Controlled Pass-By is a modification of the SPB methodology that uses a test vehicle in place of the vehicle fleet. This method has been used previously to populate some of the NZ road surface corrections database [Dravitzki et al, 2006].

It is less representative of the vehicle fleet than SPB (though this depends very much on the selection of the test vehicle) but compensates by returning a lot of control to the experimenter and reduces the number of vehicle passes required to achieve satisfactory repeatability.

Instrumentation requirements and options are the same as SPB, but a truck and driver would also be needed. See also sections 5.2.4 and 5.2.5 on coast-by noise measurement.

5.3.3 Roadside Sound Level Survey

An extensive roadside survey of sound levels was used in NZTA Research Report 28 [Barnes & Ensor, 1994] to validate the CRTN noise model for NZ, and it is proposed that a more modern equivalent of this approach could be adapted to extract light and heavy vehicle pass-by noise levels from continuous noise measurements. A similar method has been used in the US to measure pass-by levels on roads that are too busy for SPB to be practicable [Li, 2018], and has been labelled the Continuous-Flow Traffic Time-Integrated Method (CTIM).

A NZ application would require real-time traffic data to be synchronised with $L_{Aeq(t)}$ noise level measured at the wayside over multiple discrete time periods, *t*, and post-processing would statistically separate the sound level contribution from heavy vehicles from light vehicles using the traffic count data and the natural variation of traffic mix between time periods.

The measurement system would need to be developed, and accurate traffic classification data would be required. This system would have the advantage of being largely unattended, and would output the same sound level metric, $L_{Aeq(t)}$, that is used in NZ for road traffic noise modelling and assessment.

6 Summary and Conclusions

Hierarchy of truck noise generating mechanisms

- There is no international consensus on the hierarchy of truck noise generation mechanisms at most traffic speeds (section 2.1), let alone consensus on quantification. Even after distilling down to rolling (tyre/road, aerodynamics, some transmission) and propulsion (engine, exhaust, transmission) noise components a comparison of seven noise models show a broad range of predictions (sections 2.2.4 and 2.2.7).
- The CNOSSOS-EU noise model was selected as the best available representation of truck tyre/road noise as a proportion of the overall noise emission, for the purposes of this project, based primarily on its consistency with European, US, and Australian truck noise measurements (section 2.3) and the availability of algorithms for the model. However, we recommend that field measurements are performed to validate the truck vehicle source model for NZ.

NZ Heavy Vehicle Data

- The NZ vehicle classification schemes have been compared against the upcoming Statistical Pass-By standard [ISO/CD 11819-1, 2020] and recommendations for interpretation have been made in section 3.2 that will enable a practical implementation in NZ, whilst maintaining adherence to the standard.
- TMS vehicle classification data from 170 million vehicle passes has been analysed to provide an overview of truck types and movements within NZ (section 3.3). Whilst forming a small proportion of the vehicle flow on all road classifications during the day, on average, at night truck movements made up over 40% of Strategic and Primary Collector traffic and increased in speed by 5 – 10 km/h over the daytime average.

Heavy Vehicle Tyre/Road Noise

- We have re-constructed CNOSSOS-EU vehicle and traffic models (section 4.1) and used these to predict the overall noise emission based on NZ traffic data for each ONRC road classification (section 4.3.1).
- All ONRCs show cars dominating noise emission during the day, but on Strategic roads HCVs dominate between 23:00 and 05:00 (Figure 4-2), and on Arterials and Collectors HCVs and cars have similar emission levels from 00:00 to 04:00 (Figure 4-3). The MCV vehicle class is never important in determining overall $L_{Aeq(1h)}$ road noise emission, but still contributes to L_{AFmax} noise events (Figure 2-2).
- The sensitivity of the overall $L_{Aeq(24h)}$ noise level to changes in the road surface correction (section 4.3.3) is very low for trucks: in the region of 0.5 dB $L_{Aeq(24h)}$ per 3 dB of surface correction, independent of speed limit. For cars it is about 2.5 dB $L_{Aeq(24h)}$ per 3 dB at 100 km/h, and about 2 dB $L_{Aeq(24h)}$ at 50 km/h. In the more likely situation that a surface affects both cars and heavy vehicles in a similar way, the overall change is dominated by how the surface affects cars.
- When the sensitivity analysis was performed hour-by-hour (section 4.3.4) it revealed that during the night-time period, the performance of the surface with respect to truck tyres is just as influential on the overall hourly traffic noise level as its performance with respect to cars.

Measurement Methodologies

- Six measurement methodologies have been identified that would isolate truck tyre/road noise emission (section 5.2) and three methodologies that would measure the overall truck noise emission (section 5.3).

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Appendix A: Equivalency between NordTyre Test Surfaces and Typical NZ Road Surfaces

We have compared the reported SRTT CPX levels [ISO 11819-2:2017] and/or macrotexture readings [ISO 13473-1:1997] of the Twente Proving Ground (TPG) European surfaces with those made on NZ road surfaces during previous research [Jackett, 2019] and the NZTA's annual High Speed Data Survey (via the RAMM state highway database).

We find that the newly laid Stone Mastic Asphalt ("SMA 11", Figure 7-1) test surface has texture and acoustic properties similar to a fine single-coat NZ chipseal (grade 4 or 5) or a coarse NZ SMA.

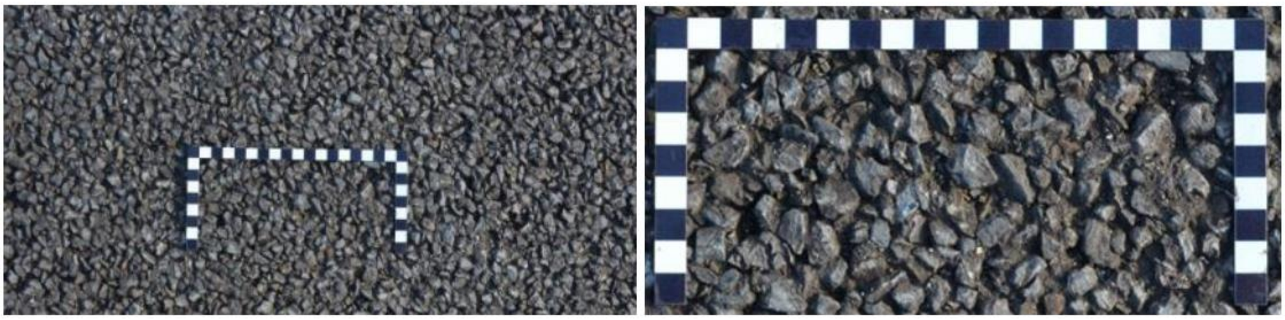

Figure 7-1: SMA 11 at Twente Proving Ground. Each black or white square is 10 mm x 10 mm. Credit: NordTyre Part 3 Report

The texture [van Blokland & Kragh, 2015], photo (Figure 7-2), and description of the Thin Surface Layer (TSL 8) asphalt "with 8 mm maximum stone size and partly porous structure" appear to be most similar to NZ's finest grade porous and semi-porous asphalts, such as PA7, EPA7, and SMA7.

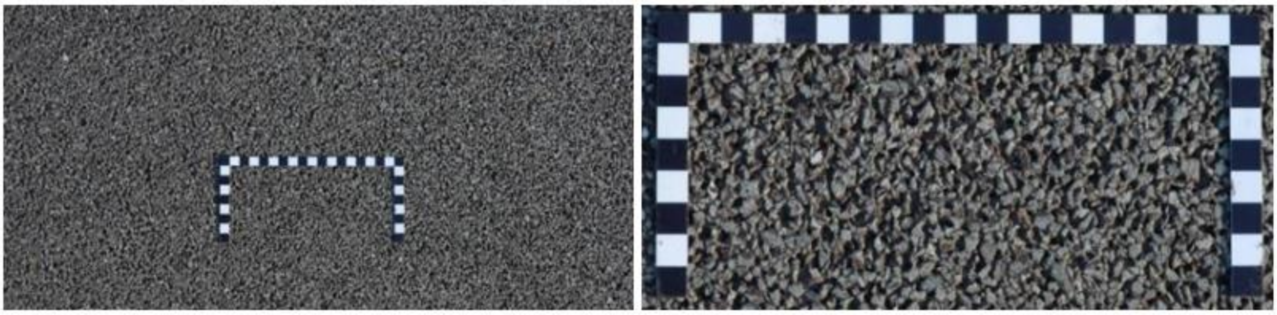

Figure 7-2: TSL 8 at Twente Proving Ground. Each black or white square is 10 mm x 10 mm. Credit: NordTyre Part 3 Report

Table 7-1 provides a comparison of available parameters between the TWP surfaces and the similar NZ surfaces.

Table 7-1: Comparison between TWP and NZ surfaces

Quantity / feature	Fine Chip Surface		Quiet Road Surface	
Location	TWP	NZ	TWP	NZ
Local Name	SMA 11	Grade 4 chip	TSL 8	EPA7*
Macrotexture (MPD in mm)	1.1	1.1	0.6	1.1
Aggregate top size (mm)	11†	10-15	8	7
CPX Level (dB $L_{CPX:P1,80}$)	98.1	100.1	Not available	93.0

* EPA7 data based on a small sample and may not be representative of typical surface parameters
† Nominally 11 mm, but compare to 10 mm grid in Figure 7-1

Appendix B: CNOSSOS-EU vehicle model

The per-vehicle rolling, propulsion, and overall sound power emission in dB L_{WA} by vehicle classification and vehicle speed, predicted by CNOSSOS-EU with the proposed revisions of Kok & van Beek (2019), under reference conditions.

	CNOSSOS-EU vehicle sound power emission (dB LwA)								
	Cat 1: PC			Cat 2: MCV			Cat 3: HCV		
Speed (km/h)	Rolling	Prop.	Overall	Rolling	Prop.	Overall	Rolling	Prop.	Overall
10	74.7	86.3	86.6	80.2	99.0	99.0	82.6	102.3	102.3
15	80.4	86.9	87.7	85.0	99.4	99.6	87.6	102.6	102.7
20	84.4	87.4	89.2	88.5	99.9	100.2	91.3	103.0	103.2
25	87.6	88.0	90.8	91.2	100.3	100.8	94.1	103.3	103.8
30	90.2	88.5	92.5	93.4	100.8	101.5	96.5	103.7	104.4
35	92.4	89.1	94.1	95.4	101.2	102.2	98.5	104.0	105.1
40	94.4	89.6	95.6	97.0	101.7	103.0	100.2	104.4	105.8
45	96.1	90.2	97.1	98.5	102.2	103.7	101.8	104.7	106.5
50	97.6	90.7	98.4	99.9	102.6	104.5	103.2	105.1	107.2
55	99.0	91.3	99.7	101.1	103.1	105.2	104.5	105.4	108.0
60	100.3	91.9	100.9	102.2	103.5	105.9	105.7	105.8	108.7
65	101.5	92.4	102.0	103.3	104.0	106.7	106.7	106.1	109.4
70	102.6	93.0	103.0	104.2	104.5	107.3	107.7	106.5	110.2
75	103.6	93.5	104.0	105.1	104.9	108.0	108.7	106.8	110.9
80	104.6	94.1	104.9	106.0	105.4	108.7	109.6	107.2	111.5
85	105.5	94.7	105.8	106.8	105.8	109.3	110.4	107.5	112.2
90	106.3	95.2	106.6	107.5	106.3	110.0	111.2	107.9	112.8
95	107.1	95.8	107.4	108.2	106.8	110.6	111.9	108.2	113.5
100	107.9	96.4	108.2	108.9	107.2	111.2	112.6	108.6	114.1
105	108.6	96.9	108.9	109.6	107.7	111.7	113.3	108.9	114.7
110	109.3	97.5	109.6	110.2	108.1	112.3	113.9	109.3	115.2

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