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Road Surface Noise Corrections

Part 2: Light Vehicles

Richard Jackett, Tiffany Lester, Iain McIver
WSP Research

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Contact Details

Richard Jackett
WSP Research
33 The Esplanade
Petone
Lower Hutt 5012
+64 4 587 0600
+64 27 548 2451
richard.jackett@wsp.com

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Prepared by
Richard Jackett

Reviewed by
Peter Cenek

Client:

Karolyn Buhring, *Waka Kotahi*
Greg Haldane, *Waka Kotahi*
Stephen Chiles, *on behalf of Waka Kotahi*

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Revision	Details
Draft 1	A complete draft report for client review, including sections and results that will probably be revised prior to publication, pending results from follow-up studies.
1.0	Addition of CPB survey and other results. Significant updates to sections 1, 2.1, 2.2, 2.4, 2.6, 3.1, 3.3, 3.4, 4.3, and Appendix E. New Chapter 5 and Appendix D.
1.1	Minor edits resulting from client review.

Disclaimers and Limitations

This report ('Report') has been prepared by WSP exclusively for Waka Kotahi NZ Transport Agency ('Client') in relation to part 2 of using CPX data to refresh the passenger car data in the *NZ Road Surface Adjustments Table* ('Purpose') and in accordance with the Acoustics and Environmental Professional Services Contract Number 2290 dated 13 December 2019 (variation dated 11/11/20). The findings in this Report are based on and are subject to the assumptions specified in "WSP road surface noise research 2021 proposal - Surface corrections for cars - 20201021" provided by email on 21 October 2020 and the subsequent discussions and emails with Waka Kotahi, including after commencement of the work. WSP accepts no liability whatsoever for any reliance on or use of this Report, in whole or in part, for any use or purpose other than the Purpose or any use or reliance on the Report by any third party.

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Abbreviations and Definitions

A-weighting	Frequency weighting of noise that mimics human sensitivity to frequency
Chipseal	Road surface whose running surface is stones (chip) embedded in binder
Corr.	Correction
CPB	Controlled Pass-By, a pass-by measurement of test vehicle SEL
CPX	Close-proximity Measurement (of tyre/road noise level)
CPX trailer	An instrumented trailer used for CPX measurements of a reference tyre
CPXP$_{80}$	CPX level, using the P1 (car) tyre carried out at a nominal speed of 80 km/h
CRTN	Calculation of Road Traffic Noise (a noise model)
Dual-chip	Chipseal specifications that include 2 distinct chip grades, e.g. RACK, 2CHIP
EEM	Economic Evaluation Manual (now Monetised Benefits and Costs Manual)
HCV	Heavy Commercial Vehicle EEM vehicle class
k	Statistical coverage factor for a desired level of confidence, e.g. k=2 is 95%
L_{A10}	The A-weighted sound level exceeded for 10% of the measurement time
$L_{\mathrm{Aeq(t)}}$	A-weighted energy equivalent sound pressure level over time period, *t*
L_{AE}	A-weighted sound exposure level (the suffix notation for SEL
L_{Amax}	A-weighted maximum sound pressure level
$L_{\mathrm{CPX:P1,80}}$	CPX level, equivalent to CPXP$_{80}$. Alternative notation used as a suffix to dB.
LCV	Light Commercial Vehicle EEM vehicle class
Mobile Road	Web-based portal to selected RAMM data (https://mobileroad.org/)
MCV	Medium Commercial Vehicle EEM vehicle class
NZ	New Zealand
NZ Adjustment	An adjustment to localise CRTN to NZ reference conditions (surface, fleet)
NZTA	NZ Transport Agency, now called Waka Kotahi NZ Transport Agency
OGPA	Open-grade Porous Asphalt, a low noise NZ road surface
Pass-by noise	The noise at the roadside as a single vehicle drives by (see SPB & CPB)
PC	Passenger Car EEM vehicle class
PC&LCV	The combined Passenger Car and Light Commercial Vehicle EEM classes
RAMM	Road Assessment and Maintenance Management (software and database)
sd	Standard deviation
SEL	Sound Exposure Level measured in dB L_{AE}, see also Appendix B.3
SLM	Sound Level Meter
SH	NZ State Highway
SPB	Statistical Pass-By measurements of fleet vehicle SEL (not to ISO 11819-1)
Surface Correction	An addition to CRTN noise level to account for surface characteristics
Surface Specification	The nominal materials, processes, and chip sizes for a surface (see below)
tyre/road noise	The noise generated by the interaction of a tyre with the road surface
vkt	Vehicle Kilometres Travelled
Waka Kotahi	Waka Kotahi NZ Transport Agency (formerly NZTA)

Surface Specification

Each named road surface type in NZ has a published NZTA specification that dictates what materials, properties, and other construction parameters it can have. However, references to a “surface specification” in this report indicate a particular and distinct set of surface material, chip/aggregate size(s), construction process, and in some cases surface thickness. Generally, this is a subset of the published NZTA specification (each of which cover a range of aggregate sizes). The *surf_material*, *chip_size*, and *chip_2nd_size* parameters are readily available from Mobile Road for existing roads, and from project engineering teams for proposed roads, so are appropriate and accessible parameters for defining a road surface specification as it relates to noise. There is evidence that variation in void content and surface thickness [Bull et al, 2021] are relevant to the performance of porous asphalts, but RAMM does not hold void data and it includes thickness data inconsistently (and not via Mobile Road). In this report, when a porous asphalt specification also considers its thickness, that will be explicitly stated (in mm). If no thickness is stated then that specification is defined without consideration of thickness.

1 Introduction

1.1 Background

Road traffic noise is an inevitable by-product of traffic on NZ's state highway network. Most of this traffic noise is generated by the physical interaction between the tyres and the road surface, and it differs substantially between surface types: chipseals are infamously 'noisy', while asphalts have a reputation as 'quiet surfaces'. As a result, selecting the appropriate surface for new or upgraded state highway roads is usually the preferred form of noise mitigation because it means reducing the traffic noise 'at source' (as opposed to much more expensive barriers, which only block noise for specific receivers).

The opportunity to optimise the road surface for noise relies on knowing each candidate surface's noise properties in advance of consenting, so that practitioners can incorporate the information into their noise models. The road surface noise corrections (or just "surface corrections") are a set of noise level corrections (in dB) for each surface specification that fulfil exactly that role.

The surface corrections were last derived in the 1990s and early 2000s [Barnes & Ensor, 1994; Dravitzki & Kvatch, 2007], and since then both tyre technology and NZ's surface specifications have evolved. Recent research indicated that some of the existing surface corrections may no longer be accurate [Jackett, 2019b]. There are also new surfaces already in use on NZ state highways for which no corrections currently exist.

Currently, cars and trucks have separate surface corrections. Recent NZ research [Jackett et al, 2020] concluded that overall road traffic noise levels are far more sensitive to tyre/road emissions from cars than from trucks, and that new surface corrections for cars should be the priority.

1.2 Purpose

Waka Kotahi NZ Transport Agency requires that the noise corrections for road surfaces in table 2.1 of the *Guide to state highway road surface noise* [NZTA, 2014] are updated to reflect the surfaces currently laid on the state highway network [NZTA NV5, 2020]. The corrections were previously specified in relation to a reference surface, asphalt AC-10, but Waka Kotahi require that a new reference is found, in part because AC-10 is being phased-out on state highways. Therefore, before the new road surface corrections can be determined, this research project will first need to define a completely new system of reference back to CRTN.

Once the reference is defined, there are two further goals:

- The relative performance of NZ road surface types (the surface corrections) will be quantified and related to the new reference. This is equivalent to updating the existing table of surface corrections.
- The 2022 NZ light vehicle fleet will be characterised for its noise emission and used to scale the absolute level of the CRTN noise prediction model. This is equivalent to a re-calibration of CRTN for modern NZ conditions, last performed by Barnes & Ensor in 1994 (i.e. the "NZ Adjustment"), although a new methodology will be required this time.

A further expected outcome of this research is that the relationship between the Waka Kotahi CPX trailer's on-road measurements and wayside noise levels will be established.

The corrections will initially be determined for cars only, with heavy vehicles to follow later. Waka Kotahi need the set of surface specifications to be complete (to the extent that a practitioner is not left to guess at a value to use in a noise assessment) but also prefer a shorter and more focused set of corrections if possible. The final set of surface corrections will be published separately by Waka Kotahi, following a review and ratification process.

Waka Kotahi has recognised that with the new corrections urgently required, and the budget and timeline constrained, an increased level of uncertainty and risk is expected. The overall aim for this research project is therefore to devise a novel and highly efficient methodology to recalibrate CRTN and determine new draft surface corrections for cars against a new NZ reference system.

1.3 Scope

The project consists of three parts, which are reported on separately:

Part 1 determined the light vehicle tyre/road noise differences between 39 NZ road surface specifications using CPX noise data collected on state highways across 5 regions of NZ. The report for Part 1, titled *Road Surface Noise Corrections - Part 1: Large CPX Survey of Road Surfaces* [Jackett, 2021], was completed in September 2021.

Part 2 relates the CPX levels found in Part 1 back to the CRTN noise model. It details the replacement of the reference surface and recalibration of CRTN for the 2022 light vehicle fleet. The core output of this work is a table of draft surface corrections direct to CRTN for cars.

Part 3 will derive draft surface corrections for heavy vehicles in 2022. That report will be called *Road Surface Noise Corrections – Part 3: Heavy Vehicles* [Jackett, 2022].

This report covers Part 2 of the project only. Within it, regular reference will be made to results in the Part 1 report.

Collectively these reports describe WSP's research findings and recommendations. The research outputs should not be interpreted as guidance for practitioners or applied to projects in advance of review and ratification by Waka Kotahi. If Waka Kotahi elects to update the surface corrections that will be communicated separately.

1.4 Outcomes

The key intended outcomes of this research project are:

- A new methodology to determine road surface corrections relative to CRTN.
- A new calibration of CRTN for the 2022 light vehicle fleet.
- A new set of draft surface corrections for cars for NZ surface specifications.
- An alternative to the AC-10 reference surface: CRTN-to-SEL-to-CPX correlation.
- A relationship between the Waka Kotahi CPX trailer levels and wayside noise levels.

2 Methodology

The methodology for this project has evolved several times in response to findings from fieldwork, and to accommodate various additional constraints. The most significant changes from the methodology originally proposed were discarding the concept of the reference surface specification and linking to CRTN via pass-by measurements of individual fleet vehicles rather than through long-term wayside measurements of fleet traffic.

This chapter presents the key aspects of the final methodology. Appendix B provides context to the methodological choices made.

2.1 High-Level Overview

The overriding measurement challenge is to establish a quantitative link between CPX surface noise data, and the noise model, CRTN.

In Part 1 [Jackett, 2021], data from a CPX survey of 700 km of state highway was used to determine representative CPX levels for each different surface type. The differences between those CPX levels are the basis of the surface corrections table, but CPX levels on their own are not useful as corrections because they lack a usable absolute reference.

On the CRTN side, a way was found of indirectly 'calibrating' it based on measured pass-by levels of individual vehicles (instead of a traffic flow of many vehicles over a long time period).

Twenty sites with a range of road surfaces were surveyed by both pass-by and CPX. The pass-by measurements captured 500 individual NZ fleet vehicles and were carefully conducted to be directly relatable to CRTN's reference conditions (it's most basic state). The twenty pairs of 'site average pass-by level' and 'site average CPX level' revealed a fairly clear pattern between the CPX level and the noise level at the wayside. The line-of-best fit then provided an equation for transforming any CPX level into a pass-by level of an 'average' fleet vehicle.

Finally, the CPX-based surface corrections from the large survey could be transformed to pass-by levels, and in turn related back to CRTN. These corrections also factor in the properties of the current light vehicle fleet, so are essentially a recalibration of CRTN for NZ conditions in 2022.

2.2 Method Outline

The methodology has been broken down into its constituent tasks and summarised in Table 2-1. Reference is provided to relevant sections of this report.

Table 2-1: Methodology outline

Task	Task Summary	Reference
1	CRTN was reverse-engineered to extract its implicit 'per car' noise level (an SEL[1]) under reference conditions.	Section 2.3 and Appendix A
2	At 10 different sites, wayside SEL measurements were taken of 500 passing cars from the NZ fleet (i.e. SPB). The measurements were conducted as close to reference conditions as possible. The main difference between sites was the road surface specification.	Section 2.4.1, Appendix C, and section 3.1.
3	At an additional 9 sites, wayside SEL measurements were taken of a test vehicle (a car, i.e. CPB) that was 'calibrated' against 6 of the SPB sites in task 2. This expanded the sample size to 19.	Section 2.4.2, Appendix D and section 3.1.
4	CPX measurements were made on the same 19 sections of road as visited for tasks 2 and 3.	Section 2.4.3, Appendix C.6, and section 3.2.
5	The SEL measurements were regressed against the CPX measurements to establish a general relationship between CPX levels and wayside levels.	Section 2.4.4 and section 3.3.
6	A very large CPX survey was conducted over the NZ state highway network (> 1000 km) and linked to data on surface type, condition and age. A representative CPX level for each different surface specification in the dataset was computed.	Section 2.5, and Part 1 report [Jackett, 2021].
7	The average CPX levels from task 5 were translated to wayside levels using the relationship from task 4. CRTN's implicit car SEL from task 1 was then subtracted, resulting in a set of draft CRTN surface corrections for cars for each surface specification, which also constitute a 'recalibration' of CRTN for the 2022 NZ light vehicle fleet.	Section 2.6 and section 4.3.

The methodology is also presented in the form of a schematic in Figure 2-1. This provides a visual link between the different tasks of Table 2-1. In particular it shows how the CPX levels are translated into SEL, and how the 'reference' level (zero) for the surface corrections table is determined. In the schematic, the methodology generally proceeds from inputs on the right to the output on the left. The values shown are just examples for the sake of illustration. Some secondary elements are missing, such as adjustment for outliers and traffic mix, and integration of CPB with SPB data.

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[1] Sound Exposure Level (SEL) captures the total sound energy of a vehicle pass-by (section 2.3.4)

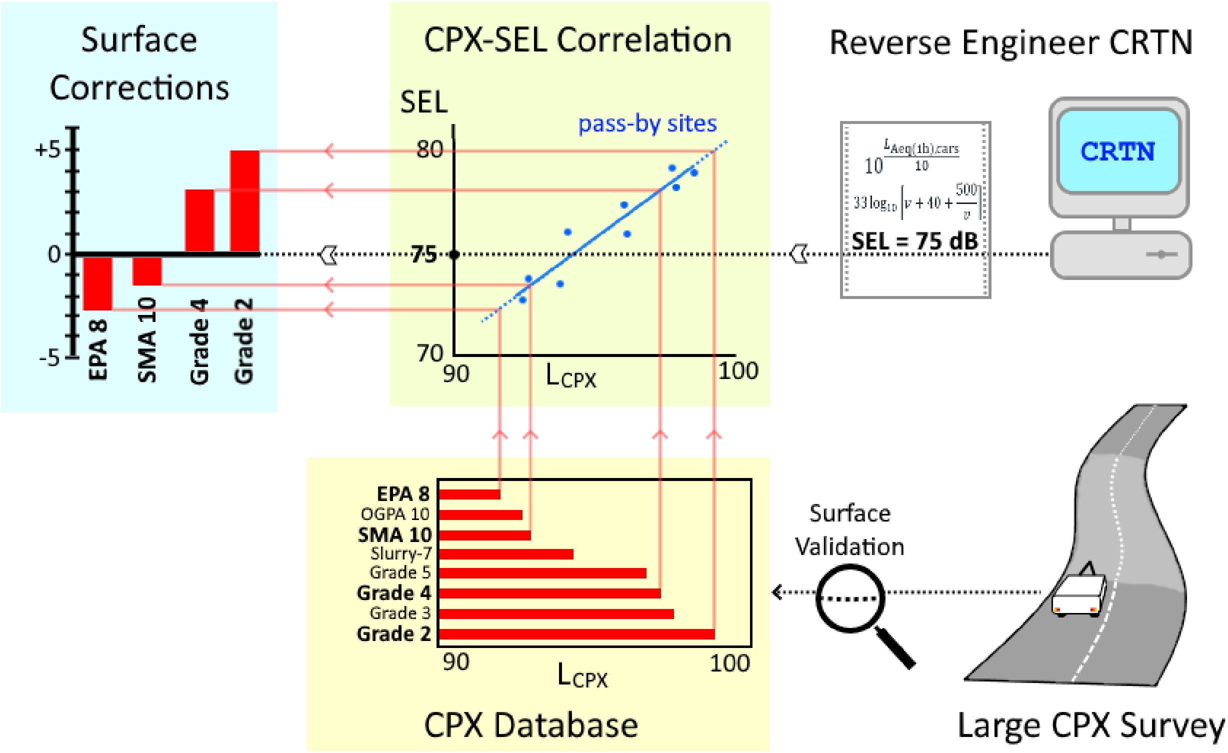

Figure 2-1: Schematic of the methodology, read from right to left (numbers are just examples)

This method leverages CPX to provide an efficient and accurate sampling of a vast number of road segments of different surface specifications and can provide corrections directly to CRTN output levels rather than via an intermediate reference surface. The NZ Adjustment is effectively incorporated into each surface correction.

2.3 Reframe CRTN in Terms of Vehicle SEL

2.3.1 Calculation of Road Traffic Noise (CRTN)

CRTN's algorithms predict road traffic noise levels at receivers based primarily on inputs of road geometry and traffic information such as volume, mix, and speed [DoT U.K., 1988]. The road surface's contribution to noise is included as a correction to the core prediction, that prediction having been made for a 'reference' surface whose effect is defined as zero[2]. The road surface corrections therefore add or subtract from the predicted level, depending on whether the surface of interest is noisier or quieter than the reference surface.

2.3.2 The Reference Surface

NZ's existing reference surface for noise, AC-10 (a smooth asphalt), has become very rare on state highways and is no longer viable (see Appendix B.1). Replacement surface specifications have been investigated [Jackett, 2020] but none were selected for adoption as a NZ reference surface. Therefore, to deliver this project a new kind of reference system needed to be developed, and the link between the real-world sound level and it's CRTN prediction needed to be re-established from scratch. CRTN itself remains unaltered, but the NZ Adjustment[2] that scales its output for NZ conditions has effectively been re-measured; essentially a recalibration of the base CRTN equation for NZ in 2022.

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[2] In NZ an additional "NZ Adjustment" of -2 dB has historically been included to account for our different reference surface and vehicle fleet compared to those used to compute the algorithms of the CRTN model.

2.3.3 Road Traffic Noise versus Vehicle Pass-By Noise

CRTN predicts noise levels resulting from a stream of moving vehicles (traffic) rather than individual vehicles. However, as discussed in Appendix B.1, a long-term survey of road traffic noise was not possible. An alternative method of recalibrating CRTN to the 2022 vehicle fleet and surfaces was sought, and it was found that this could be achieved, in theory, by finding the average pass-by sound level of an individual vehicle.

2.3.4 Reverse Engineering CRTN

The Sound Exposure Level (SEL) of a vehicle pass-by is a measure of its total sound energy emission (expressed as a sound pressure level in dB L_{AE}). The derivation in Appendix A demonstrates that CRTN's noise calculation for a traffic flow can be uniquely and completely expressed as a function of light vehicle and heavy vehicle SELs. We refer to these as "CRTN's implicit SELs" because the CRTN model was originally developed from full traffic flows [Delany et al, 1976] rather than individual pass-by measurements. CRTN effectively multiplies these SELs by the number of vehicles to predict traffic noise levels.

The analytically derived CRTN implicit SELs for light vehicles and heavy vehicles, respectively:

$$L_{\mathrm{AE,car}} = 75.3\ \mathrm{dB} \tag{2.1}$$

$$L_{\mathrm{AE,truck}} = 84.2\ \mathrm{dB} \tag{2.2}$$

The SELs above form the baseline for CRTN predictions under reference conditions.

SELs can also be measured in the field (albeit with some difficulty, see Appendix C and B.3). This means that the link between CRTN and the actual noise levels in 2022 can be completed. With reference to Figure 2-1, a measured SEL equal to the implicit SEL would correspond to a surface correction of 0 dB to CRTN.

In theory, any change in L_{AE} should cause the same change in $L_{Aeq(24h)}$ (see equations (A.2) and (A.3) in Appendix A) so surface corrections to CRTN can be determined directly from differences in SEL between surfaces, and expressed relative to the implicit SEL.

2.4 Find Relationship between CPX and SEL

2.4.1 Measure Average SEL of NZ Light Vehicle Fleet

Valid SEL measurements were made of 518 passing vehicles from the NZ light vehicle fleet. For convenience these will be referred to as "SPB" measurements, though note that they are not equivalent to the ISO 11819-1:1997 statistical pass-by methodology.

The requirement to closely mimic CRTN reference conditions[3] proved incredibly onerous when it came to selecting pass-by measurement sites (see Appendix C.1). The major limitations were speed (vehicle speeds near 75 km/h but a posted speed of at least 80 km/h), a long straight and flat road, and a flat and accessible 10+ metre verge without nearby reflecting surfaces. In the end, 9 sites in the Wellington Region and 1 site in Christchurch were identified and surveyed, covering 6 distinct surface types. The sites were as equivalent as practicable in all respects other than the road surface, with residual differences being corrected for using CRTNs own corrections where possible (e.g. speed, temperature, ground absorption).

Acoustically isolating individual vehicle pass-bys from other vehicle and background noise proved impossible during the daytime, so all SEL measurements were undertaken late at night or early morning. Measurements were performed in calm weather and after a dry spell of at least

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[3] "CRTN reference conditions" are defined in Appendix C.1. Essentially it is the CRTN chart 2 curve without any further correction: 75 km/h, no heavies, no gradient, no ground absorption, at 10 m from a long straight road.

2 days. Pass-by sound levels from passenger cars, vans, and utes were logged at a 100 ms interval with a calibrated class 1 Sound Level Meter at 10 metres from the nearside edge of the lane for the duration of the pass-by event. The speed of each vehicle was captured using a speed radar gun, which had been calibrated against a test vehicle equipped with a GPS speedometer.

The locations and details of the 10 SPB sites are given in Table 2-2. Appendix C provides full detail of site selection, vehicle selection, sound and speed measurements, and post-processing.

Table 2-2: SPB measurement sites

Site	Name	Surface	Surface Year	SEL Survey Date	GPS Lat, Long	Route Position	Posted Speed Limit (km/h)	Number of Samples
S1	Eastern Hutt Rd SB	2CHIP 3/5	2014	8/04/2021	-41.1501, 174.9919	EASTERN HUTT RD/5.690	80	113
S2	Eastern Hutt Rd NB	2CHIP 3/5	2014	30/04/2021	-41.1501, 174.9919	EASTERN HUTT RD/5.690	80	75
S3	SH2 Petone Arise NB	PA-14	2009	7/05/2021	-41.2219, 174.8681	002-0962-D/11.212	100	17
S4	SH2 Petone Arise SB	PA-14	2009	7/05/2021	-41.222, 174.869	002-0962-I/11.139	100	6
S5	Fergusson Dr WB	AC-10	2012	13/05/2021	-41.1461, 175.0043	FERGUSSON DR EAST/0.689	80	46
S6	SH2 Grounsel NB	SMA-15	2017	14/05/2021	-41.1952, 174.9202	002-0962-D/5.909	100	56
S7	SH1 Paekakariki SB	PA-10	2016	19/05/2021	-40.9978, 174.9428	01N-1035-B/0.612	80	44
S8	SH2 Te Marua NB	2CHIP 3/5	2009	25/05/2021	-41.093, 175.1302	002-0931-B/13.276	80	39
S9	Fergusson Dr EB	AC-10	2012	26/05/2021	-41.1457, 175.0032	FERGUSSON DR/0.526	80	20
S10	Western Belfast NB	40 mm EPA-7	2018	23/05/2022	-43.4551, 172.6024	01S-0333-D/0.840	80	67

Raw SEL values for each pass-by event were calculated from manually selected portions of each pass-by time series. The CRTN chart 4 correction for speed was applied to each event so that the SELs represented the reference speed of 75 km/h. Outlying vehicles were then excluded, to be accounted for separately (section 3.1.5).

Finally, SELs were logarithmically averaged for each site, and then corrected for temperature (a reference of 15°C was chosen) and ground absorption (the reference is zero absorption).

2.4.2 Expand Number of Sites Using CPB

An unexpected relationship was found between SPB and CPX measurements at the original 9 sites, which is described in section 3.3.3. Accordingly, the pass-by survey was expanded to include an additional SPB site (site S10 in Table 2-2) plus nine new CPB measurement sites using a test vehicle. The CPB sites improve the range of surfaces without improving (or harming) the estimation of the average fleet SEL.

The characteristics of the test vehicle (a Mazda3 car) were quantified by performing 75 km/h CPB measurements at 6 previously visited SPB sites (sites S1-S3, S5, S6, and S8 from Table 2-2), revealing it to be 1.9 dB quieter than the average SPB vehicle. CPB measurements at 9 entirely new sites were used to estimate the fleet SPB level at those sites, in lieu of performing a time-consuming SPB survey at each site. The additional uncertainty of this method is minimal (Appendix E.2), and the ability to control the pass-by speed greatly beneficial. Other aspects of the methodology were essentially the same as described for SPB in section 2.4.1.

The locations and details of the 9 CPB sites are given in Table 2-3. Appendix D provides full details of the methodology, investigation, and additional findings.

Table 2-3: CPB measurement sites

Site	Name	Surface	Surface Year	SEL Survey Date	Direction, lane	Route Position	Posted Speed Limit (km/h)	Number of Valid Passes
C1	SH2 Grounsel OGPA	PA 10	2015	13/05/2022	NB, left	002-0962-D/5.229	100	3
C2	SH2 Maidstone	PA 15	2017	6/05/2022	NB	002-0946-B/6.641	100	3
C3	SH2 Totara Park	PA 10	2014	6/05/2022	NB	002-0946-B/5.358	100	3
C4	SH2 Whakatikei	PA 10	2017	5/05/2022	NB, left	002-0946-B/7.556	100	3
C5	SH2 Hebden 1	PA 10	2017	6/05/2022	NB, left	002-0962-D/2.790	100	3
C6	SH2 Birchville NB	VFILL 5	2017	12/05/2022	NB	002-0946-B/1.400	80	2
C7	SH2 Birchville SB	VFILL 5	2017	12/05/2022	SB	002-0946-B/1.400	80	2
C8	SH2 Kaitoke	2CHIP 2/4	2016	5/05/2022	NB	002-0931-B/6.814	100	3
C9	SH2 Kaitoke Farm	RACK 2/4	2018	12/05/2022	NB	002-0931-B/8.509	100	3

2.4.3 Measure CPX Level for SPB and CPB Sites

The methodology requires that each site with a measured SEL also has a measured CPX level.

$CPXP_{80}$ measurements were captured past each Wellington site on 22nd and 28th April 2021, and the Christchurch site on 3rd June 2021 using the Waka Kotahi CPX trailer. The 20-metre-long measurement intervals were then re-referenced to centre on the site location, and a weighting applied to represent the contribution each 20-metre segment of road makes to the pass-by level. For each site, 220-metres of CPX data were averaged to provide the final CPX level for that site, though in practice only the nearest 60 metres of road had a significant effect on the level.

Appendix C.6 provides full detail of the measurements and post-processing.

2.4.4 Correlate CPX with Pass-By Measurements

CPX levels are higher in absolute terms than pass-by SELs because the CPX microphones sit much closer to the tyre. Both types of measurement are able to distinguish between different surfaces, and in general the change in noise level from one surface to another was expected to be a similar magnitude whether measured by the CPX or pass-by methodology[4]. This is not what was originally found from regression of SPB on CPX, so a programme of validation measurements was undertaken, and ultimately the data set was doubled in size by the addition of CPB measurements (Appendix C.6).

A weighted least-squares linear regression of SEL on CPX was performed (see section 3.3.4), producing equations to transform measurements from $L_{CPX:P1,80}$ to L_{AE} under CRTN reference conditions.

2.5 Large CPX survey of road surfaces

The methodology up to this point has been focused on establishing a link between CRTN predictions in dB $L_{Aeq(24h)}$ and the Waka Kotahi CPX trailer levels in dB $L_{CPX:P1,80}$. The difference in ‘typical’ noise emission between surface specifications is determined primarily by the CPX measurements.

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[4] CPX measures the tyre/road noise in isolation, whereas SEL also captures some noise from a vehicle’s propulsion system. However, at 75 km/h, almost all car noise emission is due to the tyre/road effect [Sandberg & Ejsmont, 2002]. Individual vehicles with audibly loud engines had already been manually excluded and were accounted for separately (section 3.1.5).

Full details of this process are provided in the Part 1 report [Jackett, 2021]. A brief summary of the process is given below.

2.5.1 CPX measurements

CPX noise levels, $L_{CPX:P1,80}$ were measured in the left-wheel-path with the P1 tyre at 80 km/h on state highways across the Auckland, Waikato, Manawatū-Whanganui, Wellington, and Canterbury regions.

2.5.2 Surface types and validation

$L_{CPX:P1,80}$ levels are averages over 20-metre-long road segments, and each was linked to its corresponding road surface specification using the RAMM state highway database. Each 20-metre segment of the 1100 km surveyed was visually validated, and about 12% were removed. Reasons included: suspect RAMM data; non-representative surface (e.g. it was on a bridge deck); extremely damaged surface. Further filtering by date resulted in a dataset of about 680 lane-km of road surface having valid CPX levels and between 6 months and 10 years old[5] at the time of measurement (Table 2-4).

Table 2-4: CPX data available for analysis after validation and filtering

Description	Sample Size (number of 20 m segments)	Equivalent Distance (lane-km)	Percentage of Total
Total Survey Data	55383	1107.7	100%
Passed Validation	48492	969.8	87.6%
Data for Analysis	34141	682.8	61.6%

2.5.3 Characterise surfaces by CPX Level

For each of the 39 distinct surface specifications[6] in the resulting dataset, CPX levels and geographical information were extracted and summary statistics computed, including measures of central tendency and variability of CPX noise emission, age effects, and geographic distribution of the sample.

Of the current top 30 surface specifications on the state highway network by sealed length[7], 26 are represented with CPX level statistics. All of the top 15 surfaces are represented.

2.6 CRTN Surface Corrections

Draft surface corrections to CRTN have been computed in section 4.3. The process for any given surface specification[6] was as follows:

1. An indicative $L_{CPX:P1,80}$ level for the for the surface type was determined by considering its summary statistics, distribution shape and width, average age, any aging effect, and any other relevant factors specific to that surface (e.g. how or where it is typically used).
2. It's equivalent $L_{AE,car}$ level was estimated using the relationship between CPX and pass-by SEL found by the process in section 2.4. Corrections were then applied to represent the mix of cars, utes, and vans in the fleet, and to reintroduce the effect of outliers.

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[5] This age range strikes a balance between maximising the size of the dataset while excluding surfaces that are not representative. It was chosen in consultation with road surface specialists at WSP and consideration of figure 4-7 in Chipsealing in NZ [NZTA, 2005].

[6] "Surface specification" refers to a construction process and material properties, see Definitions.

[7] For reference, the 30th most common surface exists on 0.5% of the network, by length.

3. CRTN’s implicit SEL (section 2.3.4), was subtracted from the $L_{AE,car}$ level for the current surface, resulting in a surface correction that can be applied directly to CRTN’s $L_{Aeq(24h)}$ output.

This process was repeated for each surface type to populate a draft table of surface corrections.

At face value the process outlined above is largely objective and quantitative, but there were some subjective aspects to the methodology that were unavoidable:

- In step 1, derivation of indicative levels for each surface has a subjective element, so these have only been included as place-holders, pending a full ratification.
- In step 2, the relationship provided from CPX to pass-by SEL is piecewise linear, with separate expressions for ‘porous’ and ‘non-porous’ surfaces, which are based off a relatively small sample of each. The distinction between categories is subjective and made tentatively: other definitions could exist (e.g. ‘asphalts’ and ‘chipseals’). As a result, there is considerable uncertainty around which category SMA should fall under, and also for the value for AC. It potentially makes a 3 dB difference to their predicted SELs and would benefit from a follow up study.
- In step 3, there may be other factors that could be applied at this stage, such as modelling safety factors. It is this step that effectively removes the NZ Adjustment as it was used up until now.

3 Relationship Between CPX and Wayside SEL

The methodology to derive this relationship was summarised in section 2.4 and is provided in detail in Appendix C.

3.1 Vehicle Pass-by SEL

3.1.1 SEL Results

Table 3-1 below summarises the results of the pass-by survey at the 19 wayside sites (see Table 2-2 and Table 2-3). Where CPB data has been used to estimate an SPB level, the SPB level is shown.

For SPB, correction for vehicle speed back to the reference speed of 75 km/h was performed on a per-vehicle basis (see section C.3). However, the average site speeds are included in column 3 of Table 3-1 to provide an indication of the magnitude of the correction (which is about 1 dB per 10 km/h). For CPB no correction was required because the test vehicle was run at 75 km/h.

The percentage of LCVs within the sample is given in column 4 of the table. Section 3.1.4 below describes how the effect of vehicle mix on light vehicle traffic noise is accounted for. Outliers (atypically noisy vehicles) were excluded from the data summarised by Table 3-1, but their effect on light vehicle traffic noise is reintroduced later (section 3.1.5).

Correction for ground absorption has been made using Chart 8 of CRTN (see section 3.1.6).

Correction for the effects of temperature on tyre/road noise has been made (see section 3.1.7).

The Site SEL in this table therefore includes corrections for speed, ground absorption, and air temperature; and excludes atypically loud vehicles and consideration of traffic mix. CPB data has been adjusted by +1.9 dB to estimate site SPB level (section 2.4.2). The expanded uncertainty at the 95% level of confidence is based on the uncertainty budgets in Appendix E.2 and E.3.

Table 3-1: Average SEL by site (SPB and CPB)

Site	Surface	Avg. Speed km/h	%LCV %	Ground Absorb, I %	Ground Absorb Corr. dB	Air Temp. °C	Temp Corr. dB	SPB Level (After Correction) dB *L*AE	Expanded Uncert. (k=2) dB
S1	2CHIP 3/5	72.5	16.8	0.00	0.00	13	-0.10	80.6	1.5
S2	2CHIP 3/5	71.1	8.0	0.00	0.00	11	-0.20	81.9	1.5
S3	PA 14	93.8	17.6	0.00	0.00	12	-0.15	75.4	1.6
S4	PA 14	93.6	16.7	0.00	0.00	12	-0.15	72.4	1.9
S5	AC 10	65.9	8.3	0.25	+0.75	5	-0.50	76.9	1.6
S6	SMA 15	89.0	19.6	0.25	+0.75	5	-0.50	79.5	1.5
S7	PA 10	80.0	22.7	0.50	+1.49	11	-0.20	71.3	1.6
S8	2CHIP 3/5	77.1	12.8	0.00	0.00	8	-0.35	82.3	1.6
S9*	AC 10	68.5	20.0	0.25	+0.75	6	-0.45	72.2*	2.5*

Site	Surface	Avg. Speed km/h	%LCV %	Ground Absorb, I %	Ground Absorb Corr. dB	Air Temp. °C	Temp Corr. dB	SPB Level (After Correction) dB L_{AE}	Expanded Uncert. (k=2) dB
S10	40 mm EPA 7	80.8	14.9	0.30	+0.90	5	-0.50	69.7	1.5
C1	PA 10	75	N/A	0.75	2.24	7	-0.4	70.4	1.5
C2	PA 15	75	N/A	0.00	0.00	17	0.1	70.3	1.5
C3	PA 10	75	N/A	0.00	0.00	17	0.1	71.1	1.5
C4	PA 10	75	N/A	0.50	1.49	17	0.1	75.2	1.5
C5	PA 10	75	N/A	0.25	0.75	17	0.1	72.6	1.5
C6	VFILL 5	75	N/A	0.00	0.00	7	-0.4	80.8	1.5
C7	VFILL 5	75	N/A	0.00	0.00	7	-0.4	78.8	1.5
C8	2CHIP 2/4	75	N/A	0.25	0.75	17	0.1	81.6	1.5
C9	RACK 2/4	75	N/A	0.25	0.75	7	-0.4	82.5	1.5

* SPB survey S9 took place in foggy conditions which affected speed measurement and overall uncertainty

3.1.2 *Speed Correction for Individual Vehicles*

SPB measurement sites were selected with 80 km/h posted speed limits wherever possible, which helped to keep the traffic speed distribution centred fairly close to the target 75 km/h reference speed at most sites. The speed distribution between individual vehicles was broad at all SPB sites, with one standard deviation being about 8 km/h.

Vehicles travelling more than ± 25 km/h from the reference speed were excluded from the analysis. Initially a tighter speed range was auditioned, but it was relaxed so that the three 100 km/h speed limit asphalt sites (Table 2-2) could contribute data. Even within this wider range the speed-corrected noise levels at the extremes are not significantly different to those close to the reference speed ($p<0.05$)[8].

The vehicle speed correction employed was the CRTN Chart 4 correction for traffic speed (*V*, in km/h) and percentage heavy vehicles (*p*), which has been reframed as an SEL correction for cars by substituting *p*=0 and reversing its sign:

$$Speed\ Correction_{cars} = -33\log_{10}\left(V + 40 + \frac{500}{V}\right) + 68.8 \qquad (3.1)$$

Equation 3.1 has been applied to the measured SEL for each pass-by, using the measured vehicle speed (as in section C.3, averaging speeds over several vehicles in a cluster where necessary) to produce pass-by SELs equivalent to the 75 km/h reference speed.

All CPB passes were conducted at 75 km/h and required no correction.

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[8] At most sites, when SELs are corrected this way, the residual speed effect is less than ± 0.2 dB per 10 km/h.

3.1.3 Correction for Traffic Speed

CRTN's speed parameter, V, represents the actual mean speed of the traffic flow [Delany et al, 1976]. Noise modellers in NZ typically fill that parameter with the posted speed limit, which is more readily and consistently available in advance. The current methodology has determined SEL for the actual vehicle speed (normalised to 75 km/h) rather than the posted speed limit, thus some adjustment was required to align with noise modelling practice.

On straight sections of NZ state highway the average speed of light vehicles is approximately 47.7 km/h in 50 km/h speed zones, and 91.9 km/h in 100 km/h speed zones [Jackett et al, 2020]. Using these coordinates to linearly interpolate actual mean speed, V_{actual}, from the posted limit, V_{posted}, yeilds:

$$V_{\text{actual}} \approx 0.884\ V_{\text{posted}} + 3.5\ \text{km/h} \qquad (3.2)$$

Therefore, the V_{posted} used in noise modelling will typically over-predict the actual speed. At V_{actual} = 75 km/h, equations (3.1) and (3.2) provide a correction of -0.62 dB to the SEL to account for the posted speed overpredicting the actual speed. This correction is applied later, in section 4.3.

3.1.4 Traffic Mix Correction

CRTN considers the total volume of a traffic flow, with adjustments for the percentage of heavy vehicles within that flow (%HCV). Light vehicles are defined as 1525 kg or less unladen weight.

New Zealand records light vehicle travel using two sub-classifications: light passenger vehicles (PC; mostly cars) and light commercial vehicles (LCV; mostly utes and vans). In 2019, the most recent year available[9], the ratio between vehicle kilometres travelled (vkt) by PCs and vehicle kilometres travelled by LCVs was 3.7:1 (or 21% LCV).

CRTN does not distinguish between these sub-classes of light vehicle, but nonetheless it is important to ensure that noise emission values derived by this study are representative of the vehicle kilometres travelled by the NZ light vehicle fleet (rather than the mix seen in the survey, which was conducted at night-time in mostly urban surroundings).

The full SPB survey captured 421 PCs (85%) and 73 LCVs (15%) in total, across 10 sites, excluding outliers. For most individual sites it was not possible to determine separate SELs for PC and LCV sub-classes, because there were insufficient isolated LCV pass-bys. After removing the atypically loud vehicles (see 3.1.5), the average LCV SEL across all sites was found to be +0.6 dB above the average PC SEL.

To adjust the final SEL for the slightly higher proportion of LCVs in the NZ vkt data compared to our survey therefore resulted in a tiny correction of +0.04 dB. Note that this excludes the effect of the higher proportion of atypically loud LCVs, which is considered separately.

3.1.5 Atypically Loud Vehicles

A small proportion of vehicles are fitted with noisy mud tyres or have particularly loud exhausts, and can be as much as 10 dB louder than a typical vehicle of their class. It is essential to include these outliers in the overall road traffic noise emission calculations because they are part of the NZ fleet, but their relative rarity (about 1 in every 55 vehicles in our sample) could skew the SEL of individual SPB sites compared to others. We have excluded outliers from individual sites to achieve the most reliable regression between SPB and CPX data, based mostly on tyre/road noise, and then accounted for these vehicles at the end via an addition to the regression constant (Table 4-2 step 5).

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[9] Ministry of Transport analysis based on change in WoF/CoF odometer readings
https://www.transport.govt.nz/statistics-and-insights/road-transport/sheet/vehicle-kms-travelled-vkt

Outlying vehicles were identified subjectively in the field by their audible characteristics or in post-processing. The survey of 483 valid light vehicle pass-bys included 9 classified as outliers: 3 passenger cars (1 in every 125) and 6 LCVs (1 in every 10, all utes). Across all sites, the average outlying car was +2.8 dB, and the average outlying LCV was +7.5 dB relative to the site average excluding outliers (in all cases logarithmically averaged, and ignoring site mix). By this definition, the audible outliers increase the overall noise emission of the passenger car fleet by less than +0.1 dB, but increase the overall noise emission of the LCV fleet by +1.6 dB.

Using the NZ 2019 vkt proportions for PC and LCV sub-classes discussed in section 3.1.4, this represents an addition of +0.43 dB to the final SEL.

A larger and more diverse sample (e.g. including more rural sites) or a different "outlier" definition might find different results. The value found here is taken as the best currently-available estimate.

3.1.6 Ground Absorption Correction

CRTN's chart 8 was used to correct the average SELs for the effect of ground absorption on site, to the reference condition of no ground absorption. The "I-value" for each site was determined from the proportion of ground that was absorbent, following the guidance and table in §2.4 of CRTN [DoT U.K., 1988].

We performed an additional sanity check on the magnitude of the CRTN correction (Appendix D.3.4), which even at 10 m from the edgeline is large, but ultimately retained the correction as written.

3.1.7 Temperature Correction

CRTN does not consider the effect of temperature on tyre/road noise emission, however more recent research indicates that there is an effect [ISO/CD TS 13471-2]. To mitigate the possible effect of late-night measurements under different, relatively cold, ambient temperatures, the average site SELs have been corrected back to a 'reference' temperature of 15°C using a coefficient of -0.05 dB/°C, regardless of the nominal surface type. These values differ slightly from those offered by ISO/CD TS 13471-2, but have been deliberately chosen to be conservative, and accommodated for as an uncertainty component on the site SEL (see Appendix E).

3.1.8 Uncertainty

Uncertainty for the SPB and CPB measurements of SEL have been calculated (Appendices E.2 and E.3) and are in the region of ±1.5 dB at the 95% level of confidence at most sites. The uncertainty varies somewhat from site to site depending mainly on the size of the sample and the difference in site average speed from the reference speed.

3.2 Site CPX Levels

3.2.1 CPX Results

CPX data as 20-metre $L_{\mathrm{CPX:P1,80}}$ levels were geometrically re-referenced to centre on the SEL site location (Appendix C.6.3) and then weighted averages of the nearest eleven 20-metre segments (Appendix C.6.4) were used to calculate a single representative CPX level for each site, as shown in Table 3-2.

Table 3-2: Corresponding CPX level for each site

Site	Surface	Route Position (Centre)	Site CPX Level dB $L_{CPX:P1,80}$	Expanded Uncert. (k=2) [Assumed] dB
S1	2CHIP 3/5	EASTERN HUTT RD/5.690 SB	101.88	1.0
S2	2CHIP 3/5	EASTERN HUTT RD/5.690 NB	102.05	1.0
S3	PA 14	002-0962-D/11.212 NB left	99.24	1.0
S4	PA 14	002-0962-I/11.139 SB left	97.18	1.0
S5	AC 10	FERGUSSON DR EAST/0.689 WB	98.28	1.0
S6	SMA 15	002-0962-D/5.909 NB left	99.63	1.0
S7	PA 10	01N-1035-B/0.612 SB	96.64	1.0
S8	2CHIP 3/5	002-0931-B/13.276 NB	101.22	1.0
S9	AC 10	FERGUSSON DR/0.526 EB	97.45	1.0
S10	40 mm EPA 7	01S-0333-D/0.840 NB left	94.69	1.0
C1	PA 10	002-0962-D/5.229 NB left	95.77	1.0
C2	PA 15	002-0946-B/6.641 NB	96.05	1.0
C3	PA 10	002-0946-B/5.358 NB	96.17	1.0
C4	PA 10	002-0946-B/7.556 NB	97.86	2.0
C5	PA 10	002-0962-D/2.790 NB left	98.38	1.0
C6	VFILL 5	002-0946-B/1.400 NB	99.88	1.0
C7	VFILL 5	002-0946-B/1.400 SB *	99.88*	1.5
C8	2CHIP 2/4	002-0931-B/6.814 NB	101.14	1.0
C9	RACK 2/4	002-0931-B/8.509 NB	101.88	1.0

* Estimated, based on the northbound CPX:P1,80 measurement (C6). Surfaces visually identical.

3.2.2 Uncertainty

Uncertainty of the CPX measurements is not known. For the purpose of this analysis the uncertainty in site $CPXP_{80}$ level has been estimated to be in the region of ± 1 dB at the 95% level of confidence, regardless of the number of passes made. These assumptions regarding CPX measurement uncertainty need to be verified if there is going to be continued use of the CPX trailer for research or compliance applications.

3.3 Relate $CPXP_{80}$ to Pass-by SEL

3.3.1 Reference Speeds

The CRTN reference speed is 75 km/h and the CPX reference speed is 80 km/h. That these speeds are fortuitously close negates the need to apply any speed correction from one to the other [ROSANNE D2.3]. Note that the distribution of individual vehicle speeds within the SEL sample has already been accounted for by correction back to the CRTN reference speed, and a further adjustment to account for the posted speed limit will be applied later (section 3.1.3).

The regression of SEL on CPX level will implicitly account for the small speed difference via its constant term.

3.3.2 Non-Homogeneity of Variances

The uncertainty in SEL varies from site to site and therefore it is appropriate to weight the least-squares regression to represent the confidence in the value of each coordinate. The weightings have been determined as the inverse of the squared combined uncertainties (k=1) for each site (c.f. the inverse variance).

3.3.3 Initial Unexpected Results

Coming into the project it was anticipated that CPXP_{80} might be linked to pass-by SEL via a single expression, and it would be close to linear with a slope of $m \approx 1$. That was what had been found in previous studies in NZ [Jackett, 2019b] and overseas [Sandberg & Ejsmont, 2002], and was in line with theory (section D.1.1).

In fact, the result from the initial survey of 9 pass-by sites (S1-S9) indicated a linear relationship with a slope closer to $m \approx 2$ ($r^2 = 0.93$, $n = 9$, $p < 0.05$):

$$SEL \approx 2.14\, CPXP_{80} - 136.6 \tag{3.3}$$

Consequently, considerable effort was devoted to revalidating the CPX trailer and the SEL measurements in case the unexpected result was due to a measurement system error. Both were found to be operating correctly (section D.2).

It was concluded that there must be some subtlety that was being missed, which might be revealed by increasing the number of sites. Subsequently, an additional SPB site was surveyed at the quietest end of the CPXP_{80} range, a 40 mm EPA 7 surface (site S10). Nine new CPB survey sites were also added and related back to the NZ fleet SEL (see 2.4.2), bringing the total number of sites to 19.

Appendix D contains details of the investigation and additional measurements, which took place during the first half of 2022.

3.3.4 Relationship Between CPXP_{80} and Pass-by SEL

Coordinate pairs for each site were formed from their respective CPXP_{80} (abscissa, from Table 3-2) and pass-by SEL (ordinate, from Table 3-1) noise levels, and all 19 sites are plotted in Figure 3-1. Site S9 was excluded from the regression calculation because of the very high uncertainty in its SPB level.

The error bars represent the 95% confidence intervals of the SEL and CPXP_{80} noise level measurement uncertainties, as previously described in this chapter.

It appeared that there were two separate linear relationships within the data set, or possibly one S-shaped relationship.

We have chosen to define this as two linear relationships, one for porous surfaces and one for non-porous surfaces. This is a subjective distinction and is only one of several possible interpretations of the empirical data; it does not have a formal theoretical basis. Other ways to group and summarise the CPX-to-SEL relationship were considered, such as asphalts / chipseals, and < 99 dB / > 99 dB $L_{\mathrm{CPX:P1,80}}$. Our observation was that the porous / non-porous distinction was the most logical source for a piecewise separation (CPX is known not to capture all the far-field effects from surface porosity [ISO 11819-2:2017]) and it also provided the best fit to the data of the options trialled.

In NZ, porous surfaces are the OGPA specifications, PA and EPA. The non-porous surfaces are the remainder: chipseals, slurries, and non-porous asphalts. There is considerable uncertainty around how to classify the SMA specifications with respect to this relationship, because there is only one SMA site in our SPB survey (S6), and it was a relatively coarse SMA 15 specification. Likewise, AC 10 (S5) appeared to fall within the non-porous set, but the excluded AC 10 site (S9) was closer to the porous set. More investigation will be required before nominally non-porous asphalts can be classified with confidence.

Figure 3-1 shows the porous and non-porous lines of best fit along with their regression equations. The porous line is about 3.5 dB quieter than the non-porous line for the same $CPXP_{80}$ level.

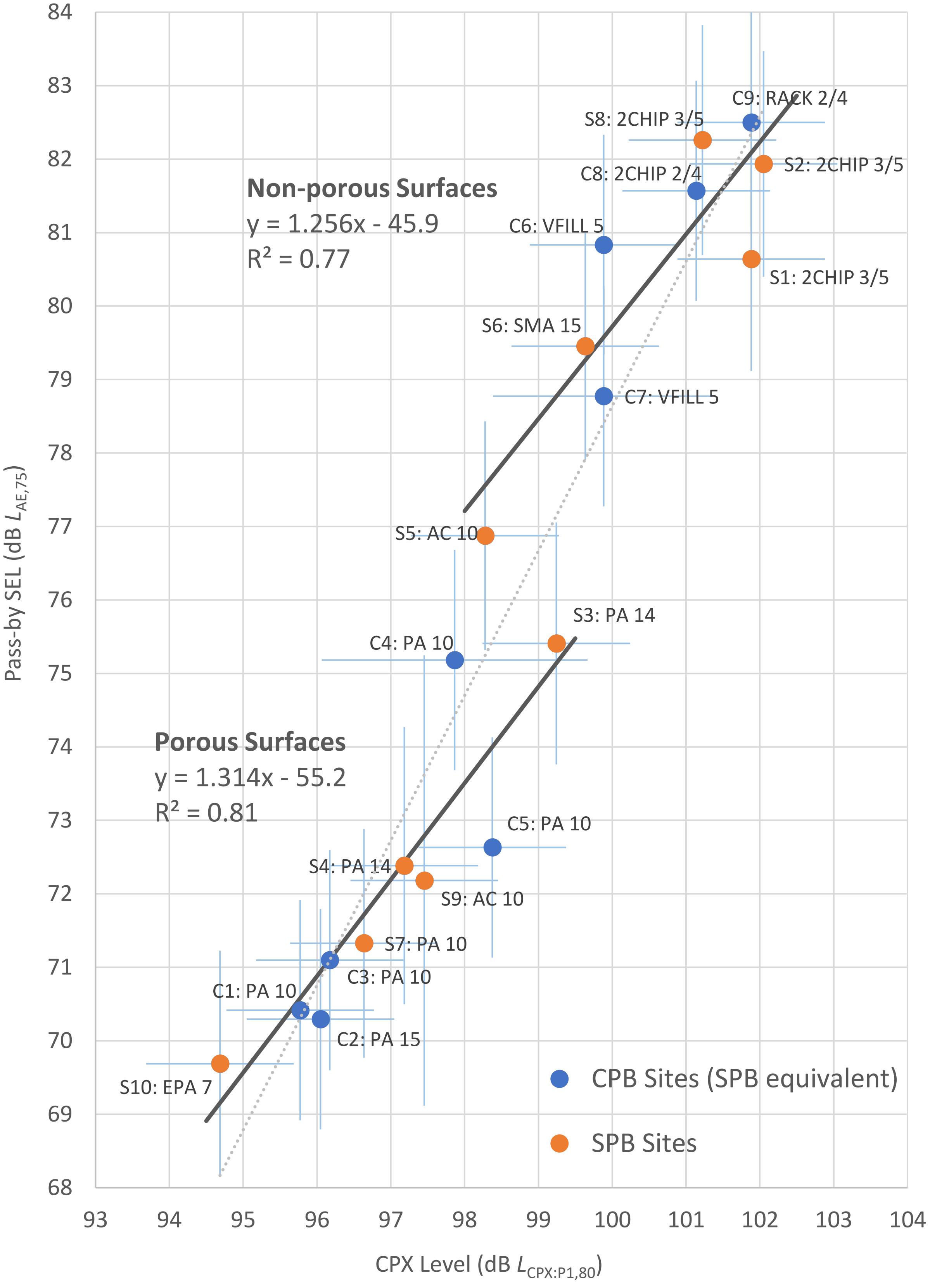

Figure 3-1: Weighted linear regression of Pass-by SEL on $CPXP_{80}$ for 19 pass-by sites

A weighted linear regression was performed[10] of SEL on $CPXP_{80}$, producing two empirical relationships,

Porous surfaces: $SEL_{por} \approx 1.314\ CPXP_{80} - 55.2$ (r^2=0.81, n=9, p<0.05) (3.4)

Non-porous surfaces: $SEL_{non-por} \approx 1.256\ CPXP_{80} - 45.9$ (r^2=0.77, n=9, p<0.05) (3.5)

The slopes of m=1.3 in equations 3.4 and 3.5 are similar to those found in previous studies [Sandberg & Ejsmont, 2002; Jackett, 2019b]. We have not attempted to explain the exact magnitude of the coefficient.

When the data are not separated by surface porosity, the linear regression of n=18 points has a slope approximating 2 (as previously seen in equation 3.3 for n=9),

Arbitrary surface: $SEL_{any} \approx 1.948\ CPXP_{80} - 116.1$ (r^2=0.92, n=18, p<0.05) (3.6)

3.4 Prediction of $L_{Aeq(24h)}$ from $CPXP_{80}$

Equations 3.4 and 3.5 represent the best available link between the $CPXP_{80}$ levels summarised by the Part 1 report and the pass-by SEL. We emphasise that this formulation relies on our interpretation that the data in Figure 3-1 are best separated into porous and non-porous groupings, with porous effectively being 3.5 dB lower at the wayside for the same $CPXP_{80}$ level. Other groupings are possible and further exploration of the porosity effect at the wayside is recommended (see section 5.2).

In this project, equations 3.4 to 3.6 have been used to translate between the CPX results of the Part 1 report, in dB $L_{CPX:P1,80}$, to the pass-by level predictions in dB L_{AE},

- Equation 3.4 has been applied to all porous surfaces, which were interpreted as including any specification of OGPA (see 4.2.3).
- Equation 3.5 applies to most other surfaces (see 4.2.1 and 4.2.4), which are assumed non-porous for the purposes of this report.
- Until such time that data exist to properly classify SMA and AC asphalt surfaces (see 4.2.2), the surface-agnostic equation 3.6 will need to be used for these surfaces, despite its slope of $m\approx2$.

The prediction of $L_{Aeq(1h)}$ follows equation A.0 in Appendix A.

The relationship to $L_{Aeq(24h)}$ and CRTN's L_{A10} is discussed in Notes 1 and 2 to Appendix A.

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[10] Real Statistics Resource Pack software (Release 7.6), Copyright (2013 – 2021) Charles Zaiontz

4 Road Surface Corrections to CRTN

The *Guide to state highway road surface noise* [NZTA, 2014] gives corrections for each listed surface in terms of a *R*c value (in dB) for cars, and a *R*t value for trucks. The approach used in this project does not require that to change. What will change is that the *R*c and *R*t values will no longer be relative to an AC-10 reference surface, but will relate directly to CRTN output. The NZ Adjustment of -2 dB will also disappear. The *R*c and *R*t values would still need to be combined with %HCV and traffic speed information using the equation on page 37 of the Guide to calculate the total correction for the road surface, *R*.

This chapter determines recommended updated values for *R*c, and rationalises the list of surfaces. *R*t values will be determined by the Part 3 report.

4.1 Selection of Indicative CPX Levels

The current surface corrections specify a single pair of *R*c and *R*t values for each distinct surface specification, without regard to the surface age or thickness. The values represent an 'average' surface, without consideration of surface variability within and between sites.

For the revised corrections table, these aspects have been reconsidered, based on the findings from the Part 1 report.

4.1.1 Surface Age

The Part 1 report (specifically section 3.3) found no evidence of substantial aging effects for chipseals and porous asphalts and suggested a relatively small aging effect for SMA. That indicative analysis considered only surfaces aged between 6 months and 10 years old.

The mean $L_{\mathrm{CPX:P1,80}}$ levels in tables 3-1 and 3-2 of the Part 1 report are indicative of the average performance of each surface at an approximate age of 4 years.

We propose that, like the existing corrections, the revised surface corrections do not need a variable to account for surface age. Therefore, the draft corrections will nominally represent each surface at age 4 years, but can be applied to surfaces up to 10 years old with reasonable confidence. In practice, it is inevitable that these corrections will also be applied to surfaces older than 10 years, which would carry an additional 'extrapolation' uncertainty.

4.1.2 Surface Thickness for Porous Asphalts

Surface thickness appears to be an important variable for tyre/road noise emission of porous asphalts, but there is limited data with which to quantify its effect for NZ surfaces. Section 3.4 of the Part 1 report contains an analysis of surface thickness effects.

Two recent studies of actual (measured) thickness in EPA-7 found CPXP_{80} effects of -2.2 dB/cm (n=9) and -0.3 dB/cm (n>1000) respectively. The two studies used different methodologies.

A study of nominal (as recorded in RAMM) thickness in PA-10 found a slope of -0.8 dB/cm (n=4566). When CPXP_{80} levels were averaged by nominal thickness the relationship was not significant (r^2=0.18, n=7, p=0.35).

There is little agreement between these three results, noting that actual and nominal thicknesses are different definitions of the independent variable (though presumably affecting the offset more than the slope).

The surface corrections require a noise level that is based on the nominal thickness, because, by definition, that is the surface thickness that is specified during construction. However, Waka Kotahi are currently changing how porous asphalts are specified (when they are used for noise mitigation) to be more explicit that the nominal thickness is a minimum to be achieved, rather than an average. It is yet to be seen what impact this will have on actual surface thickness.

A further complication is that the underlying mechanism behind the thickness effect may not be linear with thickness, and could involve an optimal thickness that is peculiar to each surface specification (that is, beyond a certain optimal thickness, adding more may make the noise worse).

Therefore, via a combination of factors, the thickness effect in porous asphalts can only be approximately defined and is likely to need revision in the near future.

For the surface corrections for this project we have assumed a thickness effect on the $CPXP_{80}$ level of -1 dB/cm.

4.1.3 Level Variation within a Specification

Within each surface specification, there is some spread in noise levels about the mean, and the distribution differs between surface specifications. The distributions are quantified for each RAMM surface specification in tables 3-1 and 3-2 of the Part 1 report via the mean and standard deviation, and via the median and quartiles. Section 3.6 of the Part 1 report provides additional analysis and discussion on the distribution characteristics of different surfaces.

In general, the chipseals and SMA have the least spread (sd ≤ 0.8 dB) and porous asphalts the most (sd ≥ 1.6 dB). The net effect is that the mean CPX level from one porous asphalt road surface could differ from a second notionally identical surface by 6 dB or more. There is overlap in distributions between the porous asphalts and the chipseals. The large spread and overlap are not represented by considering only the mean, as is the case with the existing corrections.

A range of options exist for handling variation within a specification, some of which are laid out in Table 4-1, alongside a commentary on the key benefits and risks.

Table 4-1: Options for handling variation within a specification in the corrections table

Option	Description	Commentary
1	Include measures of both central tendency and variability in the final table, so that end-users can account for them as required.	Requires additional guidance and adds complexity to the prediction process that is probably not justified for most noise assessments. The raw data would be available in the Part 1 report if it was required.
2	Instead of using the mean, select a more conservative value to represent the performance of the surface, e.g. the mean plus 1 standard deviation (the 84th percentile), or the upper quartile, etc.	Mostly transparent to the end-user, while reducing risk that a louder-than-average surface would lead to predicted levels being exceeded. The magnitude of the possible exceedance would be more uniform across specifications. As this is achieved by penalising porous asphalts more than chipseals, the range of the surface corrections would be compressed, which could potentially discourage specification of porous asphalts in some cases by understating its *average* benefit.
3	Set the indicative value as the mean, as per the status quo.	No change for the end user, but the actual surface laid effectively has a 50% chance of exceeding the predicted level, which could be by up to 3 or 4 dB in the case of OGPA.

We consider option 2 to be the most appropriate at this time. The selection of the exact percentile is subjective and needs to balance the need for confidence in the final prediction against compressing the range between surfaces too much.

We propose that the 75th percentile achieves a good balance. With that value, 1 in 4 sites would be expected to exceed their predictions due to surface variance, and the typical magnitude of exceedance for porous asphalt would reduce by a useful 1 dB. Meanwhile, it would compress the range between OGPA and chipseal by just 0.5 dB, which would not discourage the use of OGPA in most situations where it was a mitigation option.

The upper quartile for each surface specification is given in tables 3-1 and 3-2 of the Part 1 report, or could be estimated as the mean plus 0.675 times the standard deviation for normally distributed data. For context, Figure 4-1 marks the 75th percentile with an orange bar imposed on the standard normal distribution.

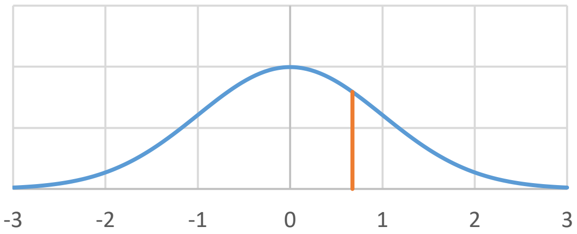

Figure 4-1: The standard normal distribution showing the location of the 75th percentile (orange)

The process detailed above aims to account, to some extent, for the different distribution widths between surface types. There may be additional adjustments and safety factors to apply to the corrections overall, but care will be required to avoid double-counting of random error.

4.1.4 Precision

The high variability of surfaces within a specification (±1 dB to ±4 dB $L_{CPX:P1,80}$) and the overall uncertainty of CRTN prediction (at least ±4 dB $L_{Aeq(24h)}$) suggest a low bar for the precision of the corrections in absolute terms. However, the relationship between once specification and another is important to the selection of surfaces for noise mitigation. With reference to the uncertainty budget in Appendix E.4, a precision of 1 dB for *Rc* will be acceptable.

4.2 Rationalisation of Surfaces

The final table of corrections needs to cover the full range of surfaces, but if specifications can be grouped whilst still maintaining accuracy then that is a desirable outcome. The analysis below considers only the *Rc* component, based on the $CPXP_{80}$ levels. An element of subjectivity is required by this process, especially for surfaces with very little $CPXP_{80}$ data. Quantification of *Rc* for each surface will follow in section 4.3, after $CPXP_{80}$ levels have been propagated through to $L_{Aeq(24h)}$.

4.2.1 Chipseal

Sections 3.2.6 and 3.5.1 of the Part 1 report found no significant difference between different types of dual-chip chipseal, no systematic effect from the smaller chip in a dual-chip specification, and unlike the existing corrections, found no significant difference in performance between single-chip and dual-chip specifications when grouped by their largest grade of chip. The noise emission of chipseals of all varieties was found to have a strong correlation to the largest grade of chip present (r^2=0.81, n=22, p<0.001).

A sensible grouping of chipseals is therefore based on the grade of the largest chip present. Chipseals using grade 2 and 3 chip have similar levels on average, while those based on grade 4, grade 5, and grade 6 have progressively lower noise levels. Grade 6 is extremely rare so should be combined with grade 5.

The corrections table need only include three entries for chipseals, in contrast to the current nine. These will be single- or multi-coat chipseals whose largest grade is:

- Grades 2 or 3
- Grade 4
- Grades 5 or 6

4.2.2 SMA

The existing corrections table provides identical values for SMA-10, SMA-11, and SMA-14.

The Part 1 report includes six specifications of SMA, from SMA-8 to SMA-15, as well as two different nominal surface thicknesses for SMA-10. The mean CPXP$_{80}$ level for each is shown in Figure 4-2, along with the number of contributing distinct sites, *n*. Several specifications are only drawn from one or two sites. The error bars in the figure represent the uncertainty in the mean at the 95% level, assuming a between-sites standard deviation of 0.8 dB applies to all SMA specifications.

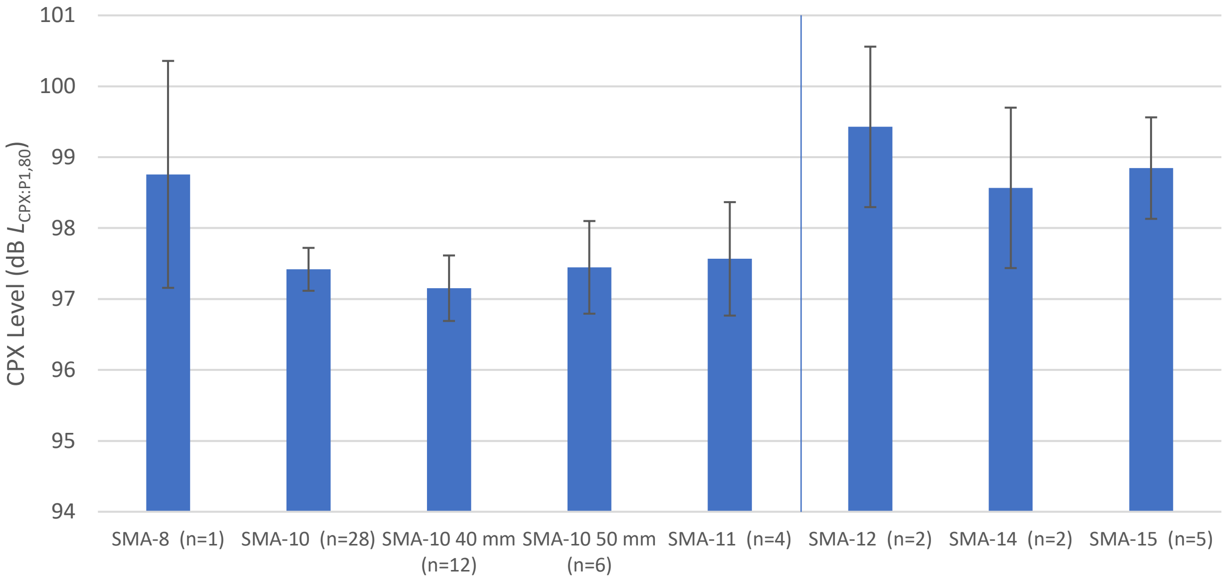

Figure 4-2: CPXP$_{80}$ levels for all surveyed SMA specifications

We suggest that SMA-8, SMA-10, and SMA-11 may be grouped together. The high SMA-8 level shown is assumed to be unrepresentative (noting that *n*=1) based on the broader pattern that smaller aggregate size typically means quieter asphalts. The correction for this grouping will be based on the SMA-10 data, which is by far the most common SMA specification in NZ.

The specifications with 12 mm aggregate or larger appear to be significantly louder, by 1 to 2 dB, and could form a second SMA group.

There is no evidence that it is necessary to consider thickness in SMA.

An age correction of +0.5 dB will be included in the SMA-10 correction to adjust it to the reference age (but is not included in Figure 4-2).

The corrections table need only consider two groupings of SMA:

- SMA-11 and smaller
- SMA-12 and larger

4.2.3 Porous Asphalt

OGPA specifications continue to evolve, with polymer-modified and epoxy-modified binders becoming more common. In general, the type of binder used is a level of detail beyond what the end-user should need to complete a noise assessment. Figure 4-3 shows that difference between the average $CPXP_{80}$ levels of PA-10 and EPA-10 (the latter being epoxy-modified) is small, and not statistically significant ($p>0.05$). The draft corrections table will therefore ignore binder type.

The error bars in Figure 4-3 represent the uncertainty in the mean at the 95% level, assuming a between-sites standard deviation of 1.6 dB applies to all OGPA specifications.

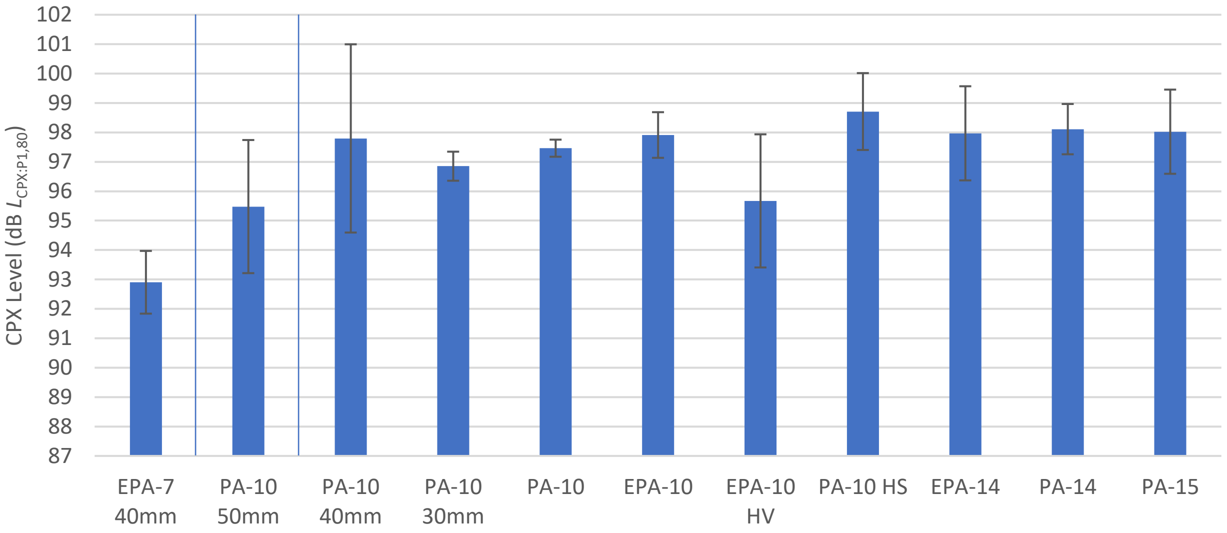

Figure 4-3: $CPXP_{80}$ levels of all surveyed porous asphalt specifications

The remaining variables for porous asphalt are the surface thickness, the nominal maximum aggregate size, and the void content.

The surface thickness effect for porous asphalts was discussed in section 4.1.2, concluding that an effect of -1 dB/cm could be adopted for PA-10 until the effect was better understood and quantified. The large uncertainty in the magnitude of the effect, and even in the definition of surface thickness itself, suggest that this set of draft corrections should not overreach on precision. Consequently, only two thicknesses of PA-10 will be defined in the draft corrections table: nominally 50 mm and 30 mm. All surfaces less than 50 mm thick will use the 30 mm value.

The nominal maximum aggregate size increases left to right in Figure 4-3. The 14 mm and 15 mm specifications are not significantly noisier than the 10 mm specifications, and these could all be grouped. The EPA-7 specification stands alone as being significantly quieter, and thus there will be one grouping for 7 mm, and one grouping for surfaces using 10 mm or larger aggregate.

The high void content specification (EPA-10 HV) in Figure 4-3 came from a single trial, where it performed worse than the standard EPA-10 in that trial [Jackett, 2019a]. The EPA-10 in that trial performed much better than the average EPA-10 site in the Part 1 report. There is insufficient data to characterise the performance of EPA-10 HV at this time and it will not be included as a separate correction.

The EPA-7 value is also based on a small sample, including the same trial site. Its performance advantage over the other surfaces in the trial was significant, but until the surface has been reproduced elsewhere, the correction should be defined conservatively. We will use its relative performance against the two EPA-10 samples within the trial to determine its correction (relative to the broader sample of EPA-10). In the trial, EPA-7 was 3.4 dB quieter than EPA-10 on average. Subtracting 3.4 dB from the value for EPA-10 in Figure 4-3 gives an indicative average for EPA-7 of 94.5 dB $L_{CPX:P1,80}$, for an upper quartile of approximately 95.5 dB $L_{CPX:P1,80}$. The only thickness available across the trial sites was 40 mm so the EPA-7 correction is only specified for this nominal thickness.

For now, the corrections table might only contain three porous surfaces:

- 30 mm thick PA-10+
- 50 mm thick PA-10+
- 40 mm thick PA-7

4.2.4 *Other Surfaces*

The surface types identified above cover over 94% of the network. The remaining surfaces are mostly dense asphalts, texturising seals, and types of slurry. These surface types are discussed individually below, drawing from the limited CPXP_{80} data for these types in the Part 1 report.

- Texturising seals
  No CPXP_{80} data exist. We propose these are treated as if they share the properties of the underlying grade of chipseal, defaulting to grade 3 if the underlying surface is unknown.

- Dense asphalts
  Data for AC-10 and UTA-10 places these surfaces fairly close to SMA-10 in terms of CPXP_{80}. We propose that all dense asphalts are assumed to have the same noise properties as the equivalent size of SMA.

- Slurry seals
  No CPXP_{80} data exist for slurry seal or cape seal. The existing corrections table places these surfaces between SMA and the finer grades of chipseal. In the unlikely event that a slurry is present or proposed as part of a noise assessment, it could be conservatively treated as a grade 5 chipseal.

Due to their rarity and/or similarity to other surface types, none of these surfaces require their own entries in the corrections tableand could be covered by written guidance.

4.3 Draft CRTN Surface Corrections for Cars

Section 4.1 described how surface aging effects, surface thickness, and surface variability between sites were accommodated in the selection of representative CPXP_{80} levels for each surface specification.

The rationalisation process described in section 4.2 has reduced the number of surface specifications from the original 44 for which CPXP_{80} levels have been measured, down to 8 broad surface classifications that we propose should be included in the surface corrections table (compare to 23 in the existing corrections table).

Those 8 CPXP_{80} levels have been propagated through an CPX-to-SEL conversion, adjusted for vehicle mix and outliers, and normalised against CRTN's implicit SEL, following the process described in Table 4-2, to obtain a draft table of surface corrections (Table 4-3).

4.3.1 *Propagation from CPXP_{80} to $L_{Aeq(24h)}$*

The propagation process in Table 4-2 below may be understood in conjunction with the methodology schematic in Figure 2-1.

The resulting data in Table 4-3 are shown for each significant step of the process.

As described in section 3.4, we have derived different CPX-SEL relationships depending on the surface type. OGPA uses equation 3.4, chipseals use equation 3.5, and for the time being, SMA and AC use equation 3.6, which is a general relationship with a slope close to $m \approx 2$.

The final column in Table 4-3 indicates the magnitude of the existing surface correction to CRTN (after applying the NZ Adjustment), albeit the surface classification definitions have changed somewhat so the closest match has been used.

Table 4-2: Process to derive the surface correction for a surface classification

Step	Output Quantity	Process or Operation	Reference
1	20-metre segment levels from $CPXP_{80}$ survey	Measured, then corrected for speed, temperature, and tyre hardness	Part 1 report
2	$CPXP_{80}$ levels for 44 surface specifications	Linked to validated surfaces and summary statistics produced	Part 1 report
3	Representative $CPXP_{80}$ levels for 8 surface classifications	Rationalised down to 8 classifications, and adjusted for surface age, surface thickness, and surface variability	Sections 4.1 and 4.2
4	Initial SEL levels for 8 surface classifications	Propagated through the CPX-SEL regression equations 3.4, 3.5, or 3.6 depending on surface type $SEL_{init} \approx m\ CPXP_{80} + c$	Section 3.3
5	SEL levels	Adjustments for traffic mix (K_1=0.04 dB), outliers (K_2=0.43 dB), and posted speed limit (K_3=-0.62 dB) $SEL = SEL_{init} + K_1 + K_2 + K_3$	Sections 3.1.3 3.1.4, and 3.1.5
6	Raw Correction (equivalent to $L_{Aeq(24h)}$)	Subtraction of the implicit CRTN SEL ($L_{AE,car}$ = 75.3 dB) $Raw\ Correction = SEL - L_{AE,car}$	Section 2.3.4
7	Draft Corrections	Further rationalisation, and rounding of raw correction to the chosen precision	Section 4.2
8	Final Corrections	Additional adjustments to draft corrections possible (e.g. tolerances, qualitative considerations), then validation, ratification, and publication.	To follow in a future publication

Table 4-3: Derivation of draft road surface corrections for light vehicles

	Step 2	Step 3	Step 4	Step 5	Step 6	**Step 7**	Existing
Surface Classification	Mean $CPXP_{80}$ dB $L_{CPX:P1,80}$	Represent-ative $CPXP_{80}$ dB $L_{CPX:P1,80}$	CPX to SEL dB L_{AE}	SEL Adjust dB L_{AE}	Raw Correction (re $L_{Aeq(24h)}$) dB	**Draft Correction (re CRTN) dB**	Existing Correction (re CRTN) dB
Grade 2 or 3	101.5	101.9	82.1	81.9	6.6	**+7**	+4.0
Grade 4	100.4	100.8	80.7	80.6	5.3	**+5**	+1.0
Grade 5 or 6	99.9	100.2	80.0	79.8	4.5	**+4**	+1.0
SMA-14	98.9	99.3	77.4	77.2	1.9	**+2**	-0.5
SMA-10	97.9	98.5	75.8	75.6	0.3	**0**	-0.5
PA-10 30 mm	97.7	98.7	74.5	74.3	-1.0	**-1**	-2.0
PA-10 50 mm	95.5	96.6	71.7	71.6	-3.7	**-4**	-4.0
PA-7 40 mm	94.5	95.6	70.4	70.3	-5.0	**-5**	--

4.3.2 Proposed Notes to the Draft Corrections

No distinction is made between single coat and multiple coat chipseals. The lowest grade (i.e. largest chip size) present in the chipseal shall be used to determine its correction. For example, a two-coat grade 3/5 surface has a surface correction of +7 dB.

SMA-10 includes all SMA mixes with maximum aggregate size 11 mm and smaller.

SMA-14 includes all SMA mixes with maximum aggregate size 12 mm and larger.

Surface thickness influences the performance of porous asphalt. Thicknesses stated in the table are minimum thicknesses in millimetres. Any porous asphalt that is less than 50 mm thick shall use the correction for PA-10 30 mm, with the exception of PA-7 40 mm, whose correction is given separately.

Where a texturizing seal has been laid on an existing road, the correction shall be determined from the underlying grade of chipseal, defaulting to grade 3 if the underlying surface is unknown.

Dense graded asphalts (e.g. AC, DGA, UTA) shall adopt the correction of SMA 10. However, if these surfaces are milled/tined with transverse grooves their noise emission may increase by an additional +5 dB or more. A tonal noise emission is also possible, dependent on the groove pattern and spacing.

Slurry seal and Cape seal shall adopt the correction of grade 5 chipseal.

Taken together, the corrections table and these notes should provide a surface correction for all surfaces that a practitioner is likely to encounter (over 99% of the state highway network is covered, by length). If the practitioner encounters a surface that they believe is not adequately covered, they are requested to contact Waka Kotahi and provide them with the specifics of the surface.

4.3.3 Interpretation

The draft corrections in Table 4-3 are generally higher than those of equivalent surfaces in the existing corrections table [NZTA, 2014]. The range is also larger between coarse chip and thick OGPA: up from 8 dB to 11 dB. The corrections are sensitive to the coefficients of the regression equations 3.4 to 3.6, and could therefore change significantly based on any further investigations into CPX and SEL measurement. The corrections for SMA in particular may need to be revised depending on whether this surface behaves more like a porous or non-porous surface, or is a different category altogether.

Due to taking the upper quartile as representative (to make comparison between surfaces fairer), the draft corrections are 0 to +1 dB higher than they would be if the mean had been taken.

The draft corrections in Table 4-3 still require validation and ratification before they are adopted.

4.3.4 Uncertainty

An uncertainty budget for the corrections is provided in Appendix E.4, and Appendix B.4 discusses uncertainties of the method, in the context of the uncertainty of CRTN itself.

The absolute uncertainty of the corrections under CRTN reference conditions, including the 're-calibration' to the current NZ light vehicle fleet, is estimated at ± 3.2 dB $L_{Aeq(24h)}$ at the 95% level of confidence.

The largest contribution arises from the potential for an incompatibility between pass-by SEL measurements and the validity of deconstructing CRTN to get an implicit SEL. This error is not quantifiable without additional validation using traffic streams.

The relative uncertainty of each correction to the reference level is considerably lower, between ± 1.8 dB for SMA, and ± 2.3 dB for chipseal and porous asphalt, at the 95% level of confidence.

Note that the NZ Adjustment and the current set of corrections also have some associated error (magnitudes unknown), some of which will be due to variability in the AC-10 reference surface. The Part 1 report indicates a standard deviation of approximately 0.8 dB for AC-10 road segments, albeit based on a small sample size.

The prediction uncertainty under CRTN reference conditions can be estimated by factoring in the variability of the population of surfaces contained within each classification, and the prediction interval of the regression to SEL. This results in an uncertainty of prediction for an arbitrary site under CRTN reference conditions that ranges from ± 5.2 dB for SMA to ± 8.7 dB for OGPA at the 95% level of confidence. The majority of the error in prediction appears to arise (directly and indirectly) due to variability of surfaces themselves.

5 Conclusions

5.1 Findings

5.1.1 CRTN's Implicit Sound Exposure Levels

CRTN was built empirically, but its core equations can be unpicked to extract implicit SEL for light and heavy vehicles under CRTN reference conditions (§2.3):

$$L_{\mathrm{AE,car}} = 75.3\ \mathrm{dB} \tag{2.1}$$

$$L_{\mathrm{AE,truck}} = 84.2\ \mathrm{dB} \tag{2.2}$$

5.1.2 Statistical Pass-by Survey

The pass-by SELs of over 500 light vehicles of the 2021 and 2022 NZ vehicle fleet were measured over 10 different sites (§3.1). The typical LCV (utes and vans) were just 0.6 dB louder than the typical car. However there was a big difference between the outliers: 1 in 50 cars were louder than the typical car by 3 dB (on average), but 1 in 10 utes were louder than the typical ute by 8 dB (on average).

5.1.3 Comparison between Pass-By and CPX Measurements

Comparing pass-by SELs to CPX measurements revealed unexpected results (§3.3). The range in SEL between the quietest sites and the noisiest was about 13 dB, whereas the corresponding range in CPX:P1,80 was just over 7 dB. Significant efforts were made to understand this, including doubling the number of measurement sites (Appendix D). Whilst not a definitive answer, for the purposes of this study we have assumed that the difference is due to an insensitivity of the CPX trailer to some properties of the road surface, nominally porosity. Consequently the relationship between CPX and pass-by SEL (Figure 3-1) has an additional variable of surface type. OGPA uses equation 3.4, chipseal uses equation 3.5, and until it can be confirmed as behaving as either a "porous" or "non-porous" surface, SMA uses the surface-agnostic equation 3.6.

Porous surfaces: $SEL_{por} \approx 1.314\ CPXP_{80} - 55.2$ (r^2=0.81, n=9, p<0.05) (3.4)

Non-porous surfaces: $SEL_{non-por} \approx 1.256\ CPXP_{80} - 45.9$ (r^2=0.77, n=9, p<0.05) (3.5)

Arbitrary surface: $SEL_{any} \approx 1.948\ CPXP_{80} - 116.1$ (r^2=0.92, n=18, p<0.05) (3.6)

5.1.4 Rationalisation of Surfaces

Eight broad surface classifications have been defined (§4.2), reduced from the original 44 specifications for which CPXP_{80} levels exist (compare to 23 in the existing corrections table). Chipseals have been defined using three classifications that are based only on the largest grade of chip in the specification. OGPA surfaces have been updated to reflect the latest specifications. Indicative CPXP_{80} levels for each classification considered the age of the sample, surface thickness, and the variation in level within a classification (§4.1). The CPXP_{80} levels represent the upper quartile of the levels likely to be measured on NZ surfaces within each classification.

5.1.5 Surface Corrections for Light Vehicles

Surface corrections for 8 surface classifications were found by a complicated process (§4.3). Indicative CPXP_{80} levels were identified, propagated through a CPX-to-SEL relationship, and corrected for vehicle mix, outliers, and actual vehicle speed vs. posted speed. That provided a pass-by SEL that could be directly compared with CRTN's implicit per-vehicle SEL, their difference defining the draft surface correction for each surface. The draft corrections represent a recalibration of CRTN for NZ light vehicles in 2022 in absolute terms, as well as providing information about the relative wayside noise levels expected from different surfaces. They have not yet been validated against road traffic noise measurements involving a mix of light and heavy vehicles or at non-reference traffic speeds.

Table 5-1: Proposed draft road surface corrections for light vehicles

Surface Classification	Indicative $CPXP_{80}$ dB $L_{CPX:P1,80}$	Equivalent light vehicle pass-by SEL dB L_{AE}	Draft Correction (re CRTN) dB
Grade 2 or 3	101.9	81.9	+7
Grade 4	100.8	80.6	+5
Grade 5 or 6	100.2	79.8	+4
SMA-14	99.3	77.2	+2
SMA-10	98.5	75.6	0
PA-10 30 mm	98.7	74.3	-1
PA-10 50 mm	96.6	71.6	-4
PA-7 40 mm	95.6	70.3	-5

5.2 Recommendations

5.2.1 Validation of the draft corrections

The draft corrections are based on a novel approach that linked $CPXP_{80}$ data to CRTN's $L_{Aeq(24h)}$ predictions via the measurement of individual vehicles at the wayside (SPB). The payoff from the high-risk methodology is high efficiency and a detailed quantification of NZ's road surfaces from a large $CPXP_{80}$ survey. The main cost is uncertainty in the absolute calibration of CRTN to the current NZ traffic fleet, because the relationship between traffic noise and pass-by noise is theoretical.

We recommend that the draft corrections for both light and heavy vehicles should be validated through wayside measurements of road traffic noise (i.e. a flow of vehicles).

A wide range of surfaces would allow the relative difference between surfaces to be validated, in addition to the absolute level. Re-using SPB or CPB sites for traffic surveys would allow many sources of systematic error to be removed. Complementing the survey with $CPXP_{80}$ measurements could provide some reduction in error arising from variation within surface types (i.e. use CPX to pick a 'typical' section of a given surface type).

A traffic survey in close-to CRTN reference conditions would allow the most direct validation of the project methodology. However, we also recommend that noise monitoring is performed at several distances from the road simultaneously, and for roads with 50 km/h and 100 km/h speed limits (see observation 5.3.2).

5.2.2 Determine why pass-by levels vary over much larger range than $CPXP_{80}$

The unexpected $m \approx 2$ result (section 3.3.3) was extensively investigated but not conclusively resolved (Appendix D). Further validation work should attempt to uncover more information about why the pass-by and CPX measurements differ by such a large amount. It will be difficult to have full confidence in the outputs of this project or the CPX trailer until the differences are understood.

5.2.3 Determine how to accommodate SMA and AC surfaces within current regime

This project's SPB survey and subsequent CPB survey both focused on measuring as broad a range of pass-by noise levels as possible to reduce the necessity for extrapolation. A consequence is that some of the intermediate surfaces were under-represented, particularly SMA. It was also the case that SMA was not prevalent within Wellington at the time, with only SMA 14 being captured. Given that the relationship from CPX to SEL proposed by this project is dependent on the surface type, the sample of SMA should be expanded.

The AC in the SPB survey provided contradictory results. Site S5 placed AC within the non-porous grouping, whereas S9 (admittedly with very large measurement uncertainty) sits closer to the porous grouping (
Figure 3-1). AC is not common on high-speed roads but does appear on local roads, low speed sections of state highways, and on highspeed ramps and intersections in Regions without access to SMA (where it is often grooved to increase texture). It would be advantageous to improve its characterisation in the corrections.

5.2.4 Investigate the effect of porosity in NZ OGPA

The way we have chosen to interpret the pairs of $L_{\mathrm{CPX:P1,80}}$ and $L_{\mathrm{AE,75}}$ plotted in
Figure 3-1 is through two linear relationships, approximately parallel, and separated in $L_{\mathrm{AE,75}}$ by approximately 3.5 dB. OGPA surfaces belong to the quieter set, and the other surfaces have been grouped in the noisier set. Without much evidence we have proposed that one possible cause of the apparent step of -3.5 dB for OGPA could be porosity, perhaps realised through acoustic absorption (section 3.3.4).

Notwithstanding that the dual linear relationship may be an aberration of the small data set or due to some other factor, it would be useful to quantify the effect of road surface porosity on the wayside noise level. This might extend to considering the effect of porosity in the road shoulder, given the striking results of the near-road ground absorption test (5.3.5).

5.2.5 Investigate tyre/road noise directivity

One hypothesis for the differences between wayside and CPX measurements is a surface dependence on the directivity of the tyre/road noise emission. This could be investigated using the CPX trailer by introducing additional microphone positions within the wheel enclosure, or on test vehicles.

5.2.6 Additional data analysis of SPB, CPB, CPX, and quasi-CPX data

This project captured a large amount of high-quality pass-by and CPX noise data that contains far more information than has been used in this project. It may be valuable for validation, for a deeper investigation of the tonal differences between surfaces, or to define the distance from a receiver beyond which the surface selection makes no difference.

5.3 Observations

5.3.1 Comparison to existing surface corrections

The draft corrections (Table 4-3) are generally higher than the existing corrections [NZTA, 2014], particularly the coarser chipseals. The range between coarse chip and thick OGPA is also larger. If these results are confirmed through validation then it could have a substantial impact on the outcome of NZS 6806:2010 noise assessments:

1. Predicted 'do-minimum' (and 'do-nothing') levels would be higher for many projects, and mitigation investigation thresholds would be expected to be triggered more often and more widely.

2. If the larger range is confirmed then NZ's quiet road surfaces may provide a greater benefit over chipseals than previously thought, further enhancing their attractiveness as a noise mitigation option.

5.3.2 *Focus on CRTN refence conditions*

The project methodology focused on replicating CRTN reference conditions quite precisely, so that pass-by measurements could be directly compared with CRTN's implicit SEL. This had the unavoidable effect of 'tuning' the corrections for the CRTN reference conditions, most notably for 75 km/h traffic and at 10-metres from the side of the road. We assume that CRTN's empirical algorithms were derived more on 'balance' than specifically for the reference conditions and then corrections added, but that is what we have effectively and unavoidably done in this project (see also Appendix B). Fortunately, the reference conditions approximate a situation of particular interest to noise assessments, the dwellings closest to high-speed roads.

5.3.3 *Subjective Observations*

During the course of the SPB and CPB surveys we spent a lot of time on and beside the road, listening to and thinking about the noise emission of approaching and passing vehicles:

- Subjectively, utes seemed to have noise characteristics close to cars in the 75+ km/h sites, and closer to the smaller MCVs in the 50 km/h site. Possibly the diesel engines typical amongst utes contributed to this perception at 50 km/h.
- At both speeds it was obvious that 'noisy utes' were the exception rather than the rule. The SPB survey analysis in section 3.1.5 showed that about 1 in 10 utes were much noisier than a typical ute, by a substantial +8 dB on average. However, a typical ute was less than 1 dB noisier than a typical car. On the other hand, outlying cars were encountered at a rate of 1 in 50 vehicles, and were less than +3 dB noisier than the typical car on average.
- Whereas a level change of 2 dB is often cited as being either imperceptible or barely perceptible to human hearing, we observed strong audible differences in both pass-by and in-vehicle noise between different chipseal surfaces with nearly identical $CPXP_{80}$ levels. For example, sites C8 (2CHIP 2/4) and C9 (RACK 2/4) differ by 0.7 dB $L_{CPX:P1,80}$ and 0.9 dB L_{AE} but site C9 seemed noticeably louder from within the vehicle and different at the wayside. We assume this is down to tonal differences between sites, perhaps due to factors such as the surface texture wavelength and sharpness of broken chip faces. Whatever the cause, it was a reminder that the perception of road noise is not completely summarised by either its CPX or wayside noise level in dB.

5.3.4 *Light vehicle fleet*

A good mix of cars, utes, and vans was captured during the SPB survey. However, we did not capture any usable motorcycle pass-by measurements, perhaps in part due to measuring at night time.

5.3.5 *CRTN's ground absorption correction*

A sanity check of the effect of ground absorption at 10-metres from the roadside was undertaken using CPB at one pair of sites (§D.3.4). We found that 100% absorption (grass) led to a wayside level 4.2 ± 1.4 dB lower than 0% absorption (tarmac/gravel), which was in the region of CRTN's chart 8 correction (3 dB).

References / Bibliography

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Appendix A Reverse Engineering CRTN for SEL

CRTN [DoT U.K., 1988] is a road *traffic* noise model, and as such it predicts noise levels resulting from a flow of vehicles, not a single vehicle. To enable a methodology based on individual vehicle pass-by Sound Exposure Level (SEL) measurements it is necessary to:

1. Determine whether CRTN's noise calculation based on a traffic flow can be uniquely and completely expressed as a function of light and heavy vehicle SELs; and,
2. Back-calculate the equivalent car and truck SELs.

The following derivation confirms that the first requirement is met, and calculates the SELs for CRTN's $L_{10(1h)}$ case (chart 2).

Generally, the equivalent sound level, L_{Aeq}, from *n* events all having the same sound exposure level, L_{AE}, over a period of time, *T*, in seconds is given by,

$$L_{\mathrm{Aeq(T)}} = 10\log_{10}\left[n\,10^{\frac{L_{\mathrm{AE}}}{10}}/T\right] \qquad (A.0)$$

Specifically, the one-hour L_{Aeq} at a location due to car traffic, $L_{Aeq(1h),cars}$, is a function of the 'per car' Sound Exposure Level (SEL), $L_{AE,car}$, and the number of cars passing the location in an hour. The latter is defined here by the hourly traffic volume in the nearside lane only, *q/2*, and percentage heavies, *p*. The proximity effect is inherent in the value of $L_{AE,car}$, which in this case is defined for a location 10 metres from the nearside carriageway edge.

$$L_{\mathrm{Aeq(1h),near,cars}} = 10\log_{10}\left[\frac{q}{2}\left(1-\frac{p}{100}\right)10^{\frac{L_{\mathrm{AE,car}}}{10}}/3600\right] \qquad (A.1)$$

$$L_{\mathrm{Aeq(1h),near,cars}} = L_{\mathrm{AE,car}} + 10\log_{10}\left[q\left(1-\frac{p}{100}\right)\right] - 38.57 \qquad (A.2)$$

Similarly, for trucks,

$$L_{\mathrm{Aeq(1h),near,trucks}} = L_{\mathrm{AE,truck}} + 10\log_{10}\left[q\,\frac{p}{100}\right] - 38.57 \qquad (A.3)$$

Cars and trucks combined have a one-hour L_{Aeq} of

$$L_{\mathrm{Aeq(1h)},near} = 10\log_{10}\left[10^{\frac{L_{\mathrm{Aeq(1h),near,cars}}}{10}} + 10^{\frac{L_{\mathrm{Aeq(1h),near,trucks}}}{10}}\right] \qquad (A.4)$$

Incorporating (A.2) and (A.3) into (A.4) and collecting terms gives the traffic flow noise level in L_{Aeq} based on $L_{AE,car}$ and $L_{AE,truck}$ at 10 metres from the nearside edgeline for one lane of traffic, under the assumption of no self-screening,

$$L_{\mathrm{Aeq(1h)},near} = 10\log_{10}\left[\left(1-\frac{p}{100}\right)10^{\frac{L_{\mathrm{AE,car}}}{10}} + \frac{p}{100}10^{\frac{L_{\mathrm{AE,truck}}}{10}}\right] + 10\log_{10}[q] - 38.57 \qquad (A.5)$$

CRTN's q represents total traffic flow in two directions, and therefore at two different distances from the receiver, whereas in (A.5) it represents half that flow at a single distance, following the definition of the L_{AE} terms. To account for this, two source emission lines are defined from (A.5) nominally 4.5 metres apart (a minor, but necessary deviation from CRTN clause 13.1), with the distant emission line adjusted for distance using CRTN chart 7

$$L_{\mathrm{Aeq(1h)},far} = L_{\mathrm{Aeq(1h)},near} - 1.25 \tag{A.6}$$

and the two emission lines, each with volume $q/2$, are combined using CRTN chart 11 to produce the overall traffic flow q noise level in L_{Aeq}, at 10 metres from the nearside lane edge:

$$L_{\mathrm{Aeq(1h)}} = 10\log_{10}\left[\left(1-\frac{p}{100}\right)10^{\frac{L_{\mathrm{AE,car}}}{10}} + \frac{p}{100}10^{\frac{L_{\mathrm{AE,truck}}}{10}}\right] + 10\log_{10}[q] - 36.14 \tag{A.7}$$

◆

Switching to CRTN, its chart 2 calculates a 1-hour L_{A10} from an hourly total traffic flow, q, across both directions and consisting only of cars with a mean speed of 75 km/h

$$L_{\mathrm{A10(1h)}} = 42.2 + 10\log_{10}[q] \tag{A.8}$$

Chart 4 of the CRTN methodology contributes an additive correction, K_4, for mean traffic speed, v, in km/h and percentage heavy vehicles, p

$$K_4 = 33\log_{10}\left[v + 40 + \frac{500}{v}\right] + 10\log_{10}\left[1 + \frac{5p}{v}\right] - 68.8 \tag{A.9}$$

Evaluating (A.8) and (A.9) at the reference speed of 75 km/h, and introducing the approximation $L_{Aeq} \approx L_{A10} - 3$ dB (see Note 2), gives $L_{Aeq(1h)}$ as a function of p, by the CRTN method

$$L_{\mathrm{Aeq(1h)}} = 10\log_{10}[q] + 10\log_{10}\left[1 + \frac{p}{15}\right] + 39.2 \tag{A.10}$$

Taking (A.7) and (A.10) as equivalent expressions for $L_{Aeq(1h)}$ as a function of q and p, based on SEL and CRTN respectively, and simplifying,

$$10\log_{10}\left[\left(1-\frac{p}{100}\right)10^{\frac{L_{\mathrm{AE,car}}}{10}} + \frac{p}{100}10^{\frac{L_{\mathrm{AE,truck}}}{10}}\right] = 10\log_{10}\left[1 + \frac{p}{15}\right] + 75.34 \tag{A.11}$$

If CRTN can be expressed in terms of $L_{AE,car}$ and $L_{AE,truck}$ then:

setting p=0 in (A.11) will provide a unique solution for CRTN's implicit $L_{AE,car}$

$$L_{AE,car} = 75.3\ dB \quad \text{for } L_{10(1h)} \tag{A.12}$$

setting p=100 in (A.11) will provide a unique solution for CRTN's implicit $L_{AE,truck}$

$$L_{AE,truck} = 84.2\ dB \quad \text{for } L_{10(1h)} \tag{A.13}$$

Equations (A.12) and (A.13) therefore show that CRTN, under reference conditions, can be mathematically expressed using these back-derived SELs for cars and trucks.

Equations (A.2) and (A.3) show that any change in L_{AE} causes the same change in $L_{Aeq(24h)}$ (in linear units they are proportional) and therefore that surface corrections derived based on SEL measurements (or translated to SEL) will also apply to CRTN output in $L_{Aeq(24h)}$.

Note 1:

The full derivation of L_{AE} for both cars and trucks above is somewhat lengthy, which hides its simplicity. A more intuitive (approximate) derivation is to consider only cars (p=0), with equation (A.2) equated to the base CRTN equation (A.8), after using the approximation $L_{Aeq(1h)} \approx L_{A10(1h)} - 3$ dB. In this case $L_{AE,car}$ falls out very quickly as 74.8 dB, but doesn't account for the two-lanes vs. one-lane effect and can't be expanded to cover heavy vehicles.

Note 2:

$L_{Aeq(1h)} \approx L_{A10(1h)} - 3$ dB represents a very small additional approximation on top of the broadly used approximation $L_{Aeq(24h)} \approx L_{A10(18h)} - 3$ dB [Abbott & Nelson, 2002], and is not expected to contribute significant additional error.

Note 3:

CRTN's 18-hour version, $L_{10(18h)}$ is defined as an arithmetic mean of the $L_{10(1h)}$ levels. However, a uniform 18-hour traffic flow of $Q = 18q$ in chart 3 will not provide the same result as q in chart 2. The $L_{10(18h)}$ estimate is lower by approximately 0.5 dB, which is then reflected in the calculated L_{AE} values. This is probably by design, to reflect a generic 18-hour traffic pattern.

An argument can be made for either the 1-hour or the 18-hour estimate of L_{AE} in terms of which is more appropriate to compare against pass-by measurements of actual vehicles. The 1-hour estimates bear more resemblance to those surveys of about 50 vehicles each and also represent the core around which CRTN was built. The 18-hour computation of L_{10} is probably more closely related to the $L_{Aeq(24h)}$ parameter output by modern realisations of CRTN. Ultimately we have chosen to use the 1-hour estimate of L_{AE}. We have included a contribution for this 1-hour / 18-hour selection in the "Validity of CRTN implicit SEL" uncertainty component in Appendix E.4.

Appendix B Methodology Discussion

B.1 Development of Methodology

The current set of road surface corrections are published in the Guide to State Highway Road Surface Noise [NZTA, 2014]. Those corrections were determined from car and truck pass-by measurements conducted adjacent a variety of road surface types using a mix of test and public (fleet) vehicles [Dravitzki & Kvatch, 2007]. Each surface correction is stated relative to a reference surface, and NZ's reference surface was determined to sit at -2 dB relative to CRTN baseline output (the NZ Adjustment) [Barnes & Ensor, 1994].

NZ's existing reference surface for noise, AC-10, is an asphaltic concrete specification with nominal maximum aggregate size 10 mm [NZTA M10, 2020]. This specification has become functionally extinct on NZ state highways because its low texture is no longer acceptable on high-speed roads for safety reasons. It is therefore no longer a viable reference surface for noise.

The key challenges for this project were therefore to find an alternative to the AC-10 reference surface, and to find an efficient methodology to measure the sound emission properties of different surfaces, and relate those first back to the reference, and then to CRTN.

The recent availability of the Waka Kotahi CPX trailer provided an opportunity to replace, or at least supplement, the previous time-consuming pass-by methodology, in which individual 20-metre-long road segments are measured at the wayside. CPX data collection occurs at high-speed: 20-metre-long road segments are collected while travelling at 80 km/h. Various potential methodologies leveraging the efficiency of the CPX trailer to sample a great length of road surface have been considered in recent reports [Jackett et al, 2020; Jackett, 2020].

A starting point for the current research project was an evolution of those methods, linking CPX levels back to CRTN outputs via long-term traffic noise measurements on a reference surface. However, the traffic monitoring approach proved incompatible with the objectives set out for delivery of the surface corrections (predominantly the budget and practical constraints).

As an alternative to traffic monitoring, a method was devised that could be fulfilled by measurement of individual vehicle passes. This involved reverse engineering the CRTN algorithms to expose implicit SELs for cars and trucks, respectively. CRTN was constructed empirically [Delany et al, 1976] as what is effectively a noise *im*mision model[11], so it is not by design, but a source parameter can be derived: SELs can be uniquely defined for cars and trucks (Appendix A). This methodology would have related CRTN's implicit average SELs (under reference conditions) to measured 2021 vehicle fleet pass-by SELs over a reference surface, with CPX measurements from a large survey also linked to the reference surface specification, completing the CRTN-to-surface equation.

The additional problem of finding a replacement reference surface for AC-10 was confronted very early in this project [Jackett, 2020], but no candidate surface was workable for all parties. However, the SEL-based methodology offered a solution, and it was determined that the reference surface concept could be abandoned entirely within this project, though somewhat reluctantly[12]. Its role would be replaced by a set of paired SEL and CPX measurements of the same exact sections of road, covering a wide range of surface types. CRTN's implicit SEL would

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[11] It is based on receivers' view of the road, rather than starting at the road source and propagating outwards.

[12] Road surface specifications can provide reproducible and stable long-term references for road traffic noise. For example, well-defined reference surfaces can be used to compare road traffic noise emission between different vehicle fleets, eras, and countries, and they provide an accessible and long-term reference for practitioners to validate acoustic measurements, predictions, and the performance of instrumentation.

link to the SEL measurements of passing fleet vehicles, which were in turn regressed against their CPX pairs, completing the link between a separate large CPX survey of surfaces and CRTN.

Redefining the surface corrections was therefore only one part of the methodology. With the move away from the AC-10 reference surface, this project has effectively become a recalibration of CRTN for the current NZ fleet. As this implies, the output of this project will have a broad effect on the overall accuracy of road traffic noise prediction in NZ.

On paper, the novel methodology that resulted was extremely efficient, as required by the constrained timeline and budget. The trade-off was that it carried significant risks, some of which are described in the next section.

In practice it retained its efficiency, despite some additional complications arising with the correlation between wayside and CPX data (see section 3.3.3). A determination on how accurate it is will need to wait for a subsequent validation study.

B.2 Risks and Assumptions

While necessary to meet the project objectives, the novel methodological design carries some risk. The most significant risks and assumptions are discussed below.

B.2.1 Equivalence between measured SEL and CRTN's implicit SEL

Although the relationship between average pass-by SEL and road traffic L_{Aeq} is well-established generally, it is not assured that the implicit SEL from CRTN (section 2.3.4) can be interpreted in the same way. For instance, CRTN natively predicts in L_{A10} but this approach leans heavily on its conversion to L_{Aeq}, though in many ways CRTN already functions like a L_{Aeq} procedure [Kean, 2008].

More significantly, it is not known what other effects or errors have been 'baked in' to the implicit SEL, given that it is a model with empirical roots. Delany et al [1976] note that many adjustments to the parameters of the model were made, either as compromises, simplifications, or for usability reasons. By reversing this process to derive a term for individual vehicle emission, it is not guaranteed that we would arrive at a value that is representative of the individual vehicles included in the original dataset. It follows that if the implicit SEL wasn't representative of the original 1970s data set, it won't be an accurate way to update the model to NZ in the 2020s. The original data are not available, so we cannot test this before undertaking the current project.

As a hypothetical example, if CRTN's distance correction curve under-predicts noise levels at long distances then it is likely that the implicit SEL would somewhat compensate for that (it would be higher) because that would have provided the best overall fit to the original CRTN input data. That is only a problem for this study because we have no way to tell how much higher the implicit SEL is due to that effect, and therefore have to take it at face value when we compare to contemporary measured SELs.

We have tried to minimise the scale of this systemic error with field measurements of SEL that match CRTN reference conditions[3] as closely as possible, essentially reducing the model down to its core chart 2 algorithm (see Appendix A note 1). The measurement location (10 m from the road) also represents something of a worst-case separation distance for receivers, where accuracy of prediction is most valued.

Nonetheless, a systematic error affecting all surfaces (and therefore all predictions made using CRTN) may exist in the draft corrections, and it is difficult to estimate its direction or magnitude. The outputs of this analysis may require further adjustment. A ratification process should be undertaken to confirm that the benefits of the updated data outweigh any new systematic errors introduced. We recommend this process includes evaluation against new or existing field measurements of road traffic noise.

B.2.2 Reliance of $L_{Aeq(24h)}$ on SEL

The methodology relies on the $L_{Aeq(24h)}$ from a flow of traffic being a simple function of the 'average' individual vehicle SEL and traffic volume (Appendix A, equation A.2). At some high density of traffic this assumption will start to break down as nearer vehicles screen other vehicles. We assume that this is a relatively small error in the context of the many compromises made in forming the CRTN model.

B.2.3 Correlation between CPX and SEL

The methodology relies on there being a reliable translation between $CPXP_{80}$ levels and SEL at the wayside.

CPX measurement effectively only captures tyre/road noise, whereas wayside measurements include other noise sources of the vehicle, such as engine and exhaust noise, as well as a higher contribution from background noise. This was mitigated by running the CPX trailer and SEL measurements at 80 km/h and 75 km/h, respectively, where tyre/road noise dominates. Additionally, the SEL methodology excluded atypically loud vehicles from the regression, so that tyre/road noise was at the forefront of that relationship, and reintroduced the outliers only after the translation to SEL had been made (section 3.1.5 and Table 4-2).

The P1 tyre is not a typical car tyre, but it appears to react acoustically to a change in surface in a similar way to a typical car tyre [Jackett, 2019b]. The Part 1 report recommended that this relationship be re-examined for coarse chipseals, in case the P1 tyre has an insensitivity in this macrotexture range. Even if there is an insensitivity, it would be unlikely to significantly impact the recalibration aspect of this project.

The pass-by measurements are the most critical measurement aspect of the project, as any systematic error will be passed onto the final corrections, and therefore to every road traffic noise prediction made in NZ using CRTN. Systematic errors affecting all wayside sites equally would lead to error in the constant term of the linear regression. Errors affecting sites differently could also lead to error in the slope of the regression. Steps have been taken in the methodology design to reduce the likelihood of systematic error contributing significantly to error in the corrections (see in particular C.1, C.2, and Appendix D), but some risk remains. Section B.4 below provides further discussion of overall uncertainty, and the uncertainty budgets in Appendix E provide additional context.

B.2.4 Implementation

This research was conducted entirely using the CRTN algorithms as they appear in the 1988 publication [DoT UK, 1988]. However, most practitioners will access CRTN via its implementation in a 3D noise modelling package (e.g. SoundPLAN is common in NZ). It is assumed that the results of this project will be directly applicable to each implementation without requiring modification. This should be confirmed as part of a future validation study.

B.3 Sound Exposure Level

The Sound Exposure Level (SEL) is a measure of sound pressure level (in dB L_{AE} re 20 μPa) that captures the total sound energy of an event, such as a single vehicle pass-by. The metric can be used to compare noise events that have different durations, such as the time that different passing vehicles contribute to wayside noise.

With respect to noise modelling, the average SEL represents the total sound contributed by each 'average' vehicle that makes up the traffic flow of a given vehicle class.

It has long been recognised that SEL pass-by measurements are significantly more difficult and time consuming to conduct than L_{Amax} pass-by measurements [ROSANNE D2.3], and this is the reason that the latter are used in most overseas studies, and in the statistical pass-by standard

[ISO 11819-1]. However, given the various constraints on the methodology of this study, SEL pass-by measurements are unavoidable, because it is only via SEL that the link to CRTN can be made.

SEL is defined as

$$SEL = 10\log_{10}\left[\frac{1}{T_0}\int_{-\infty}^{+\infty}\frac{p^2(t)}{p_0^2}dt\right] \tag{B.1}$$

Where T_0 = 1 second, p are the measured sound pressures in Pascals, and p_0 is the reference sound pressure level, 20e-6 Pa.

B.4 Uncertainty

B.4.1 Existing Uncertainty in CRTN Prediction

The original authors of CRTN [Delany et al, 1976] and a later validation study [Hood, 1987] both found that the 1975 version of the method overpredicted noise by less than 1 dB, and had an RMS error of approximately 2 dB to 2.5 dB (k=1). The implication is that CRTN, in the UK in the 1970s and 80s, had an uncertainty of prediction of ± 4 dB to ± 5 dB at the 95% level of confidence.

The current application of the 1988 version of CRTN to NZ road traffic may have an additional systematic “localisation error”, depending on the extent to which the NZ Adjustment [Barnes & Ensor, 1994] accounts for our different reference surface and vehicle fleet. Barnes & Ensor describe a prediction error of ± 2 dB for their NZ adaptation of CRTN, but that assumes that input parameters are known very precisely (incl. sand circle measurements of surface texture), and their report implies that the same data used to tune the NZ model were used to evaluate the RMS error. Logically, the residual error of the prediction should not be much less than found by Delany and by Hood for the original, unlocalised, model. We conclude that the current application of CRTN in NZ[13] probably has an uncertainty of at least ± 4 dB, but possibly more.

The Part 1 report indicated NZ road surfaces of nominally the same specification have a broad distribution about the mean, roughly ± 1.5 dB $L_{\mathrm{CPX:P1,80}}$ for chipseals and SMA, and ± 3 dB $L_{\mathrm{CPX:P1,80}}$ for OGPA, at the 95% level of confidence. If expanded using the CPX-to-SEL relationship (Equation 3.3) then those uncertainty components become ± 3 dB $L_{\mathrm{Aeq(24h)}}$ and ± 6 dB $L_{\mathrm{Aeq(24h)}}$ at the wayside, respectively. This uncertainty is inherent to NZ surfaces; it is not a function of which set of surface corrections is used (existing or draft). Hood attributed much of the residual error in CRTN to the unknown attributes of the road surface itself, and the values above indicate that this may also be the case in NZ.

B.4.2 Uncertainty of the Draft Corrections

Due to the replacement of the AC-10 reference surface with a different reference concept (section B.1), the uncertainty of the draft corrections proposed by this report also encompasses the overall uncertainty of future CRTN predictions (see B.2.3). Localisation of CRTN to the current NZ situation, which the NZ Adjustment attempted to account for, will be included in each draft surface correction. Some systematic localisation error will remain, which will apply to all road traffic noise predictions made in NZ using CRTN.

An attempt has been made to calculate the uncertainty of the corrections in Appendix E.4. There are unknowns that cannot yet be quantified (section B.2), and whose influence has had to be conservatively estimated without much objective basis. A follow-up study using road traffic noise measurements (or perhaps a meta-analysis of noise assessments) is recommended to assess the performance of the draft surface corrections in scenarios reflecting its normal usage.

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[13] The *Guide to State Highway Road Surface Noise* [NZTA, 2014] does not suggest an uncertainty for CRTN noise modelling in NZ, but does require that predictions and validation measurements match to within ± 2 dB. This would be expected to be achieved for 70% of predictions if the uncertainty is indeed ± 4 dB.

The estimate of uncertainty for the draft corrections, including the localisation components, is ± 3.2 dB at the 95% level of confidence. Unfortunately there is no equivalent uncertainty estimate available for the existing NZ Adjustment or surface corrections table to compare against. The nearest comparison is Hood's [1987] noise survey in London, which found CRTN over-prediction of slightly less than 1 dB, based on a large set of urban measurements.

It would clearly be preferable if the localisation error of the proposed set of corrections was small compared to the ± 5 dB prediction uncertainty that CRTN appears to be capable of for many road surface types. The current estimate of uncertainty for the localisation/calibration is not small compared with the prediction uncertainty, but it may be reduced in future either through a reduction in the actual error, or a refinement of the uncertainties based on objective data.

Appendix C Measurement of Wayside SEL

C.1 Measurement Site Selection

The methodology requires that SEL measurements of passing fleet vehicles are made in conditions that closely represent the CRTN reference conditions:

CRTN Reference Conditions
75 km/h traffic flow (V=75)
No heavy vehicles (p=0)
No road gradient (G=0)
10 metres from nearside edge of carriageway
1.2 metres above the road surface
Free-field propagation

Additionally, we imposed a ‘long straight road’ restriction, so that a single CRTN road segment [DoT U.K., 1988, section 11] is used to represent the passing vehicle/traffic.

Constraints on the measurement sites are derived from the CRTN reference conditions, safety requirements, suitability for a CPX survey, and practical considerations. The criteria in Table C-2 are extremely restrictive, and the number of sites satisfying all constraints is very small.

Table C-2: Constraints on pass-by SEL measurement sites

SITE FEATURE	CONSTRAINT
ROAD GEOMETRY	The road is flat and straight for a long distance either side of the site (at least 150 metres).
TRAFFIC SPEED	Speed limit of least 80 km/h to allow CPX measurement.
	Average vehicle speed close to 75 km/h (CRTN reference speed).
ROADSIDE GEOMETRY	Relatively flat, and at a similar level to the road surface to allow a SLM to be positioned 10-metres from nearside edge of the carriageway and 1.2 m above the road surface.
UNOBSTRUCTED VIEW	Acoustic propagation must be unimpeded for at least 150 metres in either direction.
	The SLM operator must be able to identify passing vehicles and measurement opportunities.
	The speed gun operator should be able to obtain readings at a shallow angle to the road.
	Motorists should have a clear view of the operators when they are working near the carriageway.
SURROUNDINGS	Minimal nearby acoustically reflective or screening surfaces (e.g. TL-5 barrier, buildings, hoardings).
	The ambient noise level is low (at least 20 dB below the L_{Amax} of passing vehicles)
	No other significant noise sources nearby (other busy roads, industrial activities, intermittent sources).
SAFETY	Site access and occupation is safe for the operators and the public.
	Does not require traffic management processes that would disrupt the traffic flow and interfere with the accuracy of measurements.

Sites covering a range of surface specifications were identified meeting the above criteria: chipseal, AC, SMA, and OGPA. A summary of sites is provided in Table 2-2.

C.2 Vehicle Selection for SPB

Qualifying vehicles were light vehicles that would fall into the EEM [NZTA, 2018] Passenger Car (PC) classification, which includes two-axle vehicles with wheelbase less than 3 metres. This includes motorbikes, cars, SUVs, vans, and utes. Non-qualifying vehicles are medium and heavy commercial vehicles (MCVs and HCVs) such as buses and trucks. Following the previous truck noise study [Jackett et al, 2020], light trucks are non-qualifying vehicles. For context, qualifying vehicles are all non-HCV traffic included in AADT traffic volumes used for CRTN noise models.

SPB measurements can be either of individual vehicles, or of a tight cluster/stream of qualifying vehicles. The SEL descriptor is sensitive to the total energy of a pass-by event and the ‘average’ per vehicle is straight-forward to extract.

Table C-3: Constraints on vehicle selection in pass-by measurement

PASS-BY FEATURE	CONSTRAINT
ACOUSTICALLY ISOLATED	No simultaneous passing traffic in another lane or direction.
	Contribution from any preceding or following excluded vehicle is negligible: not more than 20 dB below the passby L_{Amax} level. In practice, about 8 seconds is required between vehicles passing in the same direction.
	The ambient noise level is at least 25 dB below the passby L_{Amax} level.
VEHICLE BEHAVIOUR	No audible horns, sound systems, or yelling (but unlike ISO 11819-1 measurements, loud tyres, engines or exhausts are okay).
	No obvious or audible acceleration or deceleration: constant speed.
	Vehicles maintain good lane position.
WEATHER	Road surface is completely dry
	Wind speed is very low (below 5 km/h)
MEASUREMENT	Vehicle(s) classification is identified; qualifies; and is recorded.
	The speed(s) of the vehicle, or tight cluster of vehicles, is recorded.
	The L_{Aeq} sound level during the pass-by is measured at a high rate, at least every 100 ms.

Satisfying these criteria for SPB measurements at any measurement sites during the day proved to be impractical. The volume of traffic did not allow for clean pass-by measurements: measurements were polluted by preceding or following vehicles, or vehicles in other lanes. Consequently, all measurements have been made between 8pm and 6am. Night time measurements also benefited from lower ambient noise levels and lower wind speeds.

C.3 Vehicle Pass-by Speed

Individual vehicle speeds must be known to correct their pass-by SELs back to CRTN reference conditions (75 km/h).

SPB vehicle speeds were measured using a calibrated handheld police LiDAR gun, STALKER Lidar XS (SN: LJ001011). The performance of the gun under representative field conditions was validated via a set of 45 measurements of the approach and departure speed of a passenger car fitted with a GPS speedometer travelling at 70 km/h ± 1 km/h. Vehicle approach speed readings were found to be acceptably accurate on average ($\boldsymbol{\varepsilon}$ = +0.18 km/h, n = 21), but departure speed readings significantly underrepresented vehicle speed on average ($\boldsymbol{\varepsilon}$ = -3.25 km/h, n = 24).

The validation study data, which reflected actual usage and conditions, was used in preference to the factory calibration. Where possible the approach speed of vehicles was measured and taken directly as the vehicle speed. Elsewhere the departure speed was measured and corrected geometrically by a factor of 1.049. In both cases the cosine error was already accounted for in the validation data, and no additional correction was applied.

The expanded uncertainty of a single vehicle speed measurement has been determined from validation data (see Appendix D) as ± 3.2 km/h at the 95% confidence level.

CPB speeds were taken from a GPS speedometer and achieve ± 1 km/h at the 95% confidence level

C.4 Measurement of Pass-by Sound Levels

At each site a tripod-mounted sound level meter was placed 10 metres from the lane nearside edge, and 1.2 metres above the road surface.

Vehicle pass-bys were measured using a calibrated SLM [B&K 2250 SN:3027649]. The SLM was manually triggered to measure the full pass-by as a series of 100-millisecond A-weighted equivalent continuous sound pressure levels, $L_{\mathrm{Aeq(100\ ms)}}$. The average duration of a pass-by measurement was about 15 seconds, after isolating the event. At 75 km/h the middle 5 seconds of each pass-by event define its SEL to < ±0.5 dB. The vehicle class(es), speed(s), time, SLM file number, a subjective rating of pass-by quality, and any additional notes, were also recorded for each pass-by event.

A good example of a single vehicle pass-by is shown in Figure C-1.

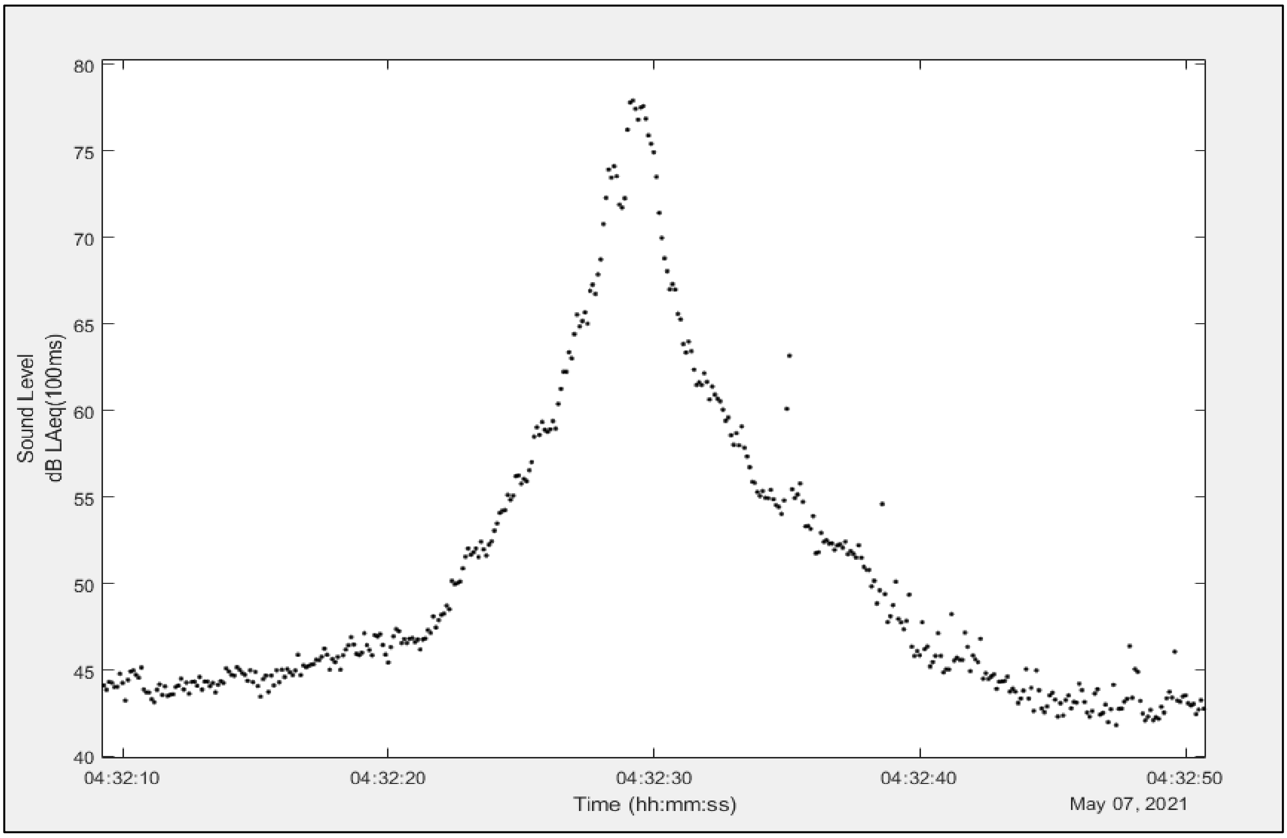

Figure C-1: A pass-by noise measurement of a single, very well-isolated, vehicle.

C.5 Calculation of CRTN Reference SEL

The SLM measurement data was extracted and post-processed using MATLAB software.

For each pass-by, the signal was plotted similar to Figure C-1, and the portion of the signal that represented the pass-by event was manually selected. Included $L_{Aeq(100\text{ ms})}$ levels were first converted to units of sound pressure, then combined into an SEL for the event using,

$$SEL = 10\log_{10}\left[\int_0^T \frac{p^2(t)}{p_0^2}dt\right] \qquad \text{(C.1)}$$

Where *T* is the pass-by duration, *p* are the measured sound pressures in Pascals, and p_0 is the reference sound pressure level, 20e-6 Pa. Equation (C.1) follows from equation (B.1), with the requirement that *p(t)* → *minimum* as *t* → 0 and *t* → ∞, which is to say that the measurement period captured almost all of the sound energy of the pass-by.

About one-third of pass-by events captured a cluster of more than one vehicle. The average SEL for each vehicle was then determined as: *event SEL* - 10 log_{10} (*number vehicles in cluster*).

CRTN's speed correction algorithm in chart 4 was then used to calculate a correction back to the reference speed of 75 km/h, and this was applied to each event SEL. Outlying vehicles, either noted as such during the field work or with obviously outlying SELs, were then excluded, to be accounted for separately (section 3.1.5).

The logarithmic average of all SELs for a site was subsequently used to determine the 'average' SEL for cars at that site. The site averages were corrected for ambient temperature back to a reference of 15°C using a coefficient of -0.05 dB/°C. Note that CRTN has no reference temperature, so 15°C was chosen for this data as it did not cause a large magnitude of correction from most of the survey temperatures and is reasonable as an 'average' year-round temperature for NZ. CRTN's chart 8 was used to correct the average SELs for the effect of ground absorption on site, to the reference condition of no ground absorption.

C.6 Determine an Equivalent CPX Level for Each Site

The methodology requires that each site with a measured SEL also has a measured $CPXP_{80}$ level.

C.6.1 CPX Measurement

$CPXP_{80}$ measurements were performed by Robin Wareing (Altissimo Consulting) and Richard Jackett (WSP) on 22nd and 28th April 2021 using the Waka Kotahi CPX trailer. 1 to 3 runs were made in the relevant lane past each SEL site (Table 2-2).

C.6.2 Post-Processing

Standard Waka Kotahi scripts processed and uploaded the CPX data to a database. Altissimo performed post-processing to geolocate measurements on local roads. WSP applied the corrections for temperature and speed, in accordance with ISO 13471 and ISO 11819-2 respectively.

C.6.3 SEL Site Position Relative to CPX Road Segments

CPX road segments are 20-metres long, regularly spaced, and are referenced to the road chainage. The SEL site locations fell at arbitrary positions within their adjacent CPX road segments. To minimise error, the CPX data have been re-referenced to centre on the SEL site location (to ± 1 m precision). This has been achieved by a logarithmic weighted average of $CPXP_{80}$ levels across each pair of CPX segments along the road, based on the position of the SEL site relative to the two segments closed to the SEL site.

The effect of re-referencing, compared to just taking the closest $CPXP_{80}$ level, is a reduction in error of approximately 0.3 dB in magnitude, on average.

C.6.4 Weighting CPX data by proximity to SEL site

Rather than adopt the closest re-referenced CPX road segment as the representative $CPXP_{80}$ level for each site, a weighted logarithmic average of the 220-metres of CPX data centred on the site location (in the appropriate lane) was used to mimic each road segment's contribution to vehicle pass-by noise.

Site-proximity weightings were derived from the average of several pass-by measurements (section C.4) at different sites for cars travelling at close to 80 km/h. The weightings were normalised to provide 0 dB of total gain across the eleven 20-metre road segments. Table C-4 presents these weightings and their locations relative to the SEL measurement site.

Table C-4: Site-proximity weighting for CPX data

Road segment ID (0 is adjacent SEL site)	Nominal minimum distance from SEL site (metres)	Weighting (dB)	Car location re pass-by	Road segment re SEL site
-5	-100	-13.10	Before pass-by	Up road
-4	-80	-9.81		
-3	-60	-6.23		
-2	-40	-2.39		
-1	-20	+3.54		
0	0	+6.21	During pass-by	At site
1	+20	+3.52	After pass-by	Down road
2	+40	-2.28		
3	+60	-4.39		
4	+80	-6.64		
5	+100	-7.75		

As expected, the CPX segments are strongly centre-weighted. The effect of applying this weighting, compared to just taking the closest re-referenced CPX level, is a further reduction in error of approximately 0.1 dB in magnitude, on average, noting that the re-referencing process described in section C.6.3 has already absorbed some of the effect of weighting.

C.6.5 Final Site CPX Level

After applying the various stages of post-processing (section C.6.2), the CPX data were re-referenced to the site locations (section C.6.3) and the Site CPX levels were derived from weighted averages of the nearest 220 metres of CPX data (section C.6.4).

Appendix D Controlled Pass-by Measurements

CPB measurements were added to the project in 2022, following unexpected results from the initial 9-site SPB and CPX surveys in 2021 (section 3.3.3).

In short, the range of the initial SPB measurements (about 11 dB) was far greater than indicated by the CPXP_{80} measurements of the same sites (a range of about 5 dB). This resulted in a difference of about 2 dB $L_{\mathrm{AE,SPB}}$ at the wayside for every 1 dB $L_{\mathrm{CPX:P1,80}}$; a slope of $m≈2$.

This appendix describes the subsequent efforts to validate the CPX and SEL measurement systems, plus the CPB methodology, the CPB results, and the implications of these for the regression of pass-by SEL on CPXP_{80} and for the broader noise research programme.

D.1 Expectations

Coming into the project it was anticipated that CPXP_{80} might be linked to pass-by SEL via a single expression, and it would be close to linear with a slope of $m≈1$.

D.1.1 Theory

CPX is a mobile nearfield measurement of mostly tyre/road noise adjacent an enclosed standardised test tyre, whereas the pass-by methodologies involve a stationary far-field measurement of a moving 4-wheeled vehicle, including engine noise and noise from other sources. The relationship between these is extremely complex and therefore, rather than attempting to link CPX to wayside SEL theoretically, an empirical relationship was sought.

The wayside relationship was expected to take the form of a typical source-receiver relationship,

$$L_{AE,SPB} \approx L_{SPB\ source} - L_{SPB\ propagation} \qquad \text{(D.1)}$$

where $L_{\mathrm{AE,SPB}}$ is a wayside receiver level in dB at 10 m from the edgeline and $L_{\mathrm{SPB\ source}}$ is the emission of a vehicle passing at 75 km/h. The propagation term, $L_{\mathrm{SPB\ propagation}}$, captures all the propagation effects, including many difficult-to-quantify geometrical and temporal elements, but between sites it is assumed to be effectively constant due to careful site selection and surveying (see section C.1) and correction for known deviations (e.g. air temperature, ground absorption, vehicle speed).

Wayside car noise at 75 km/h is dominated by tyre/road noise[4]. If the vehicle speed and the tyres are held constant between sites (obviously true for CPB, and true on average for SPB) then $L_{\mathrm{SPB\ source}}$ is predominantly a function of the road surface.

CPXP_{80} is also a function of the road surface and is expected to change with road surface characteristics in a very similar way to $L_{\mathrm{SPB\ source}}$. For example, +1 dB $L_{\mathrm{CPX:P1,80}}$ is expected to be accompanied by +1 dB $L_{\mathrm{SPB\ source}}$, etc. This is the motivation for CPX measurements in general.

If $L_{\mathrm{SPB\ propagation}}$ is mostly constant between sites, and $L_{\mathrm{SPB\ source}}$ and CPXP_{80} are similar functions of the road surface (albeit with different constant terms), then the regression of $L_{\mathrm{AE,SPB\ receiver}}$ on CPXP_{80} should result in a linear fit with slope of $m≈1$ and a constant term, *c* (which captures the various geometrical and temporal 'propagation' effects).

D.1.2 Previous NZ and Overseas Findings

Similar research has previously been conducted with the Waka Kotahi CPX trailer, looking at the CPX-to-wayside relationship [Jackett, 2019b]. In that case the wayside measurement was of the L_{Amax} parameter at 7.5 metres, rather than an SEL at 10 metres. The L_{veh} parameter was computed from L_{Amax} of many vehicle pass-bys, following ISO 11819-1:1997.

The relationship between average CPXP_{80} and average L_{veh} for 11 sites spanning 40 mm EPA 7 to a Two-coat 2/4 chipseal was statistically significant (r^2=0.94, n=11, p<0.05):

$$L_{veh,cars,80} \approx 1.26\ CPXP_{80} - 45.5 \qquad \text{(D.2)}$$

The equivalent $\mathrm{CPXP1}_{80}$ to L_{veh} comparison was plotted by Sandberg & Ejsmont [2002], with their relationship being:

$$L_{veh,cars,80} \approx 1.25\ CPXP_{80} - 44 \qquad \text{(D.3)}$$

The European ROSANNE project [D2.3, 2015] used data at different speeds from several EU states to produce the relationship (r^2=0.95):

$$L_{veh,cars} \approx 0.95\ CPXP - 15.5 \qquad \text{(D.4)}$$

These three sources show relationships between L_{veh} and CPXP that are reasonably close to one-to-one.

D.2 Validation

D.2.1 Hypotheses

In light of the unexpected results, we considered several possible factors that could have caused the slope of paired measurements of $L_{\mathrm{AE,SPB}}$ and $L_{\mathrm{CPX:P1,80}}$ to deviate from the expected slope of m≈1 across 9 measurement sites. Where possible we tested these hypotheses, and the results are summarised in Table D-5.

No faults were found with either measurement system or the processing of measurement data.

Consequently, the chosen ‘solution’ was to significantly increase the sample size to provide:
a) a more nuanced view of the relationship, in case a pattern emerged; and,
b) more confidence in whatever relationship was ultimately revealed.

Table D-5: Validation checks on the measurement data and systems

Factor	Description	Checks Performed / Discussion
1	A measurement or processing error in the $L_{AE,SPB}$ term	Instrumentation was recently calibrated, in good condition, and has been checked for linearity against a calibrated 94 dB and 114 dB sound source. The calculation of SEL from many $L_{Aeq(100ms)}$ samples has been checked by several methods, including against Brüel & Kjær's own software. L_{Amax} was also recorded during measurements and it correlates well with SEL at each site (SEL = $0.9\ L_{Amax}$ + 8.9 dB, r^2 = 0.90 was typical) and also gave a slope of $m \approx 2$ against $CPXP_{80}$. CPB measurements were subsequently undertaken at 6 SPB sites and these matched very closely with the previous SPB measurements (CPB = 1.00 SPB – 1.9, r^2 = 0.98). It does not appear to be a freak occurrence of having abnormally quiet fleet vehicles on the quiet road surfaces and vice versa. Significant systematic error in the $L_{AE,SPB}$ term is unlikely.
2	A measurement or processing error in the $L_{CPX:P1,80}$ term	The Waka Kotahi CPX trailer has been regularly evaluated against the criteria given in ISO 11819-2:2017 for CPX measurement [Waka Kotahi, 2018]. The trailer instrumentation was checked for linearity against a calibrated 94 dB and 144 dB sound source in December 2021 [14]. The CPX trailer's core instrumentation, data capture, and post-processing systems were tested against a calibrated sound level meter during a run over a range of surfaces in March 2022. There was good agreement ($L_{CPX:P1,80}$ = 1.04 L_{SLM} -3.9 dB, r^2 = 0.95) [15]. Significant systematic error in the $L_{CPX:P1,80}$ term is unlikely.
3	Other noise sources that affect $L_{AE,SPB}$ but not $L_{CPX:P1,80}$, or vice versa	Engine and exhaust noise do contribute to $L_{AE,SPB}$ but would tend to push the slope lower rather than higher, as would significant background noise (which was not observed). The CPX trailer is expected to be completely dominated by tyre/road noise. No non-tyre/road noise was audible in spot tests of recorded waveforms[14]. It is unlikely that other noise sources have an influence.

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[14] Personal communication with Rob Wareing (Altissimo), December 2021

[15] Personal communication with John Bull (Waka Kotahi), 4 April 2022

Factor	Description	Checks Performed / Discussion
4	A consequence of having a relatively small sample size in terms of number of sites (i.e. high uncertainty on slope)	The regression statistics from the initial sample of 9 sites indicate $m = 2.0 \pm 0.5$ at the 95% level of confidence. The statistics from the expanded sample of 19 sites indicate $m = 1.9 \pm 0.3$ at the 95% level of confidence if a single weighted linear regression is performed. In either case the slope is significantly different to $m=1$. It is unlikely that the result is purely due to chance.
5	A surface-dependence in the propagation term of equation D.1	Absorption or reflection may differ between different road surfaces. OGPA is porous and overseas measurements have shown an absorptive effect (see 3.4.2 of the Part 1 report). This effect hasn't yet been quantified for NZ OGPA. Absorption generally can have a large effect on wayside levels at 10 m from the road (section D.3.4). Coarse surfaces (e.g. chipseal) could cause diffuse (rather than specular) reflection. However this is unlikely to occur within the wavelengths of interest ($\lambda_{1000\ \mathrm{Hz}} \approx 300$ mm whereas $\mathrm{MPD}_{\mathrm{chipseal}} \leq 2$ mm). Although propagation effects are not necessarily correlated with the source term, if they were (e.g. in the case of absorption in OGPA) then the apparent slope between $L_{\mathrm{AE,SPB}}$ and $L_{\mathrm{CPX:P1,80}}$ could be greater than $m=1$. If this were the case it would be appropriate to introduce an additional term to account for absorption separately rather than bundle it in the source term of eq. D.1. That is effectively what the dual equations eq. 3.4 and eq. 3.5 attempt to do, albeit without evidence that absorption is the cause of the observed piecewise relationship with a step of -3.5 dB.

Factor	Description	Checks Performed / Discussion
6	Non-equivalence between nearfield and far-field measurements	If different road surface types alter the directivity of the tyre/road emission, that could lead to the laterally mounted CPX microphone providing an inconsistent estimate of L_{source} across different road surfaces. Previous tyre/road noise measurements in NZ [Fong, 1998] showed that different CPX microphone positions around a car tyre responded differently to chipseal grades, some changing in the opposite direction to others (in dB). It was proposed that different surface texture properties can activate the tyre sidewall to different extents, which the low-mounted CPX microphones may be insensitive to. The horn-effect in front and behind the tyre tread face is an important factor in tyre/road emission [Sandberg & Ejsmont, 2002], but the laterally mounted CPX microphones may not be very sensitive to this. Porous surfaces are thought to reduce the strength of the horn effect through absorption. These examples are hypothetical, but consistent with $L_{CPX:P1,80}$ being somewhat insensitive to the difference between chipseal and OGPA surfaces. Further work would be required to determine whether they have merit.

D.3 CPB Measurement Survey

In response to the unexpected results, the methodology was extended to include a set of CPB measurements. Their purpose was initially as validation of the SPB measurements at 6 sites, and when that provided a very close fit (see factor 1 in Table D-5) CPB was used to predict SPB at 9 additional sites. Additionally, a small validation of CRTN's chart 8 ground absorption correction was undertaken, also using CPB.

D.3.1 Methodology

The CPB test vehicle was a 2017 Mazda 3 (reg. KWT81) with standard 2015/60R16 radial road tyres in moderately worn condition. This vehicle was fitted with a GPS speedometer with a stated accuracy of ± 0.5 km/h. Cruise control was used to achieve 75 km/h ± 1 km/h through each pass-by site.

Wayside noise levels were measured using a tripod-mounted sound level meter, the same B&K 2250 used for the SPB measurements, as described in section C.4.

As an ad-hoc addition to the study, a second measurement microphone was mounted approximately 90 mm ahead of the left rear tyre, and 150 mm above the road surface, and connected by extension cable to a sound level meter (Rion NL-32 SN:851394) inside the car. This "quasi-CPX" set up was not comparable to a ISO 11819-2 CPX system in absolute terms, but was intended as a backup measurement to indicate the approximate CPX difference between sites in a relative sense.

Measurements were conducted over several nights between 11pm and 4am in calm dry weather, after a dry period of at least 36 hours. At each site, between 3 and 6 pass-by measurements of the test vehicle were attempted.

Average CPB SELs were calculated from the measured $L_{Aeq(100ms)}$ levels following the process described in section C.5, correcting for temperature and ground cover.

Indicative quasi-CPX $L_{Aeq(3sec)}$ levels were taken simultaneous with passing the wayside sound level meter, which will be denoted QCPX:P,75 or $L_{QCPX:P,75}$.

D.3.2 Calibration

The CPB test vehicle was related to the fleet by a set of paired measurements at 6 sites previously surveyed for SPB (denoted with asterisks in Table D-6). The average difference between the CPB and SPB results was -1.9 dB, indicating that the test car was about 2 dB quieter than a typical light vehicle from the fleet (significant at $p<0.05$ using a paired t-test with $n=6$).

D.3.3 Results

In total, 20 CPB surveys were conducted across 18 different sites. 8 sites had an OGPA surface, 8 had a chipseal surface, and there was 1 SMA site and 1 AC site. Table D-6 presents the site locations and the measured noise data.

The column CPB in dB $L_{AE,car,75}$ is the average CPB level at 10 m, corrected for temperature and ground absorption, but not adjusted to the fleet level (as in section D.3.2). The column n is the number of valid CPB measurements. The Waka Kotahi CPX trailer had previously visited all of the sites with at least 1 pass and $L_{CPX:P1,80}$ gives its average level, corrected for speed and temperature, and weighted by proximity to the site, as described in C.6. The 3-second QCPX:P,75 measurements on the test car were measured at 75 ± 1 km/h and have not been adjusted for ambient temperature (which was similar during all measurements).

Table D-6: Controlled Pass-by and quasi-CPX survey results (Mazda3 test vehicle)

Site Name	Survey RP	Surface	Survey Date	n	WK CPX dB $L_{CPX:P1,80}$	Quasi-CPX dB $L_{QCPX:P,75}$	CPB dB $L_{AE,car,75}$
SH2 NB Grounsel OGPA	002-0962-D/5.229 NB left	PA 10 2015	13/05/22	3	95.8	97.0	66.7
SH2 NB Maidstone	002-0946-B/6.641 NB	PA 15 2017	6/05/22	3	96.1	98.5	68.3
SH2 NB Totara Park	002-0946-B/5.358 NB	PA 10 2014	6/05/22	3	96.2	98.4	69.1
SH2 NB Whakatikei	002-0946-B/7.556 NB	PA 10 2017	5/05/22	3	97.9	97.3	71.7
SH2 NB Hebden 1	002-0962-D/2.790 NB	PA 10 2017	6/05/22	3	98.4	98.3	69.9
SH2 Birchville NB	002-0946-B/1.400 NB	VFILL 5 2017	12/05/22	2	99.9	104.4	79.3
SH2 Birchville SB	002-0946-B/1.400 SB	VFILL 5 2017	12/05/22	2	99.9	104.7	77.3
SH2 Kaitoke NB 1	002-0931-B/6.814 NB	2CHIP 2/4 2016	5/05/22	3	101.1	105.6	78.8
SH2 Kaitoke Farm NB	002-0931-B/8.509 NB	RACK 2/4 2018	12/05/22	3	101.9	107.2	80.3
SH2 NB Hebden 3 †	002-0962-D/2.060 NB left	PA 10 2017	6/05/22	2	96.2	101.0	71.4
SH2 NB Hebden 2 †	002-0962-D/0.513 NB left	PA 10 2017	13/05/22	0	96.4	101.1	--
SH2 Petone Station SB *	002-0962-I/11.139 SB left	PA 14 2009	22/10/21	3	97.2	100.4	69.4
Fergusson Drive WB *	Fergusson Drive East/0.689 WB	AC 10 2012	22/10/21	5	98.3	101.5	74.1
SH2 Grounsel NB	002-0962-D/5.901 NB left	SMA 15 2017	13/05/22	3	99.6	103.2	77.4
SH2 Grounsel NB *	002-0962-D/5.901 NB left	SMA 15 2017	22/10/21	3	99.6	103.2	76.6
SH2 Te Marua NB *	002-0931-B/13.278 NB left	2CHIP 3/5 2009	21/10/21	4	101.3	--	79.6
SH2 Te Marua NB	002-0931-B/13.278 NB	2CHIP 3/5 2009	5/05/22	3	101.3	106.5	80.0
Eastern Hutt Road SB *	Eastern Hutt Rd/5.690 SB	2CHIP 3/5 2014	22/10/21	4	101.9	107.9	79.5
Eastern Hutt Road NB *	Eastern Hutt Rd/5.690 NB	2CHIP 3/5 2014	22/10/21	2	102.1	107.3	79.9
SH2 Kaitoke NB 2 †	002-0931-B/7.686 NB	2CHIP 2/4 2022	5/05/22	3	--	--	79.4

* site used to 'calibrate' test vehicle against SPB

† CPB not used to estimate an SPB due to issues with $L_{CPX:P1,80}$ or $L_{AE,car,75}$ measurement

D.3.4 Validation of CRTN Ground Absorption Correction

Even at 10 m from the edgeline, CRTN chart 8 provides a very large correction of -3 dB for 100% soft ground compared to hard ground. Whilst the general approach has been to accept all CRTN corrections as-is so that it remains internally consistent following re-calibration, different ground absorption between SPB sites had the potential to alter the results of the SEL-CPX regression if the chart 8 correction over- or under-estimated the effect.

An additional set of validation measurements were performed using CPB, in the presence of very high and very low ground absorption, as a sanity check on the CRTN correction magnitude.

The Esplanade in Lower Hutt provided a flat straight section of 50 km/h road with a continuous AC-20 surface layer and adjacent sections of nominally 100% soft (grass) and 0% (gravel and tarmac) ground cover. Night-time measurements were performed with the Mazda3 test vehicle with the SLM placed 10 m from the edge of the road in the approximate positions of the orange arrows in Figure D-2. There were 5 passes measured for each position, with SEL calculated for a 3-second period centred on the peak pass-by level.

On average, pass-by SELs measured on the soft ground were 4.2 ± 1.4 dB lower than those measured on the hard ground. The CRTN correction is considered plausible and has been adopted as-is.

Figure D-2: Ground absorption validation site (at the time of measurement there were no parked cars or traffic). Image credit: Google Street View

Presumably a difference of up to 3 dB could arise due to the presence/absence of the first reflection, in which case the effect could be very sensitive to the exact location of the absorption (rather than the percentage between edgeline and microphone, which is how CRTN quantifies absorption). With soft ground almost all the way up to the 'edgeline', our trial site was as close to an ideal scenario for a sanity test, though not typical of the network and it may not have captured all the subtlety of roadside absorption.

Appendix E Calculation of Uncertainty

In general, it is the uncertainty in replicating the CRTN reference conditions that is relevant to this study, not the absolute accuracy of the CRTN model itself, which is beyond scope.

For context, the overall uncertainty at 95% coverage for CRTN predictions was computed by its authors as ± 4 dB [Delany et al, 1976] (see section B.4).

E.1 Individual Vehicle Speed

The uncertainty in the speed of each passing vehicle based on a single measurement with the STALKER Lidar Gun is calculated in the table below. The overall uncertainty is ±3.2 km/h at the 95% confidence level. Using the CRTN chart 4 equation for vehicle speed, this is translated into an effect on noise of ±0.35 dB, which is used as a component in subsequent uncertainty analyses.

Uncertainty Component	Semi-range (km/h)	Divisor[16]	Source
Reference vehicle speed	0.50	1.73	Based on E-Road[17] ± 0.5% @ 100 km/h
Speed gun correction	0.23	1.00	Correction based on sample (SE=0.23, n=45)
Speed gun resolution	0.50	1.73	Half the smallest division of the speed gun readout
E-roads GPS resolution	0.50	1.73	Half the smallest division of the E-Road device
Repeatability (1 reading)	1.50	1.00	1 SD from sample of 45 passes at exactly 70 km/h
Combined Uncertainty	1.60	km/h	
Expanded Uncertainty	3.2	km/h	at 95% confidence level (k=2)
Effect on noise (via CRTN chart 4)	0.35	dB	at 95% confidence level

If a vehicle passing at speed *V* (km/h) needs to be *corrected* to the reference speed of 75 km/h, then an additional component will apply, with a semi-range estimated as one quarter the magnitude of the CRTN chart 4 correction: ±0.03*|*V*-75| dB. Note that most of the uncertainty in this component is negated by using CRTN's own speed correction.

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[16] Divisor describes the shape of the distribution, based on the type of semi-range provided. Common values are 1.0 for a sd, 2.0 for a 95% confidence interval, and 1/√3 = 1.73 for the limits of a rectangular distribution.
[17] https://help.eroad.com/assets/Posted-Speed-FAQs-v1.pdf

E.2 Individual Vehicle SEL under CRTN Reference Conditions

The uncertainty in a single SPB SEL measurement of a passing vehicle, as it relates to CRTN reference conditions, is derived in the table below. The expanded uncertainty is typically in the region of ± 1.5 dB at 95% confidence, but varies between sites and depending on vehicle speed.

Uncertainty Component	Semi-range (dB)	Divisor	Source
Sound Level Meter: LAeq(100ms)	0.50	2.00	Estimated for type 1 Sound Level Meter, incl. mic cal (< ± 0.1 dB), drift, temperature, preamp, filters
Presence of reflections	0.20	1.73	Sites chosen to avoid reflectors. Assume reflections from less than 5% of half-pi space.
Environmental conditions	0.50	1.73	Estimated, based on no detectable wind during any measurements, and 12 m from source at Lmax.
Ground absorption	0.75	1.73	Estimated as the full step size between I values, based on CRTN §2.4 and Chart 8.
Position of microphone re lane edge (horiz)	0.26	1.73	10 m ± 0.3 m from lane edge, including mic positioning and thickness of edge marking
Position of microphone re lane edge (horiz)	0.15	1.73	1.2 m ± 0.3 m above lane, based on CRTN chart 7 correction
Temperature effect on tyre/road emission	0.50	1.73	CRTN does not consider temp. Corrected to 15°C using -0.05 dB/°C. Assume max cor. as uncertainty.
Individual vehicle speed	0.35	2.00	From speed uncertainty budget, based on ± 3.2 km/h for a single vehicle
Correction back to reference speed	0.15	1.73	Est. as ¼ magnitude of CRTN Chart 4 correction, 0.03**dV* in dB. *dV* = 5 km/h used as example.
Background noise vs. truncation	0.20	1.00	Based on manual signal selection. At the extremes, the Bkg increases SEL, truncation decreases SEL.
Repeatability	0.15	1.00	Estimated from a single vehicle driven at different speeds, corrected to reference (SD=0.11 dB)
Combined Uncertainty	0.75	dB	
Expanded Uncertainty	1.5	dB	at 95% confidence level (k=2)

CPB modifies this only slightly:

- The uncertainty in vehicle speed is ± 0.85 km/h at k=1 so the individual vehicle speed component reduces to 0.20 dB at k = 2.
- There is an additional component for the translation from CPB to SPB, which is based on paired CPB and SPB measurements at 6 sites (section D.3.2). The standard error is 0.27 dB at k=1.

The expanded uncertainty for CPB as an estimate of SPB is 1.5 dB at the 95% confidence level.

E.3 Average SEL for a Wayside Site under CRTN Reference Conditions

The uncertainty in the average SPB SEL of a wayside site, as it relates to CRTN reference conditions. This depends on the number of measurements made, *n*, and the average traffic speed, *V*. It is derived in the table below for *n* = 30 and d*V* = |*V*-75| = 10 km/h, giving a typical expanded uncertainty of ± 1.5 dB at the 95% confidence level.

Uncertainty Component	Semi-range (dB)	Divisor	Source
Sound Level Meter: LAeq(100ms)	0.50	2.00	Estimated for type 1 Sound Level Meter, incl. mic cal (< ± 0.1 dB), drift, temperature, preamp, filters
Presence of reflections	0.20	1.73	Sites chosen to avoid reflectors. Assume reflections from less than 5% of half-pi space.
Environmental conditions	0.50	1.73	Estimated, based on no detectable wind during any measurements, and 12 m from source at Lmax.
Ground absorption	0.75	1.73	Estimated as the full step size between I values, based on CRTN §2.4 and Chart 8.
Position of microphone re lane edge (horiz)	0.26	1.73	10 m ± 0.3 m from lane edge, including mic positioning and thickness of edge marking
Position of microphone re lane edge (horiz)	0.15	1.73	1.2 m ± 0.3 m above lane, based on CRTN chart 7 correction
Temperature effect on tyre/road emission	0.50	1.73	CRTN does not consider temp. Corrected to 15°C using -0.05 dB/°C. Assume max cor. as uncertainty.
Speed error (systematic)	0.13	2.00	From speed uncertainty budget, systematic error only: ± 0.13 dB @ 95%
Correction back to reference speed	0.30	1.73	Est. as ¼ magnitude of CRTN Chart 4 correction, 0.03*d*V* in dB. Depends on d*V*.
Speed error (random)	0.06	2.00	From speed uncertainty budget, random error only: ± 0.33 dB @ 95% for one vehicle. Depends on *n*.
Background noise vs. truncation	0.05	1.73	Based on manual signal selection. Bkg increases SEL, truncation decreases SEL. Depends on *n*.
Variation in fleet between visits	0.26	1.00	Surveyed fleet variability had SD = 1.4 dB. Depends on *n*.
Combined Uncertainty	0.75	dB	
Expanded Uncertainty	1.5	dB	at 95% confidence level (k=2)

E.4 Uncertainty of Draft Corrections for Cars

The uncertainty of the absolute value of the correction for each surface classification under CRTN reference conditions. This is the uncertainty achieved for the 're-calibration' of CRTN for the current NZ light vehicle fleet (before considering the uncertainty of CRTN prediction and surface variation).

Uncertainty Component	Semi-range (dB)	Divisor	Source
Uncertainty in $CPXP_{80}$	0.98	2.00	Consistency in CPX over time, assumed to be ±0.5 dB at 95%, propagated to SEL using eq. 3.6
$CPXP_{80}$ correction estimate	0.49	1.00	Standard error of the mean $CPXP_{80}$ surface correction for a classification, propagated to SEL.
Confidence interval of CPX-to-SEL regression	0.57	1.00	Calculated from weighted regression statistics. Depends on surface (example for $L_{CPX:P1,80}$ = 102 dB).
Systematic error in NZ fleet SEL	0.53	1.00	Derived from components of E.3 that could be common between sites.
Random error in NZ fleet SEL	0.23	1.00	Standard error of mean, derived from components of E.3 that should vary between sites.
Correction for outliers & traffic mix	0.20	1.73	Estimated for the corrections in section 3.1 based on measurements.
Validity of CRTN implicit SEL	2.00	1.73	Estimated. Mostly due to validity of deconstruction of CRTN. incl. SEL-to-L_{Aeq} conversion, $L_{10(1h)}$ vs. $L_{10(18h)}$.
Rounding error	0.50	1.73	Half the final resolution of 1 dB.
Combined Uncertainty	1.60	dB	
Expanded Uncertainty	3.2	dB	at 95% confidence level (k=2)

E.4.1 Uncertainty of Prediction

The expanded uncertainty in the table above is not the same as the uncertainty of prediction of CRTN. The uncertainty associated with predicting the level of any given surface *under CRTN reference corrections* requires modification of components:

- The "confidence interval" component for the regression is replaced by a "prediction interval" component, which varies depending on the value of the abscissa. As an example, $L_{CPX:P1,80}$ = 102 dB corresponds to a standard error of 1.51 dB.
- The "$CPXP_{80}$ correction estimate" component is modified to represent the range in level expected from the *actual* road surface, rather than the average road surface. This includes the range of surface types grouped within each classification, and the variability of those individual surfaces, and therefore the value of this component differs by surface classification. The standard error in $L_{CPX:P1,80}$ for each classification is propagated to SEL to find the value of the component. Typical standard errors in SEL are 2.1 dB L_{AE} for chipseal, 1.7 dB L_{AE} for SMA, and 3.8 dB L_{AE} for porous asphalt.

This results in an uncertainty of prediction for an arbitrary site under CRTN reference conditions that ranges from ± 5.2 dB for SMA to ± 8.5 dB for OGPA at the 95% level of confidence. As noted by Hood [1987], the majority of the prediction uncertainty arises from variability in the road surface.

E.4.2 Relative Uncertainty of Corrections to the Reference Level

The uncertainty of each correction relative to the reference level (CRTN's implicit SEL), under CRTN reference conditions can be derived from a subset of the components in the table.

Specifically, the *Uncertainty in* $CPXP_{80}$, the $CPXP_{80}$ *correction estimate*, the *Confidence interval of regression*, the *Random error in NZ fleet*, and the *Rounding error*. This uncertainty depends on the surface, but is typically in the region of ± 2 dB at the 95% level of confidence.