Nambucca Heads to Urunga

Low Noise Diamond Grinding

Pavement Noise Monitoring

Roads and Maritime Services | July 2019

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1 Introduction

Roads and Maritime Services has carried out low noise diamond grinding of existing concrete pavements in the Valla Beach area of the Nambucca Heads to Urunga (NH2U) project. The project was proposed as a trial to determine the noise benefit from the grinding process.

SLR Consulting Pty Ltd (SLR) has been engaged by Roads and Maritime to conduct pre and post grinding measurements of the noise emissions from the pavement surfaces at four test sites.

Measurements were made using both Statistical Passby Method (SPB) and On-Board Sound Intensity (OBSI) vehicle mounted noise measurements at each test site. The SPB method measures roadside noise levels from passing vehicles whereas the OBSI method directly measures surface noise at the interface of the road pavement and vehicle tyre.

1.1 Background and test locations

The NH2U upgrade opened in 2016. The road surface for the new highway comprised of transversely tined Plain Concrete Pavement (PCP) and two sections of transversely tined Continually Reinforced Concrete Pavement (CRCP) with a 10 mm Stone Mastic Asphalt (SMA10) surface. The sections of SMA10 were specified as low noise pavements in areas of residential clusters.

Based on community concerns regarding noise from the sections of concrete pavement, Roads and Maritime carried out a low noise diamond grinding trial in the Valla area on sections of PCP with the aim of reducing road traffic noise levels for receivers in the Valla area.

Details of the four test sites are provided in **Table 1** and are shown in **Figure 1**.

Table 1 Test Locations

ID	Name, Treatment Type and Gradient	Specific Grinding Type
Location A	Cow Creek Twin Bridges to Deep Creek Twin Bridges Low Noise Diamond Grinding 3 Pass (LNDG 3 Pass) Gradient of -2.1%	R93 Diamond Grinding of Concrete plus two passes of the diamond grinding machine: First pass: Flush grind surface with 3.2 mm wide blades spaced at 0.9 mm Second pass: Grooves at 12.5 to 16.0 mm spacing using 3.2 mm wide blades and cutting to a depth of 3 to 5 mm
Location B	Deep Creek Twin Bridges to the beginning of the southern extent of SMA10 Conventional Diamond Grinding (CDG) Gradient of -0.7%	R93 Diamond Grinding of Concrete
Location C	SMA10 No Treatment, Control Location Gradient of 1.3%	None – control location
Location D	McGraths Floodplain Low Noise Diamond Grinding 2 Pass (LNDG 2 Pass) Gradient of 1.2%	Two passes of the diamond grinding machine: First pass: Flush grind surface with 3.2 mm wide blades spaced at 0.9 mm Second pass: Grooves at 12.5 to 16.0 mm spacing using 3.2 mm wide blades and cutting to a depth of 3 to 5 mm

Figure 1 Test Locations

1.2 Road traffic noise sources

Noise from road traffic can be grouped into three main areas:

- Aerodynamic noise
- Power unit noise
- Tyre/pavement interface noise

For modern cars, aerodynamic noise sources are only significant at high speeds. According to Sandberg and Ejsmont[1] (2002), aerodynamic effects are only likely to become significant above around 120 km/h.

Power unit noise includes all mechanical noise from the vehicle such as fan noise, engine noise, exhaust noise and transmission noise. This noise is largely dependent on the engine rotational speed and the engine load. As light vehicles tend to operate in a reasonably limited engine speed range, power unit noise is largely independent of vehicle speed. At low speeds power unit noise dominates the overall levels and power unit noise is higher when accelerating than when cruising at constant speed.

Noise from the interface of the tyre and pavement surface is largely dependent on the speed of the vehicle. As speed increases, tyre/road noise becomes the dominant source and there is a 'crossover' speed above which it becomes dominant over power unit noise. The crossover speed depends on the vehicle type and driving conditions with indicative speeds presented in **Table 2**. The below reference indicates that for cars, tyre/road noise will be the dominant noise source above speeds of around 50 km/h, even when accelerating.

Table 2 Crossover Speeds from Power Unit Noise Dominant to Tyre/Pavement Noise Dominant[1]

Vehicle Type	Cruising	Accelerating
Cars made 1985-1995	30-35 km/h	45-50 km/h
Cars made 1996-	15-25 km/h	30-45 km/h
Heavy vehicles made 1985-1995	40-50 km/h	50-55 km/h
Heavy vehicles made 1996-	30-35 km/h	45-50 km/h

Note 1: Reproduced from Sandberg and Ejsmont

Note 2: Research from Hammer et al.[2] (2016) indicates that the crossover speed for cars is likely lower than shown above.

As the posted speed on NH2U is 110 km/h, the dominant source of vehicle noise at the four test sites is therefore likely to be noise from the interface of the tyre and pavement surface.

1.3 Terminology

The assessment has used specific acoustic terminology and an explanation of common terms is included in **Appendix A**. A glossary is also at the start of this document which lists the various terms used.

[1] U. Sandberg and J.A. Ejsmont: *Tyre/Road Noise Reference Book* Informex (2002).

[2] E Hammer, S Egger, T Saurer and E Bühlmann: *Traffic Noise Emission Modelling at Lower Speeds* The 23rd International Congress on Sound & Vibration (2016)

2 Measurement methodology

2.1 Pre and post grinding measurements

Details of the pre and post grinding measurements are shown below in **Table 3.**

Table 3 Pre and post grinding measurements

Item	Pre Grinding Measurements	Post Grinding Measurements
Date completed	13-15 June 2018	13-14 November 2018
Weather[1]	Maximum Temperatures: 20.3°C, 20.7°C Low humidity Clear and calm	Maximum Temperatures: 25°C, 27.4°C Low humidity Occasionally breezy and gusty Overcast late on 14 November

Note 1: Maximum temperatures taken from the Bureau of Meteorology weather station at Coffs Harbour (ID: 059151).

2.2 Statistical passby measurements

Statistical Passby Measurements (SPB) were completed at each site with reference to the requirements of ISO 11819-1, modified to include the Austroads 12-bin heavy vehicle definitions.

SPB road traffic noise measurements are an internationally standardised method of measuring the total road traffic noise from vehicles. Whist SPB measurements are generally dominated by noise from the vehicle tires, it also includes aerodynamic noise, body noise, engine and exhaust noise.

SPB measurements record noise levels of individual vehicles as they pass the test location and the results are statistically processed to give the Statistical Passby Index (SPBI). The SPBI is a measure of the acoustic emission characteristics of the pavement in question. The ISO standard also defines the Vehicle Sound Level which is the speed corrected sound pressure level for each vehicle class.

The key details of the SPB measurements are shown in **Table 4**. The measurement results are provided in **Appendix B**.

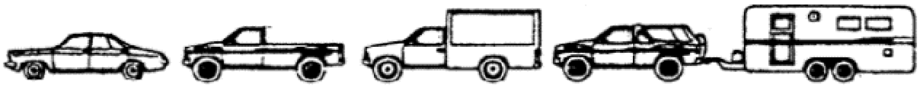
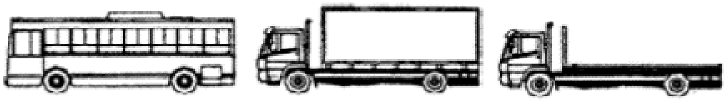
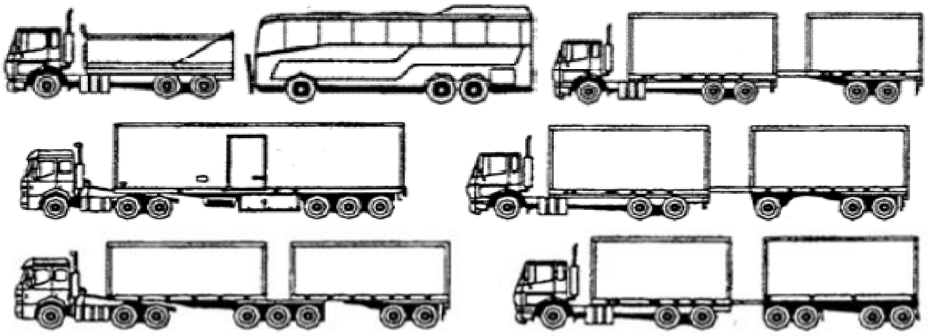
Table 4 Key Details of SPB Measurement

Item	Details
Noise measurements	
Equipment	Type 1 sound level meter
Location	At a distance of 7.5 m from the centre of the test lane and at a height of 1.2 m above the road surface.
Parameters measured	- Maximum A-weighted fast response sound pressure level for each vehicle passby. - One-third octave spectra when the sound pressure level is at a maximum for each vehicle pass-by.
Vehicle passbys	- Category 1 (Cars) – 80 - Category 2a (Dual axle heavy vehicles) – 30 - Category 2b (Multi-axle heavy vehicles) – 30 - Categories 2a and 2b (Heavy vehicles) – 80

Item	Details
Exclusions	Events identified as extraneous or influenced by other vehicles were excluded from the dataset. Sound levels only measured from vehicles judged to be moving at constant speed and which do not deviate significantly in their lateral position from the median axis of the test lane.
Other Items	
Vehicle speed	Individual vehicle speeds were measured using a radar gun with display. The radar gun was set to compensate for the angle of measurement.
Photos	Photographs were taken of the survey at each test site. These are shown in **Appendix C**.
Air temperature	Air temperature was measured in the shade with a K-Type thermocouple and was recorded at one second intervals using a thermocouple logger.
Video recording	Video recordings in MP4 format were recorded for the majority of the vehicle passbys.

SPB measurement results usually vary depending on the category of vehicle. For this reason ISO 11819-1 requires SPB measurements to be categorised into three classifications of road vehicles as shown in **Figure 2**.

Figure 2 Road vehicle classifications

Class	Description	Examples
Class 1	Short vehicles with two axles. May also include trailers	
Class 2a	Two axle trucks and buses	
Class 2b	Trucks and buses with three or more axles	

2.3 On-Board Sound Intensity testing

The OBSI road surface noise measurement method is a standardised method of measuring road surface noise. This method measures the rolling noise generated at the tyre-road interface and excludes vehicle engine, vehicle body, and aerodynamic noise.

The OBSI method measures tyre-pavement noise at the source using microphones in a sound intensity probe mounted to a test vehicle. Real time noise measurements are performed whilst the test vehicle drives along the pavement of interest.

The OBSI measurements were completed with reference to the requirements of AASHTO TP 76-06. The key details of the OBSI measurements are shown in **Table 5**.

Table 5 Key Details of OBSI Measurement

Item	Details
Vehicle	Toyota Corolla Ascent Hatch (2009)
Tyre	Yokohama ASPEC A300[1]
Parameters measured	- Raw sound pressure was recorded at a sampling frequency of 48 kHz and a bit depth of 16 on four channels simultaneously using two pairs of phase-matched microphones. - Speed and geo-position were continuously recorded using a GPS. - Temperature of both the tyres and road surface was measured before and after each run using an infrared thermometer.
Measurements made	- All data was recorded for various loops of the motorway which covered all the testing locations in both the northbound and southbound directions. Segments of the pressure traces were then extracted for analysis where the geo-position of the vehicle was in close proximity to each SPB measurement location.
Vehicle speed	The nominal speed of the vehicle was 110 km/h, which was the posted speed limit. Vehicle speed was continuously recorded using a GPS connected to a laptop. A heads-up display was provided to the driver to ensure the speed was correct and consistent.

Note 1: A photo of the tread pattern is provided in **Appendix C**.

The OBSI system is shown below in **Figure 3**.

Figure 3 OBSI System

2.4 Data analysis and post-processing

The data analysis was carried out using a bespoke Python script in a series of steps:

1. Extract suitable 7 second segments of pressure data where the geo-position of the vehicle was in close proximity to the SPB measurement location, in accordance with the requirements of AASHTO TP 76-06. Two channels recorded simultaneously were extracted.
2. Calculate a linearly averaged narrow-band spectrum of the average pressure of both channels.
3. Convert the narrow-band pressure spectrum to a 1/3 octave band pressure spectrum in the frequency domain.
4. Calculate the narrow-band sound intensity spectrum based on the cross-spectrum between the two microphone signals.
5. Convert the narrow-band sound intensity spectrum to a 1/3 octave band intensity spectrum in the frequency domain.

3 Results

3.1 SPB measurements

The results from the SPB measurements (processed in accordance with ISO 11819-1) are summarised in **Table 6**. The vehicle sound levels for individual bins (from the Austroads 12-bin classification system) within class 2b of ISO 11819-1 are provided in **Table 7**. The Statistical Passby Indices and vehicle sound levels for each PCP pavement are compared to the SMA10 pavement in **Table 8**.

The Statistical Passby Index at each location pre and post grinding is also shown in **Figure 4**, and the Vehicle Sound Level data is shown in **Figure 5** to **Figure 8** for each of the four test locations.

A high level discussion of the findings is provided in **Table 9** and graphs of the SPB measurement results as well as the breakdown of the Class 2b vehicles in the Austroad classification system for each location are in **Appendix B**.

Table 6 SPB Measurement Results

ID	Location and Treatment Type	Statistical Passby Index (SPBI)[1]			Vehicle Sound Level (dBA)			
		Pre-Grind	Post-Grind	Difference[2]	Vehicle Class	Pre-Grind	Post-Grind	Difference[2]
A[3]	Cow Creek to Deep Creek Low Noise Diamond Grinding 3 Pass	86.7	85.7	**-1.0**	Class 1	83.9	79.9	**-4.0**
					Class 2a	85.5	86.4	**0.9**
					Class 2b	90.4	90.3	**-0.1**
B	Deep Creek Twin Bridges to the beginning of the southern extent of SMA10 Conventional Diamond Grinding	87.5	85.7	**-1.7**	Class 1	83.6	81.8	**-1.8**
					Class 2a	86.2	84.9	**-1.3**
					Class 2b	91.8	89.9	**-1.9**
C	SMA10 No Treatment, Control Location	84.8	85.7	**0.9**	Class 1	81.1	81.6	**0.5**
					Class 2a	84.9	85.5	**0.6**
					Class 2b	88.8	89.9	**1.1**
D	McGraths Floodplain Low Noise Diamond Grinding 2 Pass	88.1	86.9	**-1.2**	Class 1	84.1	80.2	**-3.9**
					Class 2a	86.9	86.4	**-0.5**
					Class 2b	92.4	91.9	**-0.5**

Note 1: 100 km/h heavy vehicle reference speed for SPBI.
Note 2: Difference between pre-grind and post-grind.
Note 3: Roadworks near measurement Location A (LNDG 3 Pass) caused some vehicles to appear to be accelerating through the measurement area during pre-grinding testing.

Table 7 SPB Measurement Results – Class 2b Breakdown

ID	Location	Vehicle Sound Level[1,2] (dBA)			
		Vehicle Class	Pre-Grind	Post-Grind	Difference[3]
A[4]	Cow Creek to Deep Creek Low Noise Diamond Grinding 3 Pass	Bin 4	88.7	89.1	**+0.4**
		Bin 5-8	88.2	88.9	**+0.7**
		Bin 9	92.2	90.1	**-2.1**
		Bin 10+	92.7	91.9	**-0.8**
B	Deep Creek Twin Bridges to the beginning of the southern extent of SMA10 Conventional Diamond Grinding	Bin 4	91.3	87.6	**-3.7**
		Bin 5-8	89.2	88.2	**-1.0**
		Bin 9	92.0	90.7	**-1.3**
		Bin 10+	92.9	92.1	**-0.8**
C	SMA10 No Treatment, Control Location	Bin 4	90.3	88.0	**-2.3**
		Bin 5-8	87.6	87.0	**-0.6**
		Bin 9	90.4	89.5	**-0.9**
		Bin 10+	90.3	91.3	**+1.0**
D	McGraths Floodplain Low Noise Diamond Grinding 2 Pass	Bin 4	89.3	91.1	**+1.8**
		Bin 5-8	91.8	89.1	**-2.7**
		Bin 9	92.4	91.7	**-0.7**
		Bin 10+	93.9	93.3	**-0.6**

Note 1: Due to the small number of vehicles observed in bins 5 to 8, these vehicles have been grouped together. Similarly, vehicles in bins 11 and 12 have been included into bin 10. It is noted that using linear regression with small sample sizes can introduce errors.
Note 2: 100 km/h heavy vehicle reference speed for SPBI.
Note 3: Difference between pre-grind and post-grind.
Note 4 Roadworks near measurement Location A (LNDG 3 Pass) caused some heavy vehicles to appear to be accelerating through the area during pre-grinding testing. This is not expected to influence the noise levels of light vehicles.

Table 8 SPB Measurement Results – Difference between PCP and SMA10 Pavements

ID	Location	Statistical Passby Index (SPBI)[1]				Vehicle Sound Level (dBA)				
		Pre-Grind	Diff[2]	Post-Grind	Diff[2]	Vehicle Class	Pre-Grind	Diff[2]	Post-Grind	Diff[2]
A[3]	Cow Creek to Deep Creek Low Noise Diamond Grinding 3 Pass	86.7	**+1.9**	85.7	**0.0**	Class 1	83.9	**+2.8**	79.9	**-1.7**
						Class 2a	85.5	**+0.6**	86.4	**+0.9**
						Class 2b	90.4	**+1.6**	90.3	**+0.4**
B	Deep Creek Twin Bridges to the beginning of the southern extent of SMA10 Conventional Diamond Grinding	87.5	**+2.7**	85.7	**0.0**	Class 1	83.6	**+2.5**	81.8	**+0.2**
						Class 2a	86.2	**+1.3**	84.9	**-0.6**
						Class 2b	91.8	**+3.0**	89.9	-
D	McGraths Floodplain Low Noise Diamond Grinding 2 Pass	88.1	**+3.3**	86.9	**+1.2**	Class 1	84.1	**+3.0**	80.2	**-1.4**
						Class 2a	86.9	**+2.0**	86.4	**+0.9**
						Class 2b	92.4	**+3.6**	91.9	**+2.0**

Note 1: 100 km/h heavy vehicle reference speed for SPBI.
Note 2: Difference between subject pavement and Location C (SMA10).
Note 3: Roadworks near measurement Location A (LNDG 3 Pass) caused some heavy vehicles to appear to be accelerating through the area during pre-grinding testing. This is not expected to influence the noise levels of light vehicles.

Figure 4 Summary of Statistical Passby Index at All Locations

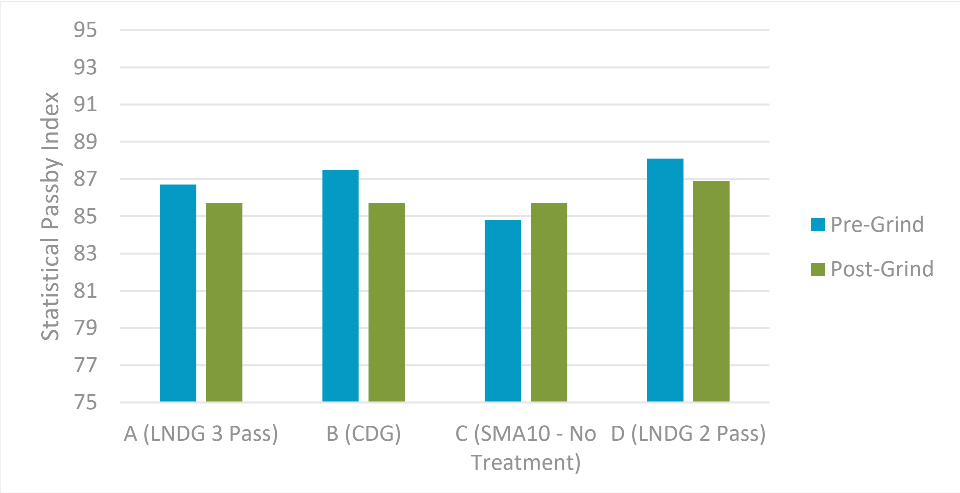


Figure 5 Summary of Vehicle Sound Level Data – Location A (LNDG 3 Pass)

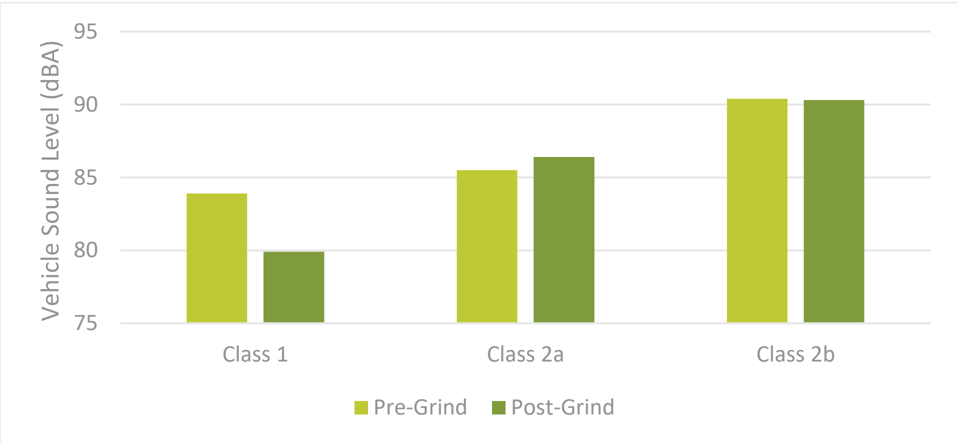


Figure 6 Summary of Vehicle Sound Level Data – Location B (CDG)

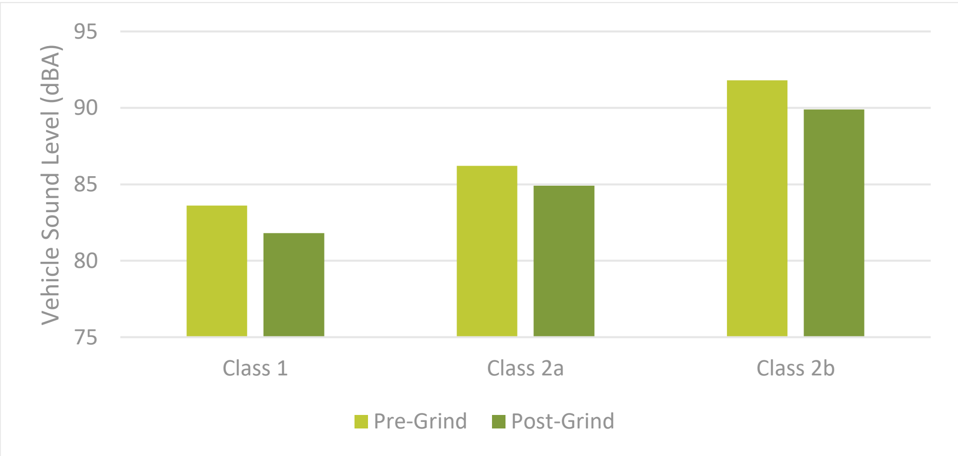


Figure 7 Summary of Vehicle Sound Level Data – Location C (SMA 10 - No Treatment)

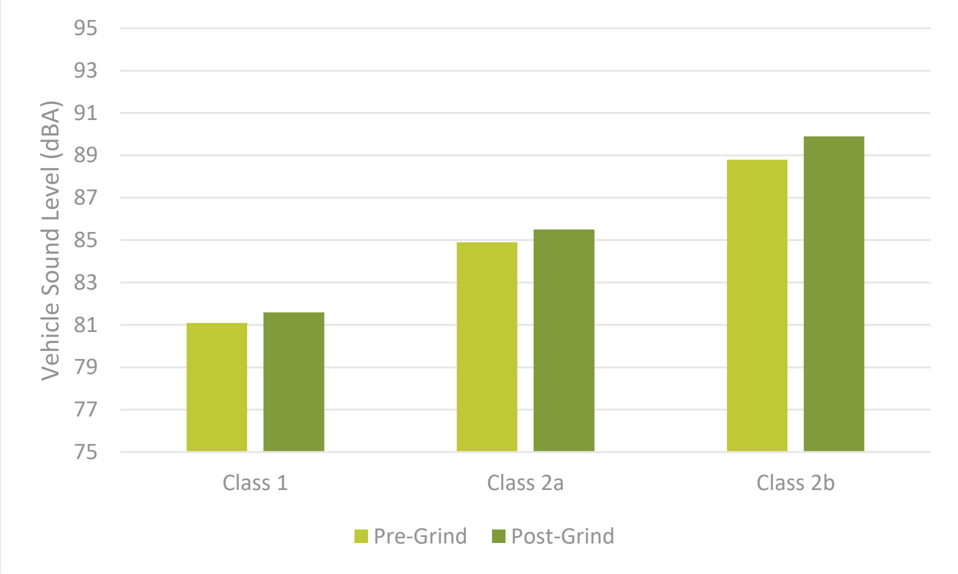


Figure 8 Summary of Vehicle Sound Level Data – Location D (LNDG 2 Pass)

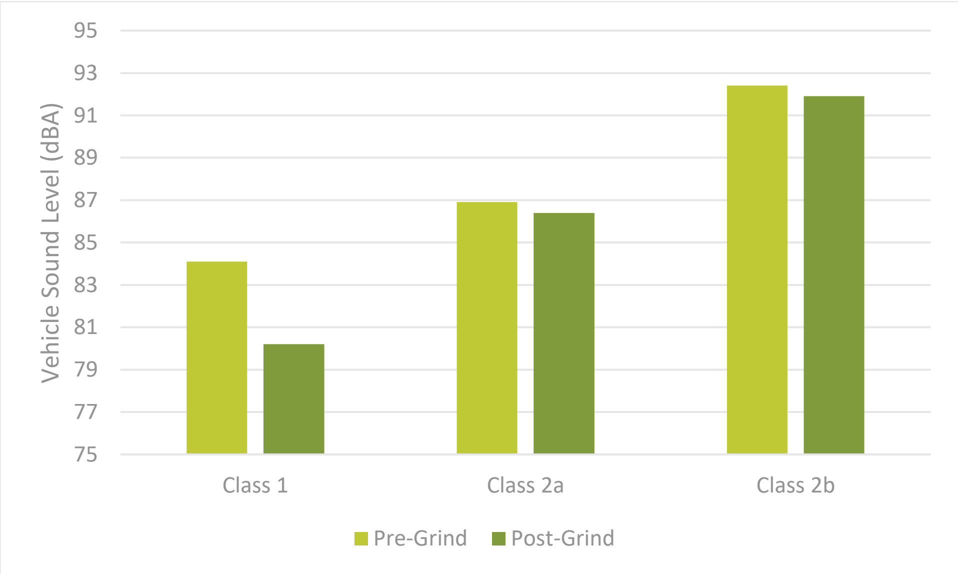


Table 9 Discussion of Key Observations

Location	Name	Grinding Type[1]	Observations
A	Cow Creek Twin Bridges to Deep Creek Twin Bridges	3 pass method consisting of a conventional diamond grind, a flush diamond pass, and a grooving pass.	• Attended subjective observations suggest that roadworks located approximately 300 m from the test site during pre-grinding measurements may have resulted in vehicles accelerating slightly harder through the test section compared with post-grinding observations. This influence was subjectively observed to be most apparent for heavy vehicles. • Location shows a SPBI of -1.0 which indicates the grinding has reduced noise levels at this site, however the effect is likely to have been influenced to some degree by vehicles accelerating in the pre-grinding measurements. • Class 1 vehicles show a significant reduction in vehicle sound levels, whereas Class 2a and 2b are approximately consistent between the pre and post measurements.
B	Deep Creek Twin Bridges to the beginning of the southern extent of SMA10	Conventional diamond grind only	• Location shows a SPBI of -1.7 which indicates the grinding has reduced noise levels at this site. • Reductions are generally consistent across all three vehicle classes.
C	SMA10	No treatment, control location	• This location has an SMA10 pavement and is a control. No works were completed at this site. • Location shows a SPBI of +0.9 which indicates noise levels were higher in the post grinding measurements compared to pre-grinding. • Marginal increases are seen in all three classes.
D	McGraths Floodplain	2 pass method consisting of a flush diamond pass and a grooving pass.	• Location shows a SPBI of -1.2 which indicates the grinding has reduced noise levels at this site. • Reductions are seen in all three classes, but are more apparent in Class 1 compared to Class 2a and 2b vehicles.

Note 1: Specific details regarding each grinding type are provided in **Table 1**.

The SPB measurements shown in **Table 6** and **Figure 4** indicate the post-grinding SPBI at Location D (LNDG 2 Pass) is around 1 dB higher than the other three sites, which is primarily due to the higher Class 2a and Class 2b levels. Post-grind Class 1 levels at Location D (LNDG 2 Pass) are similar or better than the other three sites.

The post grinding SPBI and Vehicle Sound Level results are very similar across all four sites. This indicates that the ground PCP can produce similar noise levels to SMA10.

Locations A (LNDG 3 Pass) and D (LNDG 2 Pass) showed that grinding reduced the vehicle sound levels by around 4 dB for Class 1 vehicles with only negligible reductions for Class 2b vehicles. Location B (CDG) showed that grinding reduced the vehicle sound levels of both Class 1 and Class 2b vehicles by around 2 dB.

When reviewing the results in **Table 7** and the scatter plots in **Appendix B,** the following is noted:

- Separating the measurements into the Austroad classification system results in small sample sizes for the various bins. This introduces uncertainty to the regression analysis. It is expected that tyre/road noise follows a $30\log_{10}$(speed) relationship, however this does not occur for the Austroad subcategories of Class 2b vehicles due to low vehicle numbers.
- Small speed ranges and grouping of different vehicles types also introduces uncertainty to the regression analysis.
- There is inherent variability in noise levels emitted by trucks within the same class or bin categories.
- The validity of the SPB method depends on the mix and speed of vehicles being consistent across all locations and across the pre-grind and post-grind scenarios. This was not able to be controlled and did not always occur.

These factors contributed to the uncertainty of the some of the measurements. It is also noted that there is inherent variability in roadside noise levels emitted by trucks within the same class or bin category, whereas noise from light vehicles is generally seen to be more consistent.

Further discussion on the reduction of vehicle sound levels is presented in the following sections.

3.1.1 Location A (LNDG 3 Pass) SPB results discussion

Temporary road works were being completed on the northbound and southbound carriageway near to Location A (LNDG 3 Pass) during the pre-grinding SPB measurement survey period.

Traffic management for the works reduced carriageway speeds to 80 km/h south of Valla Road which resulted in northbound heavy vehicles accelerating through test Location A (LNDG 3 Pass) during the pre-grinding measurements.

The pre and post grinding SPB results from Location A (LNDG 3 Pass) are shown in **Figure 9** to **Figure 11** as the logarithmic average for Class 1, Class 2a and Class 2b vehicles respectively. The difference between the two data sets as well as the differences between Location A (LNDG 3 Pass) and the SMA10 pavement are also shown on the graphs.

The vehicle sound levels are compared directly to the SMA10 pavement in **Figure 12** through to **Figure 14**.

Figure 9 Vehicle Sound Level (Lveh) – Class 1

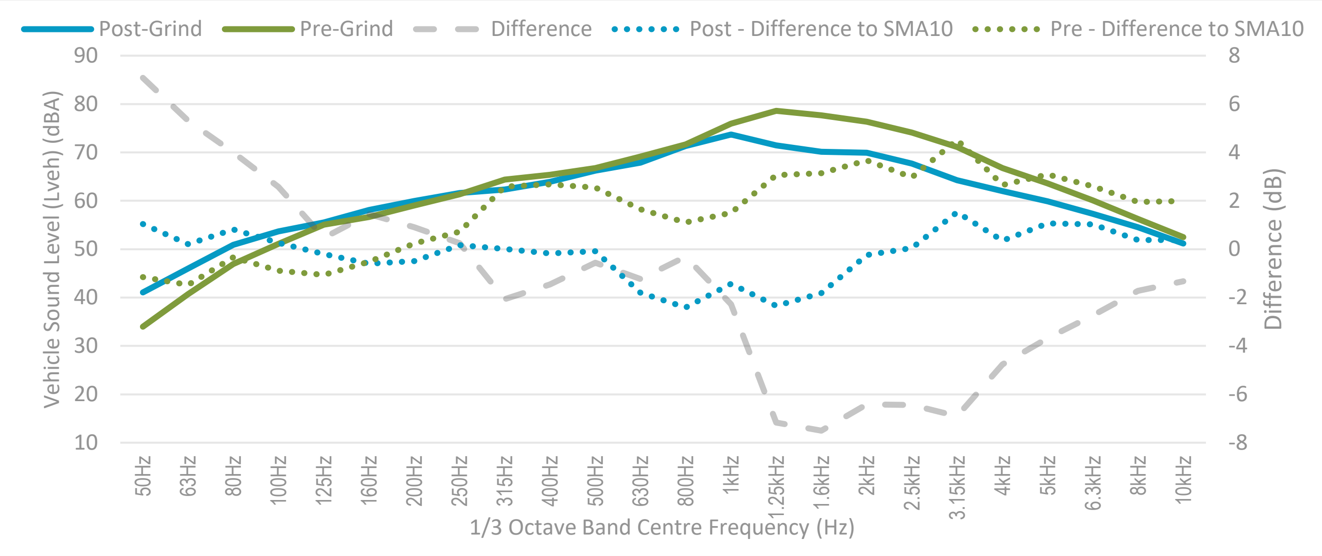


Figure 10 Vehicle Sound Level (Lveh) – Class 2a

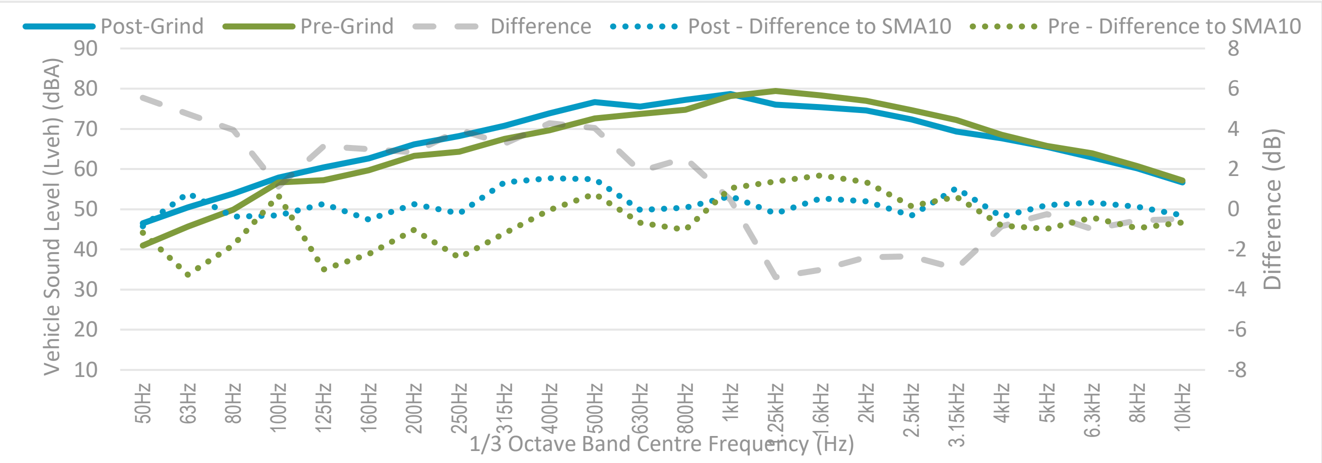


Figure 11 Vehicle Sound Level – Class 2b

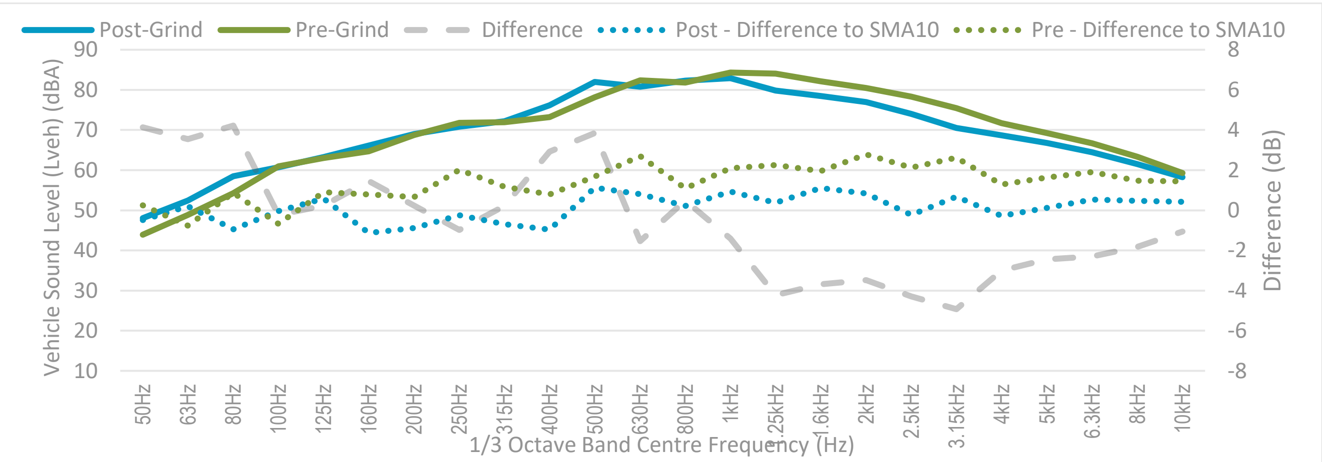


Figure 12 Vehicle Sound Level (Lveh) – Class 1 compared to SMA10

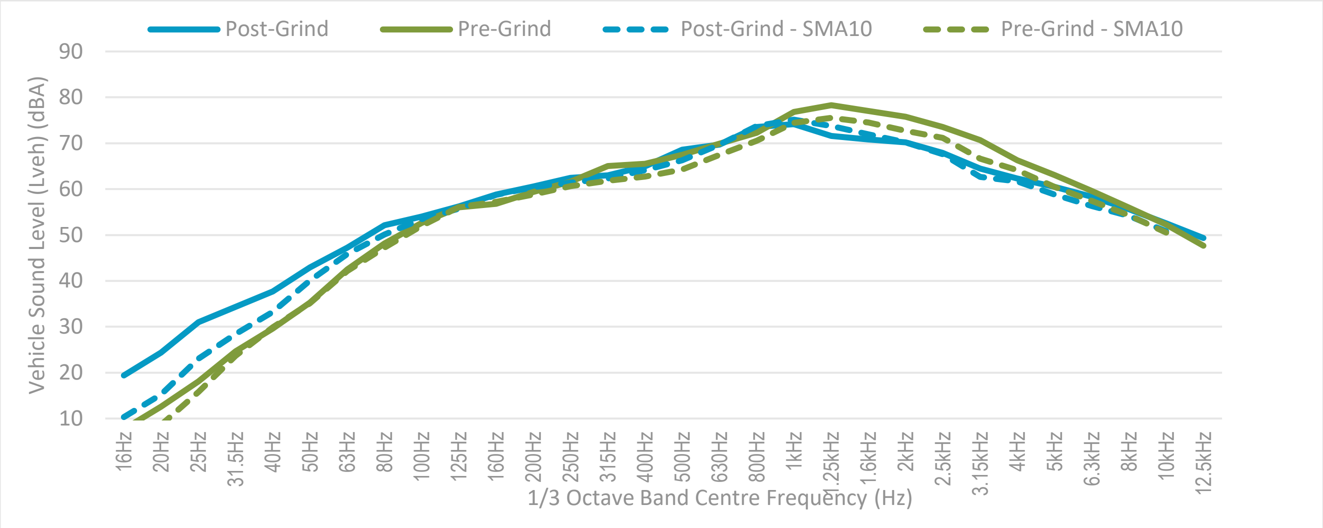


Figure 13 Vehicle Sound Level (Lveh) – Class 2a compared to SMA10

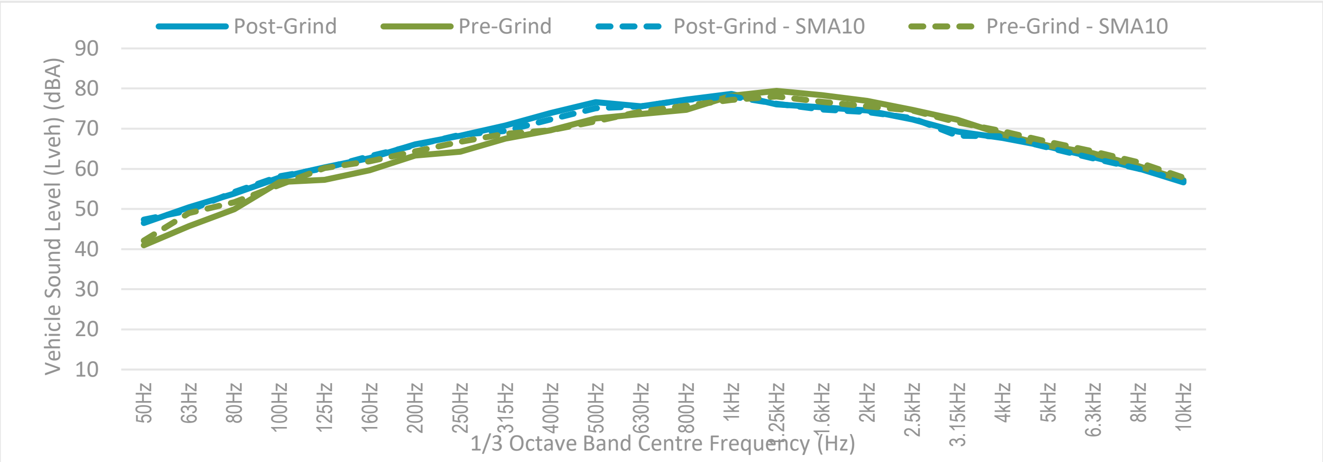
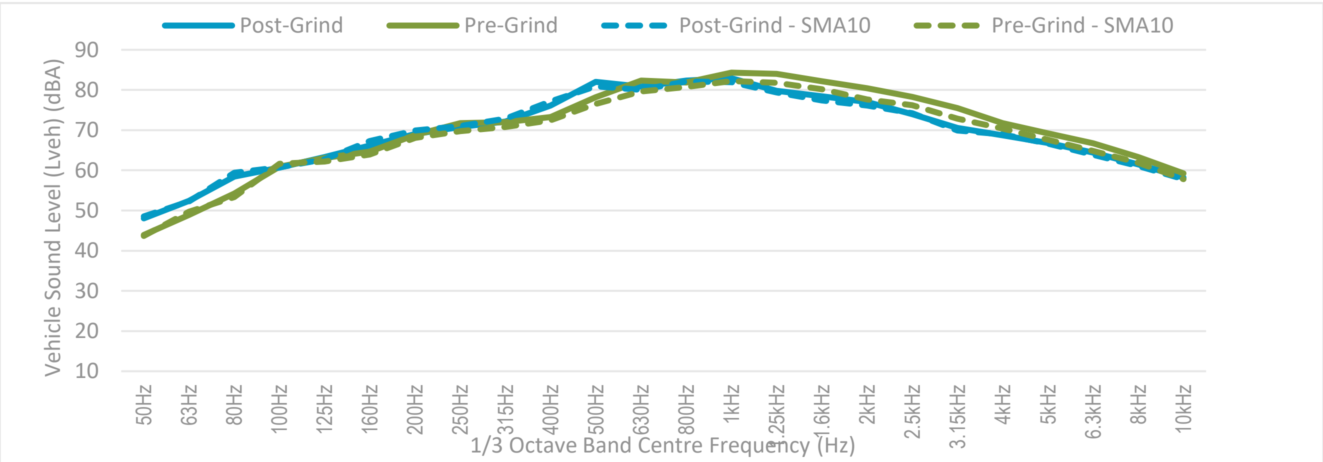


Figure 14 Vehicle Sound Level (Lveh) – Class 2b compared to SMA10



The data in **Table 6** indicates that the difference between the pre and post measurements at Location A (LNDG 3 Pass) decreased the SPBI by 1.0. The above graphs show the post-grind noise measurements have a reduction in high frequency noise between 1 kHz and 4 kHz for all classes, with the effect being most prominent for Class 1 vehicles. This indicates that the grinding has reduced road surface noise emissions at this location.

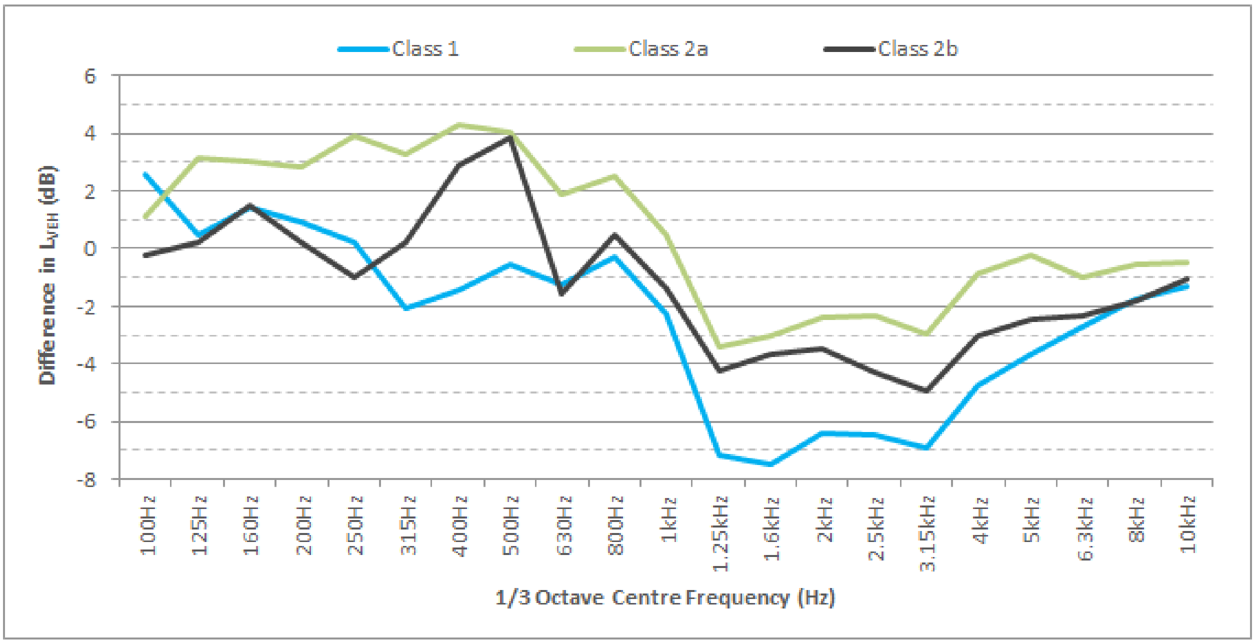
Increases in noise for the post grinding measurements are seen at frequencies below 100 Hz, potentially due to meteorological effects, such as increased wind noise during the post grinding measurements. The weather during the pre and post grinding measurements were markedly different, as noted in **Table 3**.

It is likely that the SPB results for this location were influenced to some degree by the atypical vehicle acceleration during pre-grinding measurements. The results from the OBSI measurements at this location are provided in **Section 3.2.1**. OBSI measurements are not affected by engine noise meaning the OBSI results for this location are likely more representative of the actual change due to the pavement grinding alone.

The difference in vehicle sound level spectra for all three vehicle classes at Location A (LNDG 3 Pass) is shown in **Figure 15**. The figure shows that grinding has reduced Class 1 vehicle noise by around 2 dB between 315 Hz and 800 Hz, and by up to 8 dB between 1.25 kHz and 5 kHz.

Class 2a and Class 2b vehicle show similar effects, however to a lesser degree than Class 1.

Figure 15 Difference in Vehicle Sound Level (L_{VEH}) – Location A (LNDG 3 Pass)



3.1.2 Location B (CDG) SPB results discussion

The pre and post grinding SPB results from Location B (CDG) are shown in **Figure 16** to **Figure 18** as the logarithmic average for Class 1, Class 2a and Class 2b vehicles respectively. The difference between the two data sets as well as the differences between Location B (CDG) and the SMA10 pavement are also shown on the graphs.

The vehicle sound levels are compared directly to the SMA10 pavements in **Figure 19** through to **Figure 21**.

Figure 16 Vehicle Sound Level (Lveh) – Class 1

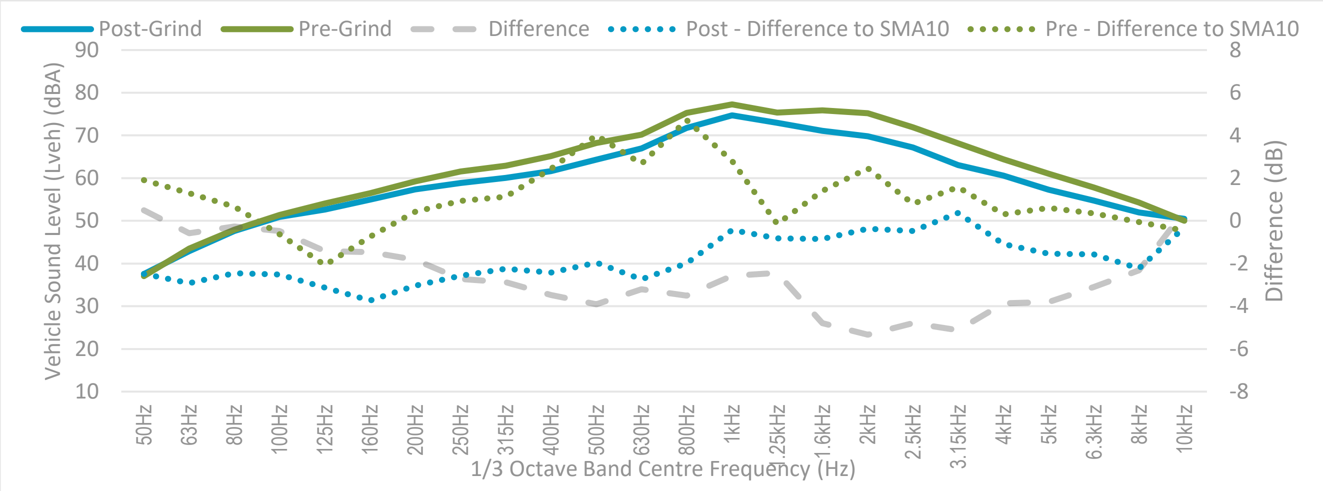


Figure 17 Vehicle Sound Level (Lveh) – Class 2a

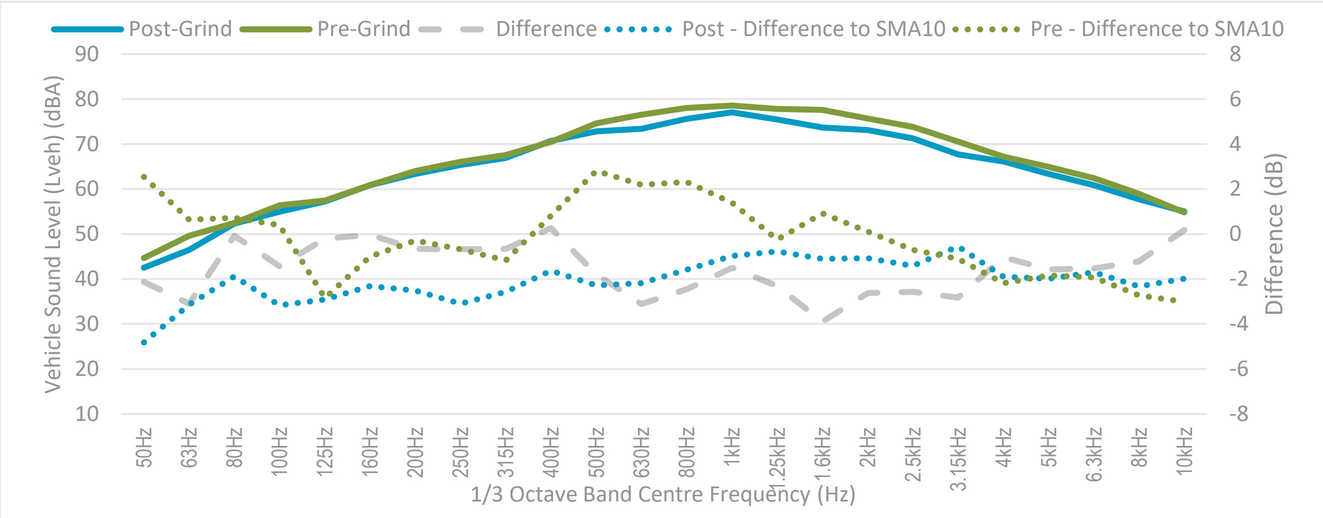


Figure 18 Vehicle Sound Level – Class 2b

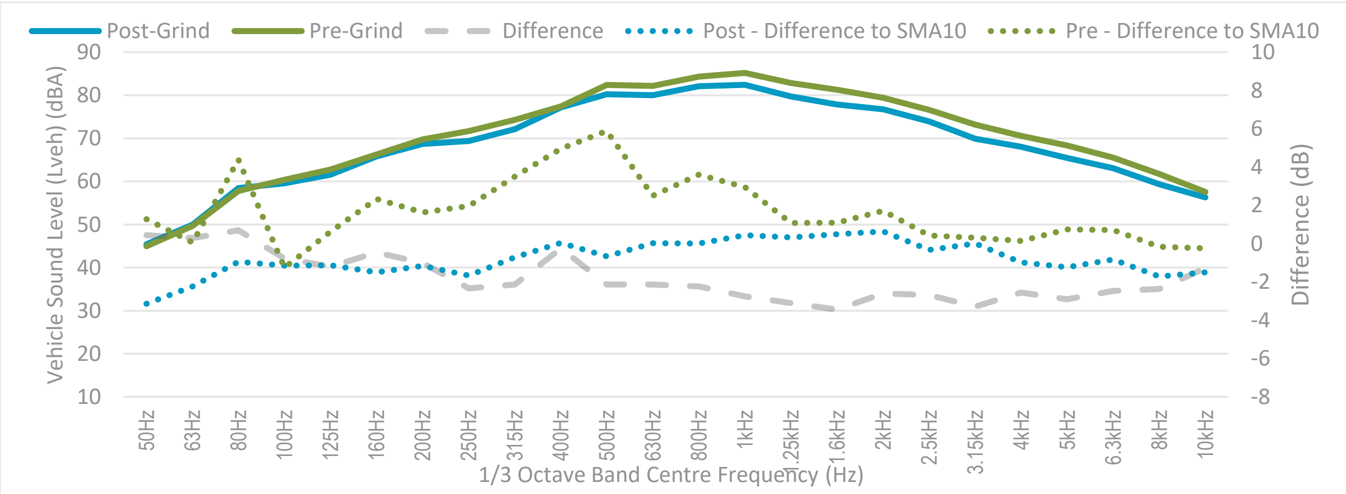


Figure 19 Vehicle Sound Level (Lveh) – Class 1 compared to SMA10

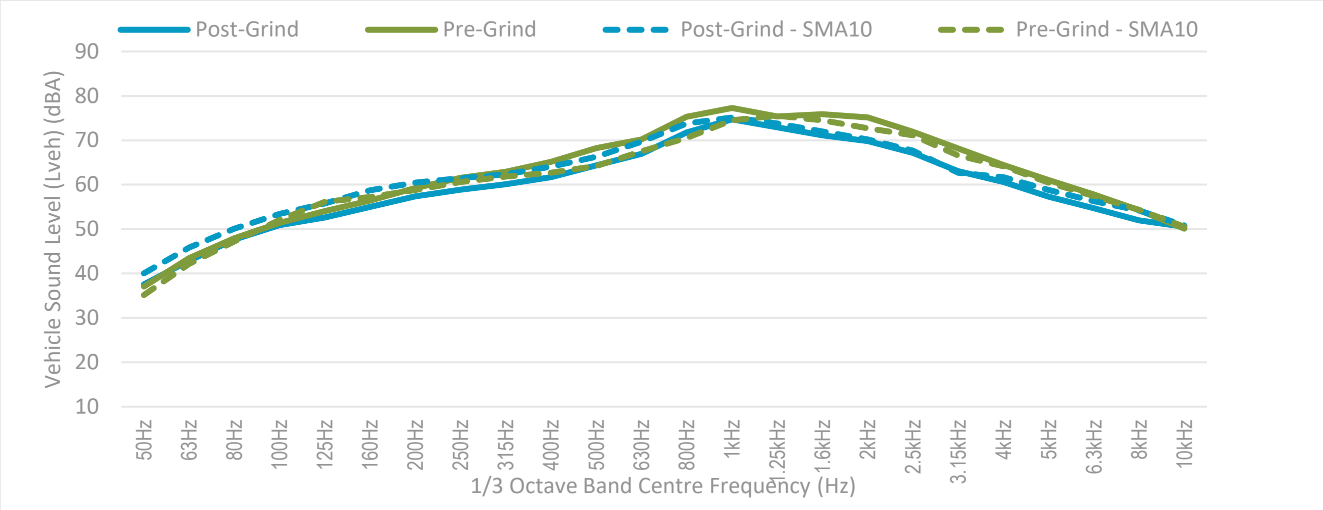


Figure 20 Vehicle Sound Level (Lveh) – Class 2a compared to SMA10

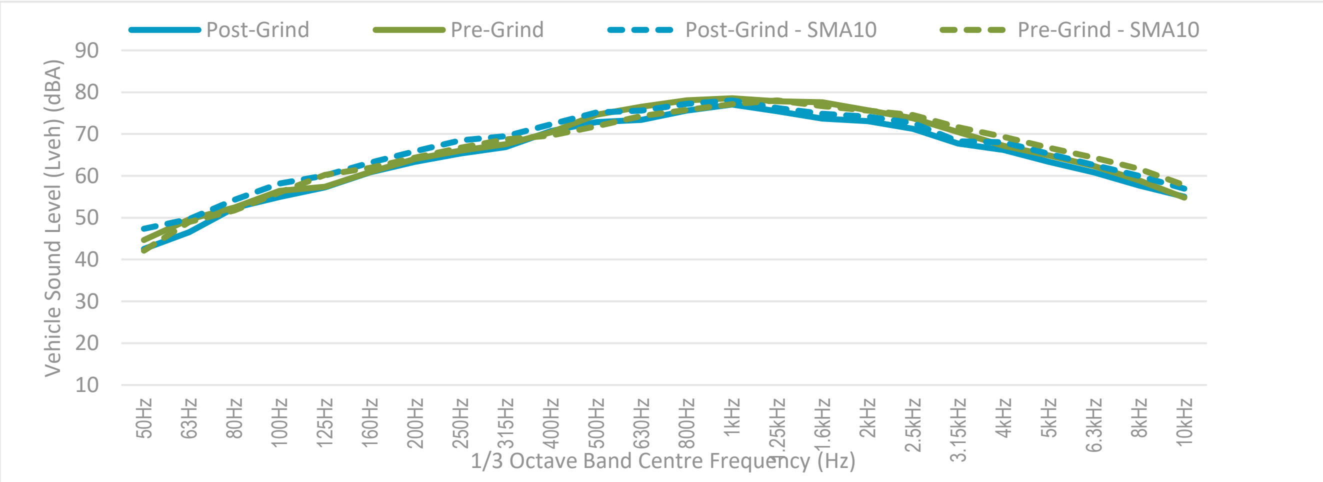
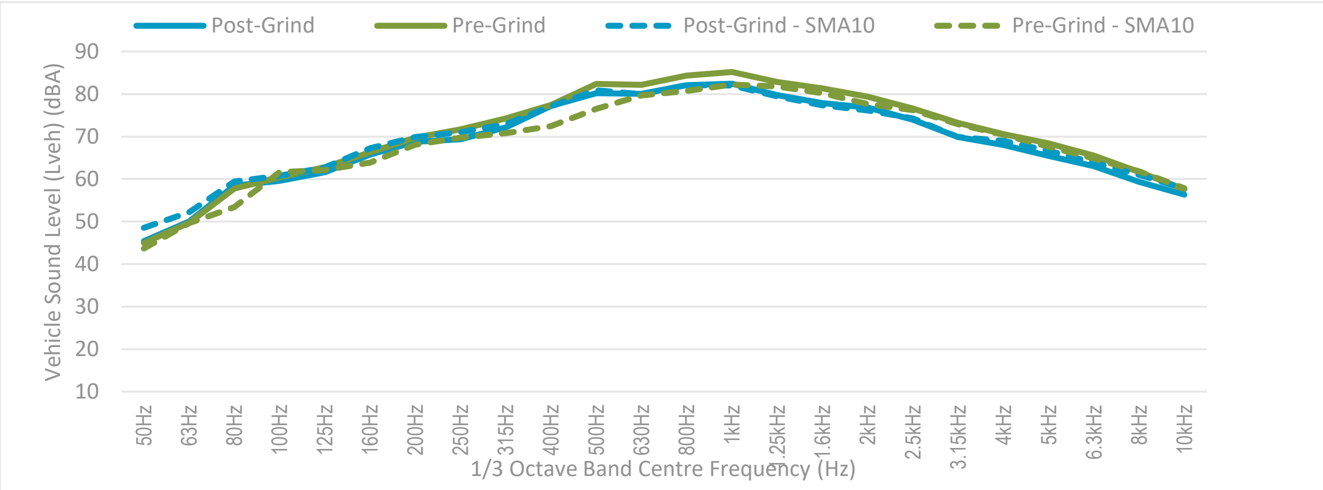


Figure 21 Vehicle Sound Level (Lveh) – Class 2b compared to SMA10

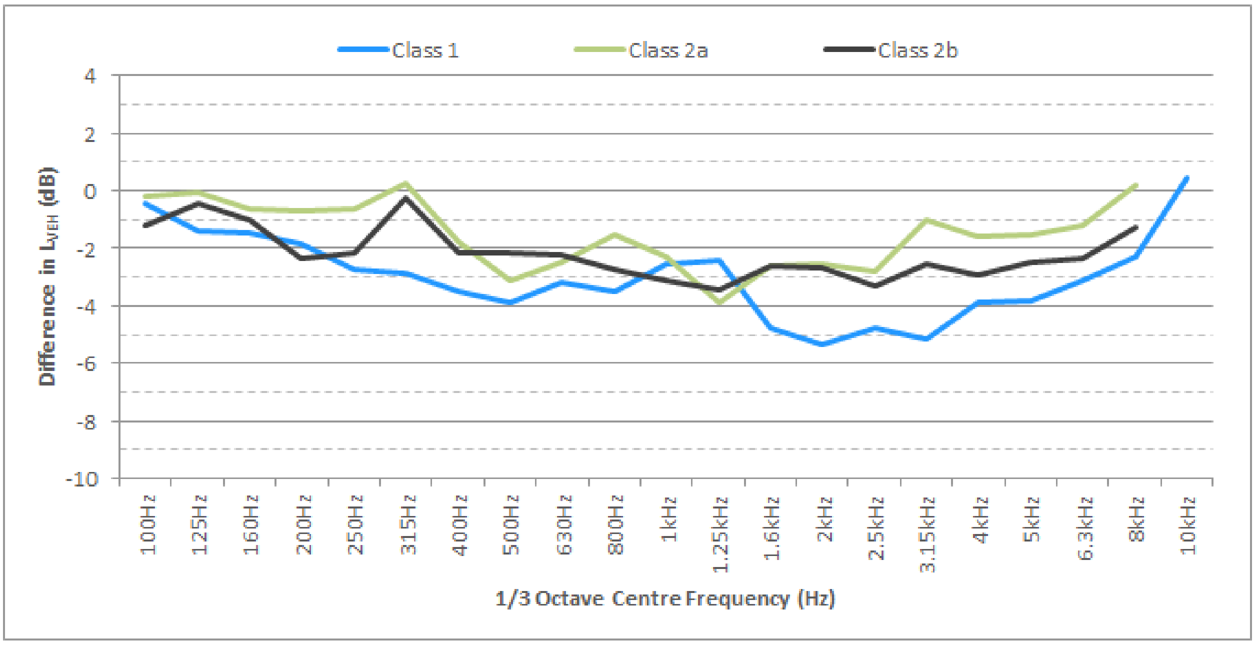


The data in **Table 6** indicates that, post-grinding, at Location B (CDG) the SPBI reduced by 1.7. The above graphs show the vehicle sound level reductions were largely consistent across the vehicle classes, however the effective frequency range was seen to vary between classes.

The difference in vehicle sound level spectra for all three vehicle classes at Location B (CDG) is shown **Figure 22**. The figure shows that grinding has reduced Class 1 vehicle noise by around 2 to 4 dB between 200 Hz and 800 Hz, and by at around 4 to 5 dB between 1.6 kHz and 5 kHz.

Class 2a and Class 2b vehicles show similar reductions, however to a lesser degree than Class 1.

Figure 22 Difference in Vehicle Sound Level (L_{VEH})



3.1.3 Location C (SMA10) SPB results discussion

The pavement surface at Location C was SMA10 and the site was used as a control. No pavement works were performed between the two noise surveys.

The pre and post grinding SPB results from Location C (SMA10) are shown in **Figure 23** to **Figure 25** as the logarithmic average for Class 1, Class 2a and Class 2b vehicles respectively. The difference between the two data sets is also shown on the graph.

Figure 23 Vehicle Sound Level (Lveh) – Class 1

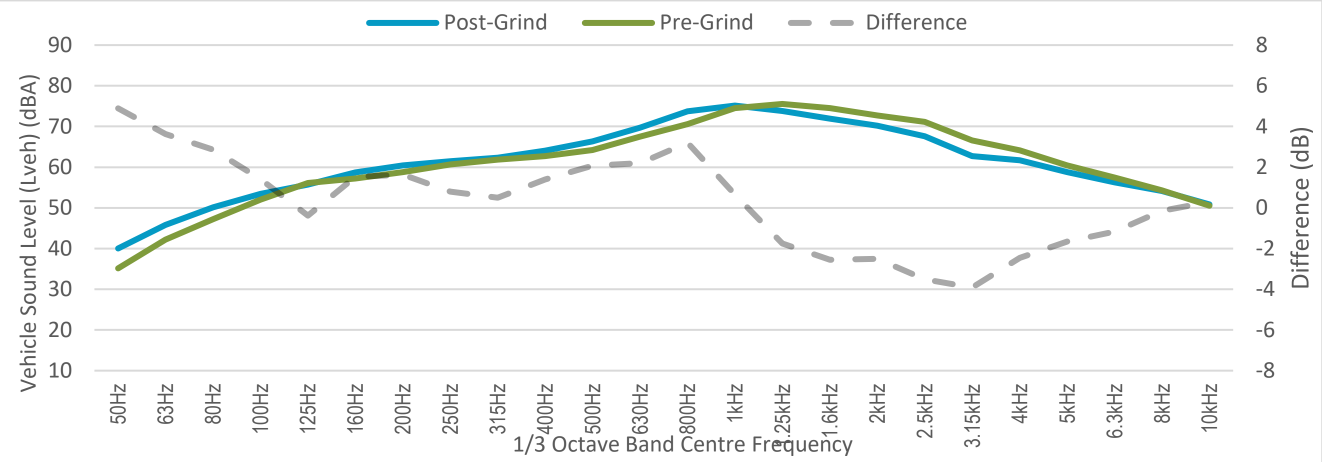


Figure 24 Vehicle Sound Level (Lveh) – Class 2a

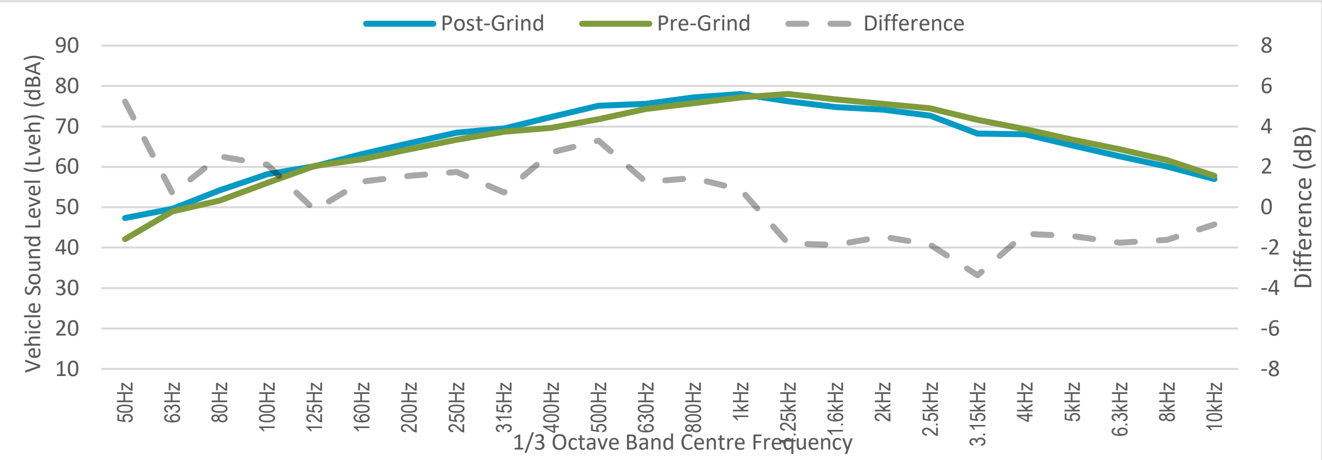
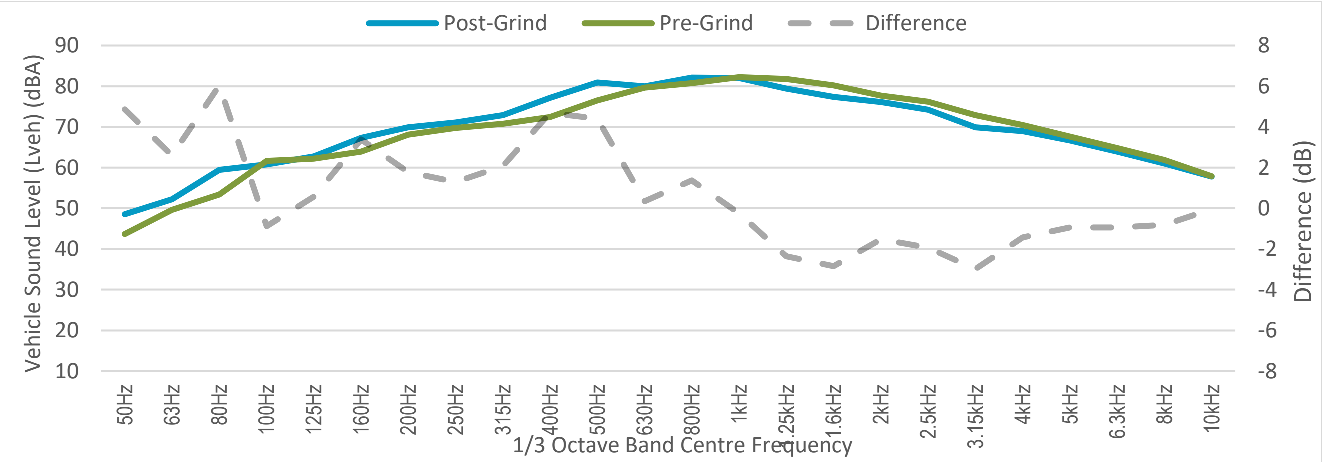


Figure 25 Vehicle Sound Level – Class 2b



The data in **Table 6** indicates that SPBI increased by 0.9 between the pre and post measurements at Location C (SMA10).

The above graphs show the post-grinding measurements generally had an increase in frequencies below 100 Hz, potentially due to meteorological effects, such as increased wind noise during the post grinding measurements.

The difference between the pre-grind and post-grind noise levels is expected to be due to the inherent uncertainties of the SPBI method, this is discussed in detail in **Section 3.1**.

3.1.4 Location D (LNDG 2 Pass) SPB results discussion

The pre and post grinding SPB results from Location D (LNDG 2 Pass) are shown in **Figure 26** to **Figure 28** as the logarithmic average for Class 1, Class 2a and Class 2b vehicles respectively. The difference between the two data sets as well as the differences between Location D (LNDG 2 Pass) and the SMA10 pavement are also shown on the graphs.

The vehicle sound levels are compared directly to the SMA10 pavements in **Figure 29** through to **Figure 31**.

Figure 26 Vehicle Sound Level (Lveh) – Class 1

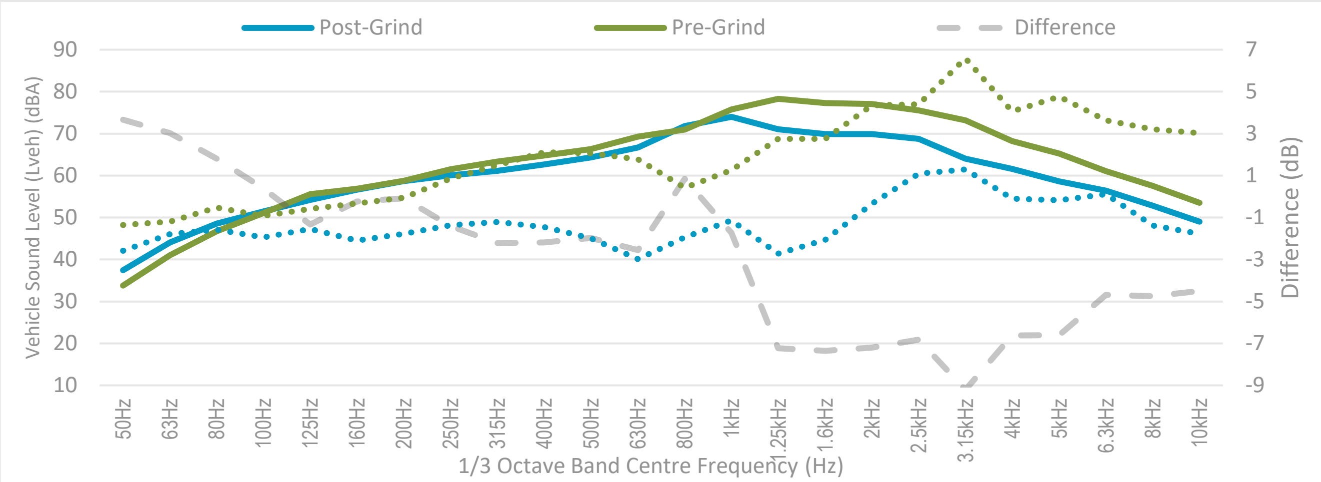


Figure 27 Vehicle Sound Level (Lveh) – Class 2a

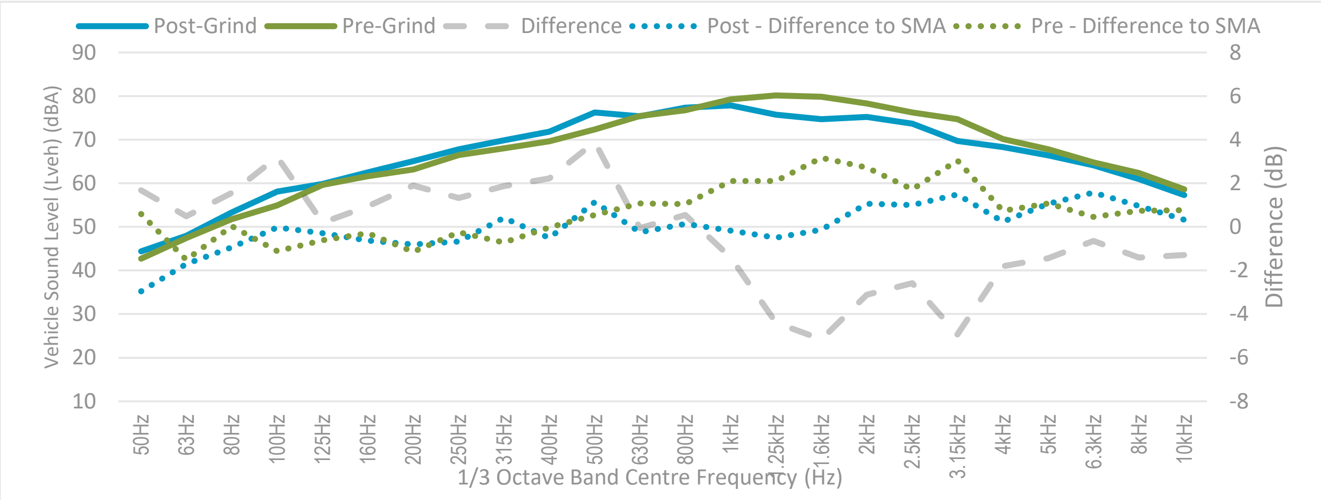


Figure 28 Vehicle Sound Level – Class 2b

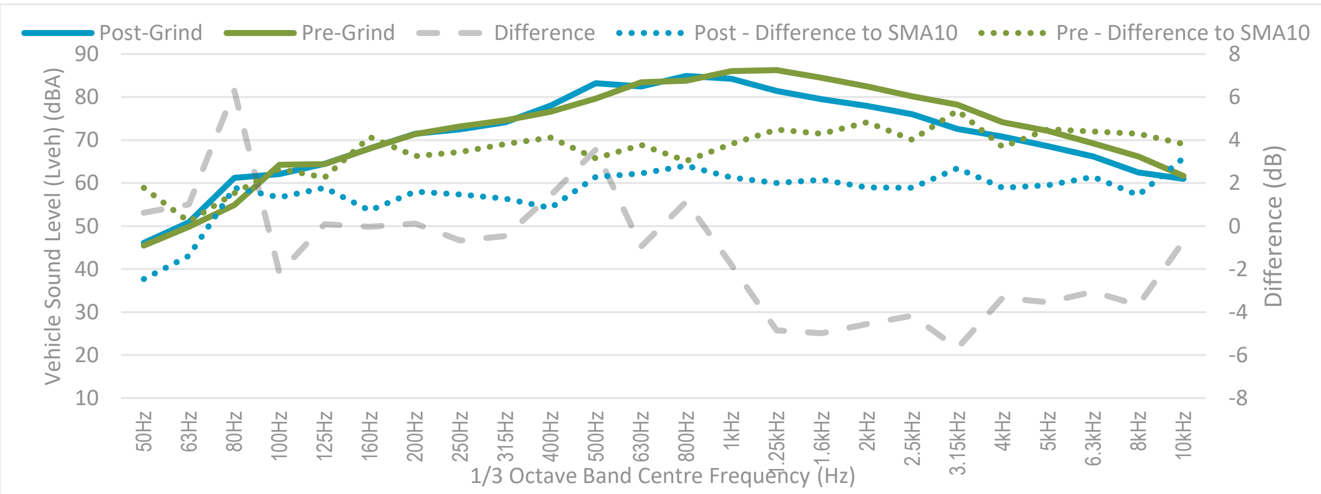


Figure 29 Vehicle Sound Level (Lveh) – Class 1 compared to SMA10

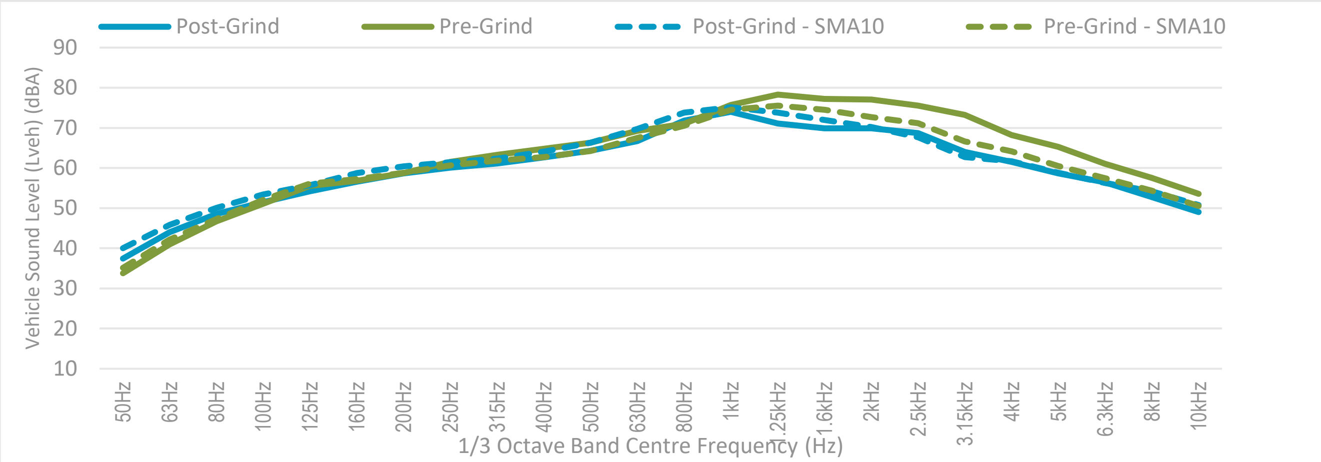


Figure 30 Vehicle Sound Level (Lveh) – Class 2a compared to SMA10

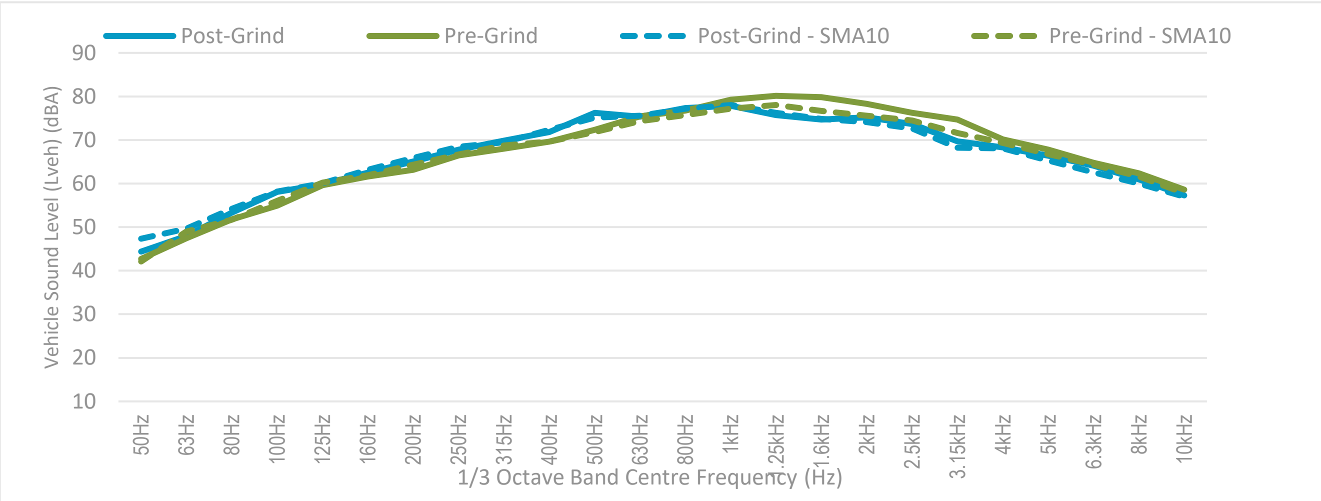
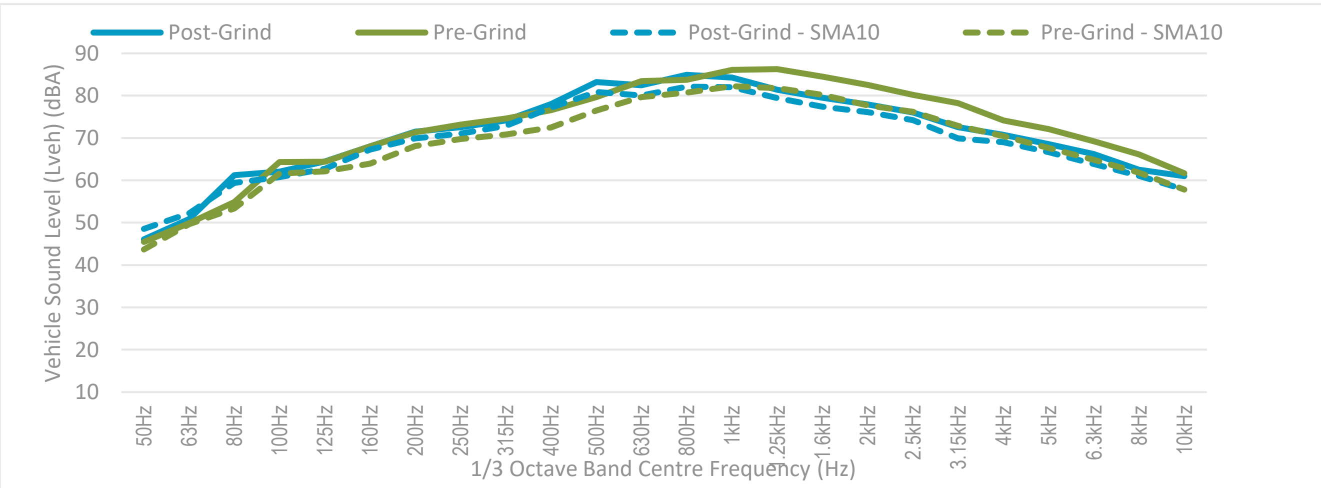


Figure 31 Vehicle Sound Level (Lveh) – Class 2b compared to SMA10



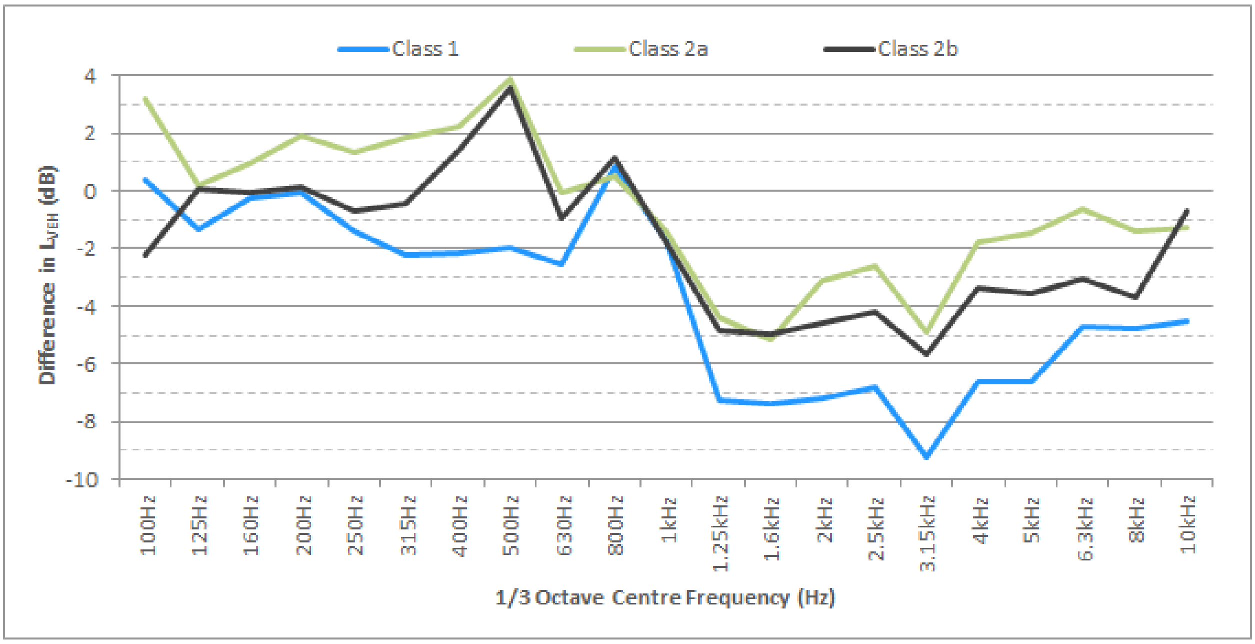
The data in **Table 6** indicates that, post grinding, the SPBI at Location D (LNDG 2 Pass) reduced by 1.2. The above graphs show the vehicle sound level reduction was most significant for Class 1 vehicles.

The difference in vehicle sound level spectra resulting from grinding at Location D (LNDG 2 Pass) is shown in **Figure 32**. The figure shows that grinding was most effective at frequencies above 800 Hz for all vehicle classes.

The grinding at Location D (LNDG 2 Pass) reduced Class 1 vehicle noise by around 2 dB between 200 Hz and 800 Hz, and by around 7 dB between 1.25 kHz and 5 kHz. Class 2a and Class 2b vehicle show similar reductions, however to a lesser degree than Class 1.

Class 2a and Class 2b post grinding noise levels were around 3 dB higher at 500 Hz which influences the overall noise level reduction for these categories.

Figure 32 Difference in Vehicle Sound Level (L_{VEH})



3.2 OBSI measurements

The results from the OBSI measurements are summarised in **Table 10** and **Figure 33**. The differences between the PCP pavements and the SMA10 pavement are also summarised in **Table 11**. A detailed discussion on the results is provided for each of the measurement locations in **Sections 3.2.1** to **3.2.4**.

Table 10 OBSI Measurement Results - Northbound Carriageway

ID	Name	Measured OBSI Noise Levels (400 Hz to 5 kHz)					
		Pre-Grind		Post-Grind		Difference[1]	
		Linear	A-Weighted	Linear	A-Weighted	Linear	A-Weighted
A	Cow Creek to Deep Creek Low Noise Diamond Grinding 3 Pass	108	108	102	102	-6.1	-6.3
B	Deep Creek Twin Bridges to the beginning of the southern extent of SMA10 Conventional Diamond Grinding	107	107	105	105	-1.5	-1.8
C	SMA10 No Treatment, Control Location	105	105	104	104	-0.3	-0.5
D	McGraths Floodplain Low Noise Diamond Grinding 2 Pass	108	108	101	101	-6.1	-6.3

Note 1: Difference presented to one decimal place.

Figure 33 Summary of OBSI Measurements at All Locations

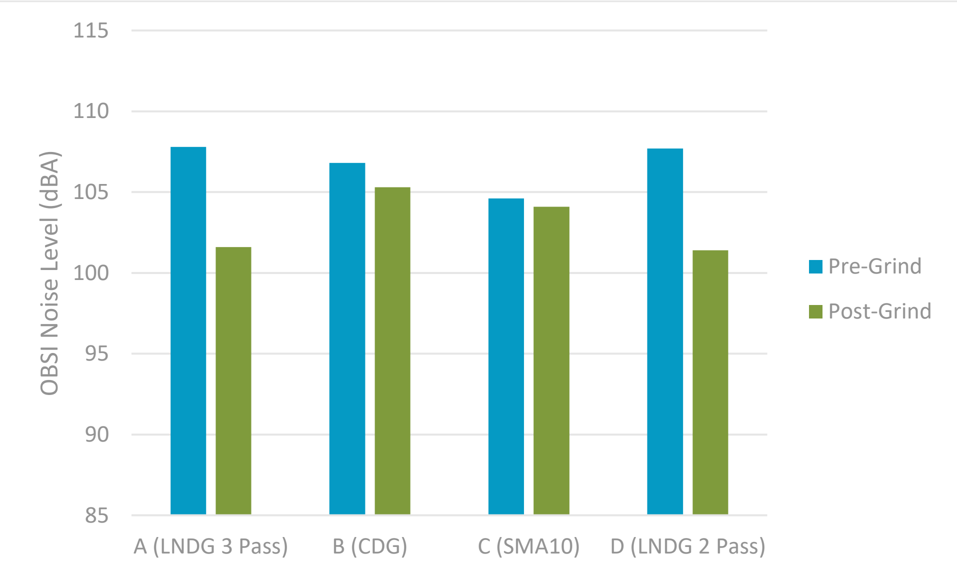


Table 11 OBSI Measurement Results – Comparison of PCP Pavements to SMA10

ID	Name and Treatment Type	Measured OBSI Noise Levels (400 Hz to 5 kHz)							
		Pre-Grind				Post-Grind			
		Linear	Diff[1]	A-weighted	Diff[1]	Linear	Diff[1]	A-weighted	Diff[1]
A	Cow Creek to Deep Creek Low Noise Diamond Grinding 3 Pass	108	**+3.0**	108	**+3.2**	102	-2.8	102	**-2.6**
B	Deep Creek Twin Bridges to beginning of the southern extent of SMA10 Conventional Diamond Grinding	107	**+1.9**	107	**+2.1**	105	+1.0	105	**+1.2**
D	McGraths Floodplain Low Noise Diamond Grinding 2 Pass	108	**+2.8**	108	**+3.1**	101	-3.0	101	**-2.7**

Note 1: Difference between this result and the equivalent result on the SMA10 pavement.

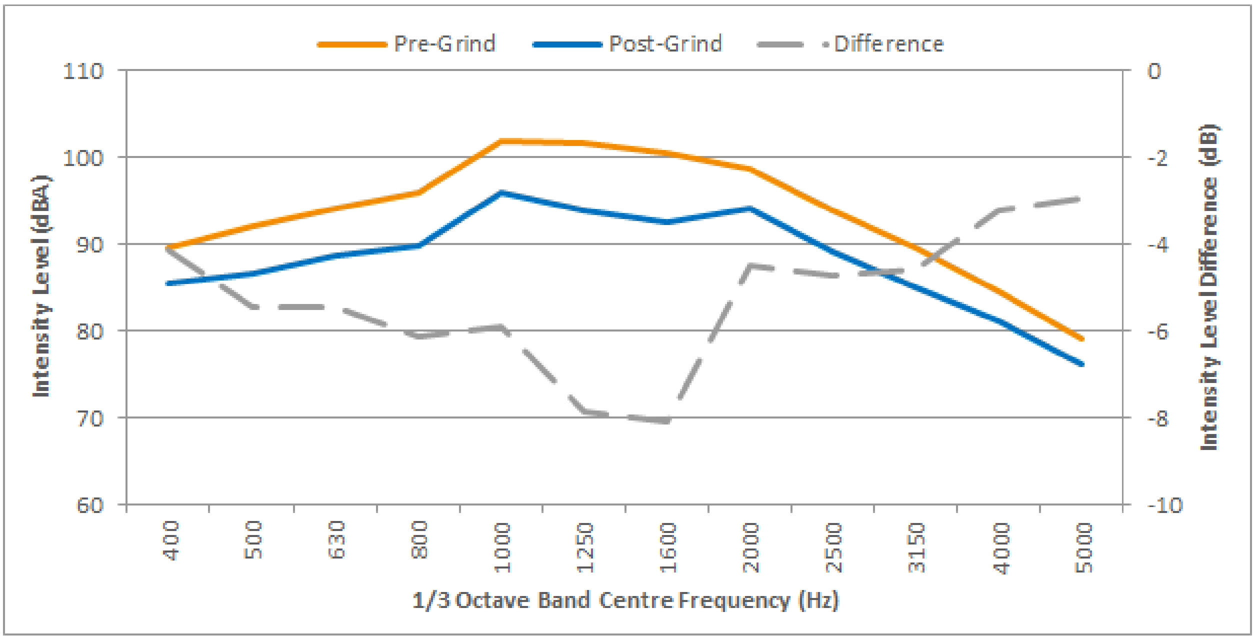
The above analysis shows that the post grinding pavement noise measured using OBSI are lower than the pre-grinding levels at all sites. The greatest reduction is seen at Location A (LNDG 3 Pass) and D (LNDG 2 Pass) where reductions of around 6 dB were measured. Location B (CDG) had a reduction of around 2 dB. Location C (SMA10) showed a marginal change, reflecting the inherent variability in pavement noise over time, which is as expected as this is the control location where no works took place to the SMA10 surface.

It is noted that the measured OBSI intensity and pressure levels did not vary significantly across the test sections, indicating that the sections were generally homogeneous.

3.2.1 Location A (LNDG 3 Pass) OBSI results discussion

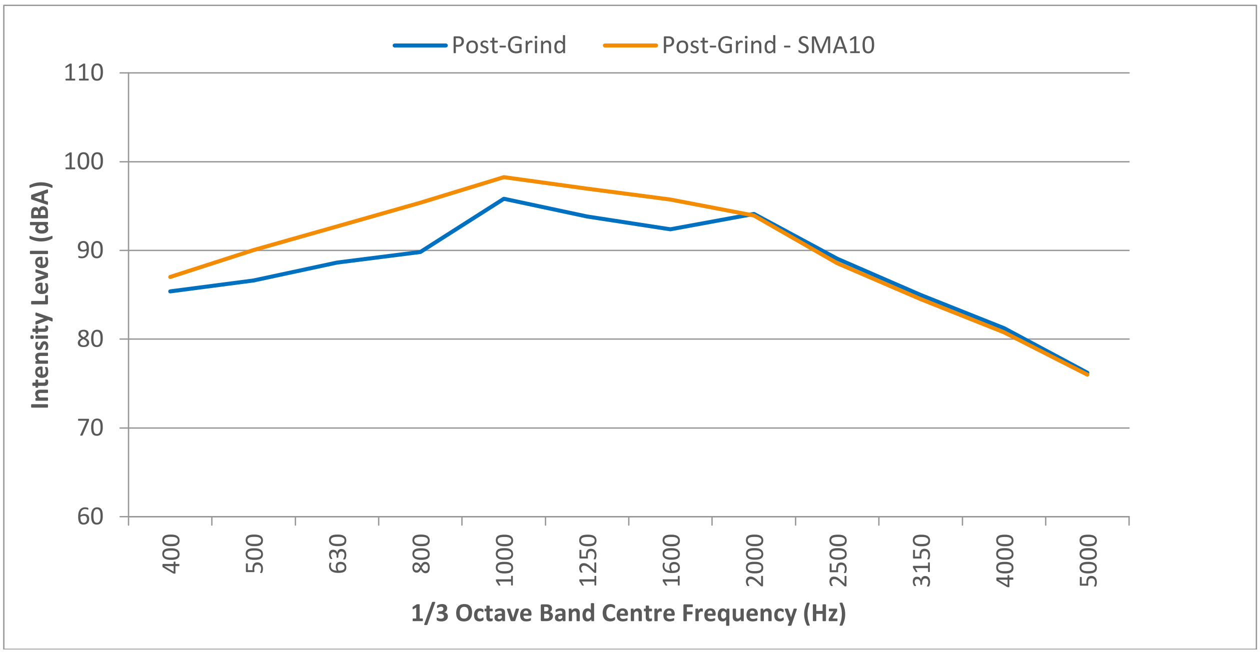
The pre and post grinding OBSI results from Location A (LNDG 3 Pass) are shown in **Figure 34**. The difference between the two data sets is also shown on the graph.

Figure 34 Pre-grind and Post-grind OBSI Levels – Location A (LNDG 3 Pass)



The data in **Table 10** indicates that the grinding works at Location A (LNDG 3 Pass) reduced the OBSI measured noise intensity level by 6.3 dBA. The post-grind OBSI noise intensity level for Location A (LNDG 3 Pass) is plotted alongside the post-grind OBSI noise intensity level for Location C (SMA10) in **Figure 35**.

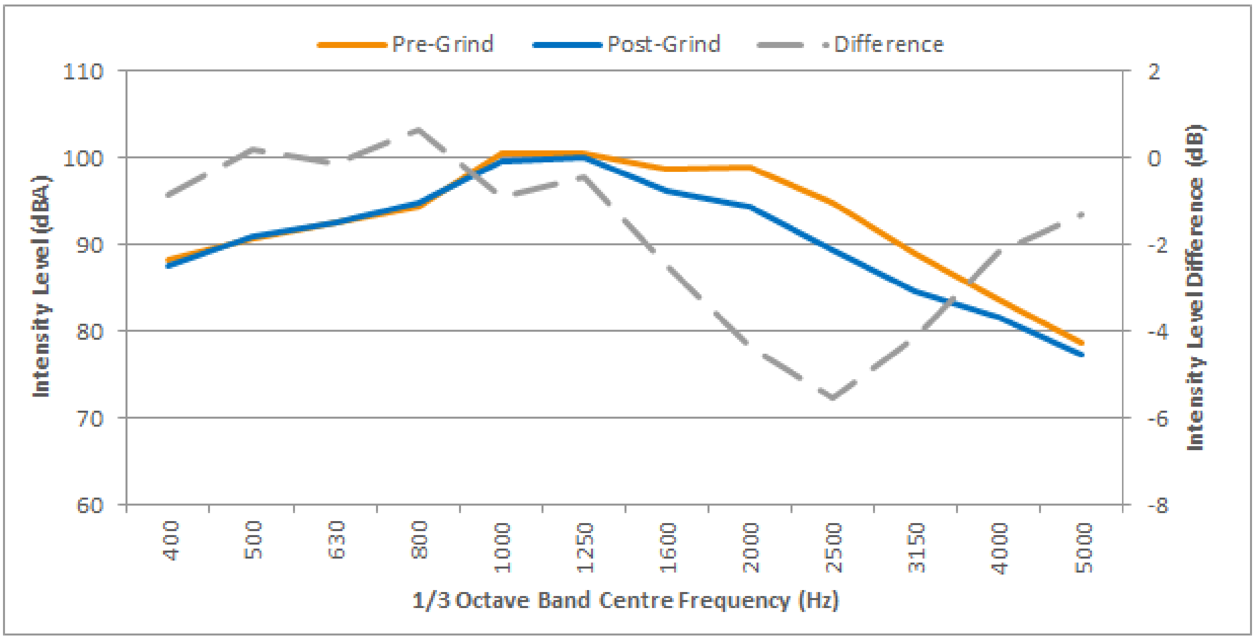
Figure 35 Comparison of Post-Grind OBSI Levels between Location A (LNDG 3 Pass) and Location C (SMA10)



3.2.2 Location B (CDG) OBSI results discussion

The pre and post grinding OBSI results from Location B (CDG) are shown in **Figure 36**. The difference between the two data sets is also shown on the graph.

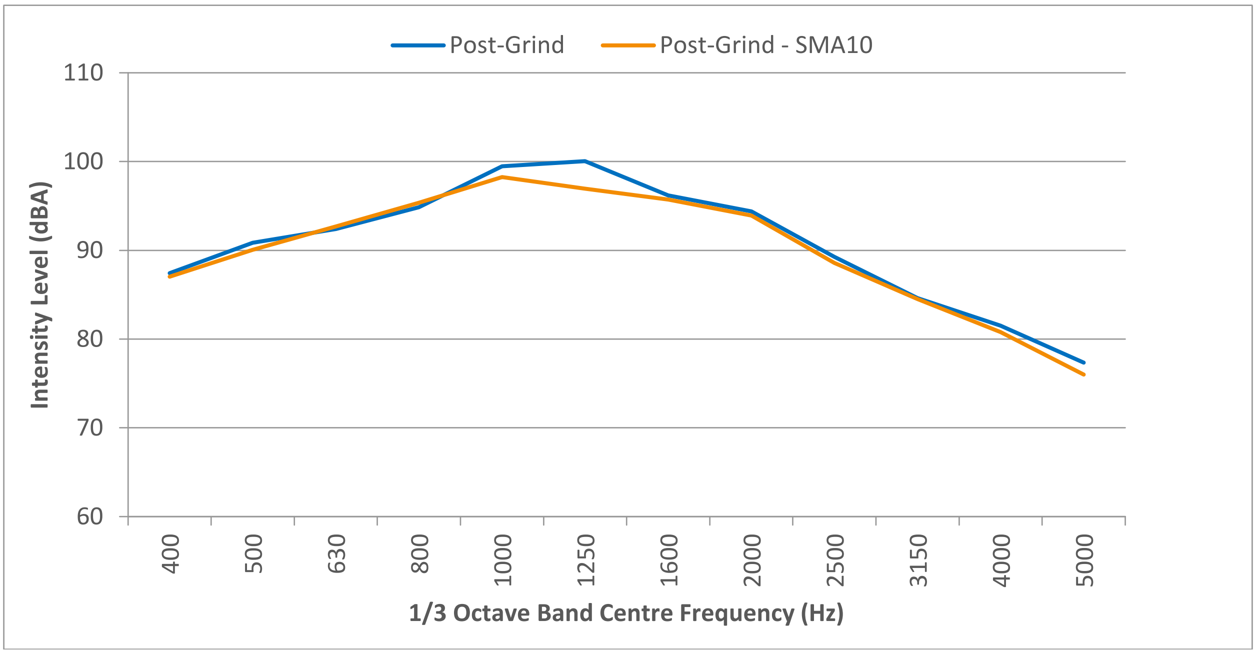
Figure 36 Pre-grind and Post-grind OBSI Levels – Location B (CDG)



The data in **Table 10** indicates that the grinding works at Location B (CDG) reduced the OBSI measured noise intensity level by 1.8 dBA. The above graph shows that the highest reduction in pavement noise occurs around the 2.5 kHz band, which is generally consistent with the difference measured at the wayside location in the SPB measurements.

The post-grind OBSI noise intensity level for Location B (CDG) is plotted alongside the post-grind OBSI noise intensity level for Location C (SMA10) in **Figure 37**.

Figure 37 Comparison of Post-Grind OBSI Levels between Location B (CDG) and Location C (SMA10)

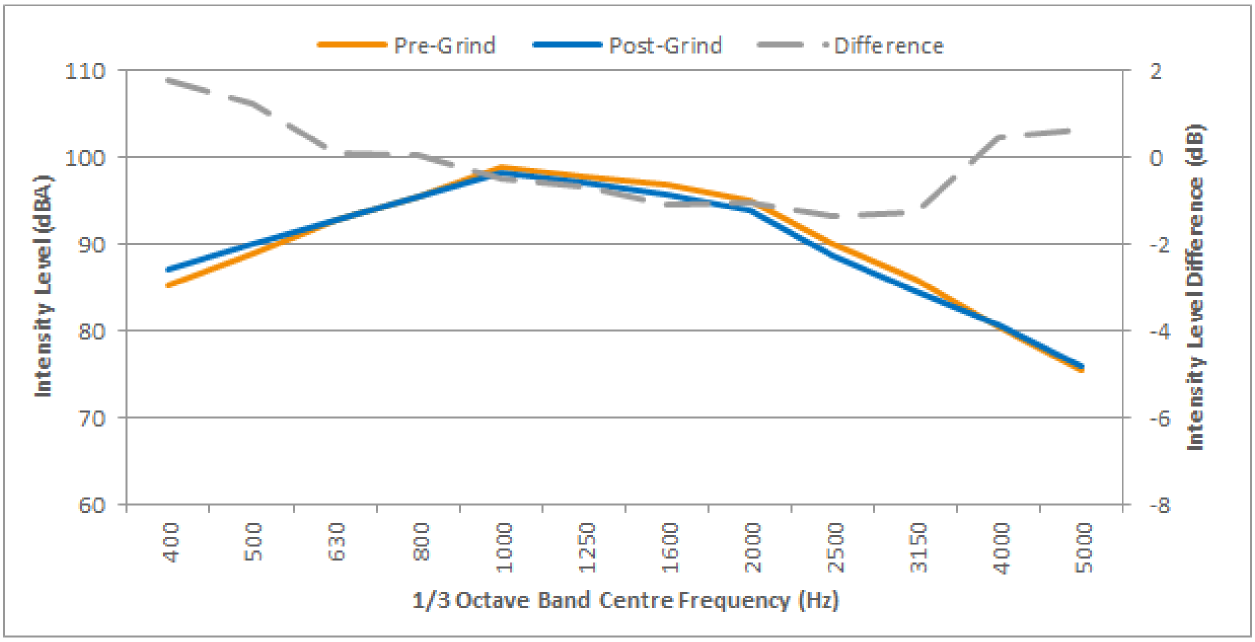


3.2.3 Location C (SMA10) OBSI results discussion

The pavement surface at Location C was SMA10 and the site was used as a control. No pavement works were performed between the two noise surveys.

The pre and post grinding OBSI results from Location C (SMA10) are shown in **Figure 38**. The difference between the two data sets is also shown on the graph.

Figure 38 Pre-grind and Post-grind OBSI Levels – Location C (SMA10)

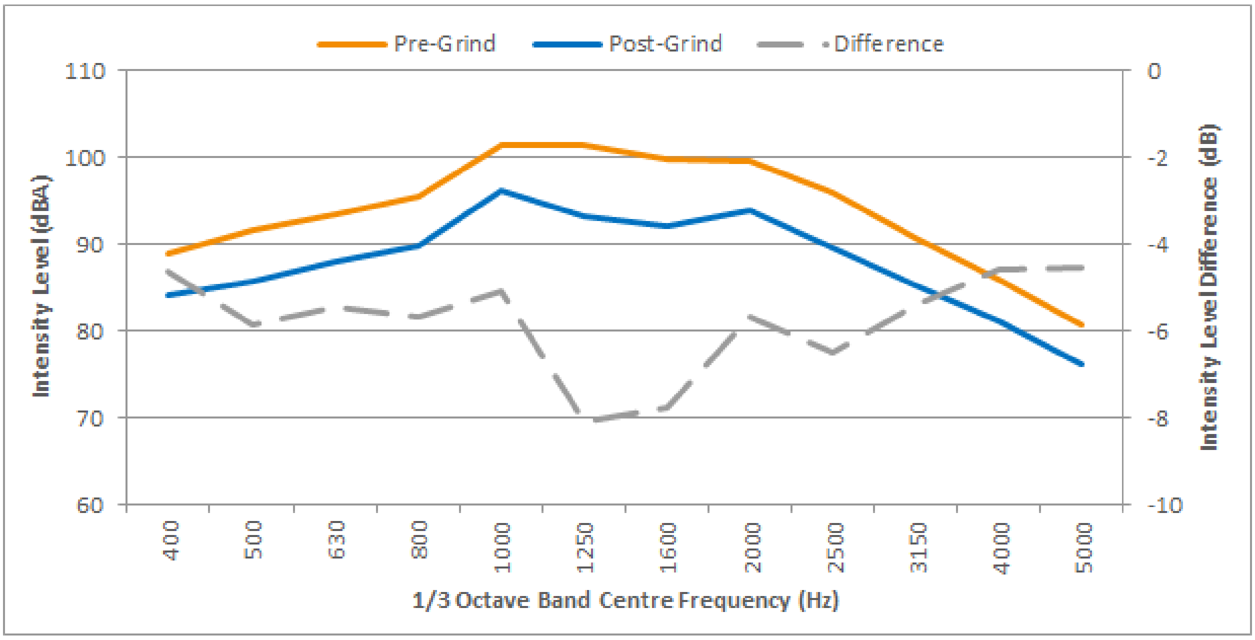


The data in **Table 10** indicates that the difference between the pre and post measurements at Location C (SMA10) was marginal, with a slightly reduced intensity level of 0.5 dBA. The above graph shows that the pavement noise levels at this location were mostly consistent between surveys and were within around ±1 dB for 1/3 octave bands between 500 Hz and 5 kHz. This is generally consistent with the wayside noise measurements, where a small increase in overall measured levels of less than 1 dB was seen.

3.2.4 Location D (LNDG 2 Pass) OBSI results discussion

The pre and post grinding OBSI results from Location D (LNDG 2 Pass) are shown in **Figure 39**. The difference between the two data sets is also shown on the graph.

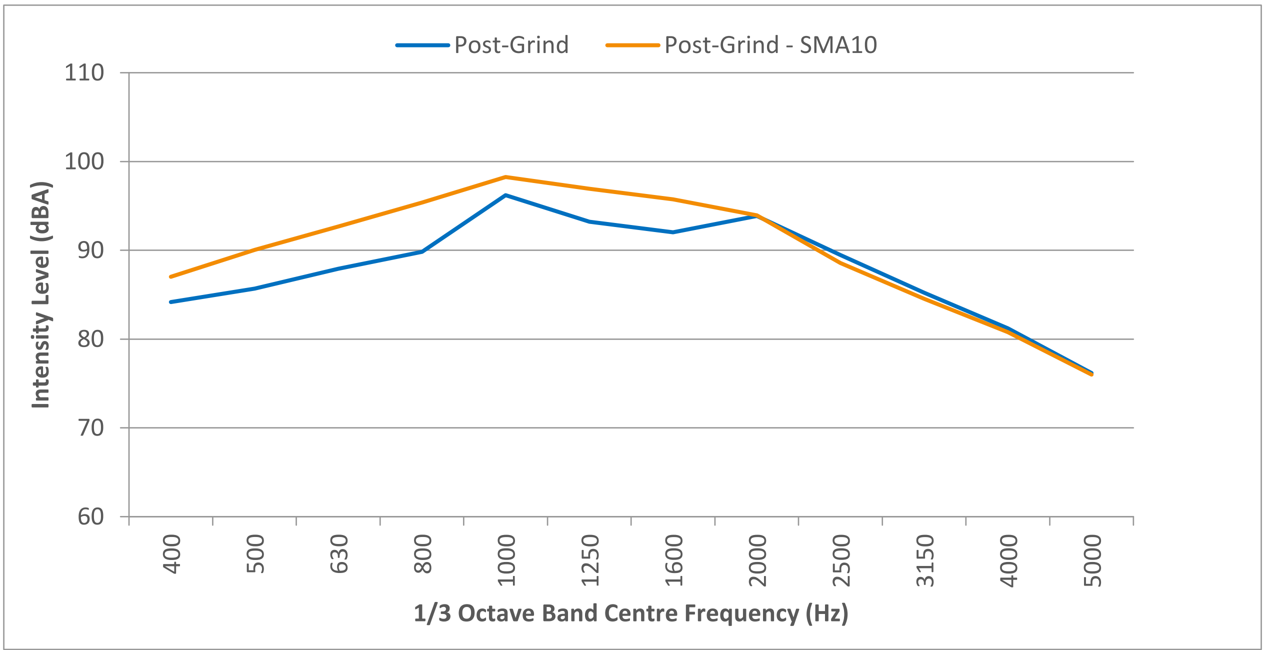
Figure 39 Pre-grind and Post-grind OBSI Levels – Location D (LNDG 2 Pass)



The data in **Table 10** indicates that the grinding works at Location D (LNDG 2 Pass) reduced the OBSI measured noise intensity level by 6.3 dBA. The above graph shows that the highest reduction in pavement noise occurs between 1.25 kHz and 2.0 kHz, which is generally consistent with the difference measured at the wayside location in the SPB measurements.

The post-grind OBSI noise intensity level for Location B (CDG) is plotted alongside the post-grind OBSI noise intensity level for Location C (SMA10) in **Figure 40**.

Figure 40 Comparison of Post-Grind OBSI Levels between Location D (LNDG 2 Pass) and Location C (SMA10)



4 Conclusion

Roads and Maritime Services trialled low noise diamond grinding of existing concrete pavements in the Valla Beach area of the Nambucca Heads to Urunga project.

Measurements were made using both Statistical Passby Method and On-Board Sound Intensity vehicle mounted noise measurements at each test site.

The Statistical Passby Method measurements show a general trend of lower noise levels after the grinding trial. The most significant reductions were typically seen in Class 1 vehicles (cars), with the reduction in Class 2a and 2b (heavy vehicles) being more variable depending on the location. The variation in the Class 2a and 2b vehicle sound levels is expected to be due to the inherent variability in roadside noise levels emitted by trucks within the same categories and the relatively small sample size of vehicles in these classes.

The On-Board Sound Intensity measurements also found lower noise levels post grinding.

The diamond ground concrete pavements produced comparable noise levels to the traditionally ‘low noise’ 10 mm stone mastic asphalt pavement.

APPENDIX A

Acoustic Terminology

Nomenclature

The following table lists key nomenclature used in this report.

Table A1 Nomenclature

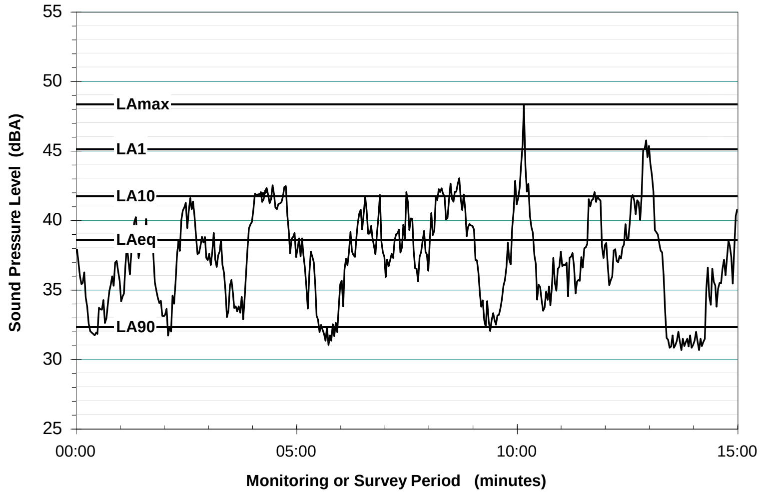
a, a_w	(Vibration) acceleration, the subscript 'w' refers to weighting / frequency correction used. Units are m/s^2.
dB	Decibel, a unit of sound or vibration which is described as a ratio of the result to a fixed reference value. All sound pressure levels (L_{pA}, L_A, L_{Aeq} etc.) quoted in this report are referenced to 20 micro Pascals (dB re 20µPa). Vibration velocity levels (L_v) quoted in this report are referenced to 1 nanometre per second (dB re 10-9 m/s), noting that some US criteria use dB re 10-6 in/s.
L_{Amax}	The maximum A-weighted noise level associated with a sampling period.
$L_{Amax,5}$	The "typical maximum noise level" for a train pass-by event. For operational rail noise, L_{Amax} refers to the maximum noise level not exceeded for 95% (5th highest percentile) of rail pass-by events measured using the 'slow' (sometimes denoted by subscript 'S') response setting on a sound level meter.
L_{A1}	The A-weighted noise level exceeded for 1% of a given measurement period. This parameter is often used to represent the typical maximum noise level in a given period.
L_{A10}	The A-weighted noise level exceeded for 10% of a given measurement period and is utilised normally to characterise average maximum noise levels.
L_{Aeq}	The A-weighted average noise level. It is defined as the steady noise level that contains the same amount of acoustical energy as a given time-varying noise over the same measurement period.
L_{A90}	The A-weighted noise level exceeded for 90% of a given measurement period and is representative of the average minimum background noise level (in the absence of the source under consideration), or simply the "background" level.
L_w, L_{wA}	'Sound power' (L_w) refers to the total rate of sound generation of a given item of plant. This quantity is independent of the distance from the plant item (analogous to the wattage power of a light-bulb) and allows direct comparison of the relative acoustic 'size' of different plant items. From this data, the sound pressure level (or noise level) at any offset distance from the plant can be calculated (analogous to the light intensity from a light-bulb – the greater the distance, the less intense).

Noise

The terms "sound" and "noise" are almost interchangeable, except that in common usage "noise" is often used to refer to unwanted sound. Sound (or noise) consists of minute fluctuations in atmospheric pressure capable of evoking the sense of hearing.

The symbol L_A represents A-weighted sound pressure level (SPL). Common noise level descriptors that may be utilised are illustrated in the following figure and are described below.

Figure A1 Example of typical noise indices



The following table presents examples of typical noise levels.

Table A2 Guide to sound pressure level ranges for selected environments (dB re 20µPa)

Subjective Evaluation	L_{Aeq}	Comments / Examples
Intolerable. Onset of pain. Exceeds daily exposure limit in under a second.	140	Military jet engine at 30 metres
	130	2kW disaster warning siren at 1 metre
Very loud. Risk of exceeding daily noise exposure limit in under a minute.	120	Jet aircraft take-off at runway edge
	110	Rock concert; freight train main horn at 25 metres
Loud. Onset of risk to exceeding daily recommended noise exposure limit.	100	225mm angle grinder at 1 metre, car horn at 3 metres
	90	Heavy industrial factory interior
Noisy	80	Shouting at 1 metre, kerb side of busy street
	70	Freeway at 20 metres
Moderate	60	Normal conversation at 1 metre, department stores
	50	General office areas
Quiet	40	Office air conditioning background level
Very quiet	30	Bedroom in quiet suburban area
Almost silent	20	Whisper, rural bedroom at night
	10	Human breathing at 3 metres
	0	Threshold of typical hearing

The human ear responds to changes in sound pressure over a very wide range. The loudest sound pressure to which the human ear responds is ten million times greater than the softest. The decibel (abbreviated as dB) scale reduces this ratio to a more manageable size by the use of logarithms.

The ability to discern a change in noise level varies between individual listeners, however it is reasonable to suggest that a change of up to 3 dB in the level of a sound is difficult for most people to detect, and a 3 dB to 5 dB change corresponds to a small but noticeable change in loudness. A 10 dB change is readily noticeable, indicative of a doubling (or halving) in loudness.

APPENDIX B

Statistical Passby Measurement Results

Figure B1 Location A (LNDG 3 Pass), Pre-Grind – Class 1

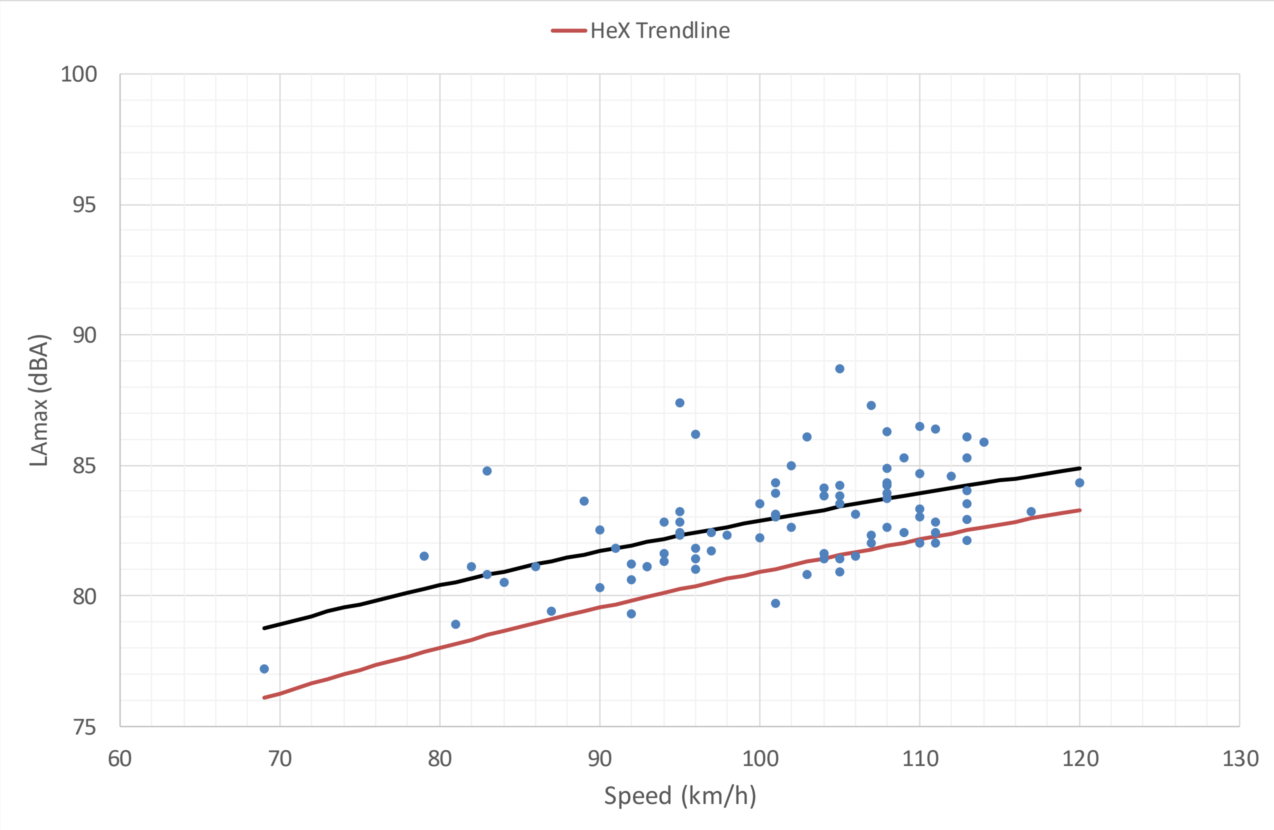


Figure B2 Location A (LNDG 3 Pass), Pre-Grind – Class 2a

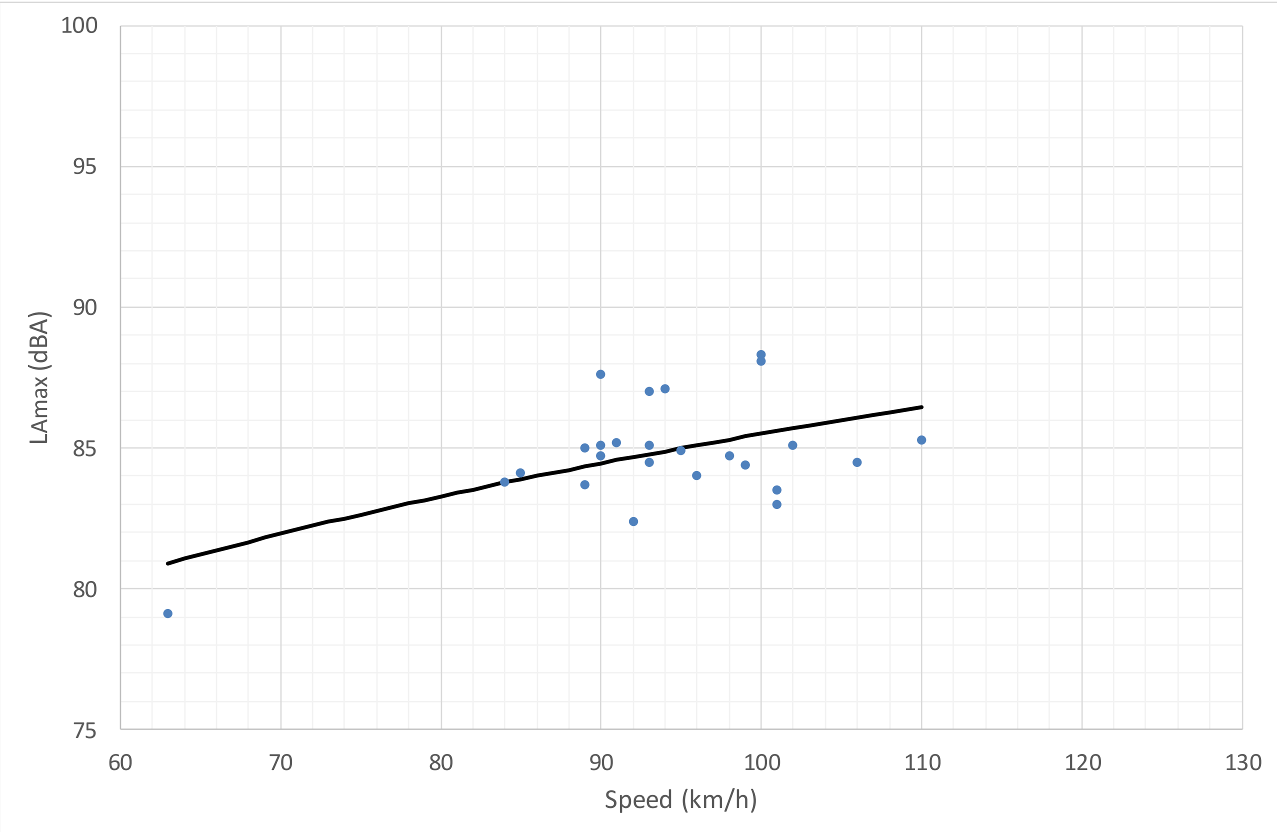


Figure B3 Location A (LNDG 3 Pass), Pre-Grind – Class 2b

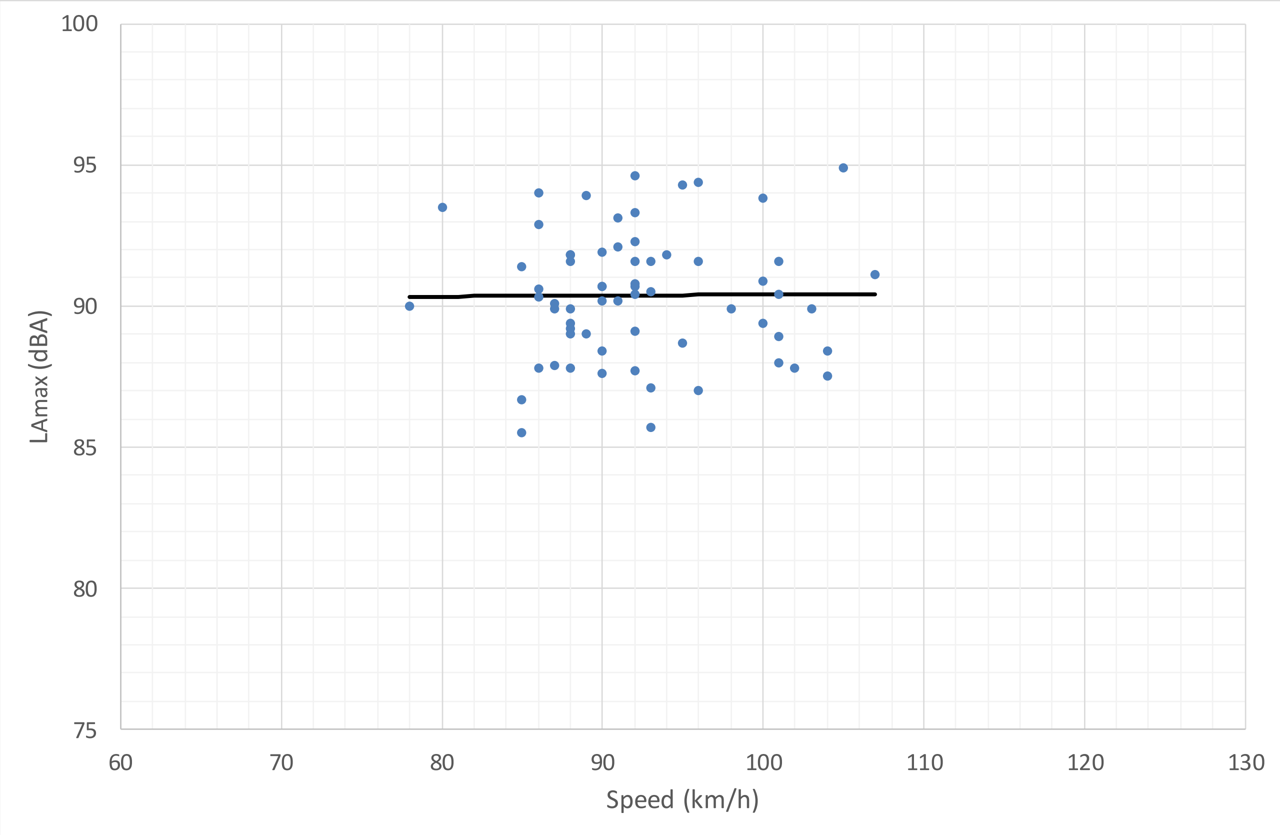


Figure B4 Location A (LNDG 3 Pass), Pre-Grind – Bin 4

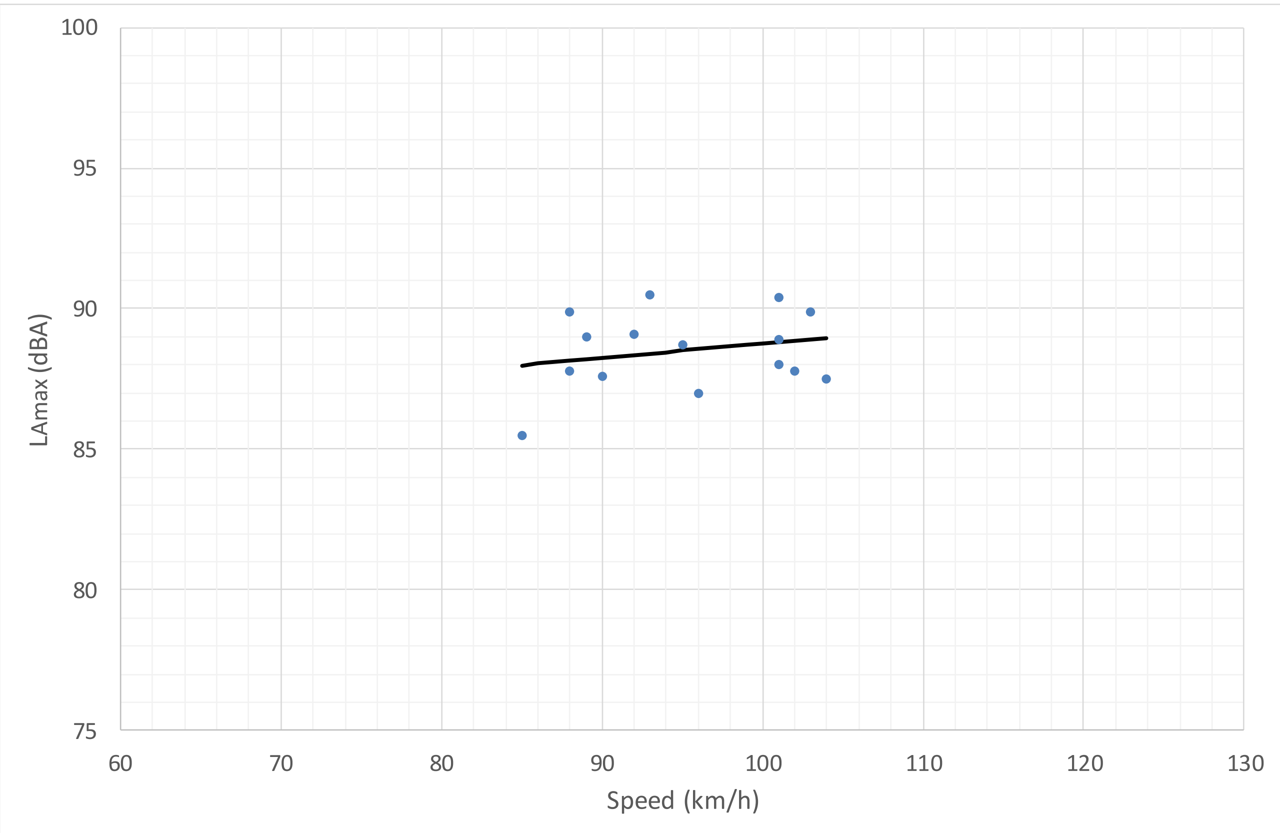


Figure B5 Location A (LNDG 3 Pass), Pre-Grind – Bins 5 to 8

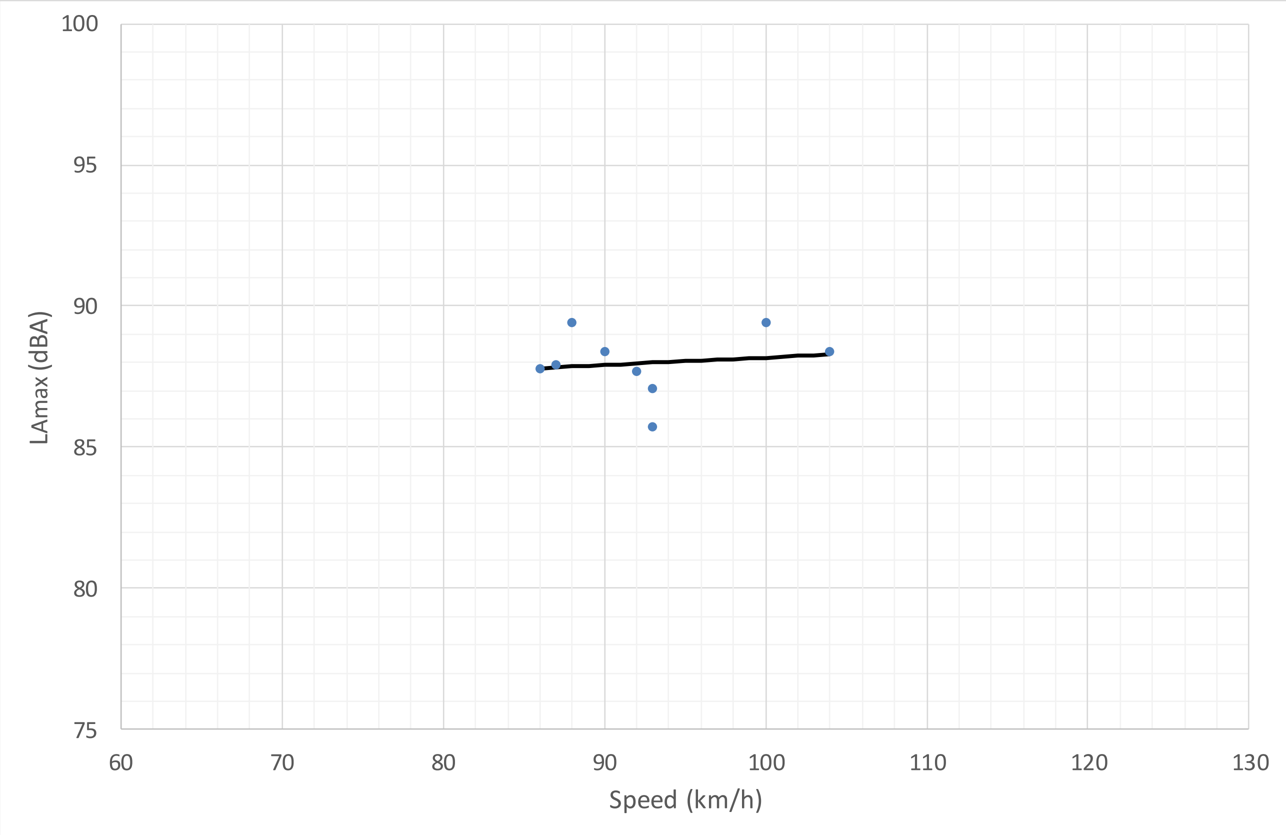


Figure B6 Location A (LNDG 3 Pass), Pre-Grind – Bin 9

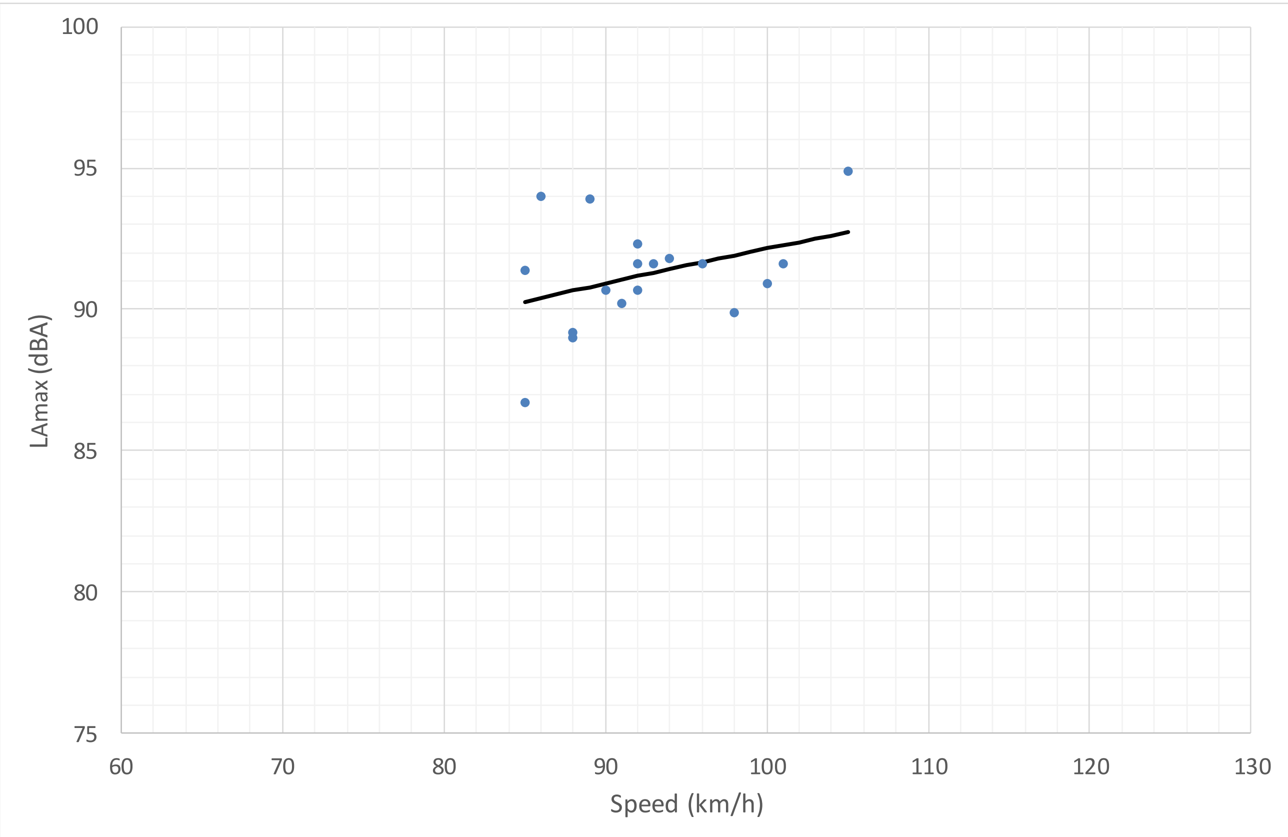


Figure B7 Location A (LNDG 3 Pass), Pre-Grind – Bins 10+

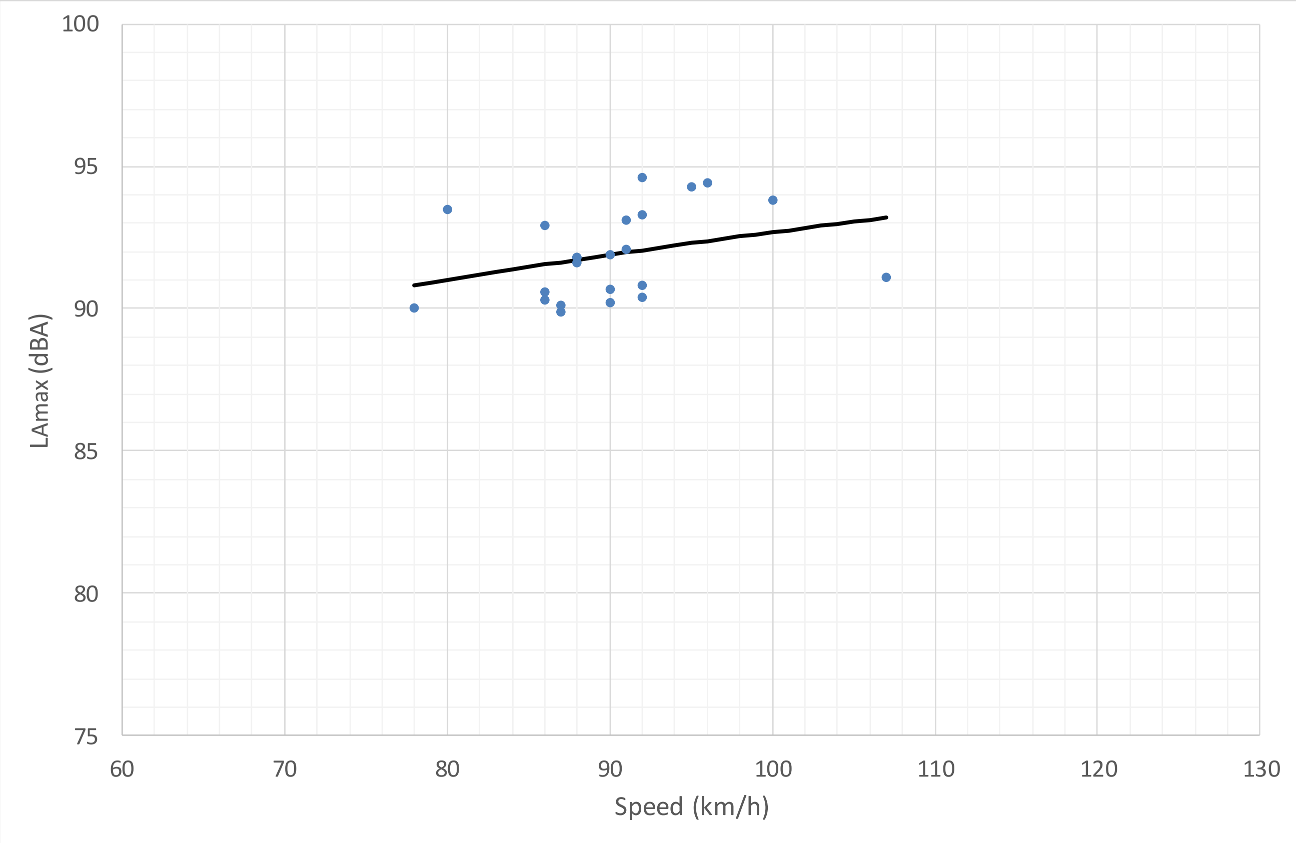


Figure B8 Location A (LNDG 3 Pass), Post-Grind – Class 1

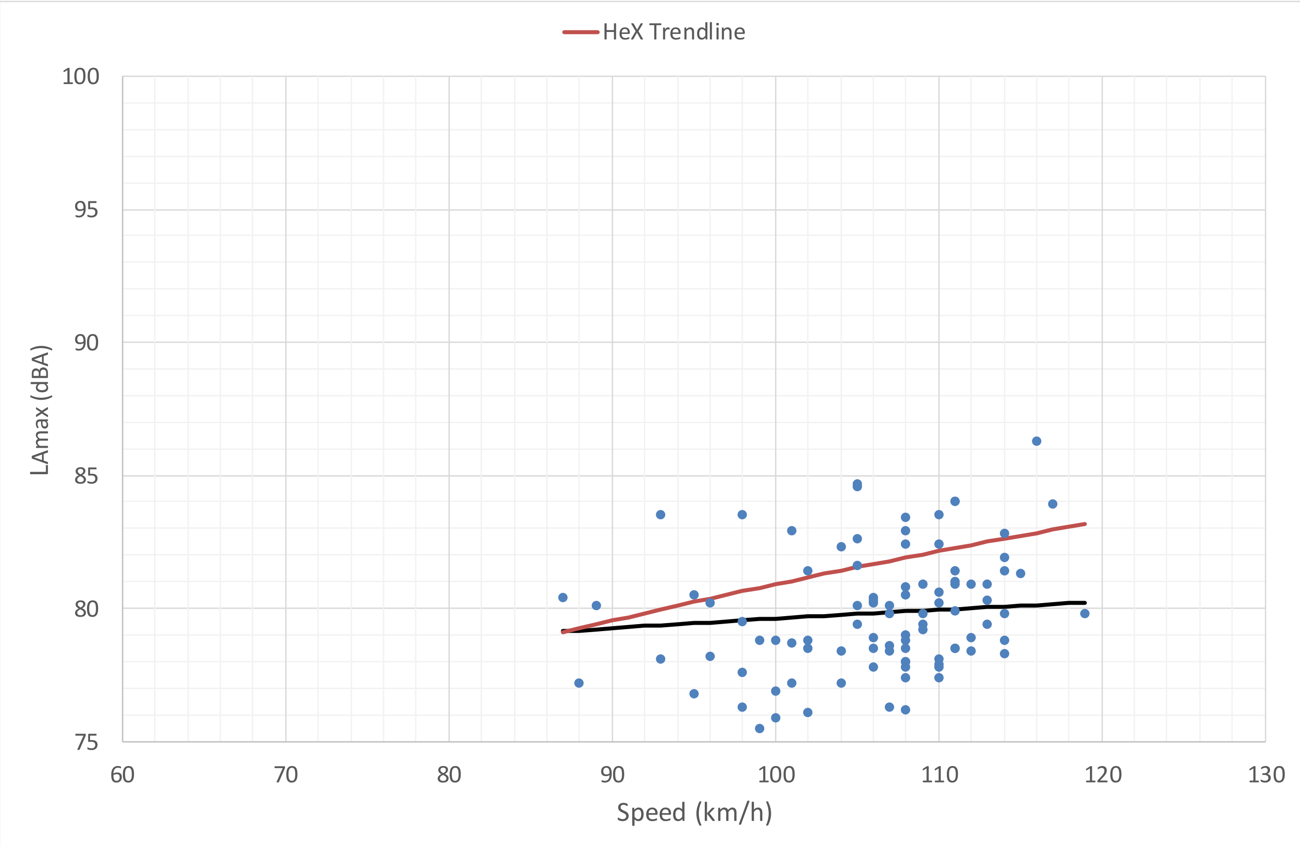


Figure B9 Location A (LNDG 3 Pass), Post-Grind – Class 2a

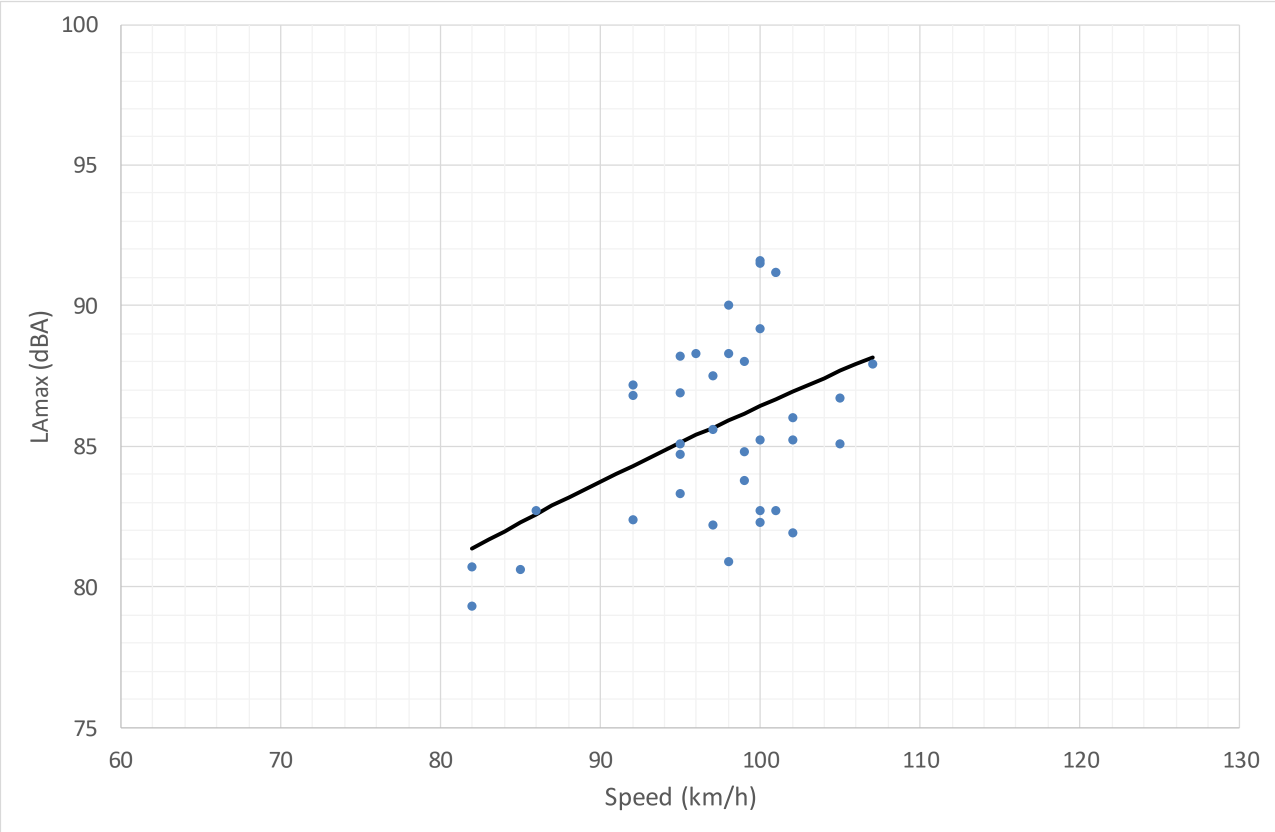


Figure B10 Location A (LNDG 3 Pass), Post-Grind – Class 2b

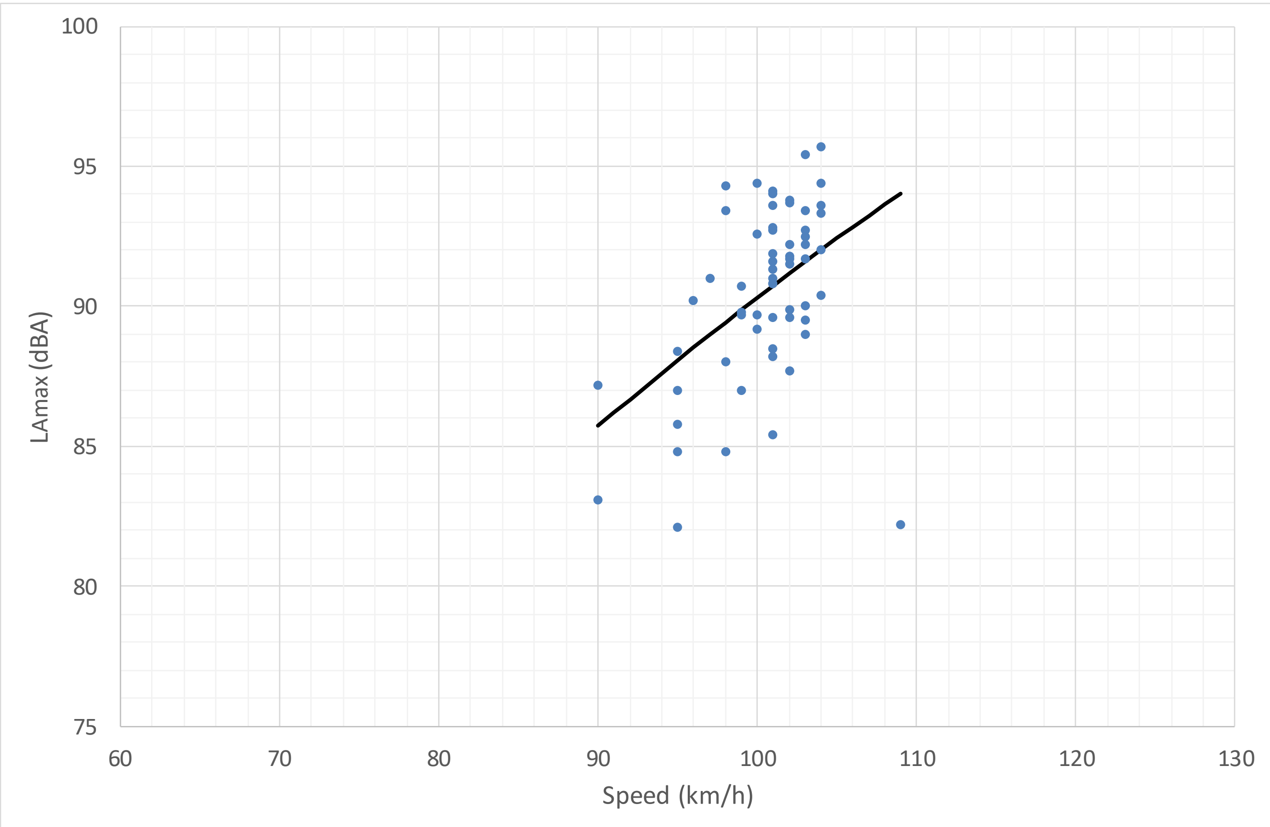


Figure B11 Location A (LNDG 3 Pass), Post-Grind – Bin 4

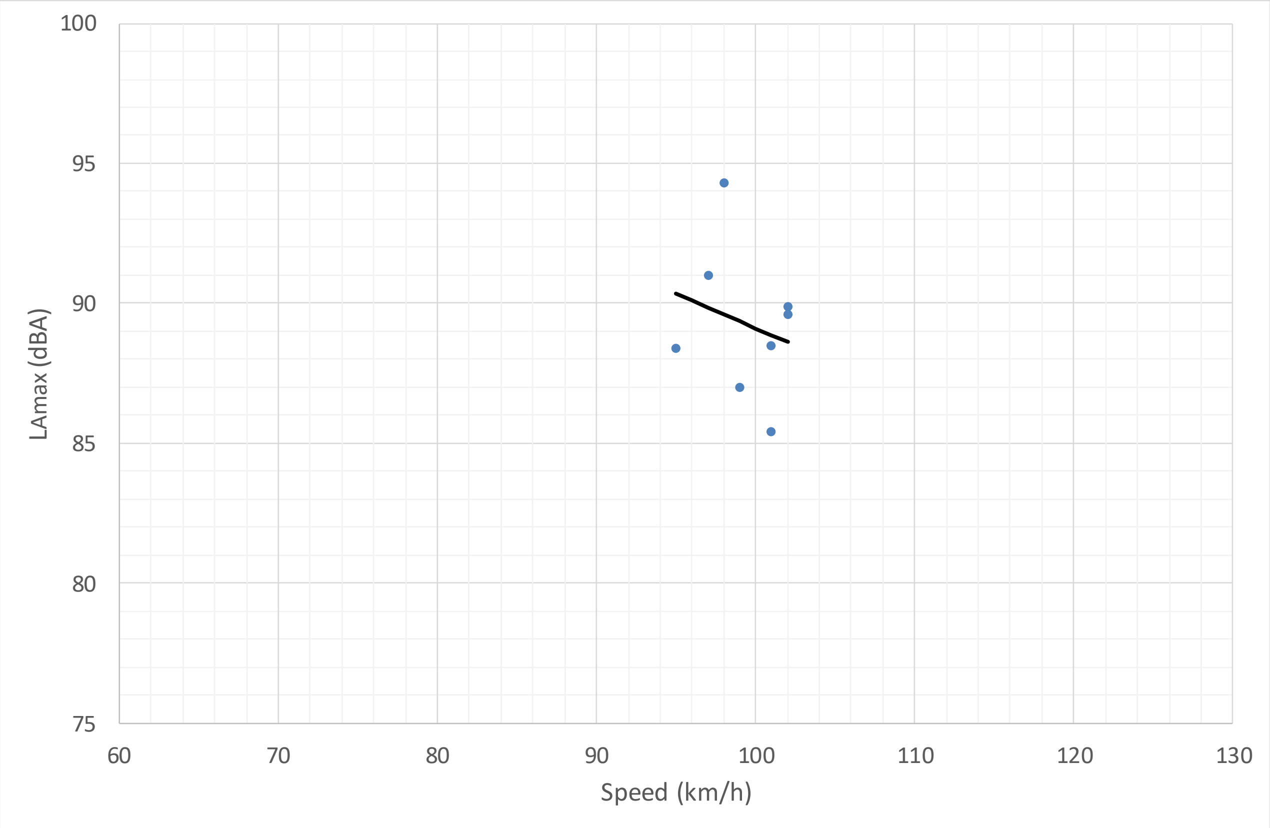


Figure B12 Location A (LNDG 3 Pass), Post-Grind – Bins 5-8

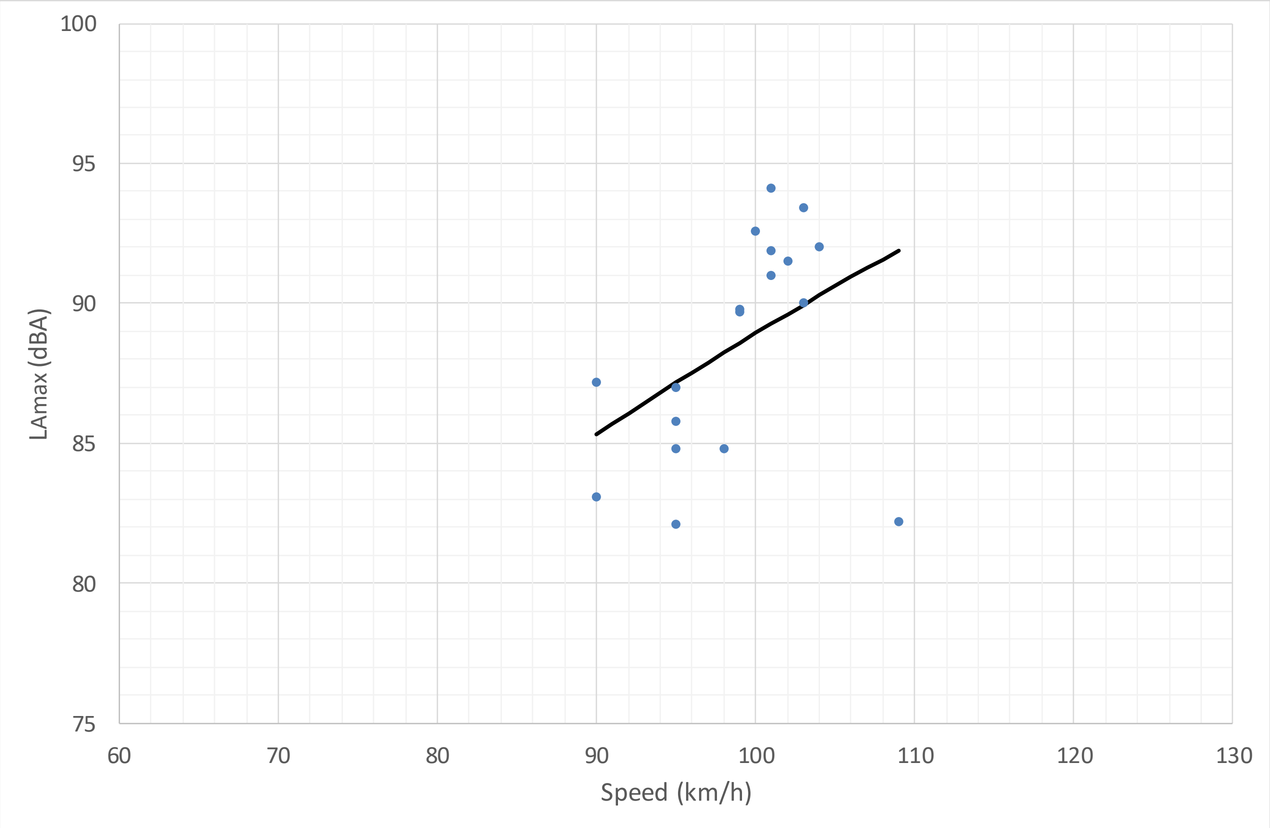


Figure B13 Location A (LNDG 3 Pass), Post-Grind – Bin 9

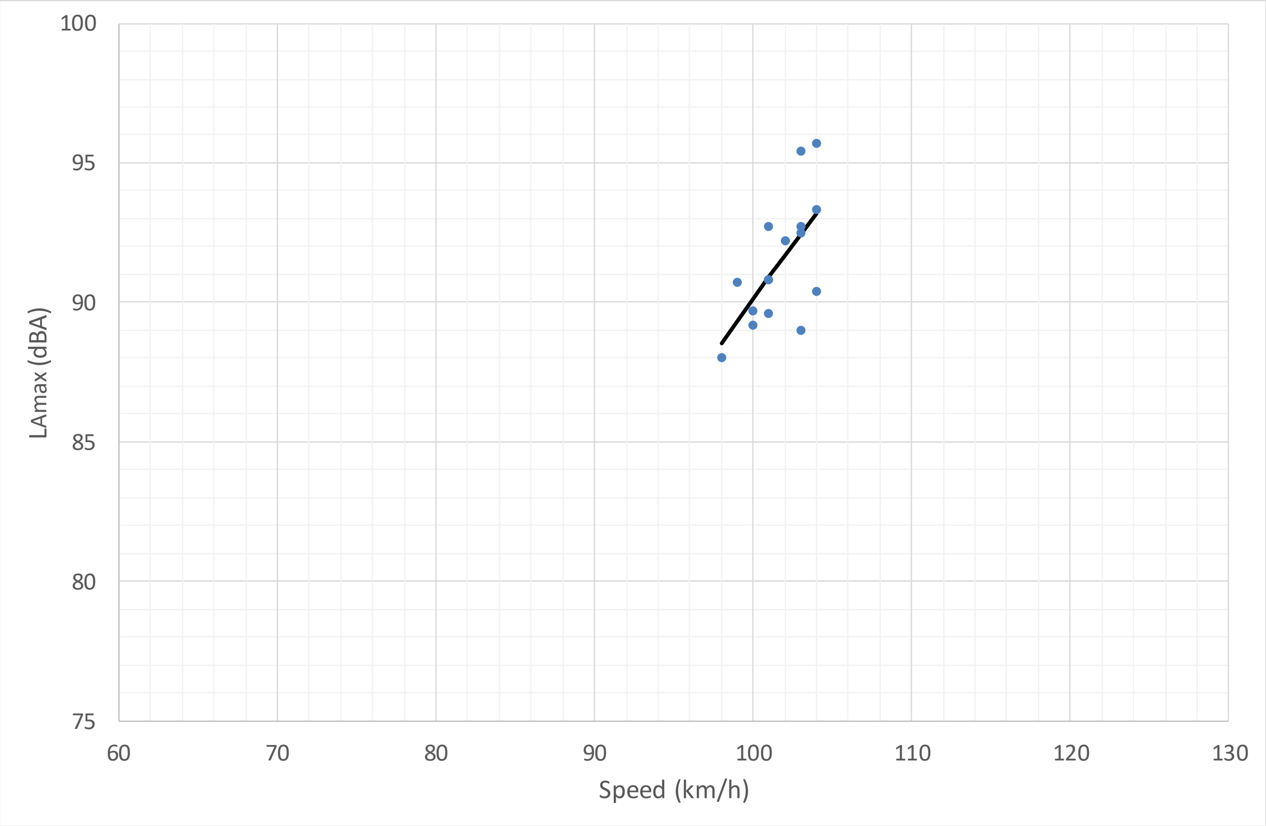


Figure B14 Location A (LNDG 3 Pass), Post-Grind – Bins 10+

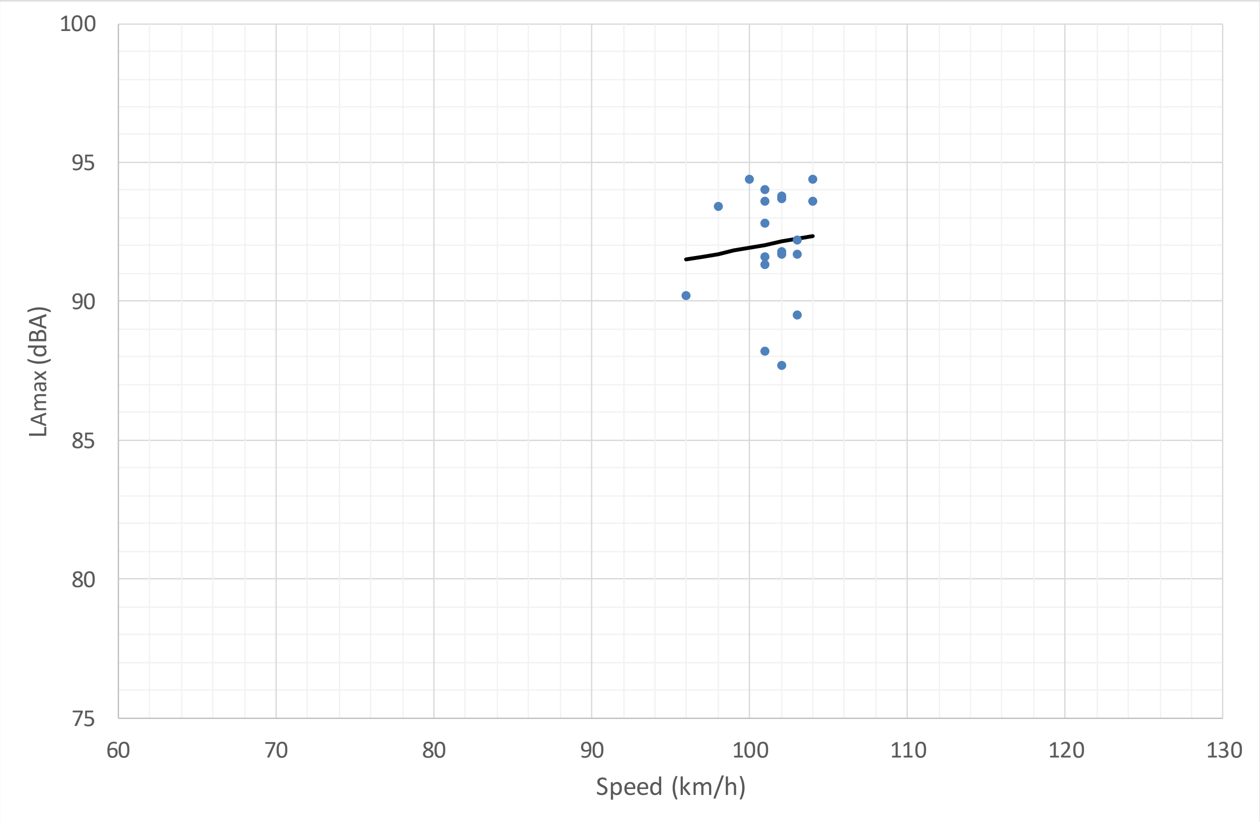


Figure B15 Location A (LNDG 3 Pass), Class 2b Vehicle Breakdown

Figure B16 Location B (CDG), Pre-Grind – Class 1

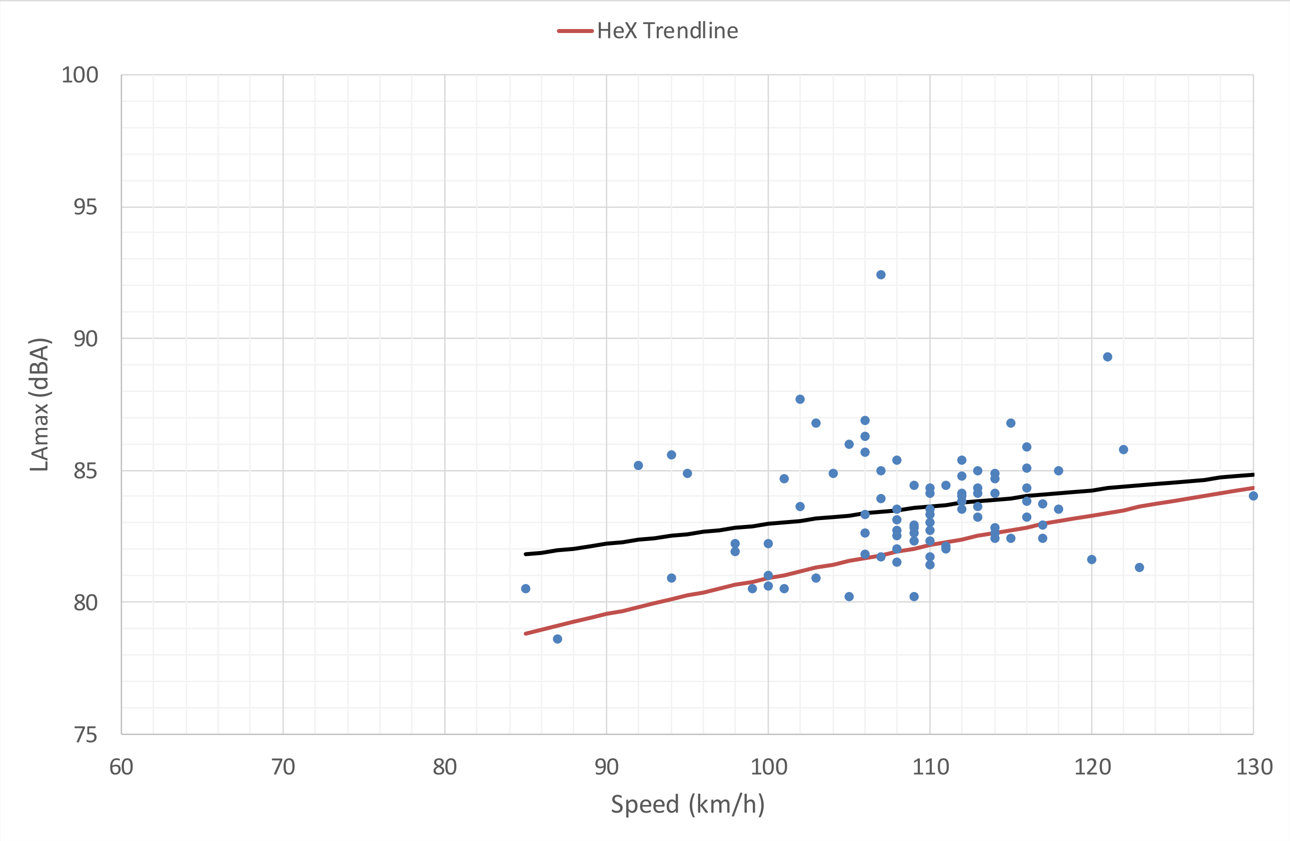


Figure B17 Location B (CDG), Pre-Grind – Class 2a

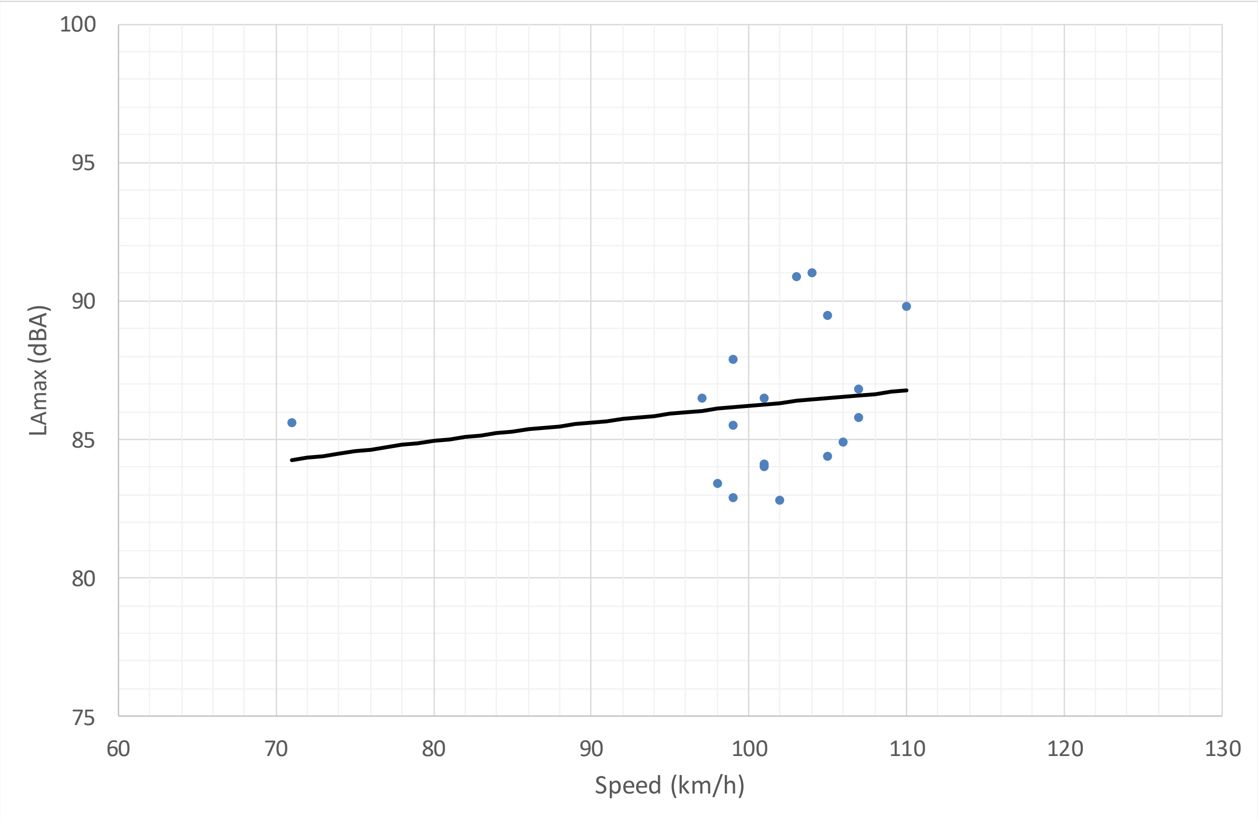


Figure B18 Location B (CDG), Pre-Grind – Class 2b

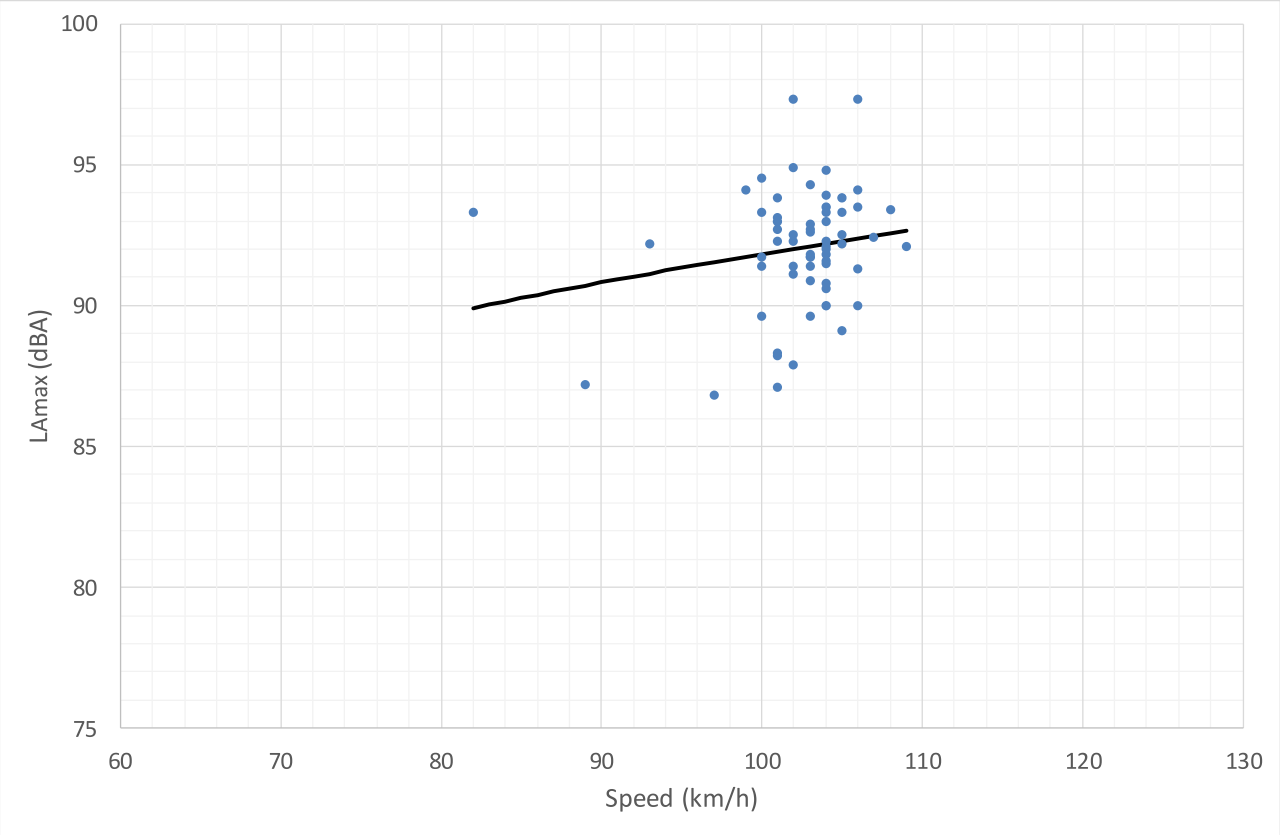


Figure B19 Location B (CDG), Pre-Grind – Bin 4

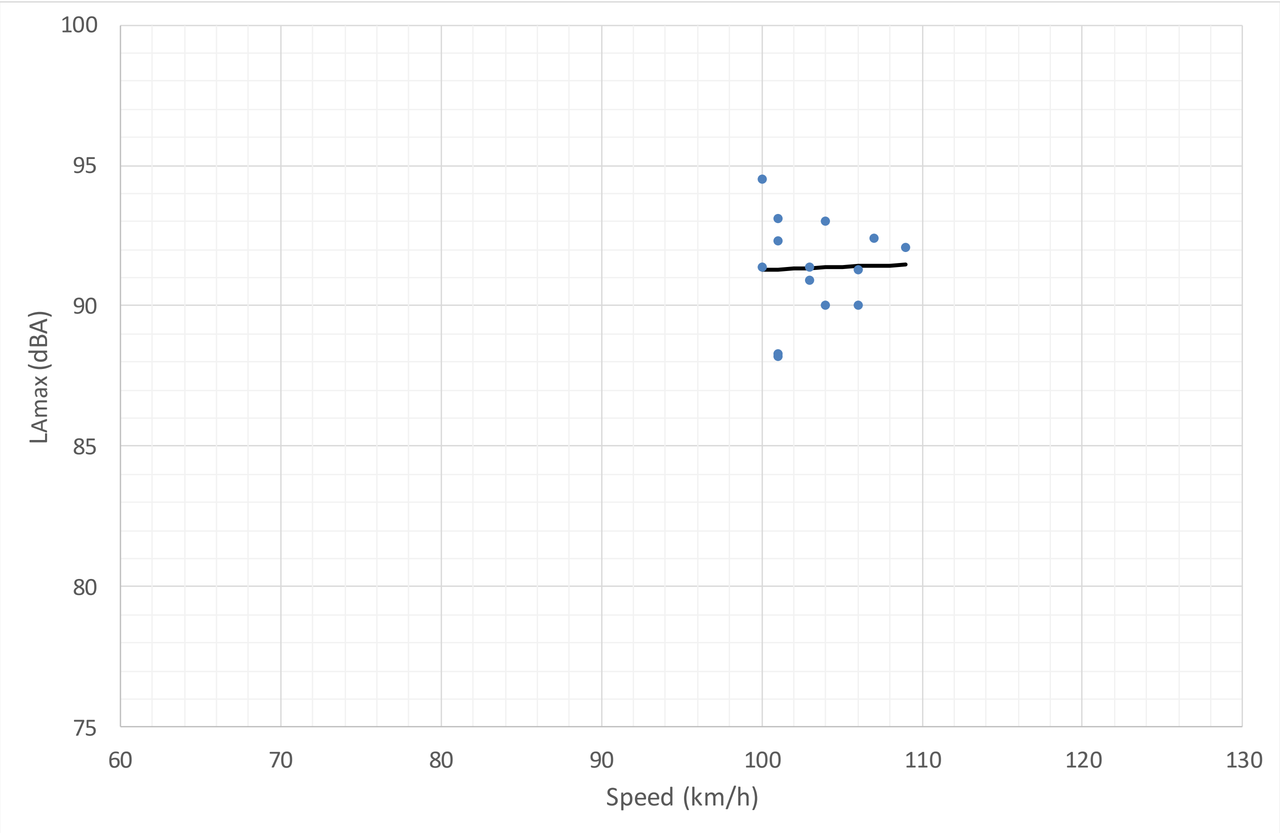


Figure B20 Location B (CDG), Pre-Grind – Bins 5 to 8

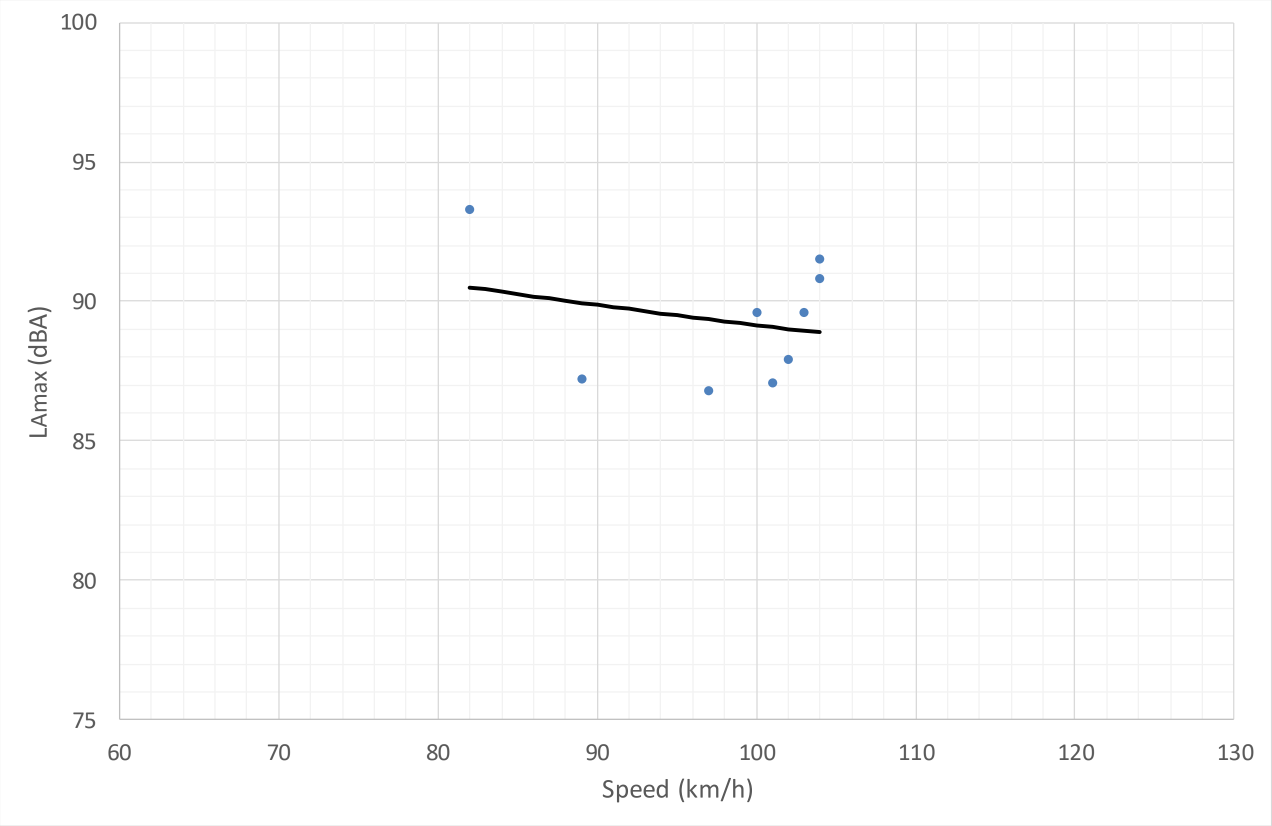


Figure B21 Location B (CDG), Pre-Grind – Bin 9

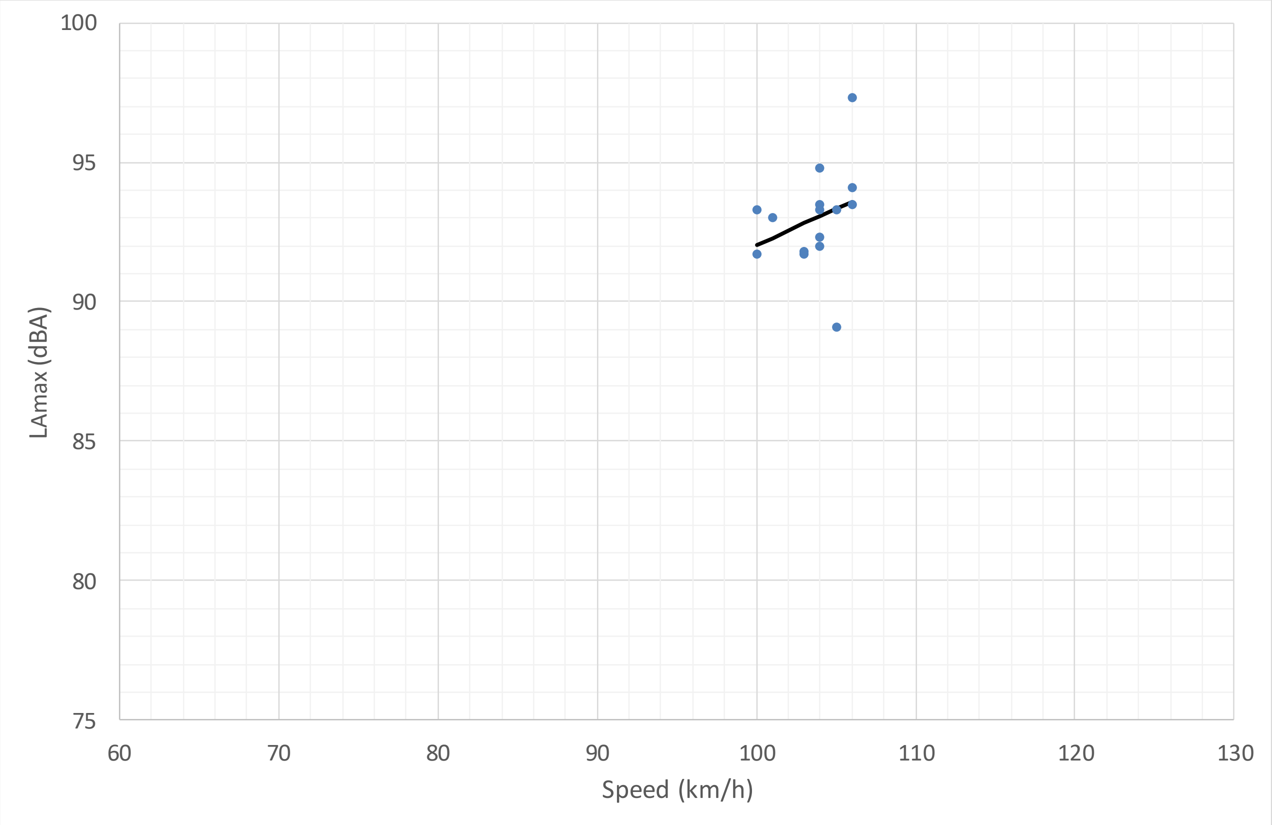


Figure B22 Location B (CDG), Pre-Grind – Bins 10+

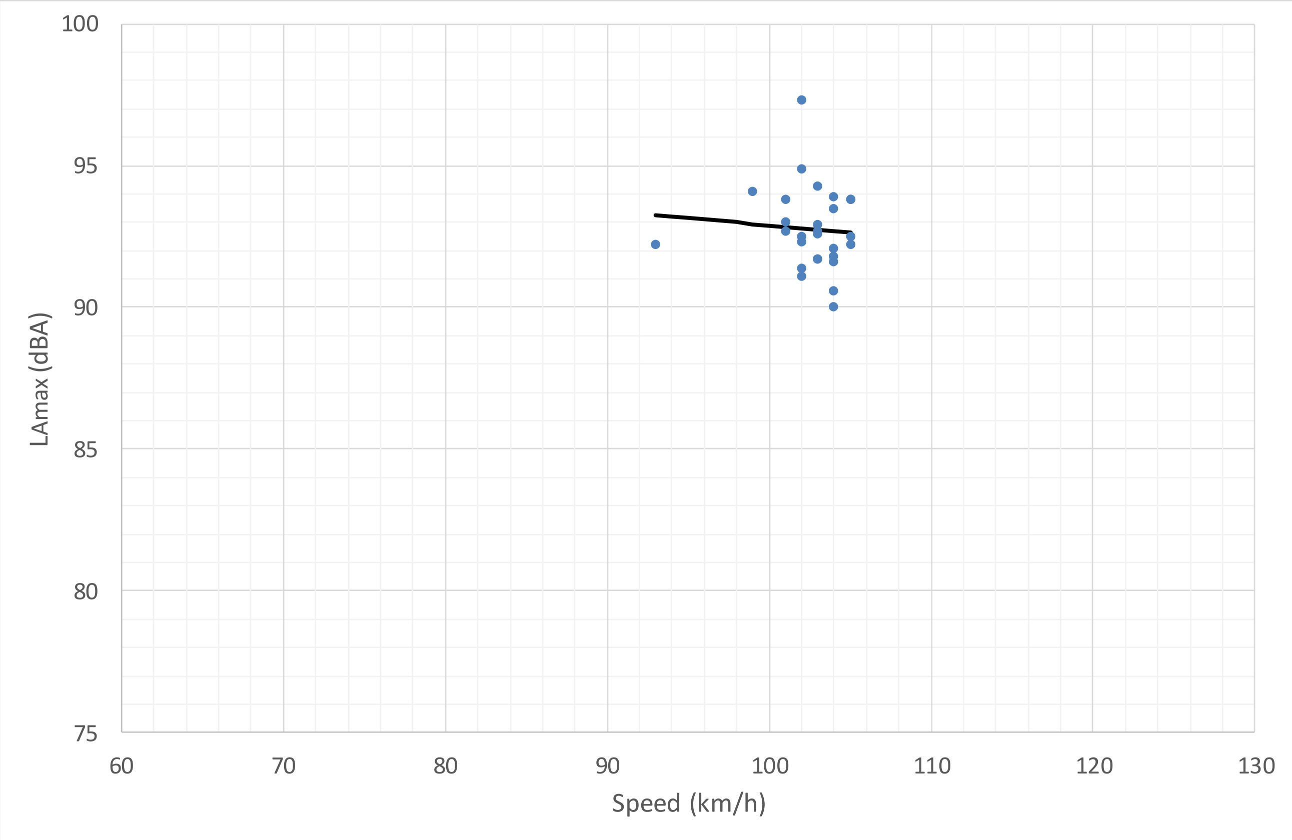


Figure B23 Location B (CDG), Post-Grind – Class 1

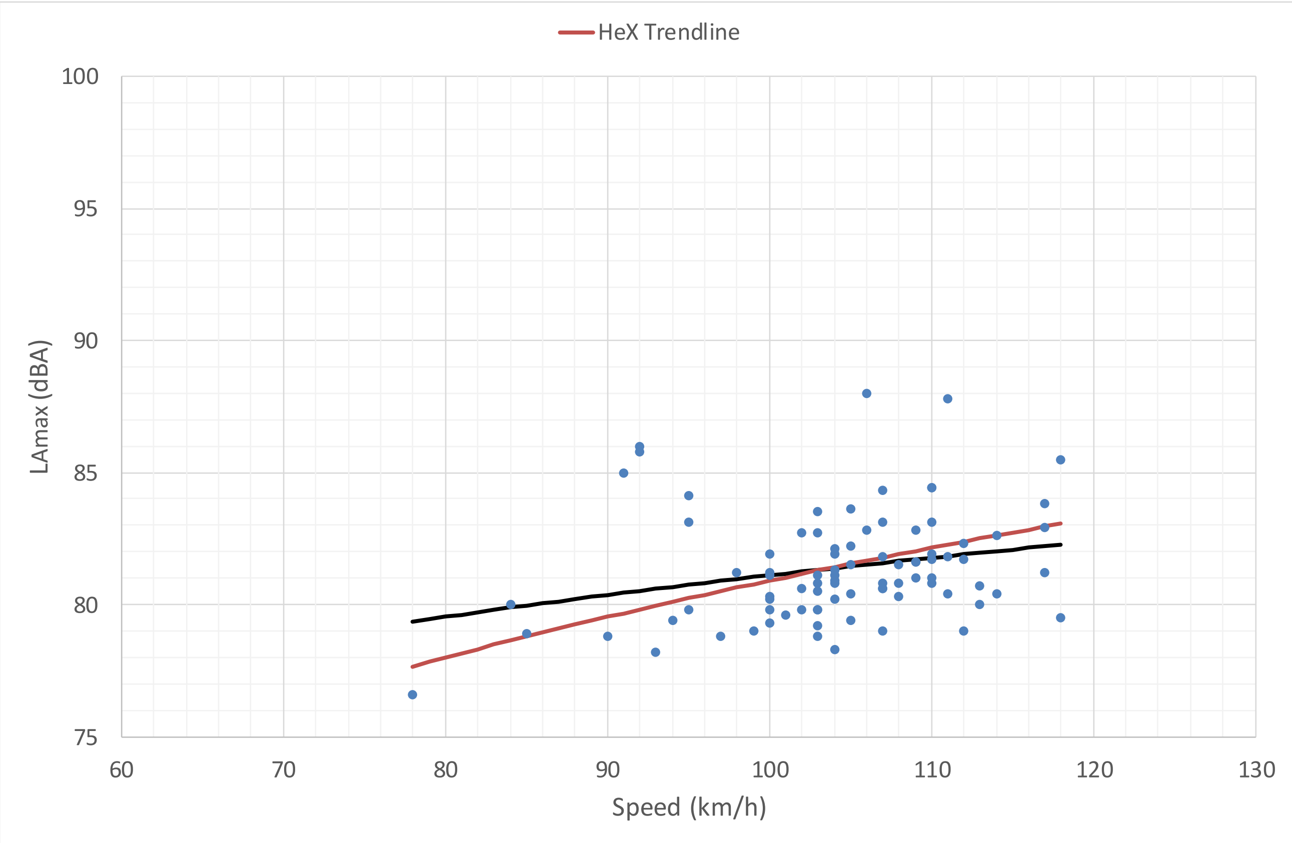


Figure B24 Location B (CDG), Post-Grind – Class 2a

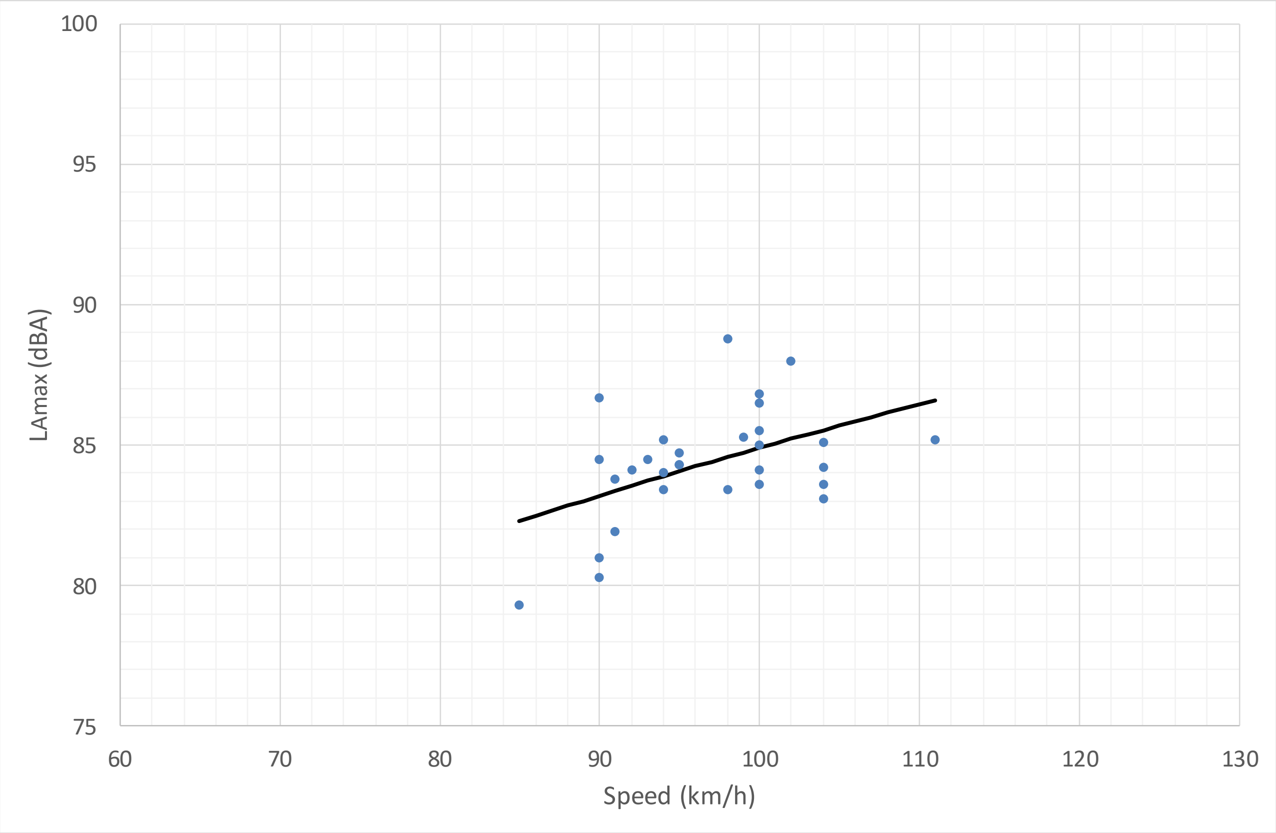


Figure B25 Location B (CDG), Post-Grind – Class 2b

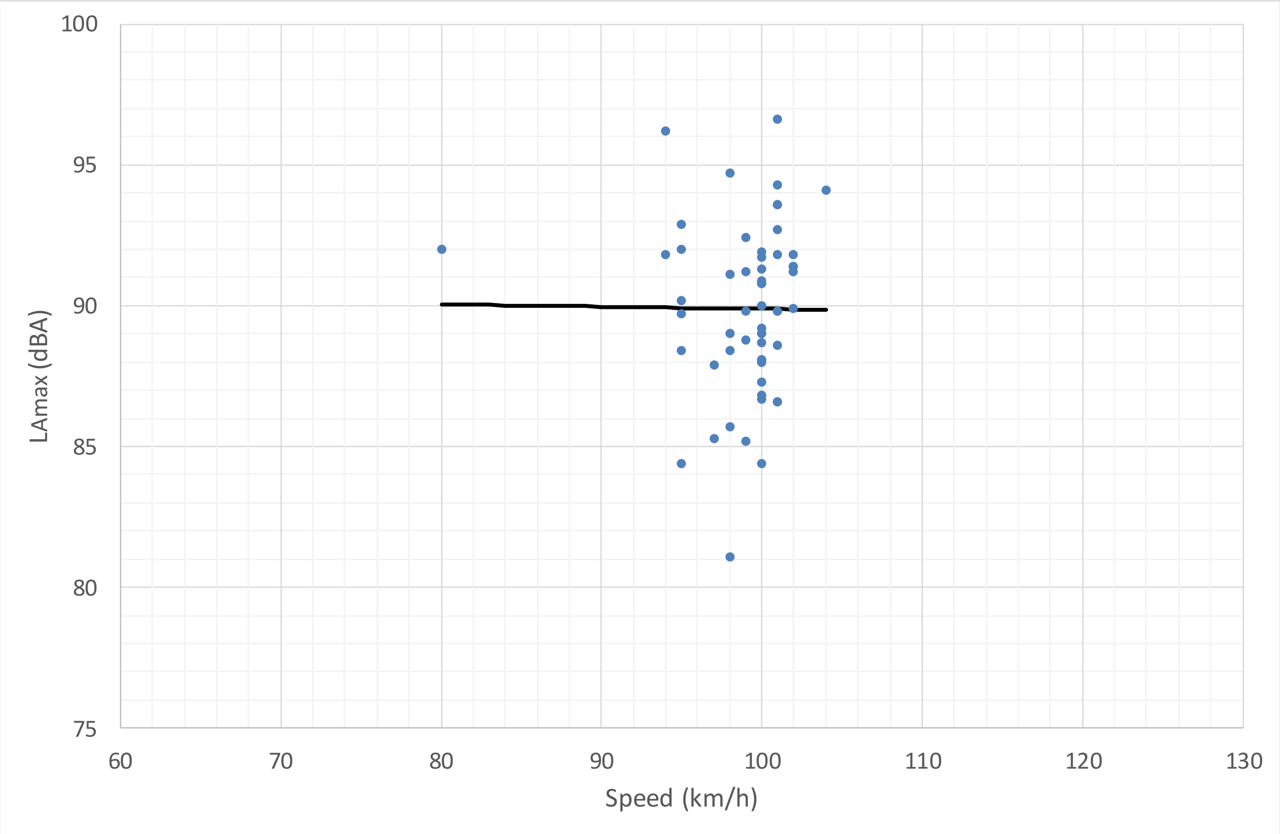


Figure B26 Location B (CDG), Post-Grind – Bin 4

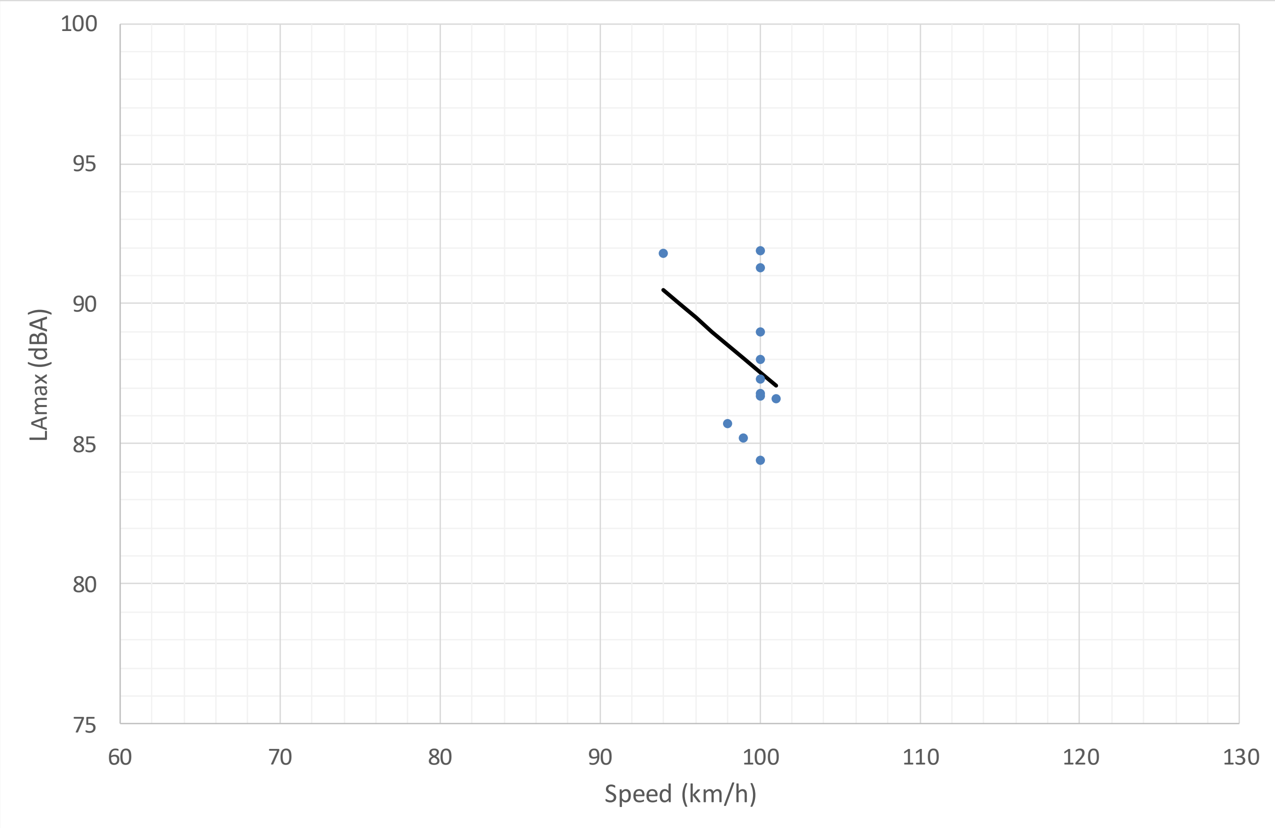


Figure B27 Location B (CDG), Post-Grind – Bins 5 to 8

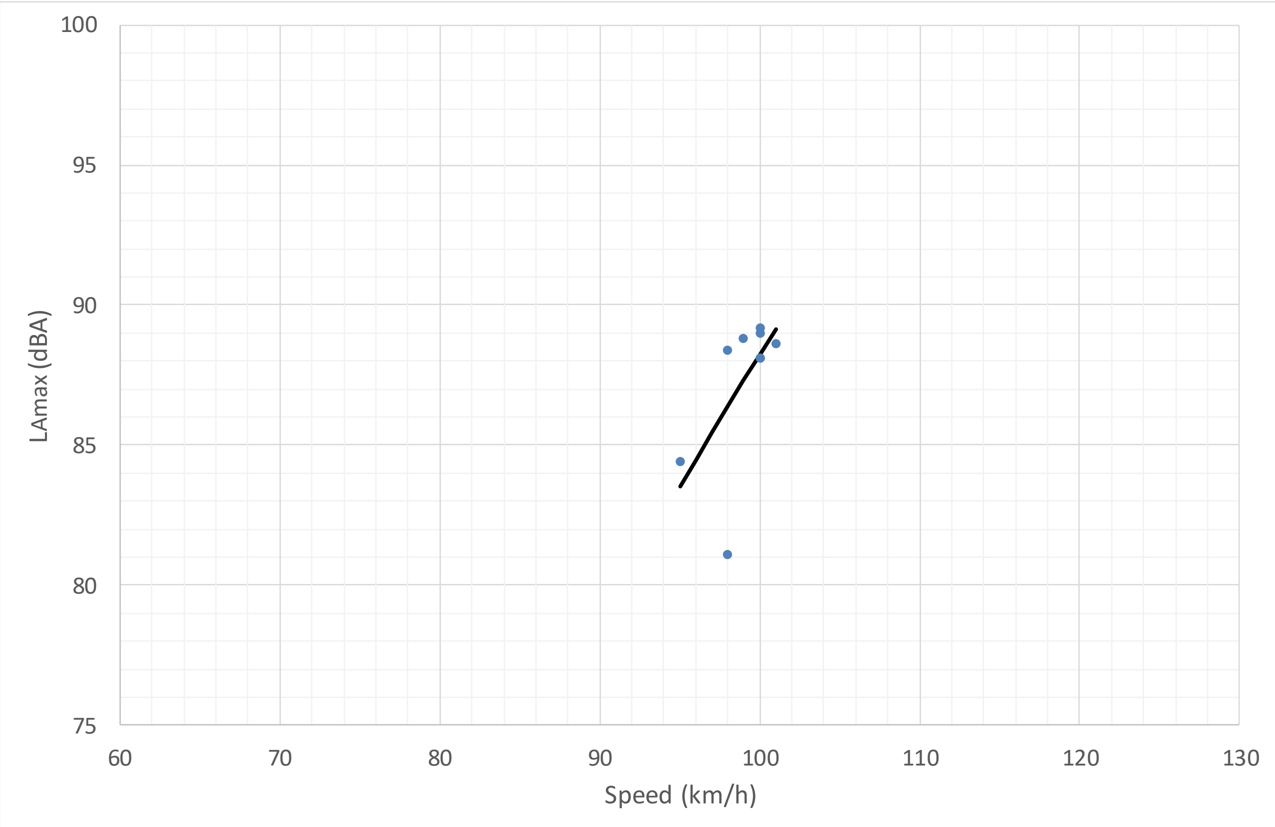


Figure B28 Location B (CDG), Post-Grind – Bin 9

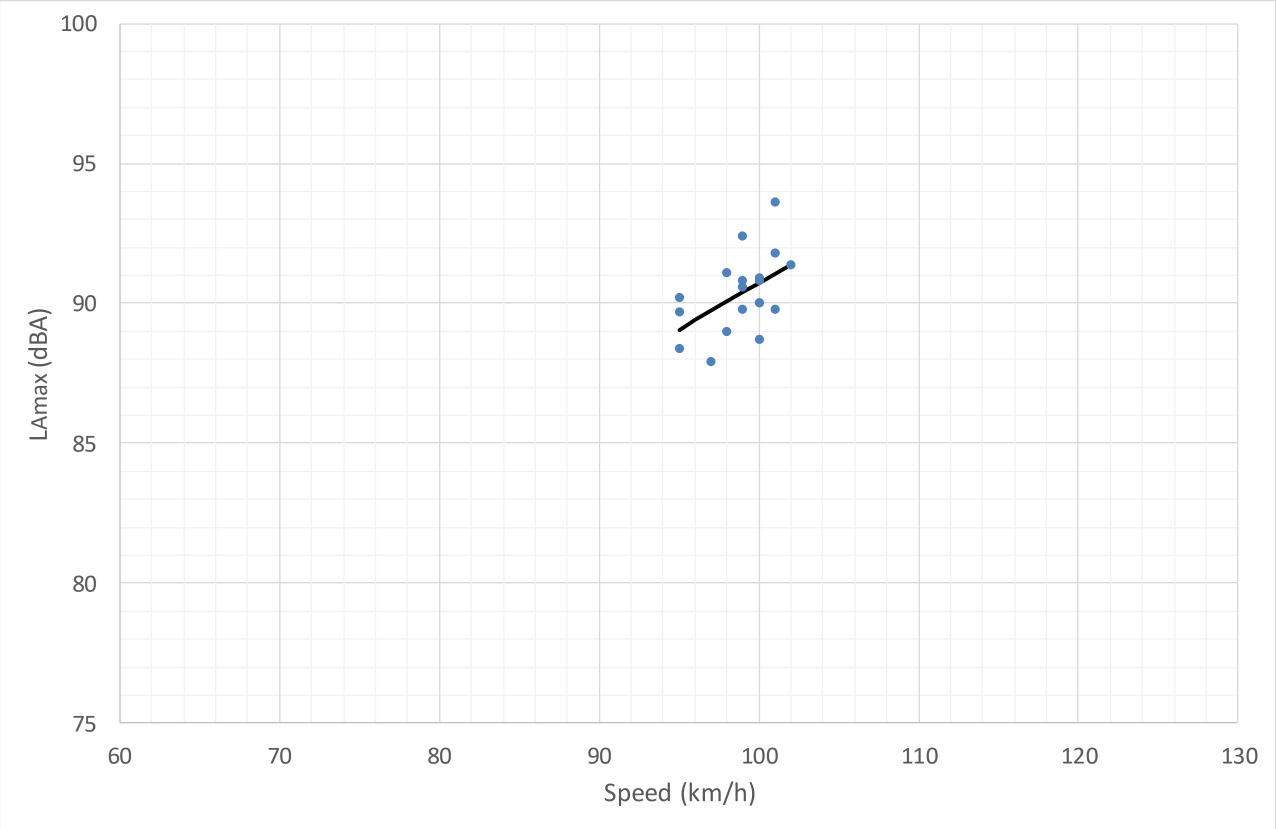


Figure B28 Location B (CDG), Post-Grind – Bins 10+

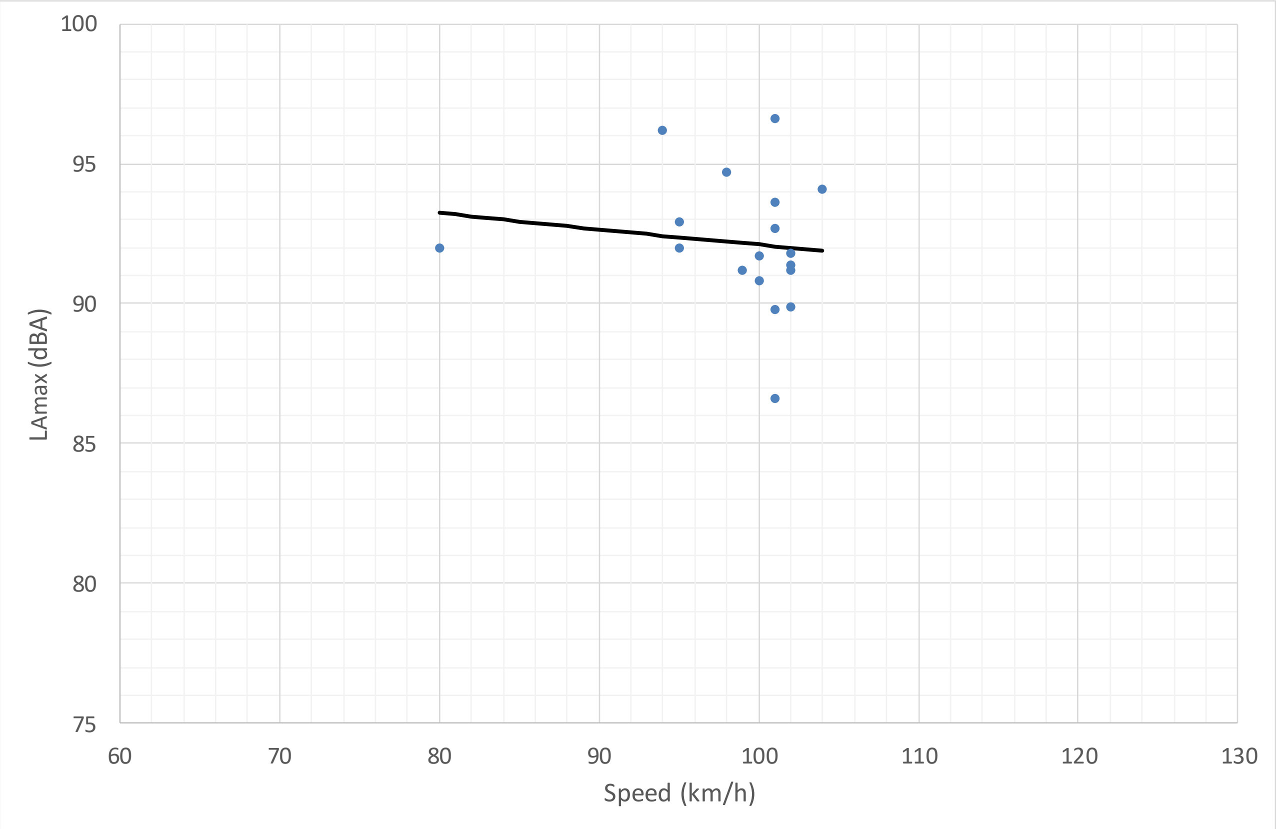


Figure B30 Location B (CDG), Class 2b Vehicle Breakdown

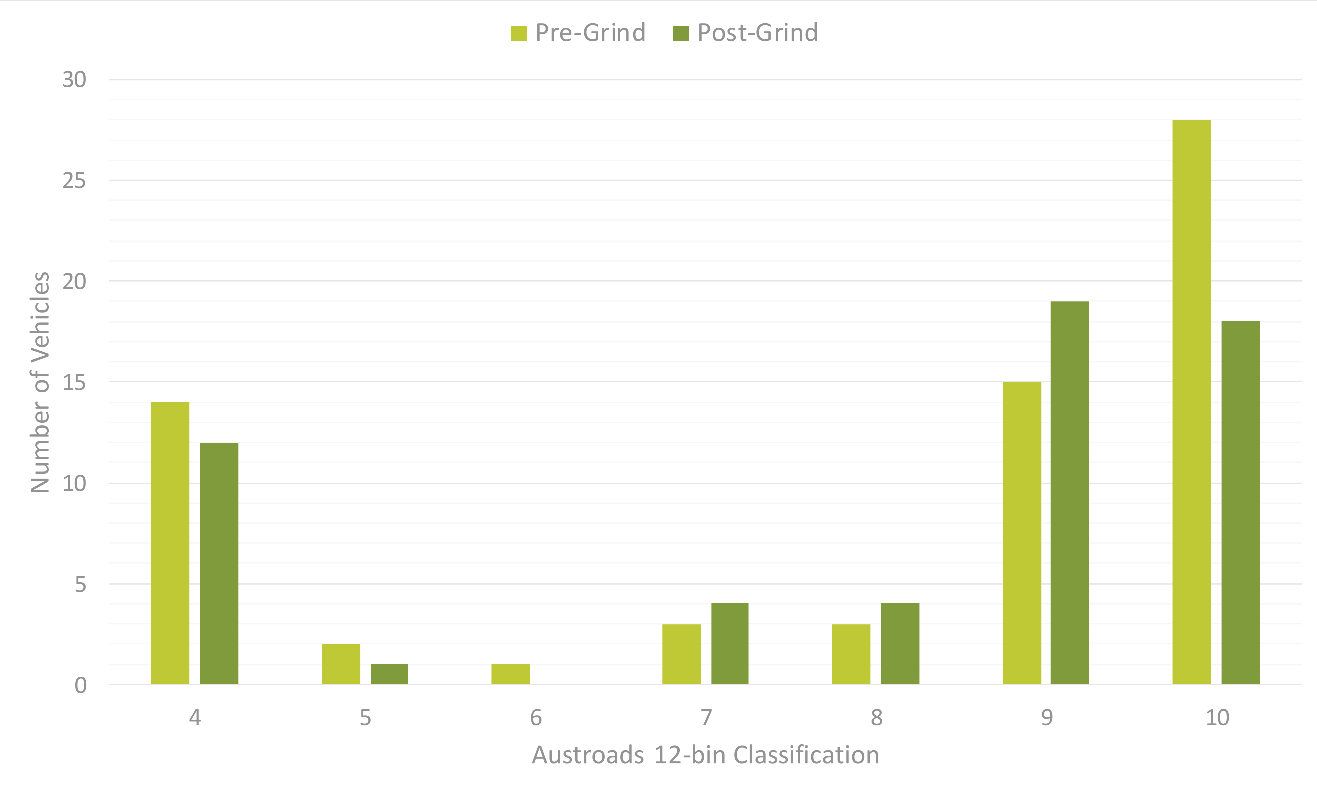


Figure B31 Location C (SMA10), Pre-Grind – Class 1

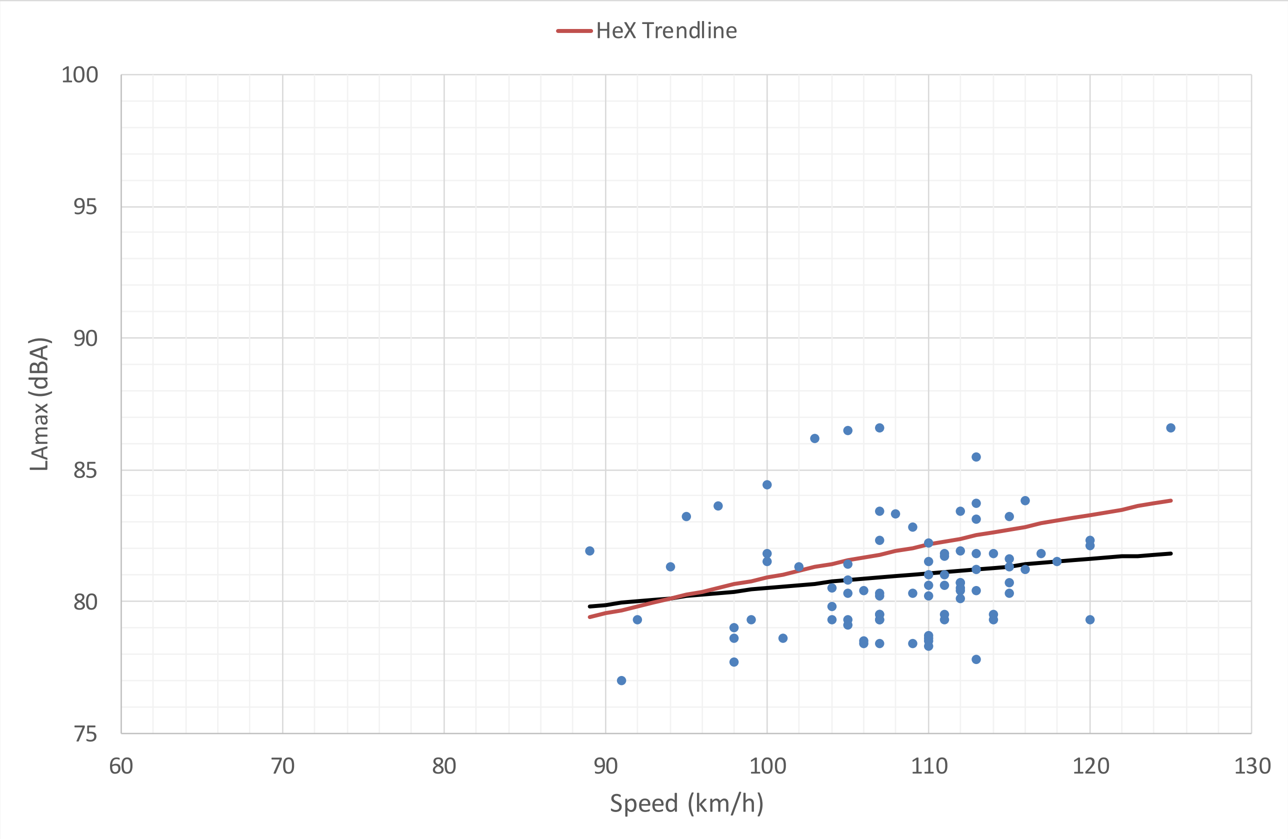


Figure B32 Location C (SMA10), Pre-Grind – Class 2a

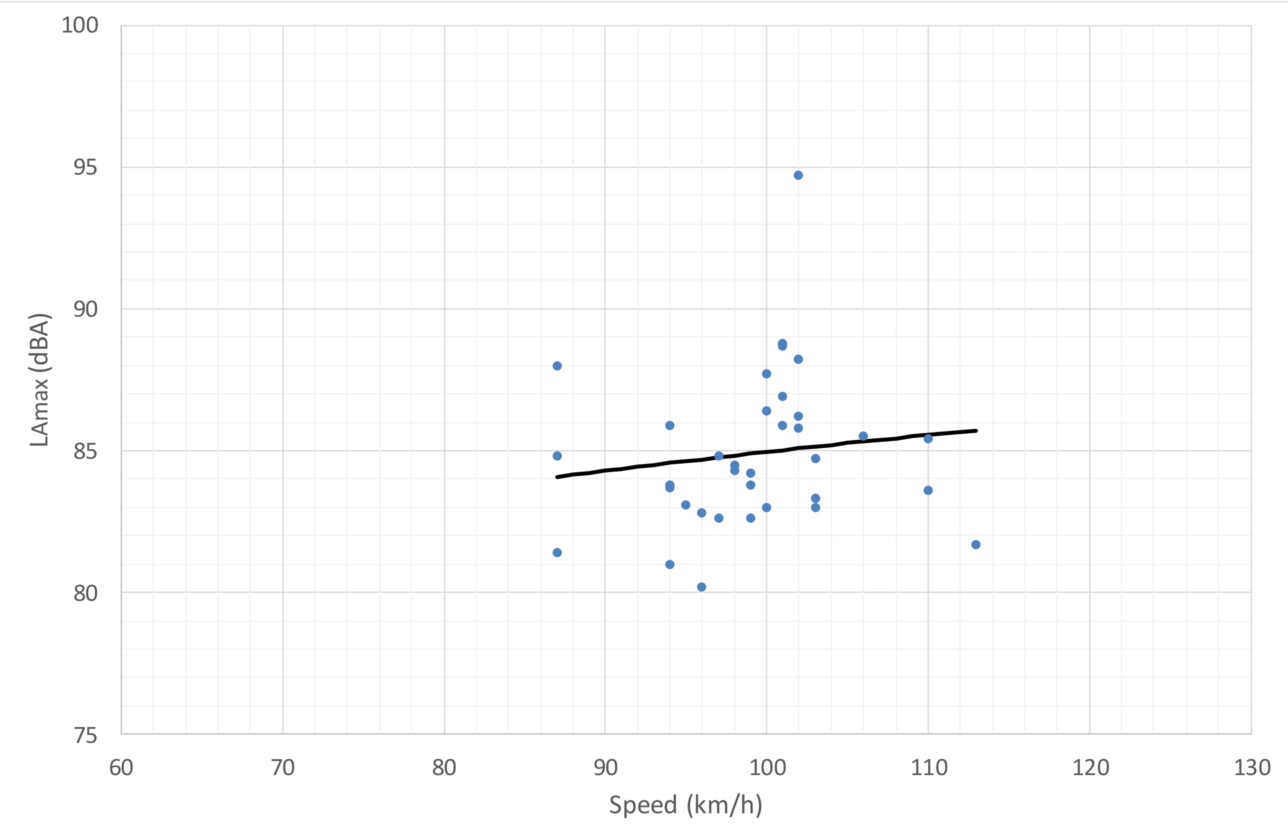


Figure B33 Location C (SMA10), Pre-Grind – Class 2b

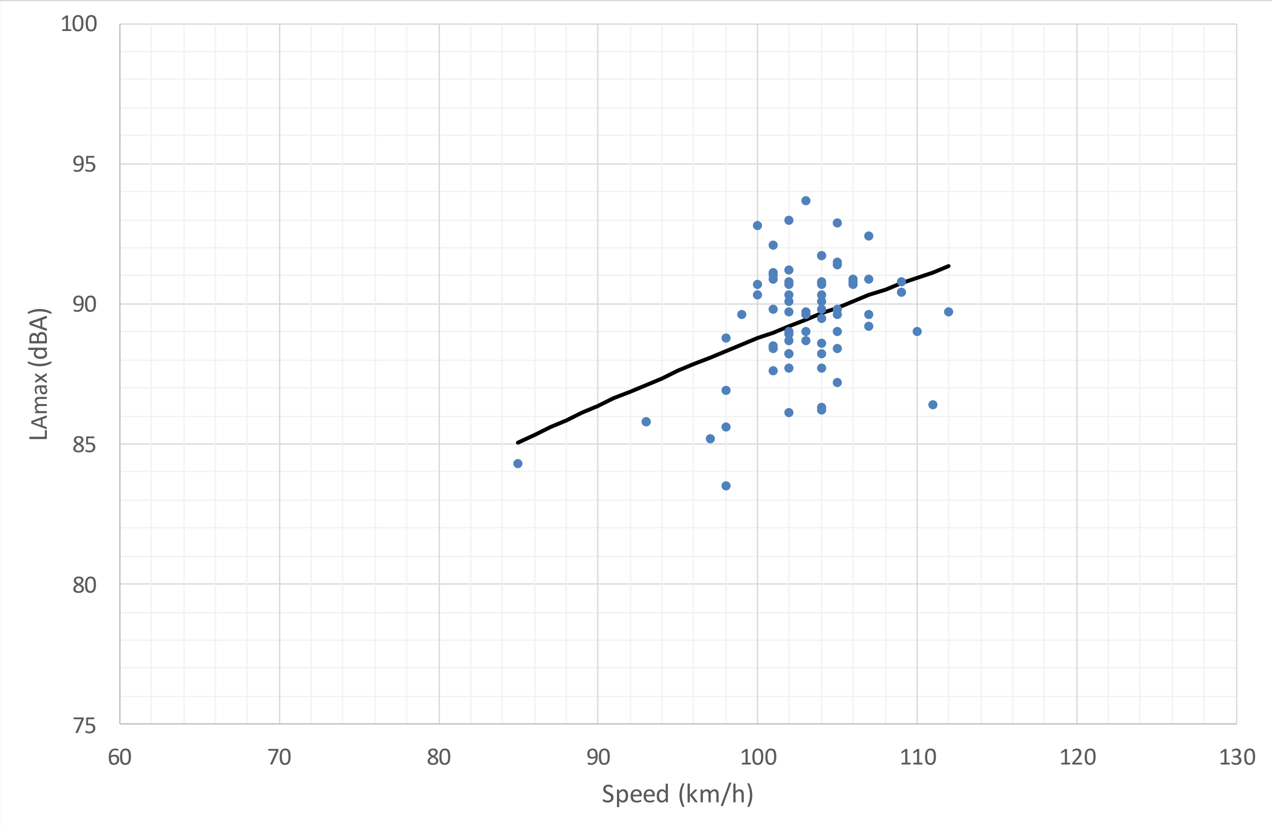


Figure B34 Location C (SMA10), Pre-Grind – Bin 4

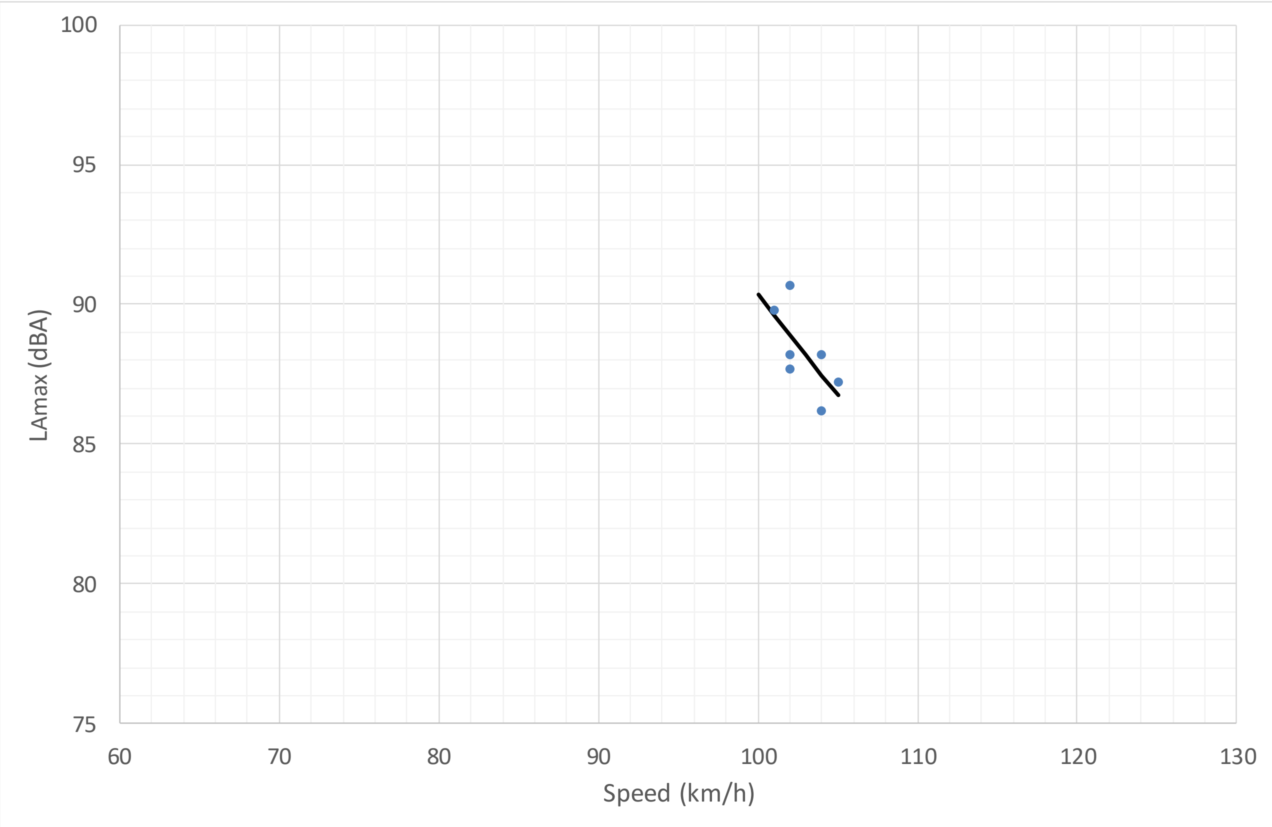


Figure B35 Location C (SMA10), Pre-Grind – Bins 5 to 8

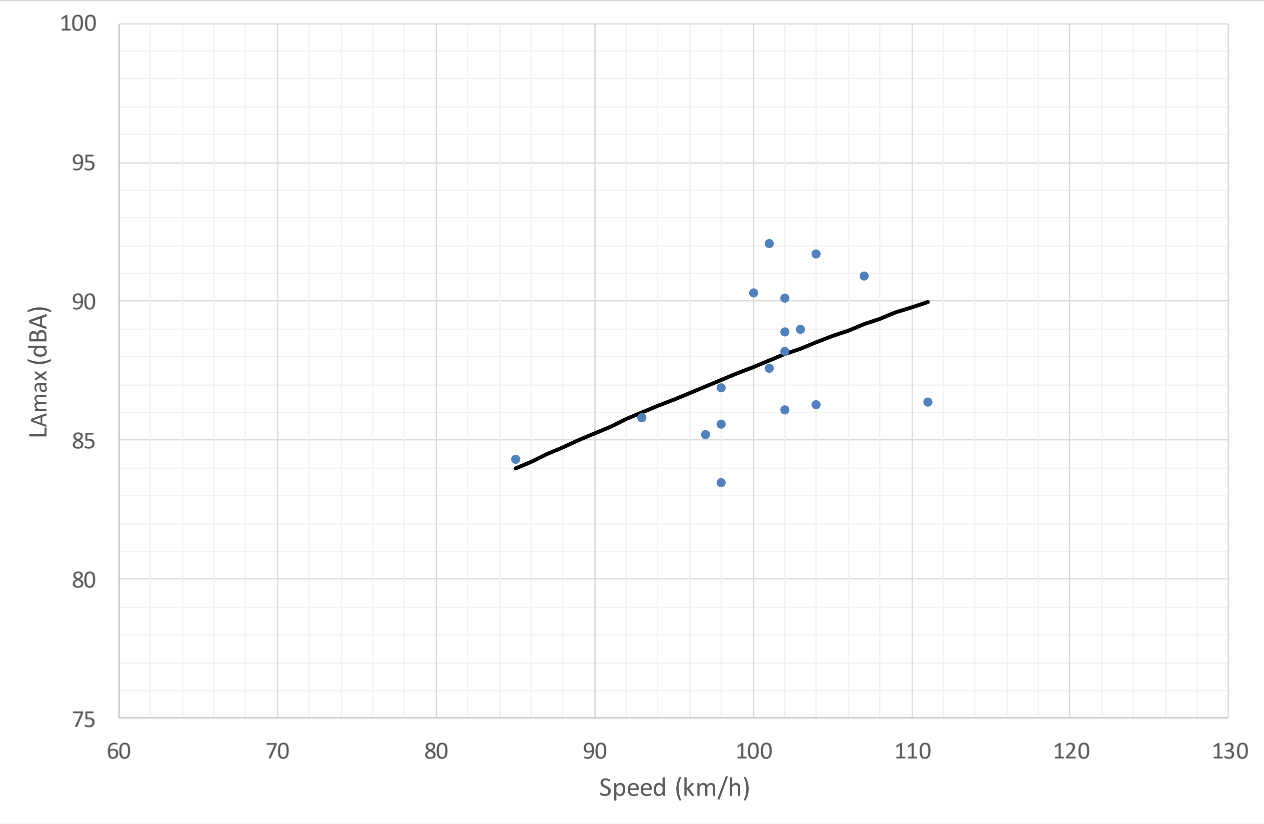


Figure B36 Location C (SMA10), Pre-Grind – Bin 9

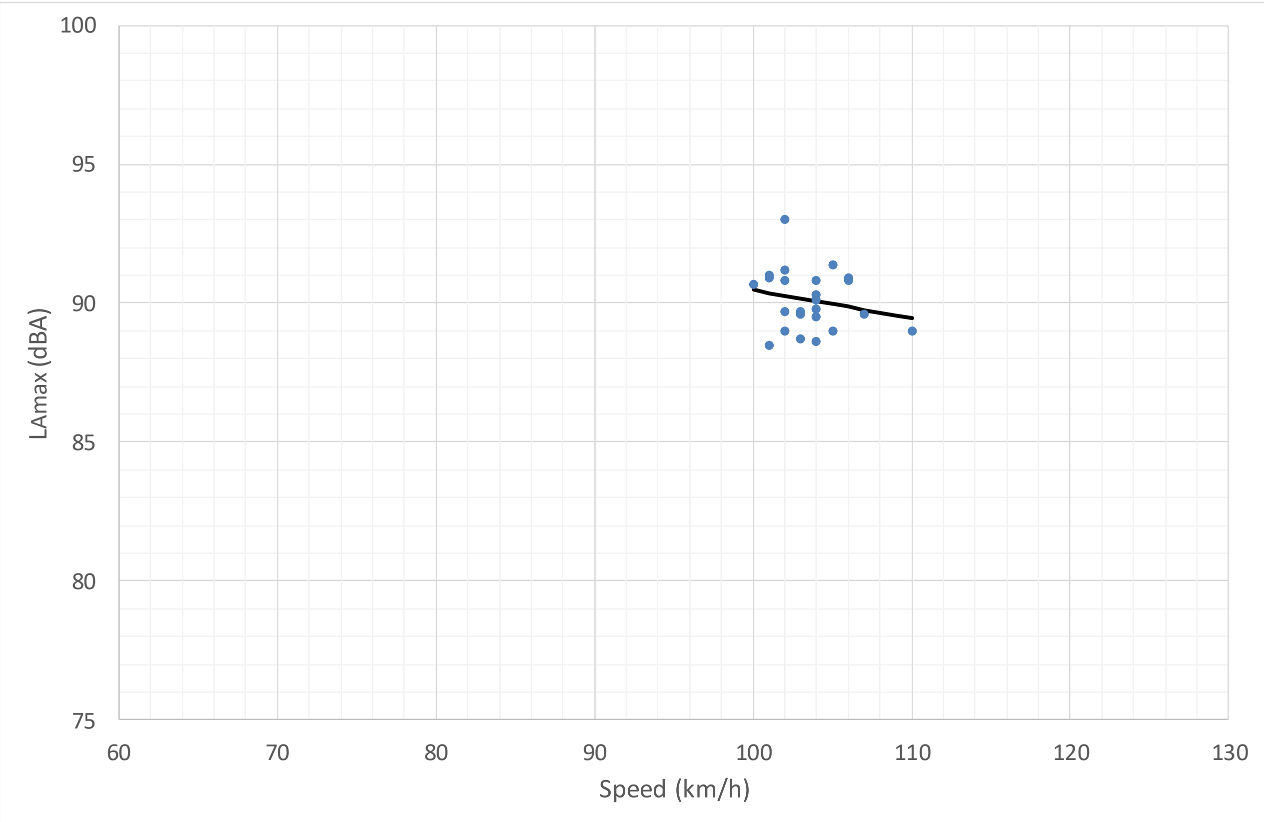


Figure B37 Location C (SMA10), Pre-Grind – Bins 10+

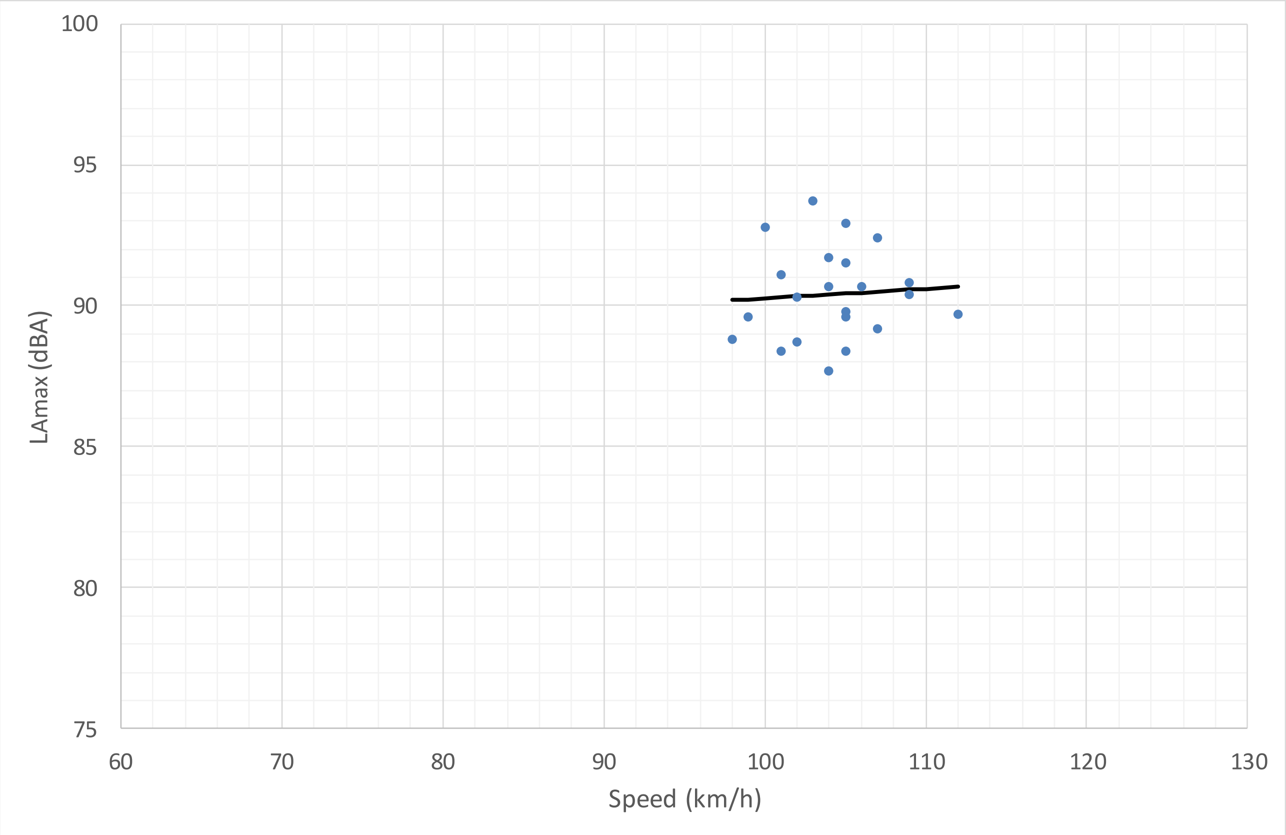


Figure B38 Location C (SMA10), Post-Grind – Class 1

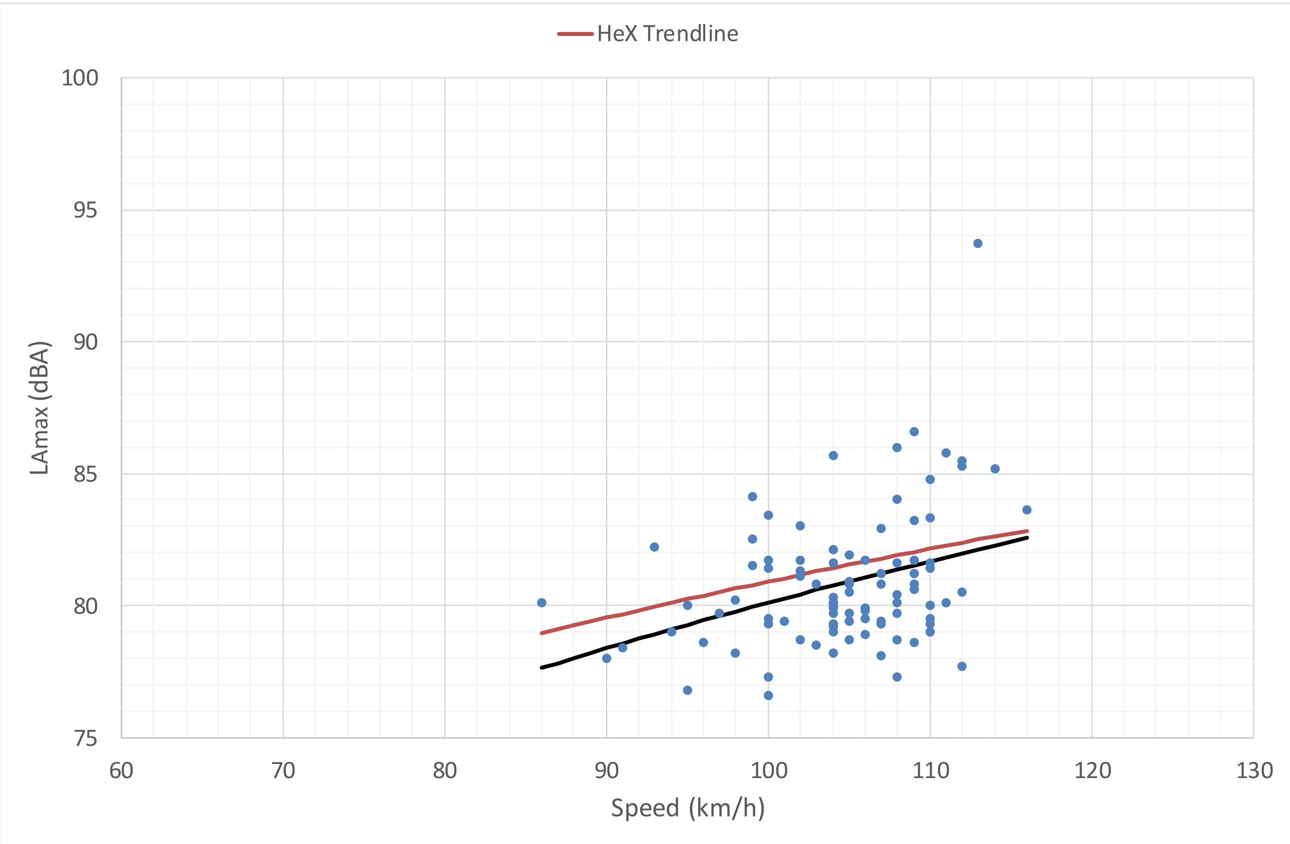


Figure B39 Location C (SMA10), Post-Grind – Class 2a

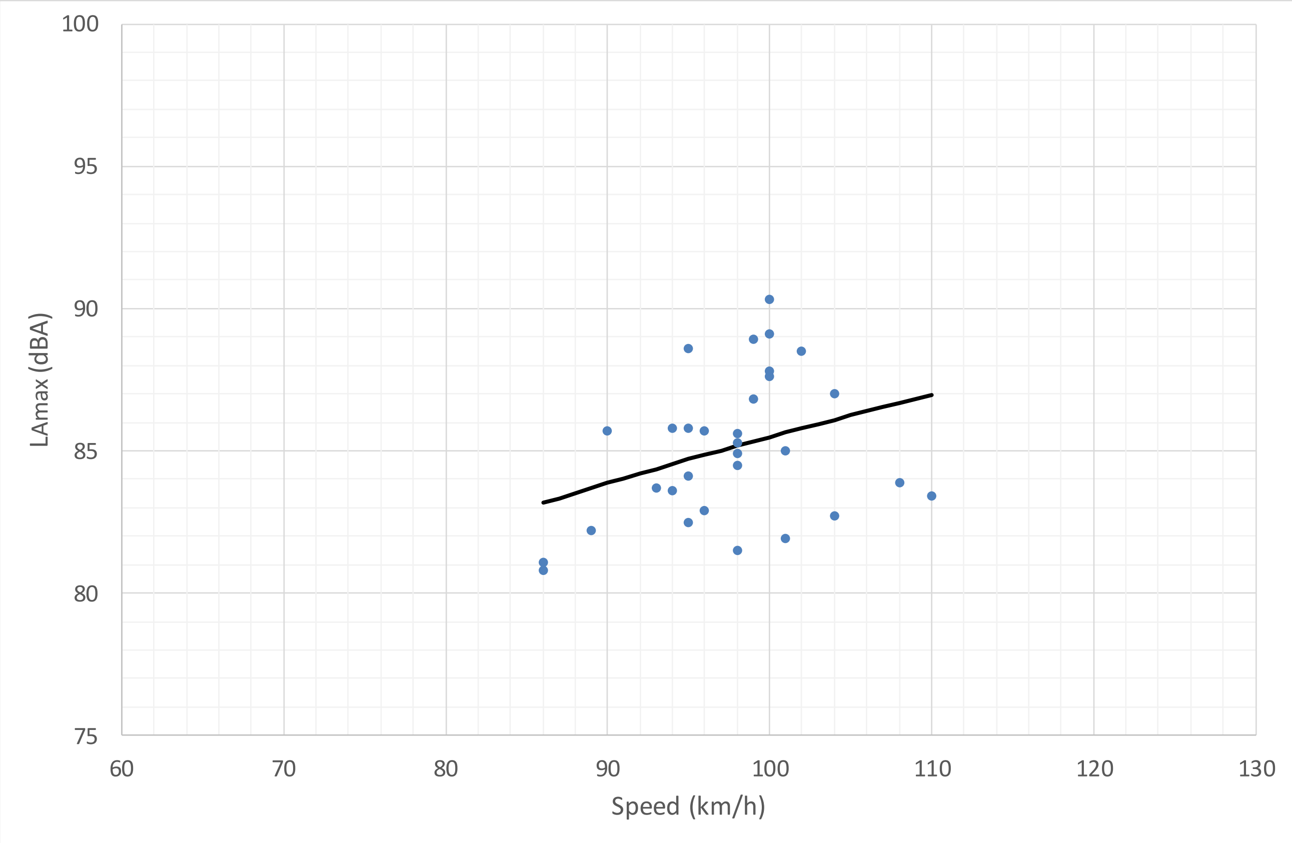


Figure B40 Location C (SMA10), Post-Grind – Class 2b

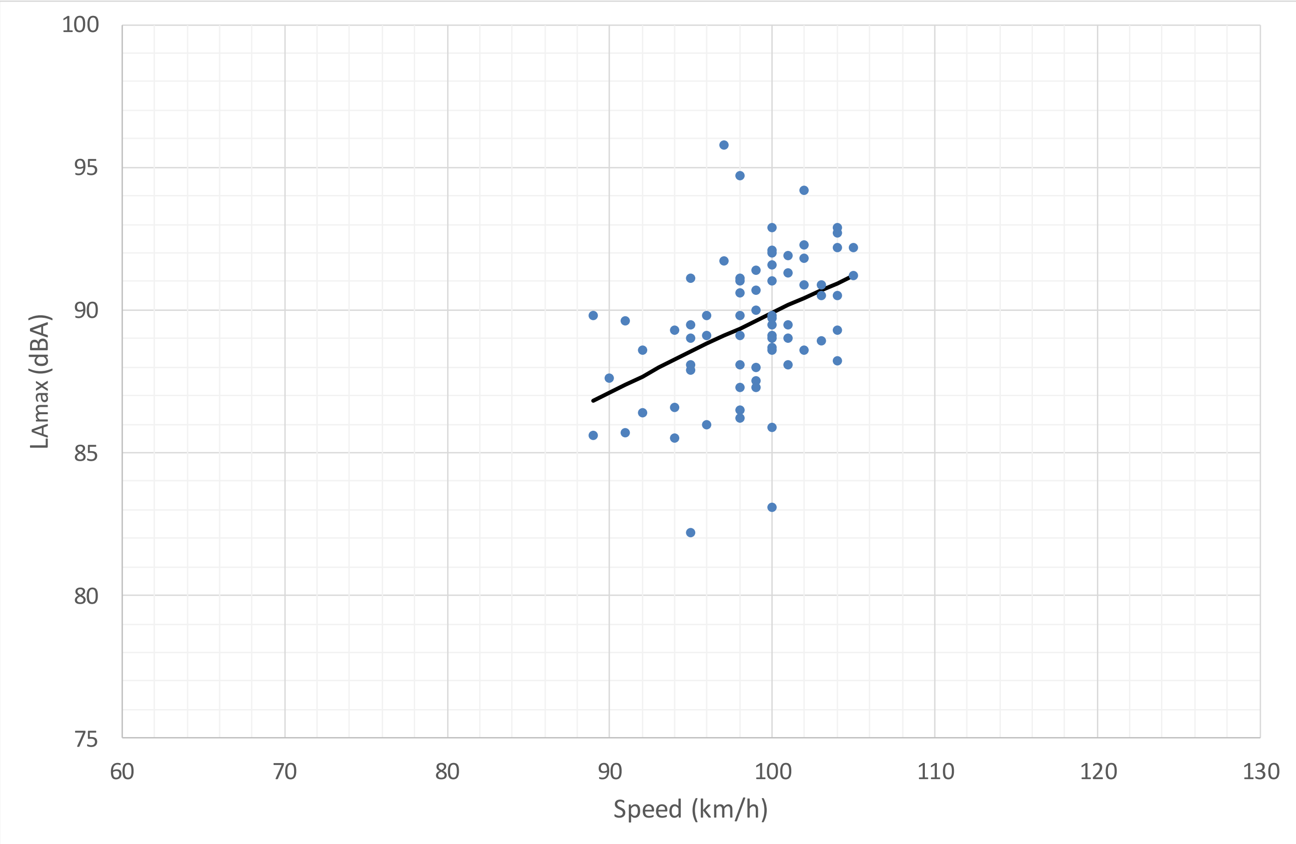


Figure B41 Location C (SMA10), Post-Grind – Bin 4

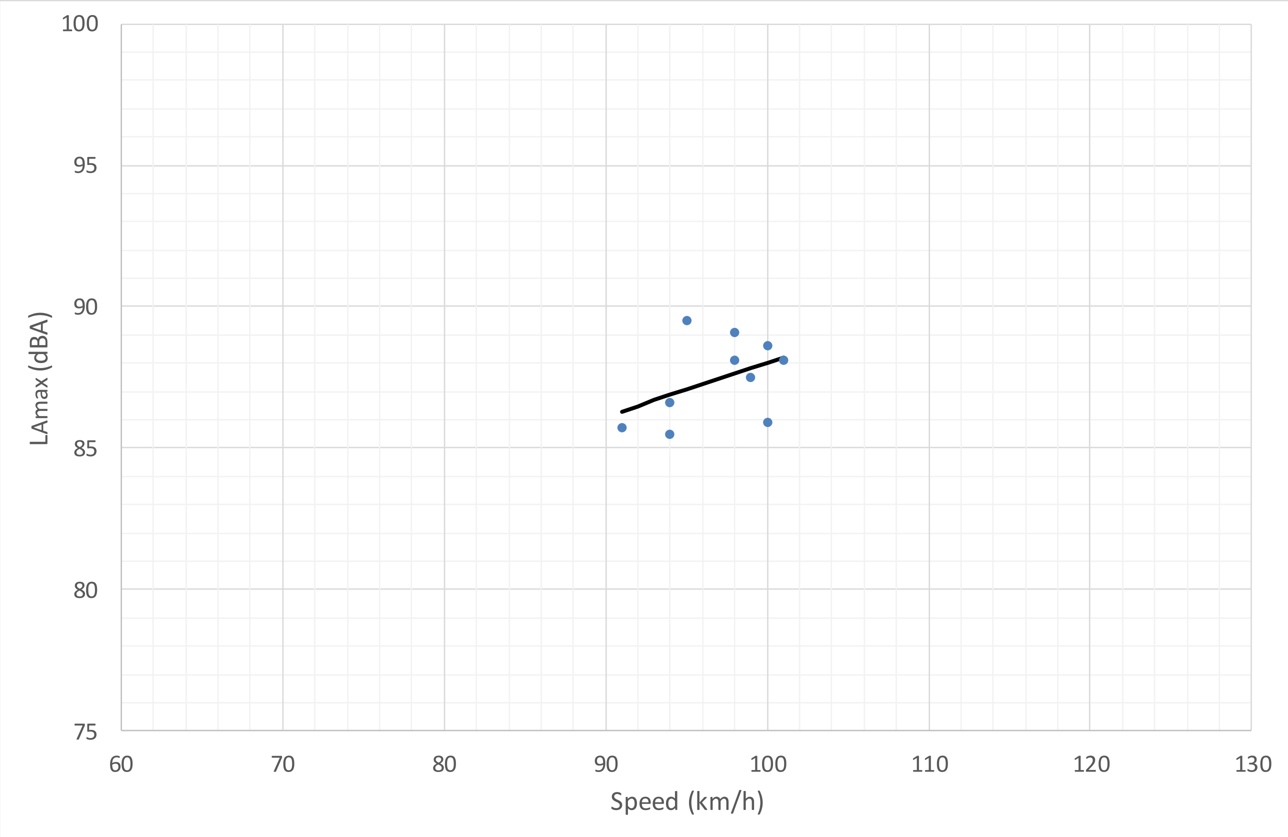


Figure B42 Location C (SMA10), Post-Grind – Bins 5 to 8

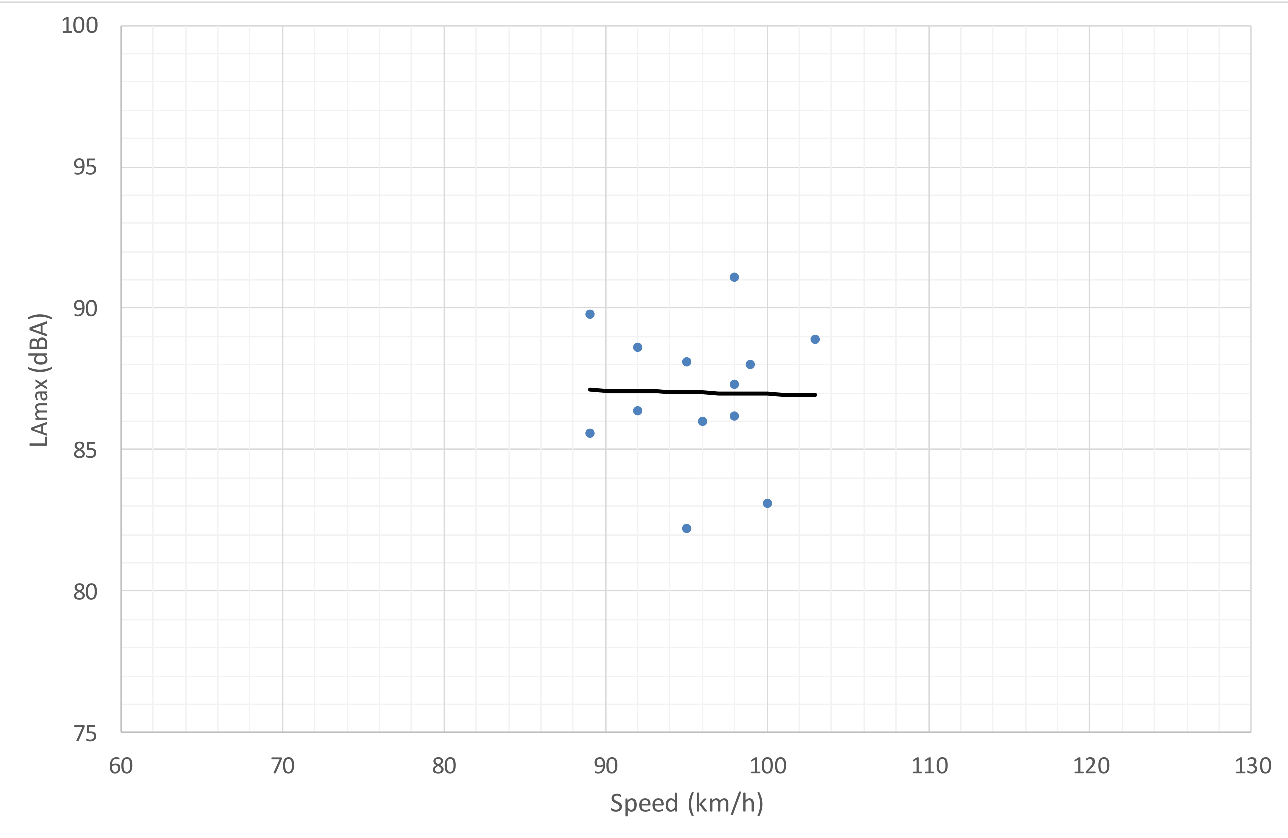


Figure B43 Location C (SMA10), Post-Grind – Bin 9

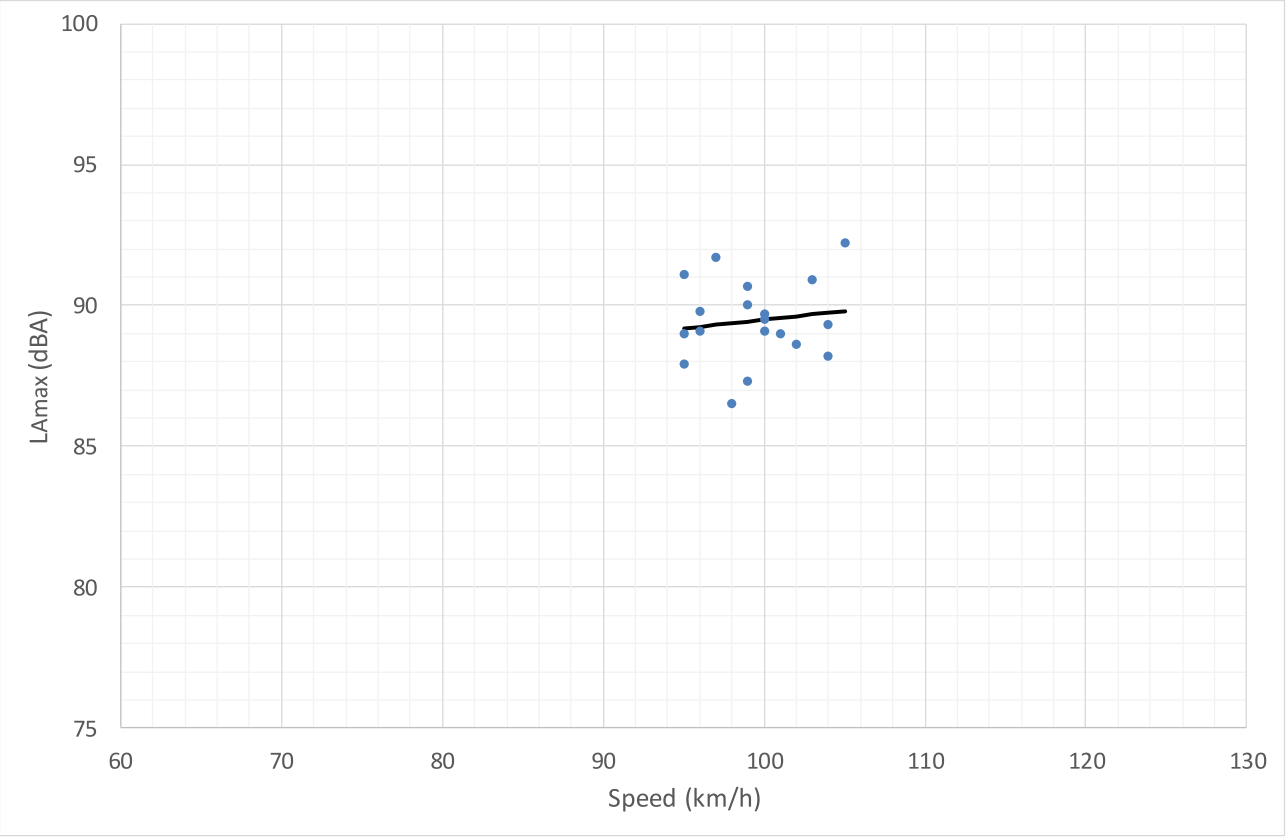


Figure B44 Location C (SMA10), Post-Grind – Bin 10+

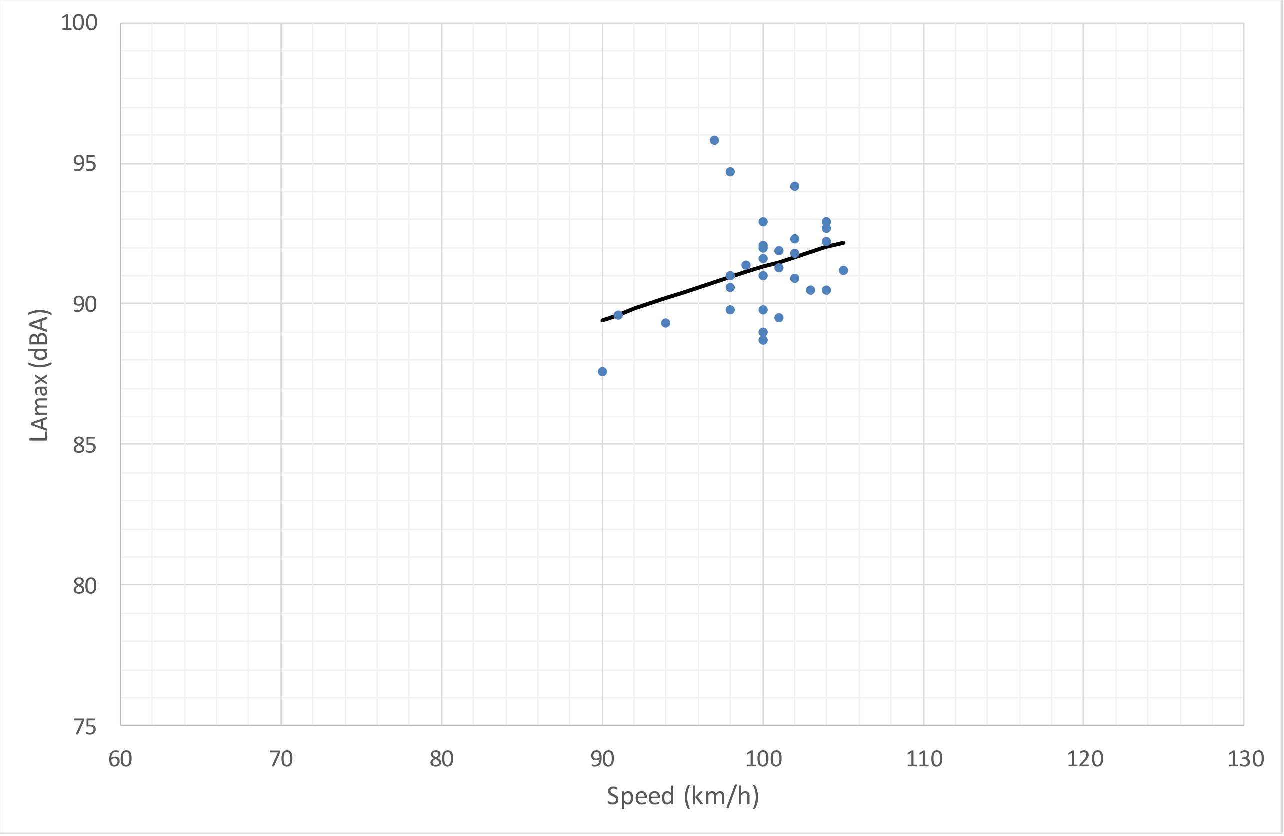


Figure B45 Location C (SMA10), Class 2b Vehicle Breakdown

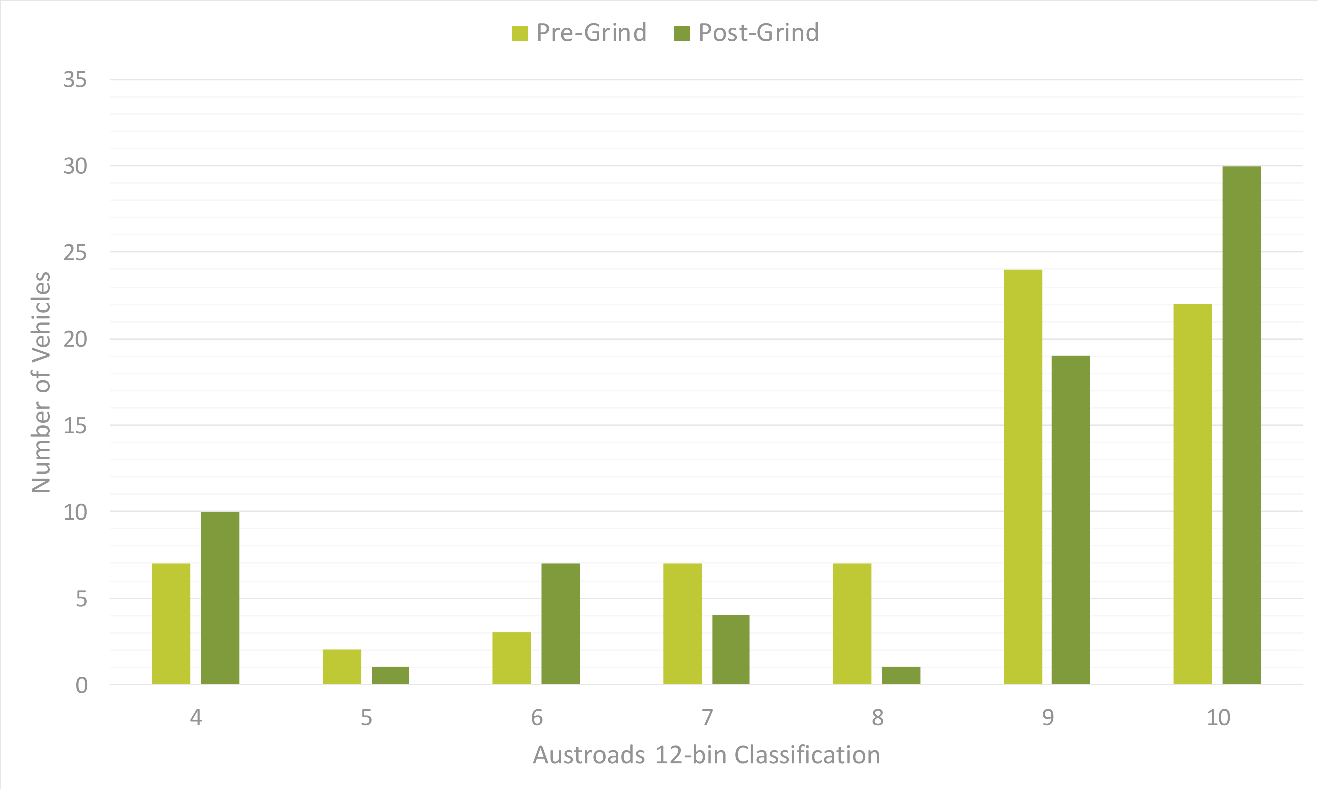


Figure B46 Location D (LNDG 2 Pass), Pre-Grind – Class 1

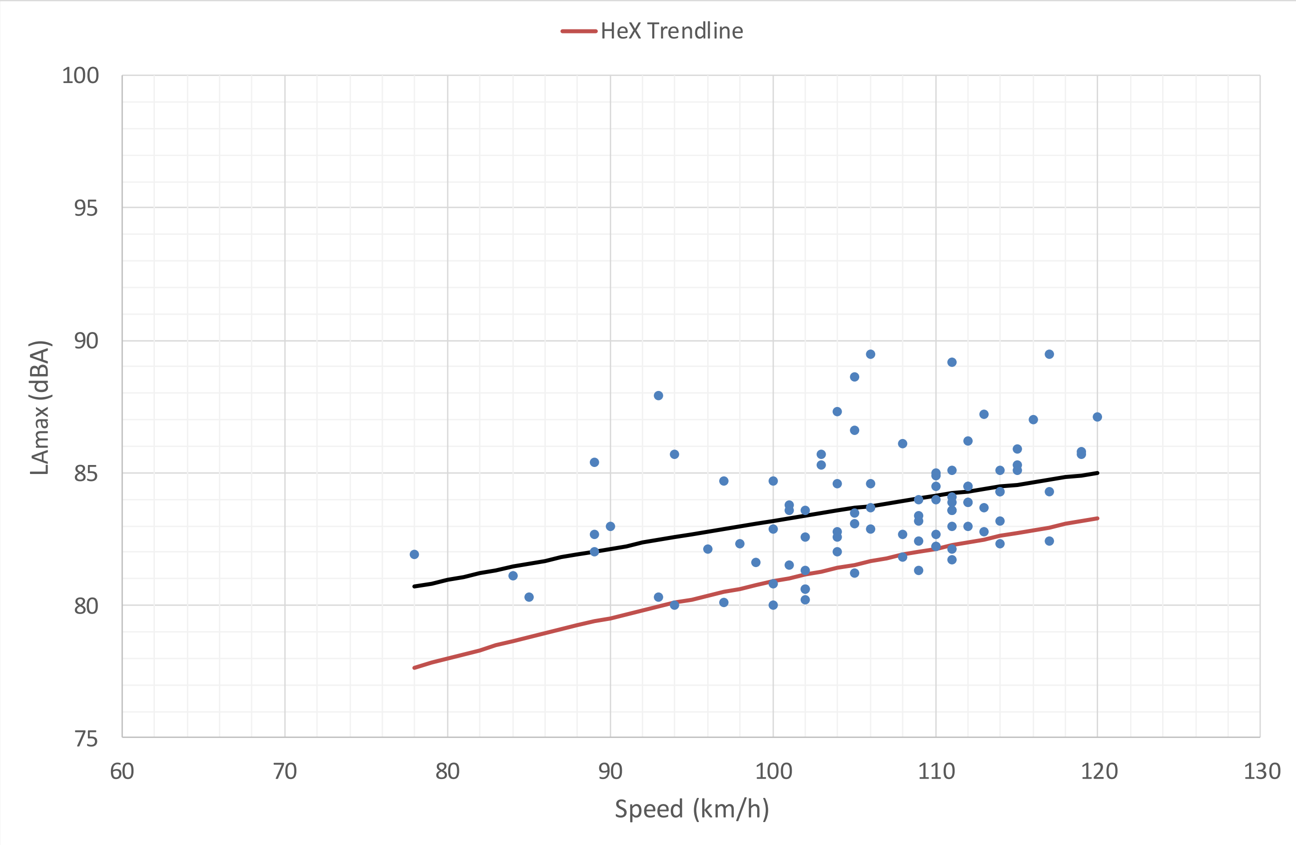


Figure B47 Location D (LNDG 2 Pass), Pre-Grind – Class 2a

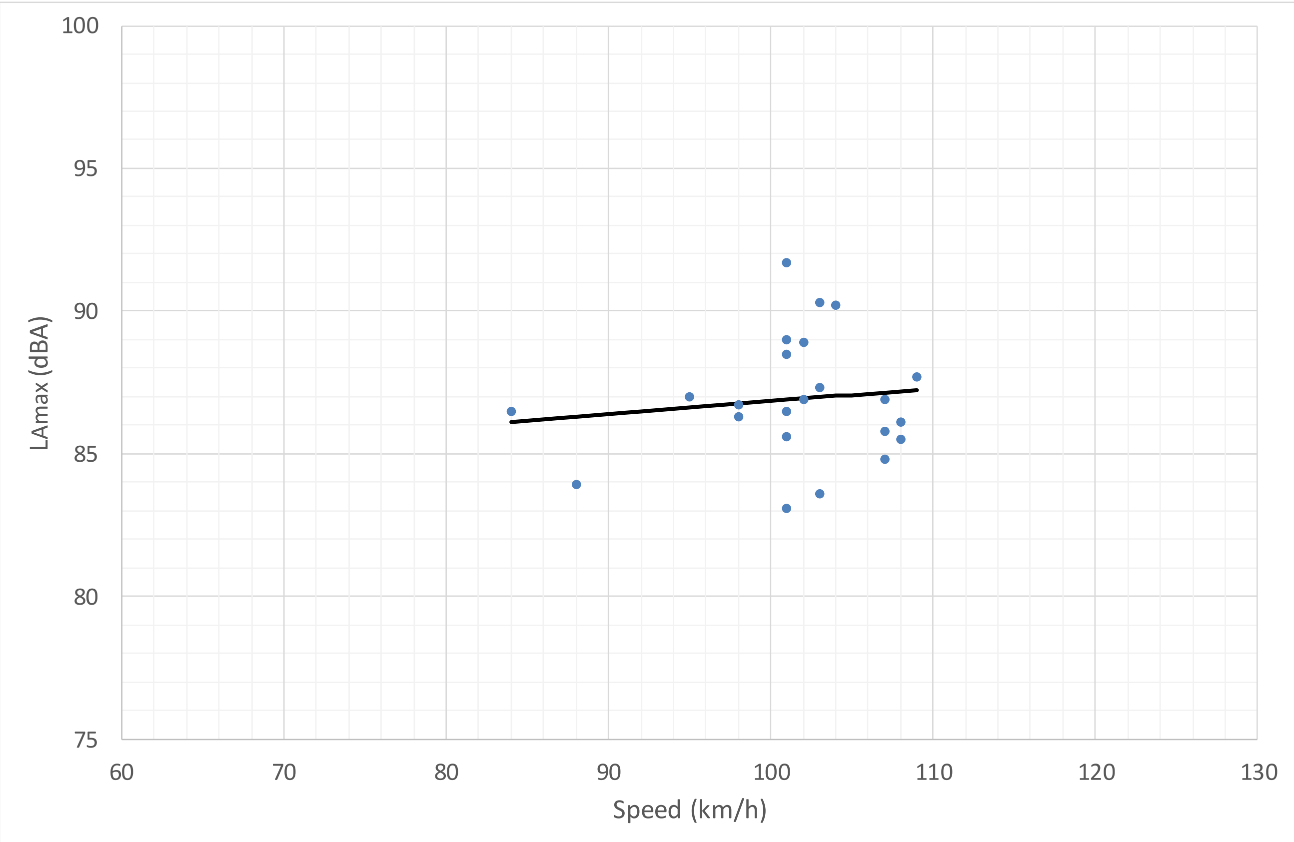


Figure B48 Location D (LNDG 2 Pass), Pre-Grind – Class 2b

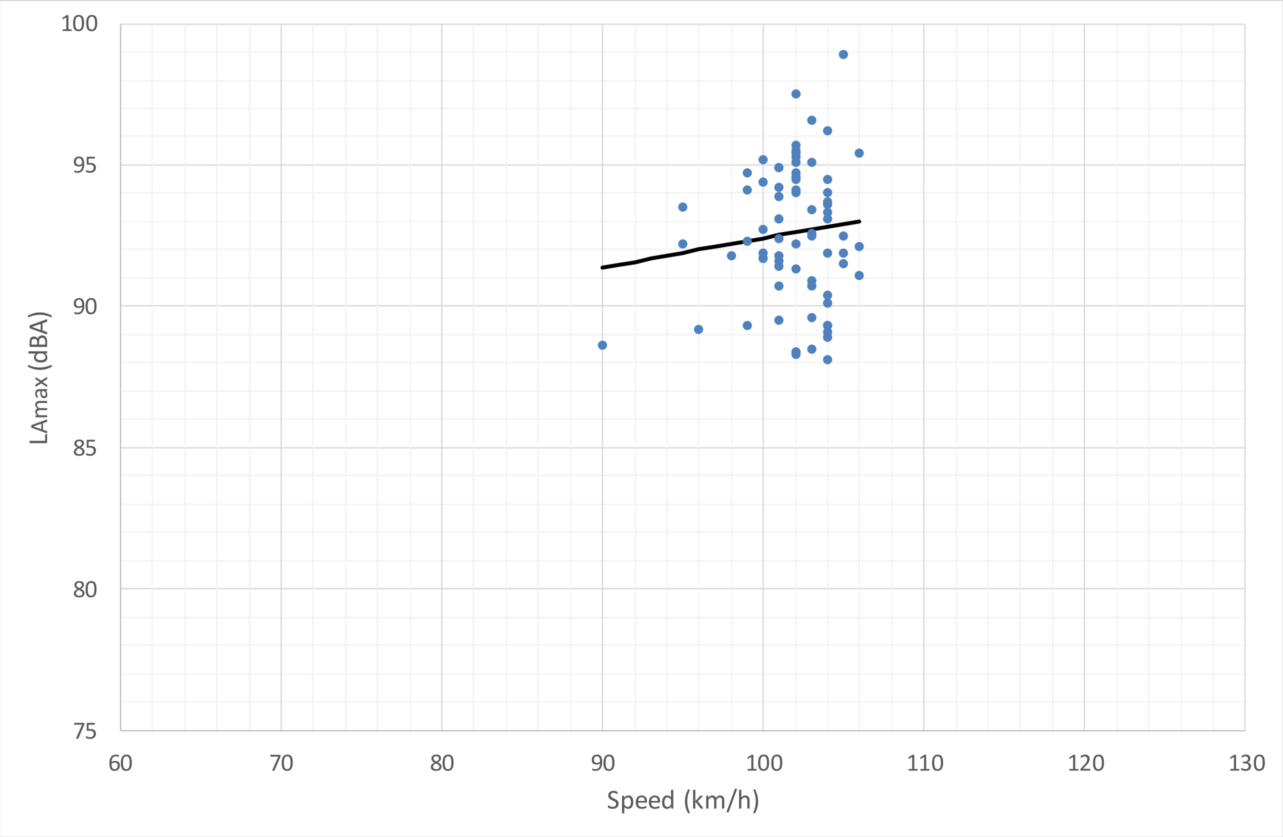


Figure B49 Location D (LNDG 2 Pass), Pre-Grind – Bin 4

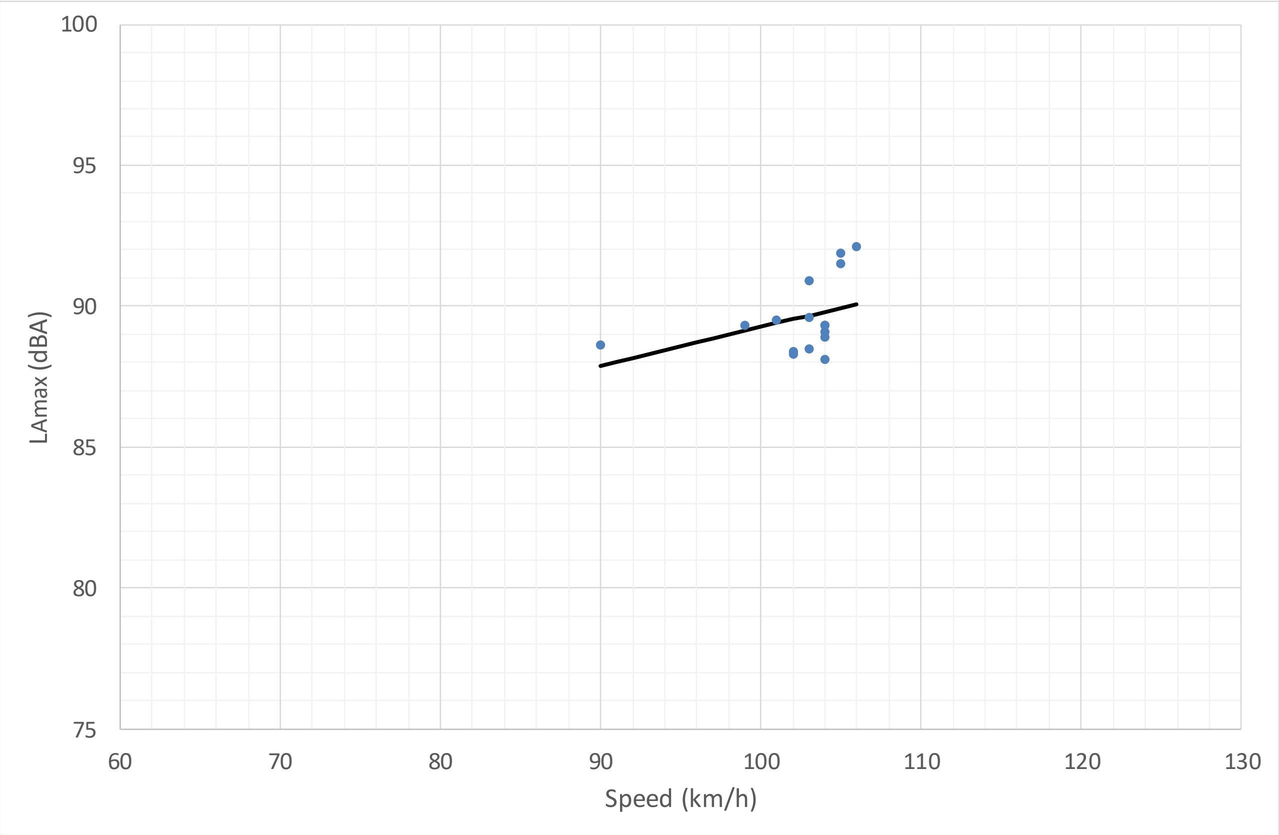


Figure B50 Location D (LNDG 2 Pass), Pre-Grind – Bins 5 to 8

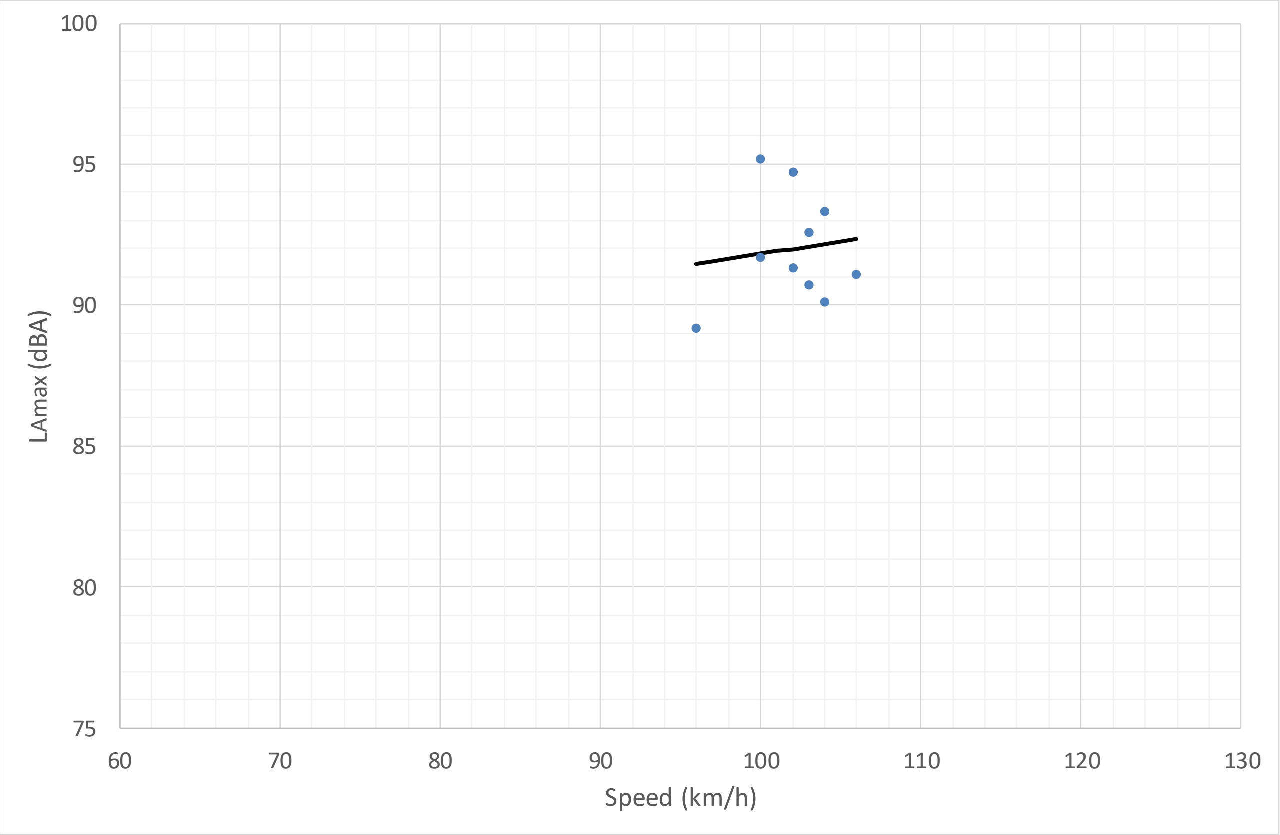


Figure B51 Location D (LNDG 2 Pass), Pre-Grind – Bin 9

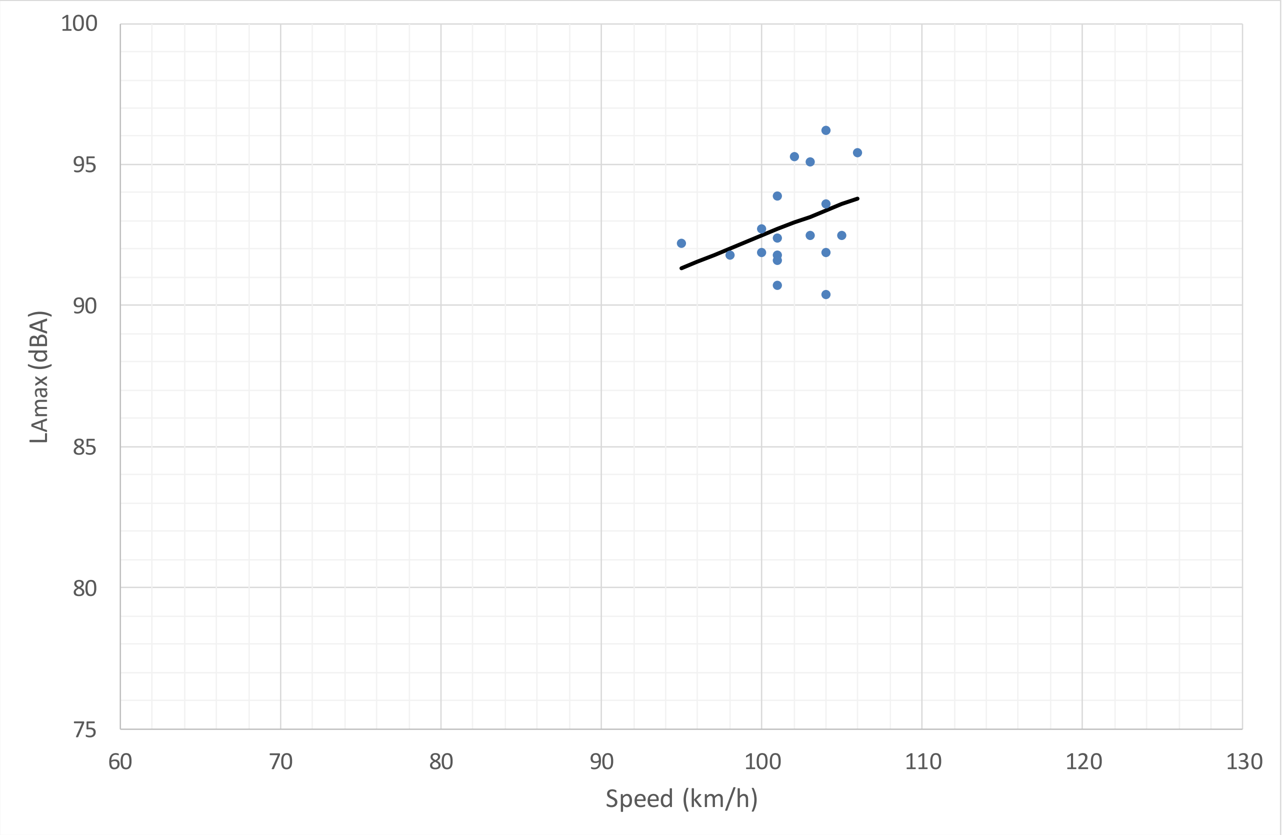


Figure B52 Location D (LNDG 2 Pass), Pre-Grind – Bins 10+

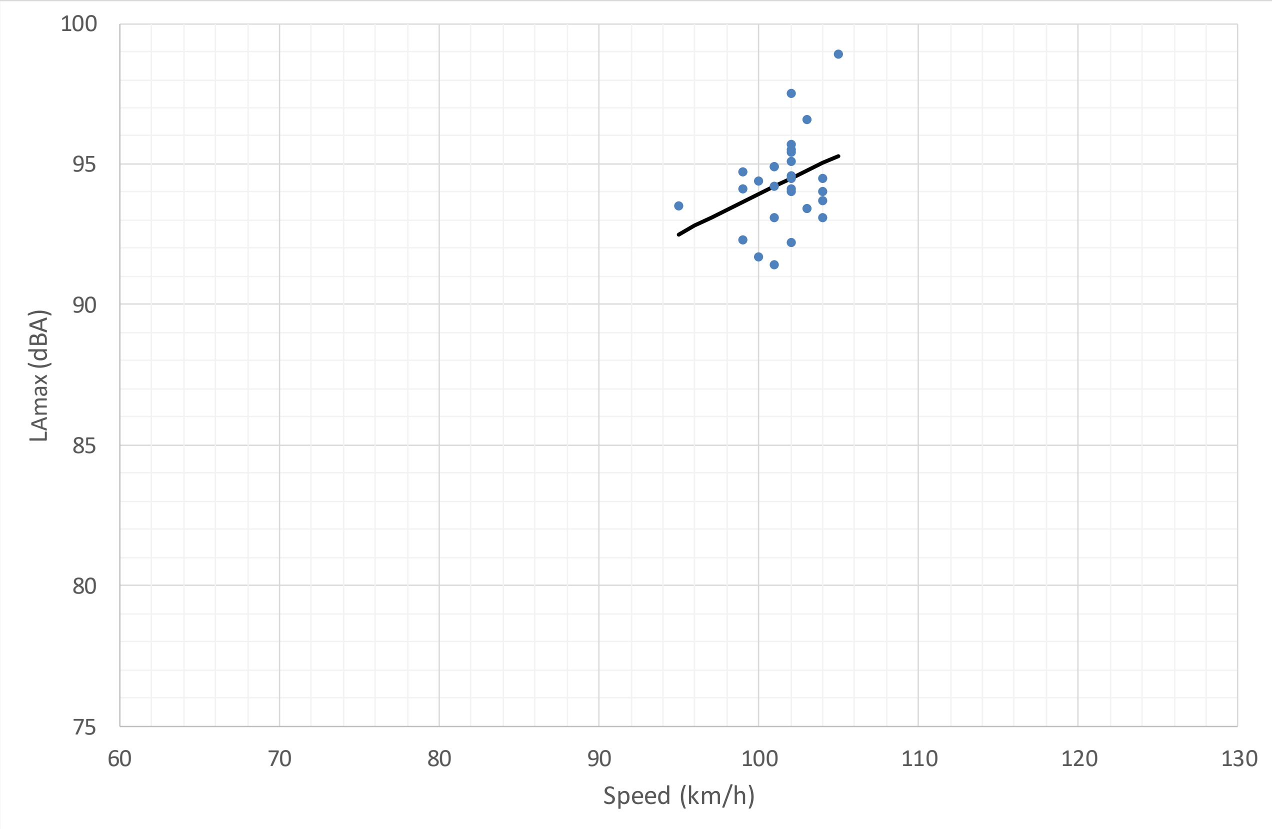


Figure B53 Location D (LNDG 2 Pass), Post-Grind – Class 1

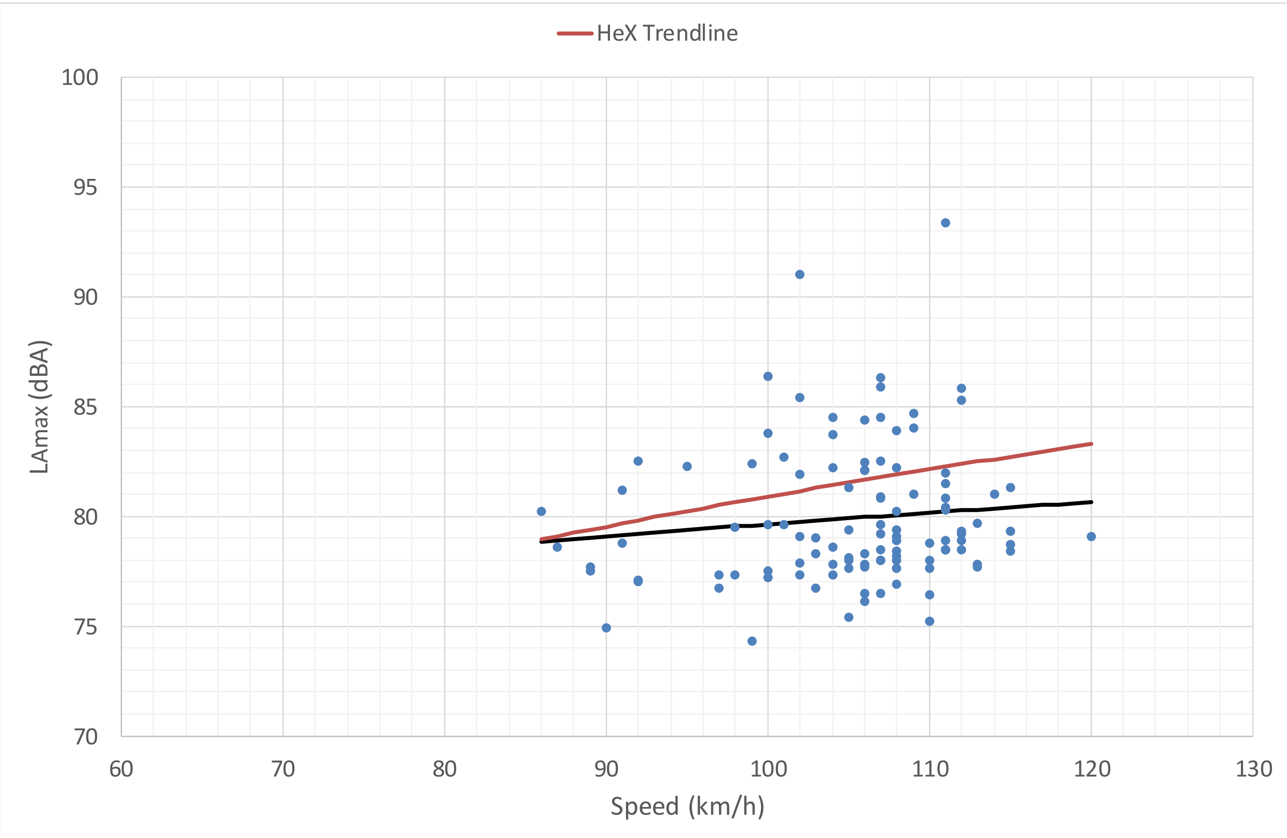


Figure B54 Location D (LNDG 2 Pass), Post-Grind – Class 2a

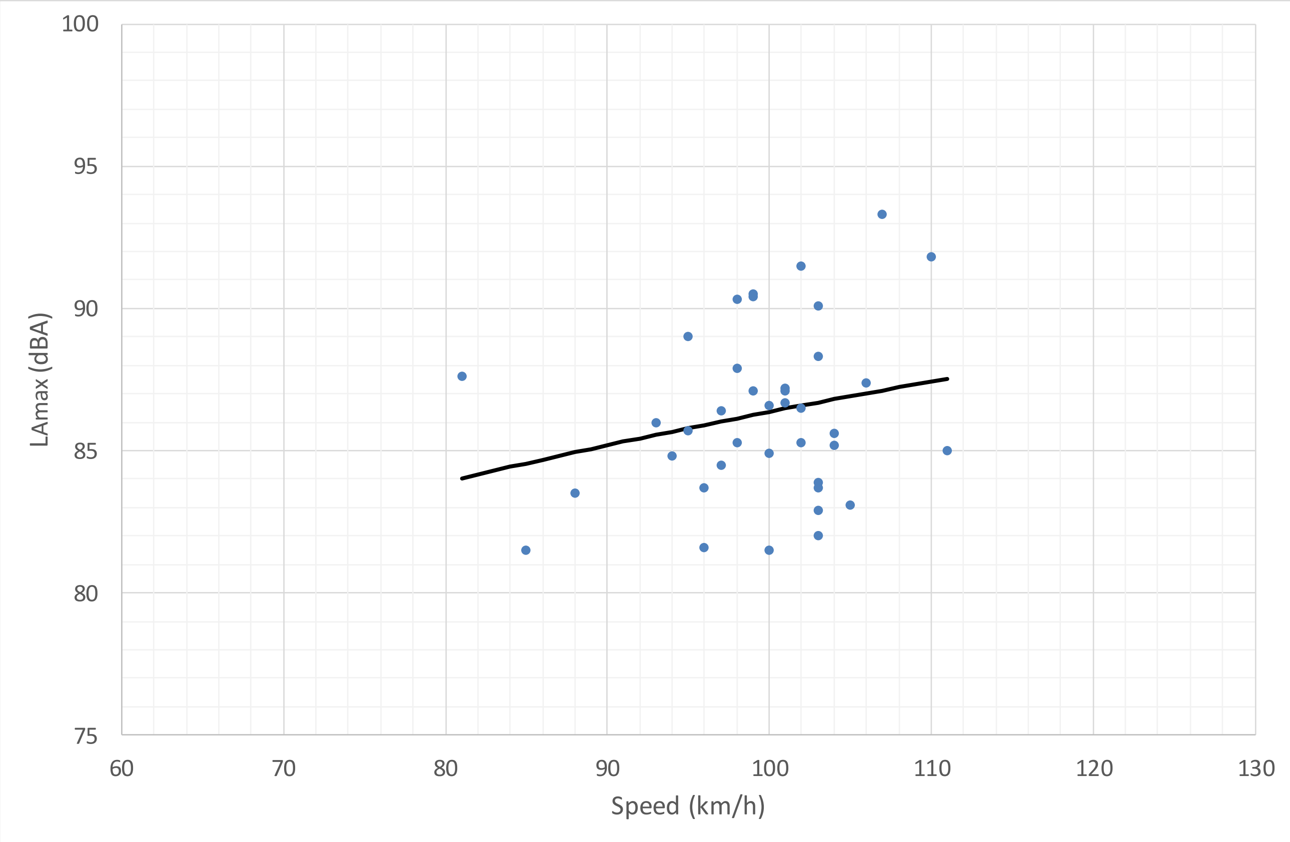


Figure B55 Location D (LNDG 2 Pass), Post-Grind – Class 2b

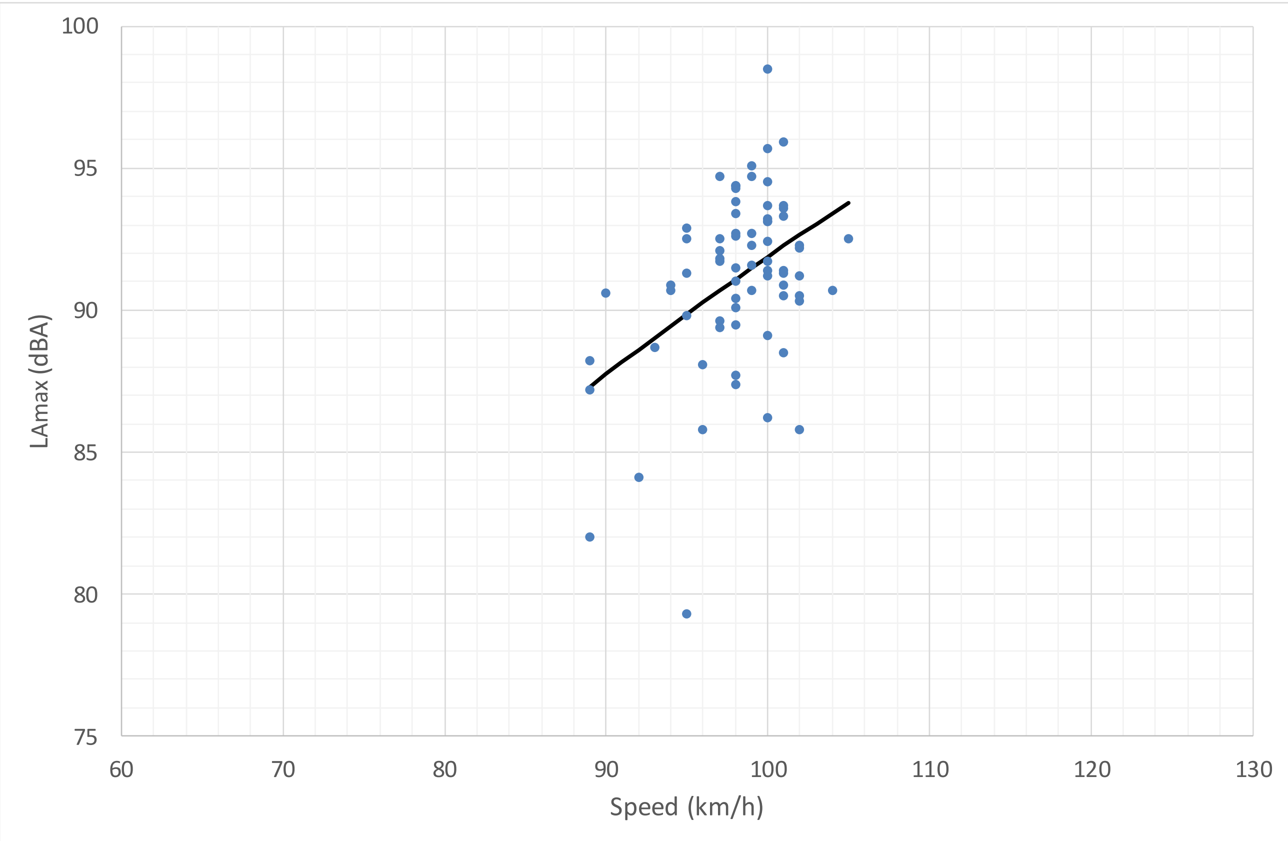


Figure B56 Location D (LNDG 2 Pass), Post-Grind – Bin 4

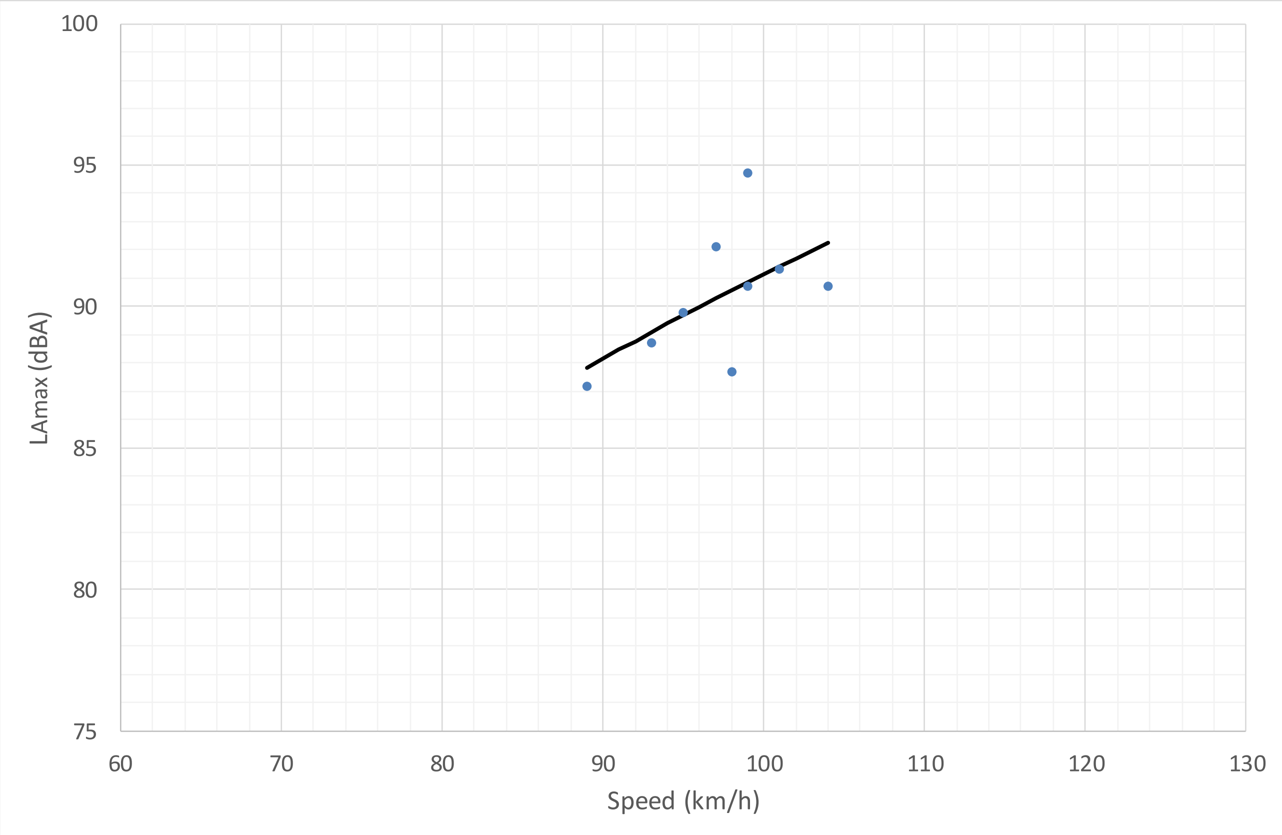


Figure B57 Location D (LNDG 2 Pass), Post-Grind – Bins 5 to 8

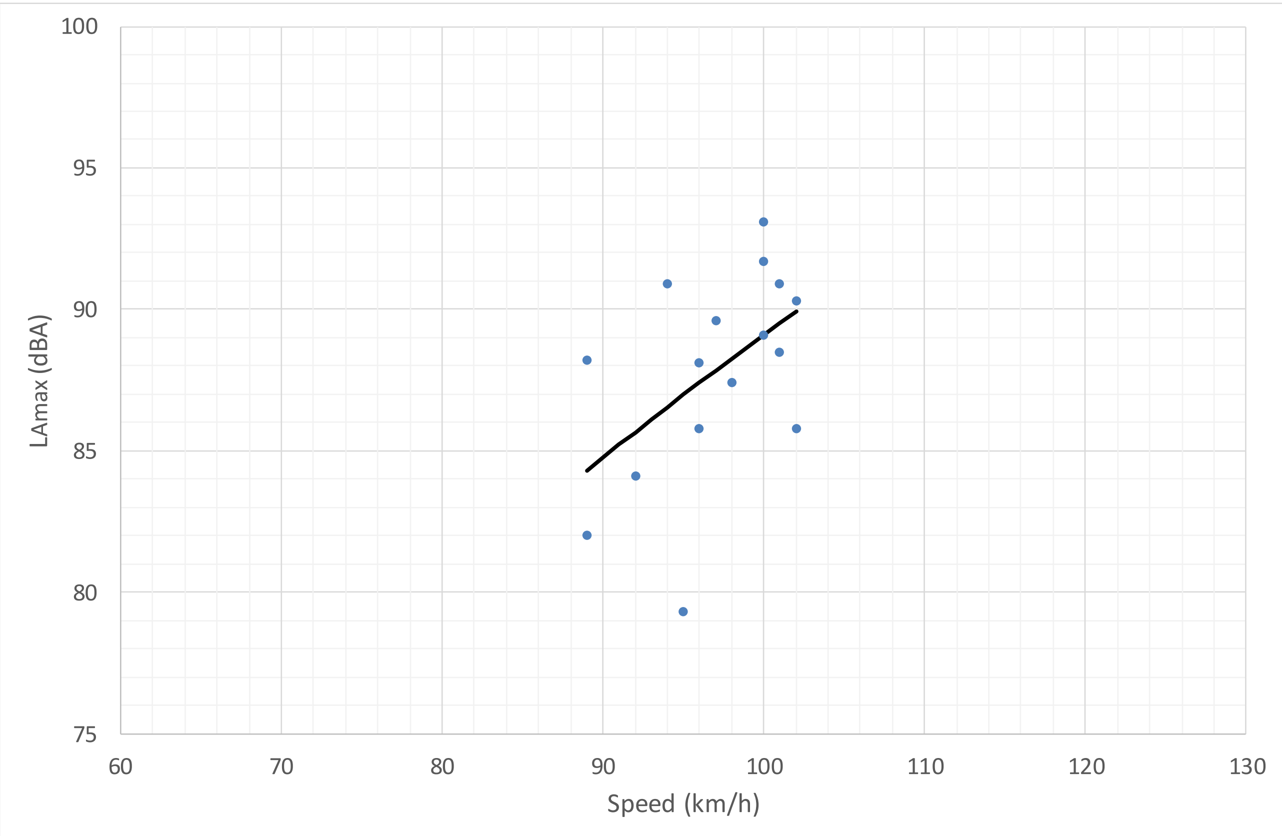


Figure B58 Location D (LNDG 2 Pass), Post-Grind – Bin 9

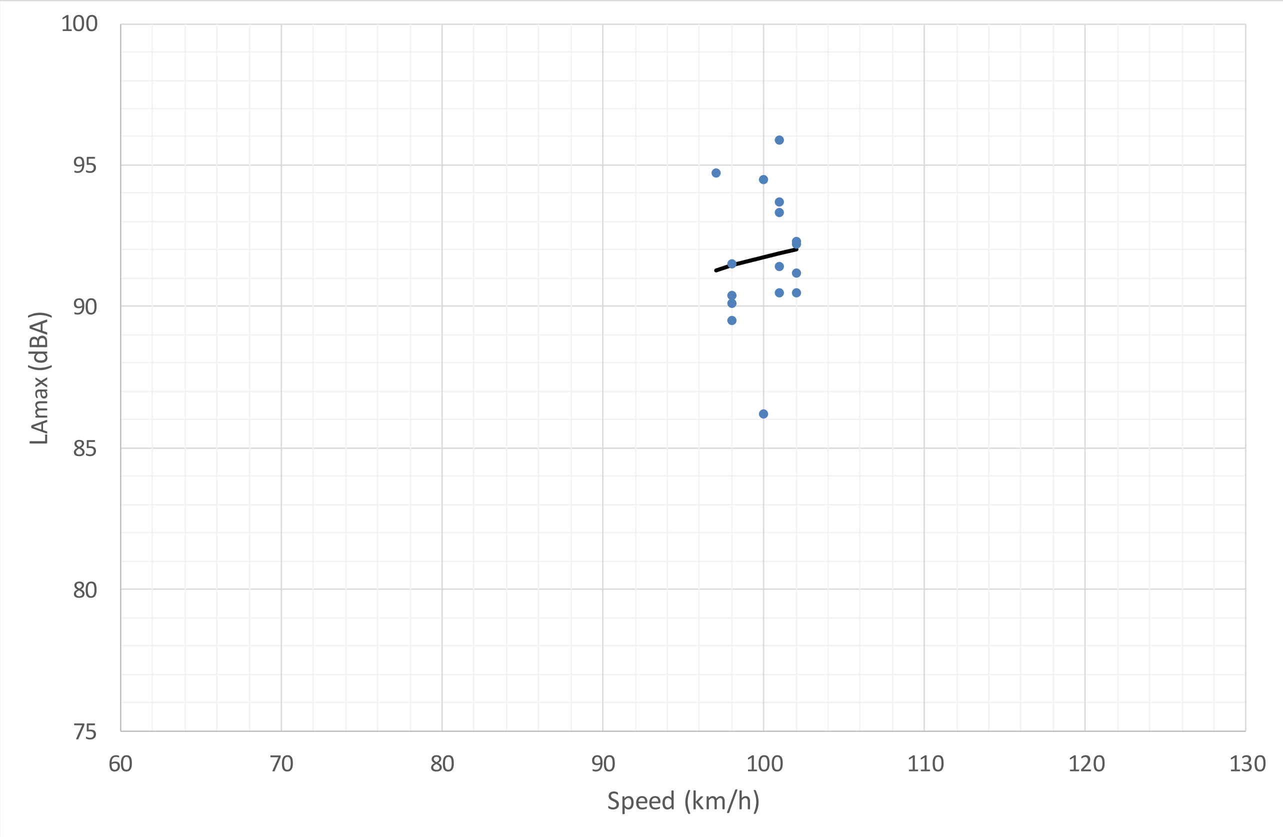


Figure B59 Location D (LNDG 2 Pass), Post-Grind – Bins 10+

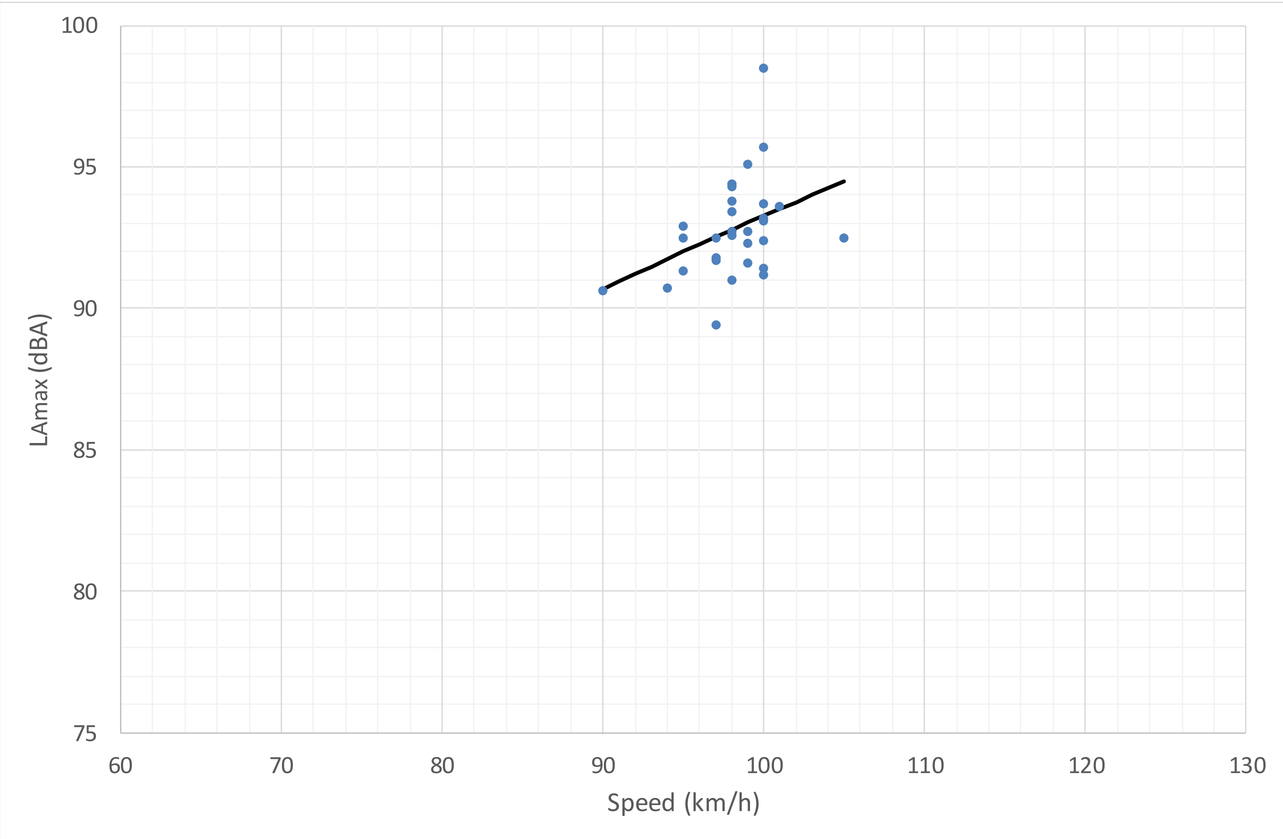


Figure B60 Location D (LNDG 2 Pass), Class 2b Vehicle Breakdown

APPENDIX C

Site Photographs

Statistical Passby Measurements - Location A (LNDG 3 Pass) Pavement

Figure C1 Location A (LNDG 3 Pass) – Pavement Pre-Grid

Figure C2 Location A (LNDG 3 Pass) – Pavement Post-Grind

Statistical Passby Measurements - Location B Pavement

Figure C3 Location B – Pavement Pre-Grind

Figure C4 Location B – Pavement Post-Grind

Statistical Passby Measurements - Location C Pavement

Figure C5 Location C – Pavement Pre-Grind

Figure C6 Location C – Pavement Post-Grind

Statistical Passby Measurements - Location D Pavement

Figure C7 Location D – Pavement Pre-Grind

Figure C8 Location D – Pavement Post-Grind

Statistical Passby Measurements – Typical Setup

Figure C9 Typical SPBI Measurement Setup – Location A (LNDG 3 Pass) Pre-Grind

OBSI Measurements – Tyre Tread

Figure C10 Yokohama ASPEC A300 Tyre Tread

Figure C11 Yokohama ASPEC A300 Tyre Tread

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