BUS NOISE ASSESSMENT REPORT

12/12/2023

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1 INTRODUCTION

HDR was recently commissioned to guide and advise the City of Stratford, Ontario in their transition from diesel to zero emission buses. The engines of these electric and hybrid buses generally reduce the exterior noise emitted during travel in comparison to their diesel counterparts, particularly at low speeds (≤20 kmh). The purpose of this document is to summarize HDR's findings on noise between bus types, and to suggest future actions for the city to take.

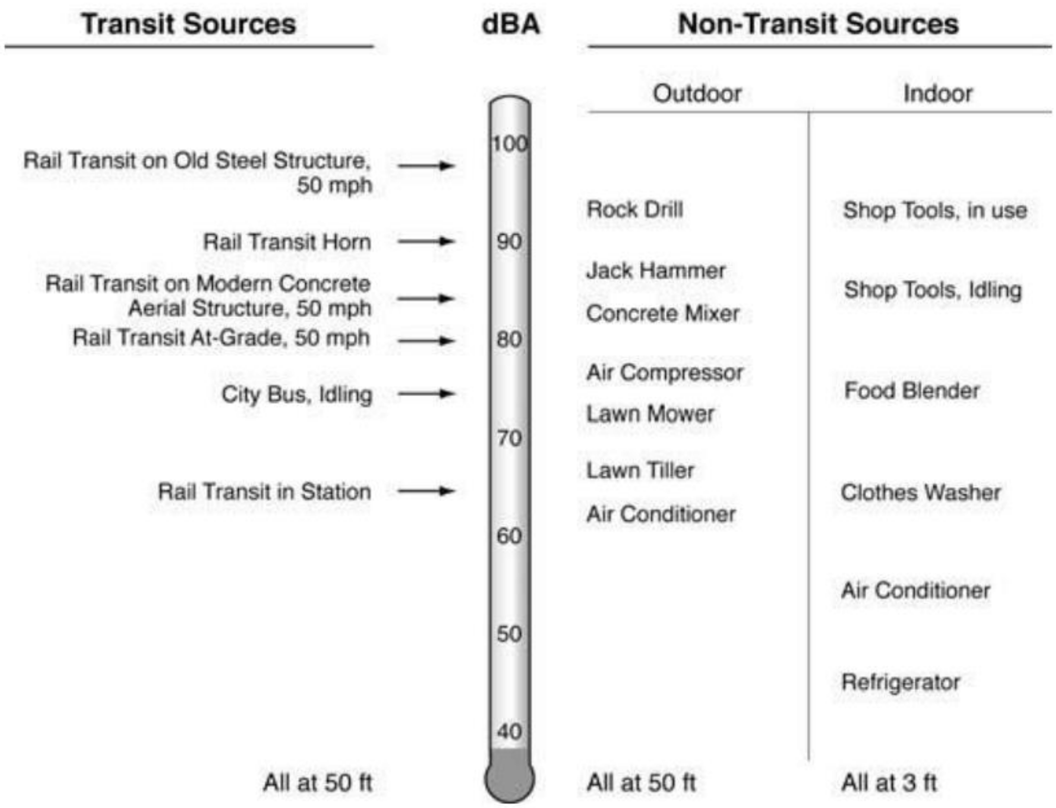
First, we will briefly go over the fundamentals of sound, before moving on to look at the interior noise for each bus our clients have interest in. Then, we will cover a total of 6 documents on exterior noise separately. Following, we will show how this exterior noise propagates over a distance, and end with a summary of results.

1.1 Sound Basics

Sound is made up of tiny fluctuations in air pressure. Sound is characterized by its amplitude (how loud it is), frequency (or pitch), and duration. Sound, within the range of human hearing, can vary in amplitude by over one million units. Therefore, a logarithmic scale, known as the decibel (dB) scale, is used to quantify sound intensity and to compress the scale to a more manageable range. Noise is simply defined as unwanted sound; the terms noise and sound are often used interchangeably.

The human ear does not hear all frequencies equally. In fact, the human hearing organs of the inner ear deemphasize very low and very high frequencies. The most common weighting scale used to reflect this selective sensitivity of human hearing is the A-weighted sound level (dBA). The range of human hearing extends from approximately 3 dBA to around 140 dBA (all sound pressure levels in this report are relative to 20 micropascals). Figure 1 provides typical A-weighted levels for various noise sources.

Figure 1. Typical Noise Levels



Source: FTA, 2018

Because of the logarithmic scale, sound levels cannot be simply added or subtracted. If sound energy is doubled, the sound level only increases by 3 dB. However, a doubling of sound energy is not perceived by humans as a doubling of loudness. A 3-dB change is considered a just noticeable difference, a 5-dB change is considered a noticeable difference, and a 10-dB change is considered a doubling or halving of loudness.

Environmental sound levels are often expressed over periods of time, allowing time-varying signals to be represented by sound levels averaged over intervals (for example, a one-hour period). One metric used to describe environmental sound is the equivalent average sound level (Leq). The Leq represents a constant sound that, over the specified time period, has the same acoustic energy as the time-varying signal. In contrast, Sound Exposure Level (SEL) is equivalent to the total sound energy over a period of time rather than the average. Additionally, L_{Max} is the maximum sound level recorded over a period of time.

1.2 Measurement Methods

For the purposes of the data requested by the client, SEL values are preferred, due to their use as a reference within Federal Transit Administration (FTA) guidance. These will be obtained from L_{Max} measurements taken of buses passing by a microphone at a constant speed. There are primarily two standards for this type of measurement: ISO 11819-1 Measurement of the influence of road surfaces on traffic noise Part 1 Statistical pass-by method, or SAE J366b Exterior Sound Level for Heavy Trucks and Buses. In the former a receiver is placed 7.5 m from the road centerline and 1.2 m above the road surface, while in the latter it is placed 50 ft away (15.24 m) from the road centerline, at a height of 4 ft (1.22 m).

2 PENN STATE/ALTOONA BUS DATA- INTERIOR NOISE

The Pennsylvania State University (Penn State) has performed substantial testing on various buses over the years in cooperation with the FTA. In particular, they have done these tests for the three electric buses currently under consideration by our client in Stratford. These buses are the Forest River Bus LLC Ford E-450 Cutaway Shuttle Bus, the Nova Bus LFSe+, and the New Flyer XE40.

Unfortunately, their tests of the LFSE+ were partial and did not include noise testing, but the others had extensive assessment including both exterior and interior noise tests on these vehicles. But due to their method of measuring pass-by noise, which involved measurements during acceleration rather than constant speed, their exterior results are incomparable to the rest of our collected documents. For this reason, we will focus solely on their interior noise measurements.

For their analysis, they took measurements during three conditions. In the first, the bus is stationary with its engine and components turned off, and a white noise generating device emitting a constant 80 dBA is stuck to the side of the vehicle. In the second, the bus accelerates from a standstill to 35 mph. In the third, the bus operates at constant speeds between 0 mph and 55 mph, and any rattling or vibration is noted. The results of the first test can be seen in Table 1. Additionally, to provide greater context to the electric bus measurements, we also include data for two similarly sized diesel buses from the same manufacturers: the Forest River Bus INC Model Concorde II F-650 and the New Flyer D40LF.

Table 1. Interior Noise Test 1 Sound Levels in dBA

Location	Forest River Diesel	Forest River Electric	New Flyer Diesel	New Flyer Electric
Driver's Seat	44.9	47.1	52.9	46.5
Front Passenger Seats	49.7	47.0	49.4	47.4
In Line with Front Speaker	47.7	47.9	48.0	46.9
In Line with Middle Speaker	49.8	46.5	49.3	47.7
In Line with Rear Speaker	50.5	47.3	46.2	47.9
Rear Passenger Seats	46.8	46.7	46.5	45.5

Source: Penn State New Flyer and Forest River test data, (2006-2022)

In this test, the buses all had quite comparable noise levels, implying that they all will have similar interior sound contributions from exterior sources like surrounding traffic. Table 2 shows data from the second test.

Table 2. Interior Noise Test 2 Sound Levels in dBA

Location	Forest River Diesel	Forest River Electric	New Flyer Diesel	New Flyer Electric
Driver's Seat	73.1	63.3	75.2	69.3
Front Passenger Seats	71.6	62.9	76.6	66.4
Middle Passenger Seats	69.5	62.9	78.8	68.5
Rear Passenger Seats	68.6	63.4	78.5	70.2

Source: Penn State New Flyer and Forest River test data, (2006-2022)

In this test, the electric buses have substantially lower operation noise than their diesel counterparts. Additionally, for the third test, nothing was detected for any bus. With the combination of these three results, we can conclude that overall interior noise levels are reduced in switching from diesel to electric. We will now move onto exterior noise analysis.

3 EXTERIOR NOISE LITERATURE REVIEW

HDR reviewed information in the following papers/reports:

1. Transit Noise and Vibration Impact Assessment Manual, FTA, 2018.

2. Modelling noise reductions using electric buses in urban traffic. A case study from Stuttgart, Germany, Felix Laib et al. / Transportation Research Procedia 37 (2019) 377–384. Accessed November 27, 2023. https://doi.org/10.1016/j.trpro.2018.12.206

3. Tsoi, K., Becky P.Y. Loo, Xiangyi Li, and Kai Zhang. 2023. "The co-benefits of electric mobility in reducing traffic noise and chemical air pollution: Insights from a transit oriented city." *Environment International* 178, 108116. Accessed November 27, 2023. https://doi.org/10.1016/j.envint.2023.108116

4. Misanovic, S., D. Taranovic, M. Maljkovic, and B. Milicic. 2022. "Measurement noise level of E-bus HIGER KLQ6125GEV3 on the polygon." *IOP Conf. Ser.: Mater. Sci. Eng.* 1271, 012018. Accessed November 27, 2023. Measurement noise level of E-bus HIGER KLQ6125GEV3 on the polygon - IOPscience

5. Ross, J., Michael A. Staiano. 2007. "A comparison of green and conventional diesel bus noise levels." Paper presented at NOISE-CON 2007, Reno, Nevada, October 22-24.

6. Doran, BR., K. Crossland, S. Wilkening, V Warren. 2022. "Investigation of the external noise emitted from electric buses in New Zealand and the need for acoustic vehicle alerting systems to improve road user safety." *Waka Kotahi NZ Transport Agency research report* 703. Accessed November 27, 2023. Research Report 703 Investigation of the external noise emitted from electric buses in New Zealand and the need foracoustic vehicle alerting systems to improve road user safety (nzta.govt.nz)

3.1 FTA Transit Noise and Vibration Impact Assessment Manual

The FTA Transit Noise and Vibration Impact Assessment Manual provides reference SEL values for diesel, electric, and hybrid buses. These reference levels assume the receiver is 50 feet from the roadway, the bus is traveling a constant 50 mph, and normal roadway surface conditions. It should be noted that the document states that SEL for hybrid buses should be considered on a case-by-case basis. Table 3 shows the FTA reference SEL values.

Table 3. FTA Reference SEL Values for Different Bus Types

Source	Reference SEL, dBA
Diesel Buses	82
Electric Buses	80
Hybrid Buses	83

Source: FTA, 2018

Many of the bus noise emission values HDR identified are reported as L_{Max}, and are measured at different receiver distances and pass-by speeds. Therefore, HDR converted them into SEL by correcting for speed and distance to facilitate comparisons with the FTA reference SEL values at 50 feet and 50 mph. This is done by Equation F-4 in the FTA manual,

$$SEL_{ref} = L_{Amax} + 20\log\left(\frac{D_{meas}}{50}\right) - 25\log\left(\frac{S_{meas}}{50}\right) + 3.3.$$

Here, D_{meas} is the distance between the source and receiver in feet, and this term in FTA Equation F-4 converts each pass-by speed to a 50 foot receiver distance. Additionally, S_{meas} is the speed of the moving vehicle in miles per hour, and this term in FTA Equation F-4 converts each pass-by speed to 50 mph. For reference, 50 mph equals 80 kmh, 50 kmh equals 31 mph.

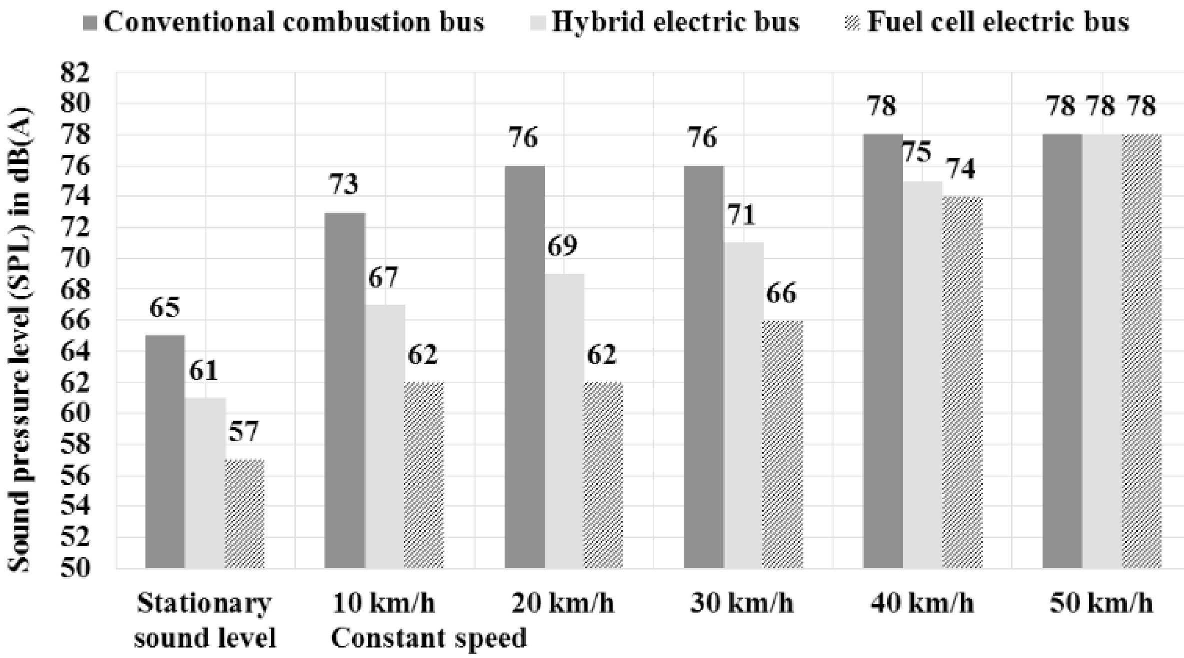
It is important to keep in mind that even though all speeds are being converted to 50 mph references, each data point reported in an individual paper has a unique speed and L_{max} associated with it. For this reason, we will refer to the speed of each measurement as the "measurement speed" to not confuse it with its value when corrected to 50 mph. Additionally, hereafter any SEL values presented are corrected to 50 feet and 50 mph.

3.2 Modelling noise reductions using electric buses in urban traffic. A case study from Stuttgart, Germany. (Laib et al.)

The researchers implemented methods in ISO 11819-1 (Measurement of the influence of road surfaces on traffic noise. Part 1: Statistical pass-by method) to measure bus pass-by noise from a diesel bus (IC-bus: type Mercedes Citaro O 530, 40 feet long), a hybrid bus (HE-bus: type Volvo 7900 HA, 60 feet long, articulated), and an electric bus (FCE-bus: type Mercedes Citaro O 530 B Hybrid, 40 feet long). Please note that as FCE is a fuel cell electric bus, it operates by a slightly different process than a battery electric bus. Despite this, it is fair to assume that the noise levels between the two are similar.

The research team performed pass-by measurements when the buses were stationary and for 10 kmh increments up to 50 kmh. Figure 2 shows the resulting L_{Max} values for each scenario.

Figure 2. LMax values for different bus types at different speeds.



Source: Laib et al.

The electric bus is substantially quieter than the diesel, and the hybrid bus is moderately quieter at speeds of 30 kmh and below. Above these speeds, the noise from the different bus types become comparable with each other.

Table 4 shows the conversions to SEL.

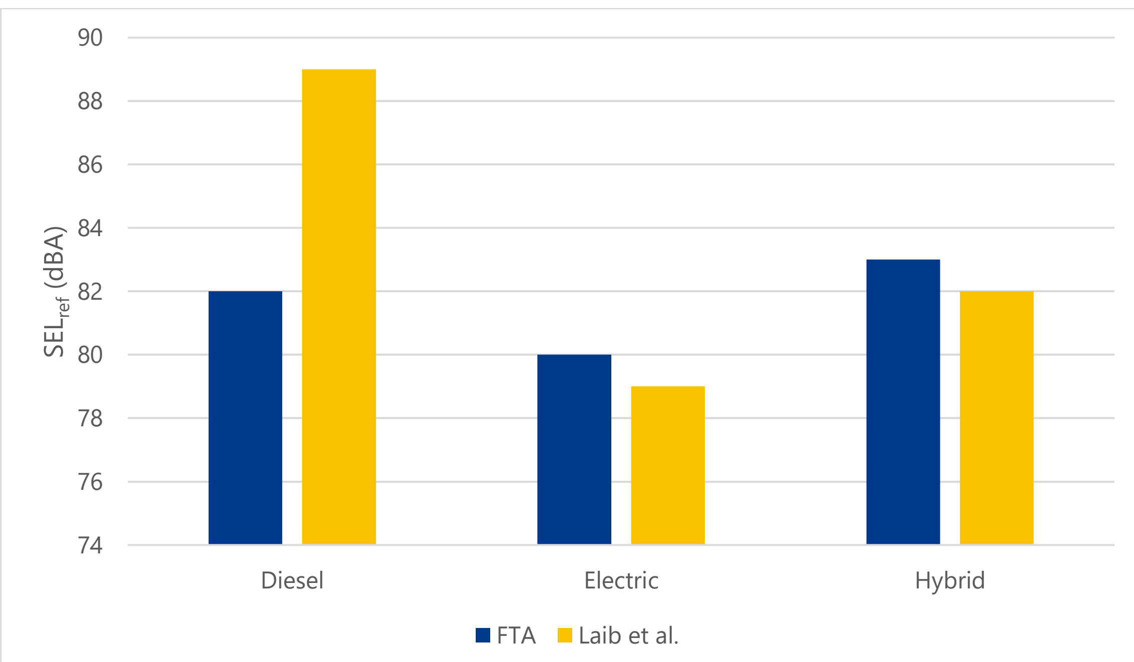
Table 4. LMax and SEL Values for Different Bus Types in dBA

Measurement Speed (kmh)	Diesel L_{Max}	Diesel SEL	Electric L_{Max}	Electric SEL	Hybrid L_{Max}	Hybrid SEL
0	65	N/A	57	N/A	61	N/A
10	73	93	62	82	67	87
20	79	91	62	74	69	81
30	76	84	66	74	71	79
40	78	83	74	79	75	80
50	78	80	78	80	78	80
Decibel Average	N/A	89	N/A	79	N/A	82
FTA	N/A	82	N/A	80	N/A	83

Source: Laib et al., FTA 2018

Hybrid buses show much lower SEL values than diesel at speeds of 20 kmh and below, while electric shows the same at 30 kmh and below. To better compare with FTA, we also show it and the average SEL value for each bus type in Figure 3.

Figure 3. Comparison of Laib et al. with FTA SEL Values



Source: Laib et al., FTA 2018

Presenting the data this way, it is evident that the researchers' diesel bus SEL values are much greater than the FTA's reference SEL for diesel buses and SEL values for electric and hybrid buses show closer agreement with FTA values.

3.3 The co-benefits of electric mobility in reducing traffic noise and chemical air pollution: Insights from a transit oriented city. (Tsoi et al.)

This paper summarizes bus pass-by noise levels measured by other research teams. All measurements utilized methods in ISO 11819-1 (Measurement of the influence of road surfaces on traffic noise. Part 1: Statistical pass-by method). Tsoi, et al. also solely measured pass-by noise from diesel and electric buses, not hybrid. Once again, research teams measured bus noise levels from stationary buses and moving buses when speeds changed in 10 kmh increments up to 50 kmh. These measurement results are presented as L_{Max} values. Table 5 summarizes bus specifications from Tsoi et al. Table 5

Table 5. Bus Makes and Specifications within Tsoi et al.

Paper	Bus Type	Make	Specifications
Borén	Diesel	Unknown	Length: 40 ft
	Electric	Solaris Urbino 12	Length: 40 ft
Mathes et al.	Diesel	Unknown	Length: 40 ft
	Electric	Unknown	Length: 40 ft
Praticò and Fedele	Diesel	Unknown	Unknown
	Electric	Unknown	Unknown

Source: Tsoi et al.

Only one bus make was identified within the paper, but most were identified as 40 feet long. Table 6 shows the paper's collected data.

Table 6. LMax and SEL Values for Different Bus Types in dBA within Tsoi et al.

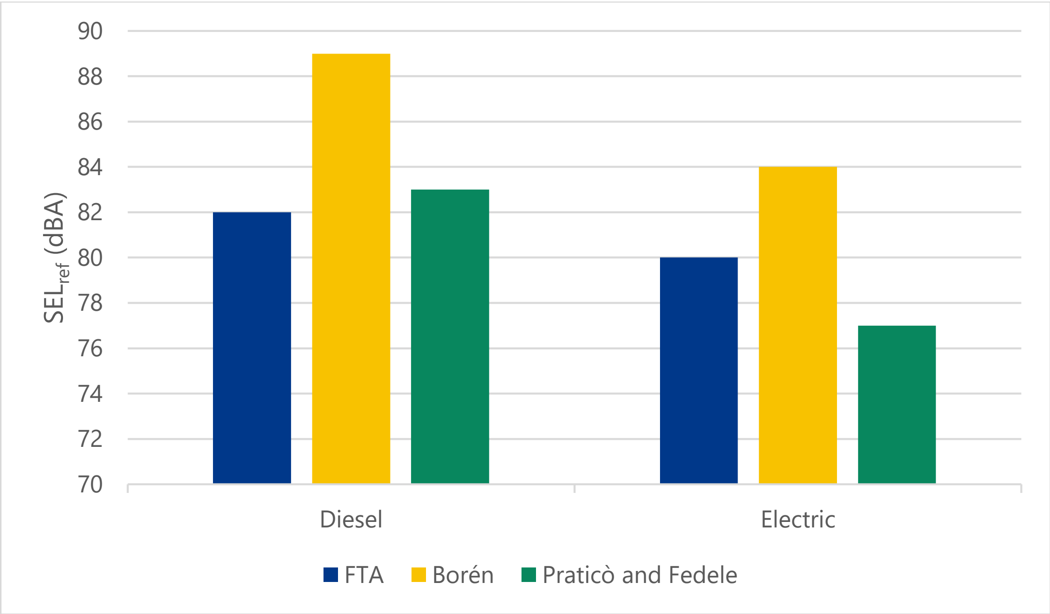
Report	Measurement Speed (kmh)	Diesel L_{Max}	Diesel SEL	Electric L_{Max}	Electric SEL
Borén	0	**75.2**	**N/A**	**68.6**	**N/A**
	10	**75.2**	**95**	**68.6**	**88**
	20	**75.2**	**87**	**68.6**	**81**
	30	**75.2**	**83**	**68.6**	**76**
	40	**73.9**	**79**	**70.4**	**75**
	50	**78**	**80**	**73.6**	**76**
	Decibel Average	**N/A**	**89**	**N/A**	**83**
Mathes et al.	0	**56.8**	**N/A**	**48.3**	**N/A**
	50	**77.8**	**80**	**76.1**	**78**
Praticò and Fedele	0	**67.1**	**N/A**	**59.2**	**N/A**
	10	**68.9**	**89**	**61.8**	**82**
	20	**70.7**	**83**	**64.4**	**77**
	30	**72.5**	**80**	**67**	**75**
	40	**74.3**	**79**	**69.6**	**74**
	50	**76.1**	**78**	**72.2**	**75**
	Decibel Average	**N/A**	**84**	**N/A**	**77**
FTA	N/A	**N/A**	**82**	**N/A**	**80**

Source: Tsoi et al., FTA 2018

Bus noise levels in Table 6 exhibit less variance with speed, and electric buses are quieter than diesel by varying amounts.

Figure 4 shows a comparison of FTA and the SEL averages of each bus type. Note that Mathes et al. is not included, as they provide only one relevant SEL value.

Figure 4. Comparison of Tsoi et al. with FTA SEL Values



Source: Tsoi et al, FTA 2018

The figure above shows that SEL values reported by Borén are consistently higher than the other SEL values for both diesel buses which are comparable to each other. Borén's SEL values for electric buses are also higher than the others, and Praticò's SEL values for electric buses are the lowest of the group.

3.4 Measurement noise level of E-bus HIGER KLQ6125GEV3 on the polygon. (Misanovic et al.)

The research team utilized methods in ISO 11819-1 (Measurement of the influence of road surfaces on traffic noise. Part 1: Statistical pass-by method) to measure pass-by noise from an electric bus (Higer KLQ6125GEV3, 40 feet long), a diesel bus (MAZ 203, 40 feet long), and a natural gas powered bus (MAZ 203 CNG, 40 feet long). Bus speeds included 30 kmh and 40 kmh. Table 7 shows results and conversions.

Table 7. LMax and SEL Values for Different Bus Types in dBA from Misanovic et al.

Measurement Speed (kmh)	Diesel L_{Max}	Diesel SEL	Electric L_{Max}	Electric SEL	Hybrid L_{Max}	Hybrid SEL
30	75.6	83	67.3	75	73.1	81
40	75.5	80	70.0	75	71.5	76
FTA	N/A	82	N/A	80	N/A	83

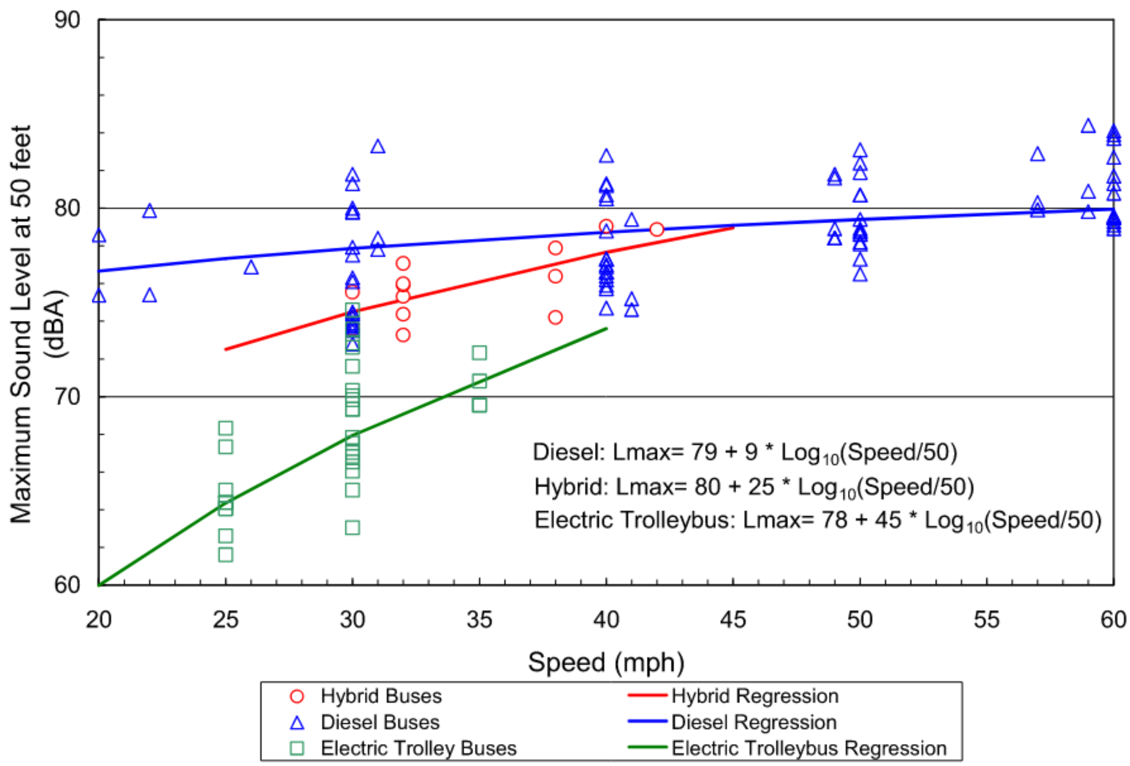
Source: Misanovic et al., FTA 2018

Similarly to Laib et al, the electric bus is moderately quieter than the diesel bus at 30 kmh, but as speed increases, this difference decreases. Due to the small amount of speeds analyzed, a graph is not needed, with their diesel results being nearly equal to FTA, their electric results being moderately lower, and their hybrid slightly lower than FTA SEL values.

3.5 A comparison of green and conventional diesel bus noise levels. (Ross et al, Noise-Con 2007)

The researchers implemented methods of SAE J366b (Exterior Sound Level for Heavy Trucks and Buses) for diesel, electric, and hybrid buses. They obtained L_{Max} data from two diesel buses (one MCI and one Neoplan 4700 series, 40 feet long) from 20 to 60 mph (32 kmh to 97 kmh), one hybrid bus (Irisbus Civis, 60 feet long and articulated) from 28 mph to 42 mph (45 kmh to 52 kmh), and one electric trolleybus (no make given) from 25 mph to 35 mph (40 kmh to 56 kmh). Figure 5Using their collected data points (shown as triangles, circles, and squares) the research team performed a linear regression to create a prediction model for maximum sound levels at varying speeds. Their results are in Figure 5.

Figure 5. LMax values for Different Bus Types from Ross et al.



Source: Ross et al.

The diesel buses exhibit little variation in sound level across all speeds, while the hybrid bus is moderately quieter at low speeds, becoming comparable as speed increases before reaching the diesel buses' noise level at about 45 mph. In contrast, the electric bus is substantially quieter than the diesel buses at low speed, before becoming moderately quieter than both hybrid and diesel at a speed of 40 mph. Table 8 shows this more clearly for specific speeds.

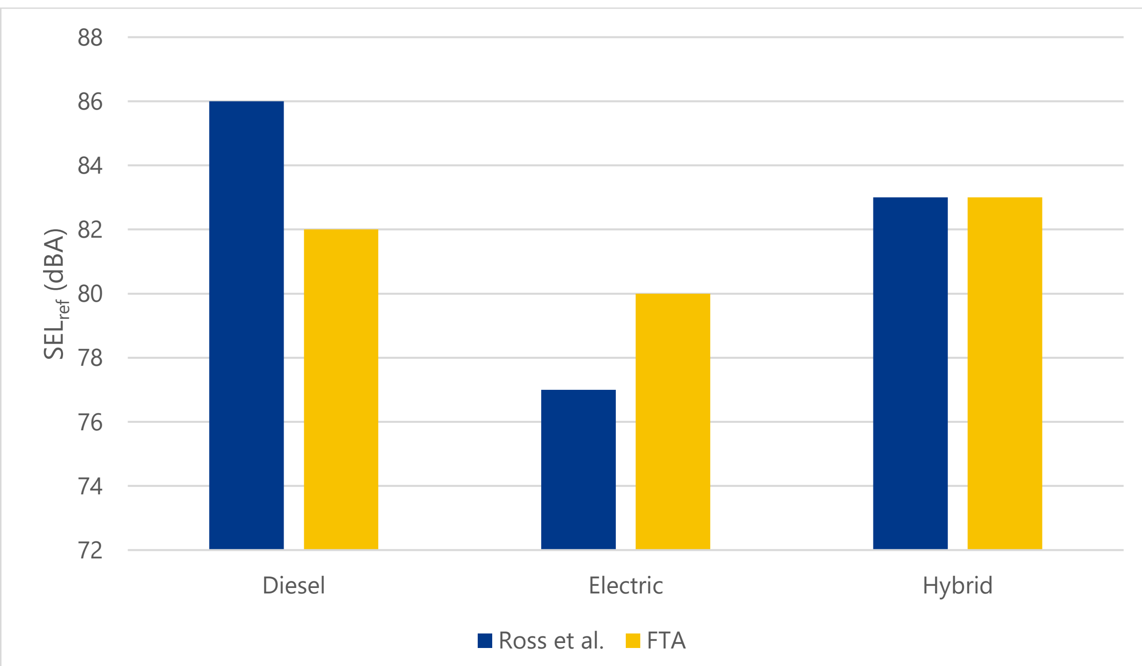
Table 8. LMax and SEL Values for Different Bus Types in dBA from Ross et al.

Measurement Speed (mph)	Measurement Speed (kmh)	Diesel L_{Max}	Diesel SEL	Electric L_{Max}	Electric SEL	Hybrid L_{Max}	Hybrid SEL
20	30	75	89	60	73	N/A	N/A
30	50	77	86	68	77	74	83
40	65	78	84	74	79	78	83
50	80	79	82	N/A	N/A	80	83
Decibel Average	N/A	N/A	86	N/A	77	N/A	83
FTA	N/A	N/A	82	N/A	80	N/A	83

Source: Ross et al., FTA 2018

Surprisingly, the electric bus is shown to be much quieter than the diesel buses at a higher range of speeds than the other studies, being 9 dBA lower at 50 kmh. Figure 6 shows this as graphical comparison.

Figure 6. Comparison of Ross et al. with FTA SEL Values



Source: Ross et al., FTA 2018

Their results show higher SEL values for diesel buses that are higher than FTA's values and lower for electric buses. SEL values for hybrid buses exhibit close agreement for hybrid.

3.6 Investigation of the external noise emitted from electric buses in New Zealand and the need for acoustic vehicle alerting systems to improve road user safety. (Doran et al.)

This research team performed measurements differently than the previous four research teams. They placed sound level meters 5 m and 10 m from the road centerline and obtained equivalent sound energy levels (L_{Aeq}) for diesel and electric buses at various constant pass-by speeds. Note that they did not state microphone heights nor bus makes. Table 9 summarizes their measured Leq values and the resulting SEL values.

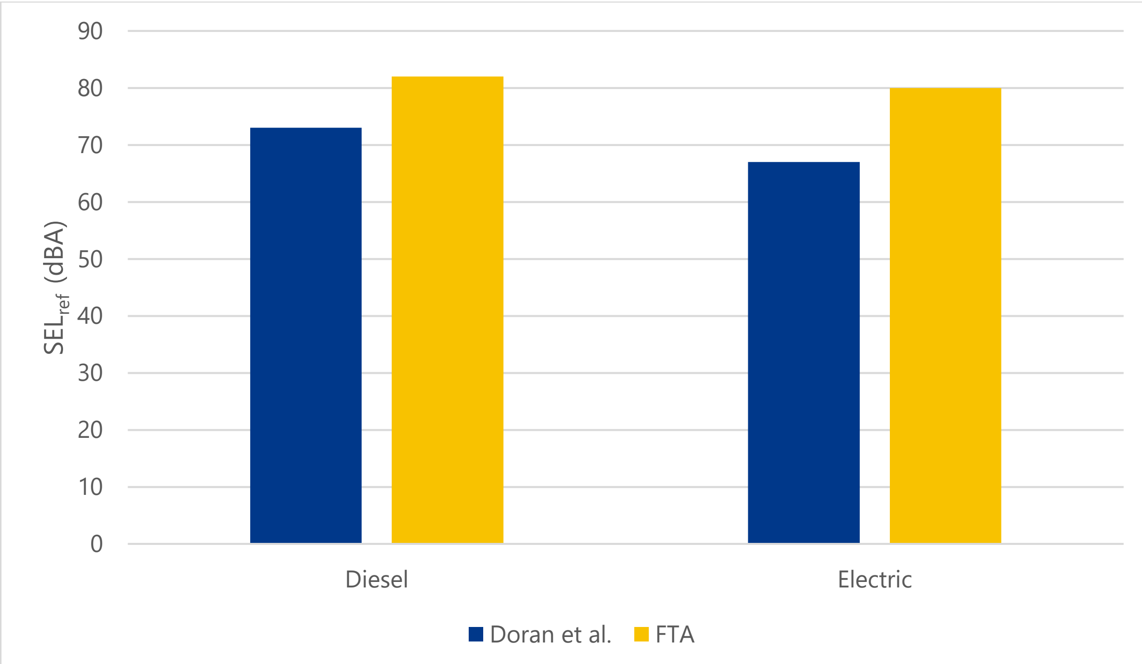
Table 9. Leq and SEL Values for Different Bus Types in dBA from Doran et al.

Measurement Receiver Distance (m)	Measurement Speed (kmh)	Diesel L_{eq}	Diesel SEL	Electric L_{eq}	Electric SEL
5	10	63	79	55	71
	30	63	67	62	66
	50	66	65	69	68
10	10	58	74	51	67
	30	59	63	58	62
	50	62	61	65	64
Decibel Average	N/A	N/A	73	N/A	67
FTA	N/A	N/A	82	N/A	80

Source: Doran et al., FTA 2018

In this data, we interestingly see the electric bus begin to become comparable in noise to the diesel at speeds as low as 30 kmh, even becoming louder than it at a high speed of 50 kmh. This is surprising, as since L_{eq} is the average sound level over a period, we would expect to SEL values obtained from it to be lower than those obtained from L_{Max} values. Figure 7 shows a graphical comparison.

Figure 7. Comparison of Doran et al. with FTA SEL Values



Source: Doran et al., FTA 2018

Their results for the average SEL are lower than the FTA values, likely because HDR utilized L_{eq} values to calculate SEL using FTA Equation F-4 rather than L_{Max} values.

3.7 Summary of Bus SEL Values

HDR averaged the SEL data per measurement speed and bus type from each of the previously mentioned research papers. Additionally, HDR calculated the overall average SEL per bus type across all measurement speeds. Table 10 presents this data for diesel buses.

Table 10. Calculated Diesel SEL Averages per Measurement Speed

Measurement Speed (kmh)	SEL (dBA)
10	91
20	88
30	83
40	83
50	80
Overall	86
FTA (50 mph, 80 kmh)	82

Source: FTA, 2018.

The calculated average SEL for diesel buses is 4 dBA higher than the FTA reference SEL value, however the FTA reference speed is higher than the speed corresponding to previous SEL values. Additionally, SEL decreases with measurement speed. Table 11 presents similar data for electric buses.

Table 11. Calculated Electric SEL Averages per Measurement Speed

Measurement Speed (kmh)	SEL (dBA)
10	83
20	78
30	74
40	76
50	76
Overall	79
FTA (50 mph, 80 kmh)	80

Source: FTA, 2018.

Electric bus SEL decreases with measurement speed up to 30 kmh, where it reaches a minimum, before increasing again at speeds up to 50 kmh. Additionally, the calculated average is 1 dBA lower than the FTA reference, however the reference speeds are different. Table 12 shows similar data for hybrid buses.

Table 12. Calculated Hybrid SEL Averages per Measurement Speed

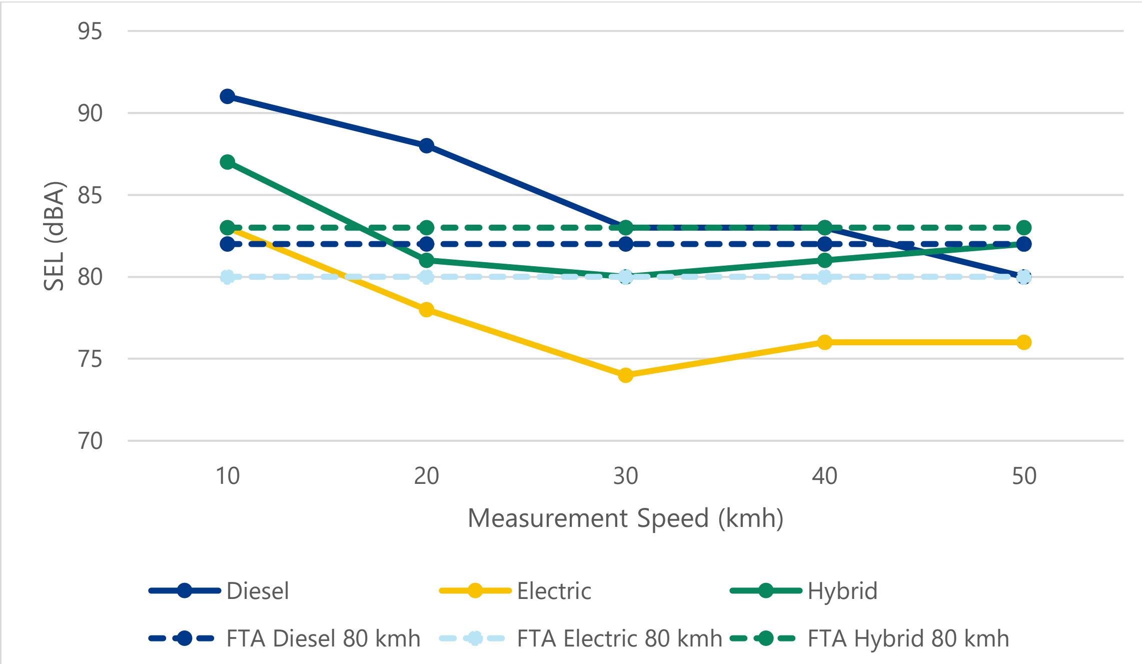
Measurement Speed (kmh)	SEL (dBA)
10	87
20	81
30	80
40	81
50	82
Overall	81
FTA (50 mph, 80 kmh)	83

Source: FTA, 2018.

The calculated, overall hybrid SEL is 2 dBA lower than the FTA reference although the reference speeds are different. Also, SEL begins high at 10 kmh, before dropping off at 20 kmh and fluctuating only in 1 dBA increments between higher speeds.

Figure 8 shows the measurement speed data from the past three tables graphically.

Figure 8. Calculated Average SEL Comparison by Measurement Speed



Overall, SEL values for electric buses are quieter than diesel and hybrid at speeds of ≤30 kmh. Interestingly however, while the gap between diesel and electric narrows above these speeds, they are not as close as most literature suggests. SEL values for hybrid buses are quieter than diesel buses at speeds of ≤20 kmh, but become comparable as speed increases, and are louder than diesel buses at 50 kmh.

4 AVERAGE SEL VALUES

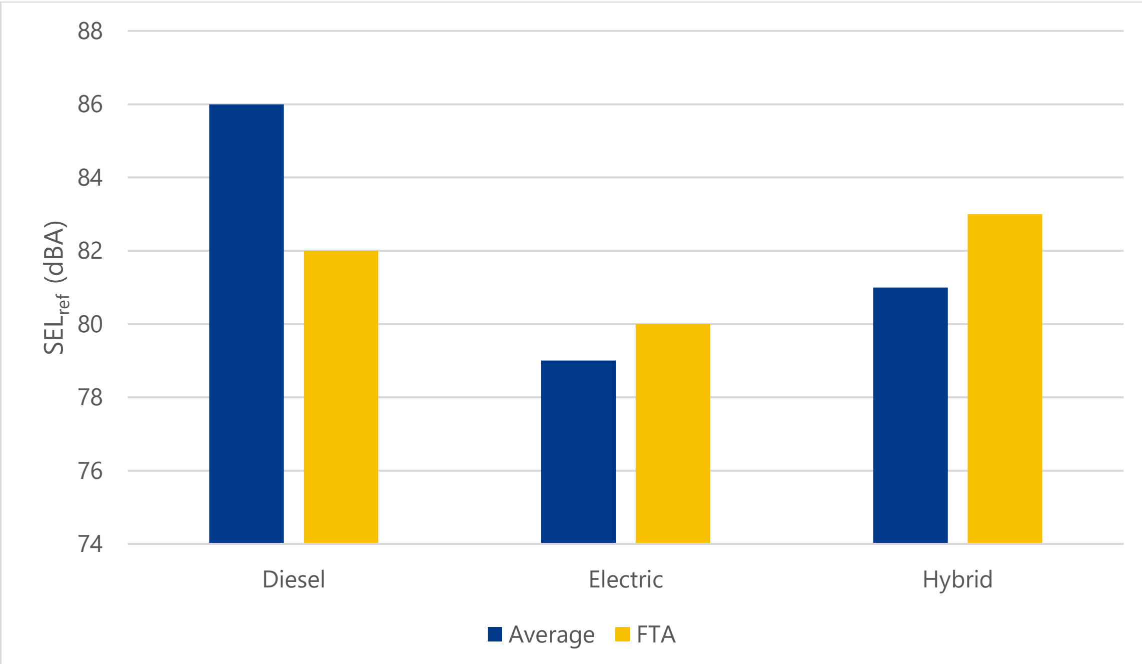
Using all the collected research data, HDR calculated average SEL_{ref} values (corrected for speed and measurement distance) for the three bus types and compared them with the FTA SEL values. Table 13 and Figure 9 summarize these results.

Table 13. Overall Average SEL Values for Different Bus Types in dBA Compared with FTA

Bus Type	Diesel	Electric	Hybrid
Total Average SEL_{ref} (dBA)	86	79	81
FTA SEL_{ref} (dBA)	82	80	83

Source: FTA, 2018

Figure 9. Overall average SEL values for different bus types in dBA compared with FTA



Source: FTA, 2018

Here, the researched data produced a higher estimate of diesel noise than the FTA, while it produced a slightly lower SEL for electric and hybrid buses.

5 PROPAGATING AVERAGE BUS NOISE LEVELS

Using the average SEL values, HDR propagated bus noise beyond 50 feet to see how it attenuates with distance. HDR utilized FTA Table 4-23. SEL is first converted to a 1-hour L_{eq} by FTA Equation 4-34, which is

$$L_{eq(1hr)} = SEL_{ref} + 10\log(V) + 25\log\left(\frac{S}{50}\right) - 10\log\left(\frac{S}{50}\right) - 35.6.$$

Here, V is the average hourly volume of vehicles, which in this case is 1, and S is the average vehicle speed, which is 50 miles per hour.

Then, these $L_{eq(1hr)}$ values are given a correction to represent propagation over a distance. This is done for buses by FTA Equation 4-47, which is

$$C_{distance} = -10\log\left(\frac{D}{50}\right) - 10G\log\left(\frac{D}{29}\right).$$

Here, D represents the distance away in feet, and G is the ground factor, which changes depending on how acoustically absorptive the ground cover is. HDR evaluated two ground absorption scenarios that represent the range of possible ground absorption values. In the first, the ground is fully acoustically reflective, and so G is equal to 0. This represents sound propagating over paved ground, smooth ice, or calm open water which approximates an urban environment. In the second, the ground is considered acoustically absorptive and so G must be calculated. This represents sound propagating over grass, bare soil, vegetation, etc. This is done by FTA Equation 4-43 and Equation 4-44. The latter is

$$H_{eff} = \frac{H_s + 2H_b + H_r}{2}.$$

Here, effective height H_{eff} considers source height H_s, barrier height H_b, and receiver height H_r. There is no barrier, so $H_b = 0$. Additionally, since the source is a city bus and the receiver is a human, we use each's standard height as stated in FTA Table 4-26. Thus, $H_s = 3$ feet, and $H_r = 5$ feet, which leads to $H_{eff} = 4$ feet. FTA Equation 3-34 states that if $H_{eff} \leq 5$ feet, then $G = 0.66$.

Table 14 shows calculated L_{eq} values at distances between 50 feet to 500 feet for the researched average SEL values over both acoustically reflective and absorptive ground.

Table 14. Leq vs Distance Based on Average SEL

	Acoustically Reflective Ground L_{eq} (dBA)			Acoustically Absorptive Ground L_{eq} (dBA)		
Distance (ft)	Diesel	Electric	Hybrid	Diesel	Electric	Hybrid
50	51	43	46	49	42	44
100	48	40	43	44	37	39
150	46	38	41	41	34	36
200	45	37	40	39	32	34
250	44	36	39	38	30	33
300	43	35	38	36	29	31
350	42	35	37	35	28	30
400	42	34	37	34	27	29
450	41	34	36	33	26	28
500	41	33	36	33	25	28

Bus noise propagating over acoustically reflective ground attenuates by 10 dBA over 500 feet, while propagation over absorptive ground attenuates by 16 dBA over 500 feet. Table 15 shows similar data based on FTA default SEL values.

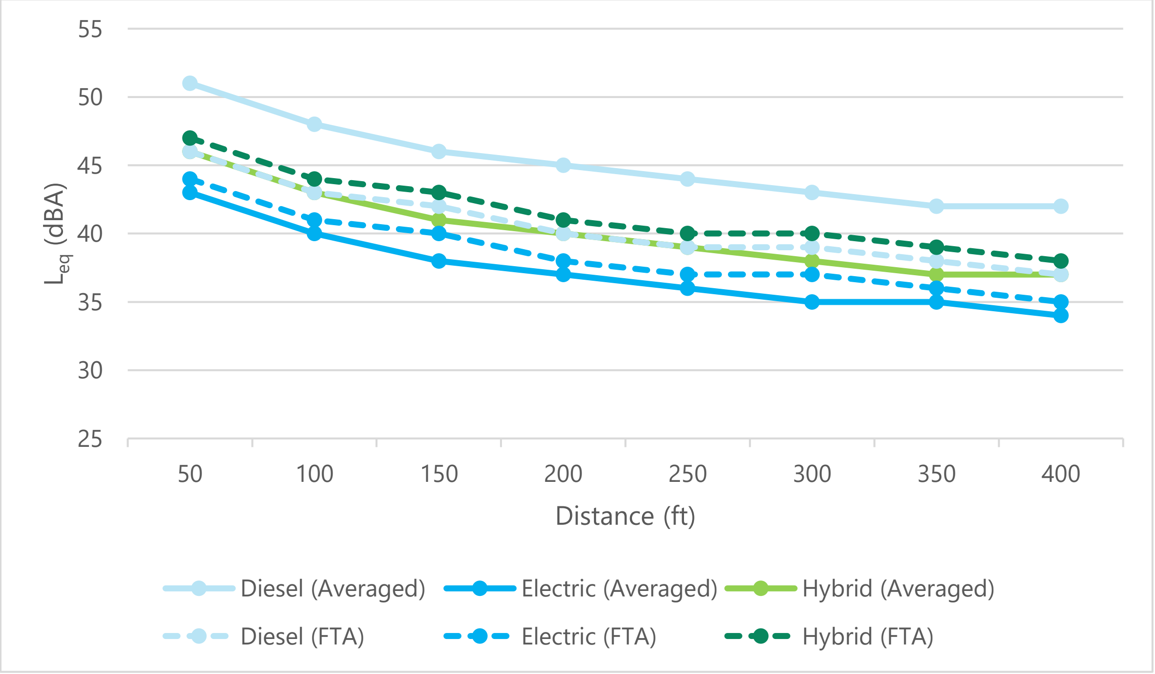
Table 15. Leq vs Distance Based on FTA SEL

	Acoustically Reflective Ground L_{eq} (dBA)			Acoustically Absorptive Ground L_{eq} (dBA)		
Distance (ft)	Diesel	Electric	Hybrid	Diesel	Electric	Hybrid
50	46	44	47	45	43	46
100	43	41	44	40	38	41
150	42	40	43	37	35	38
200	40	38	41	35	33	36
250	39	37	40	33	31	34
300	39	37	40	32	30	33
350	38	36	39	31	29	32
400	37	35	38	30	28	31
450	37	35	38	29	27	30
500	36	34	37	28	26	29

Source: FTA, 2018

As the same propagation formula was applied, the same attenuation trend is achieved for the FTA values and the calculated overall average values. Figure 10 shows this propagation graphically for the acoustically reflective ground case.

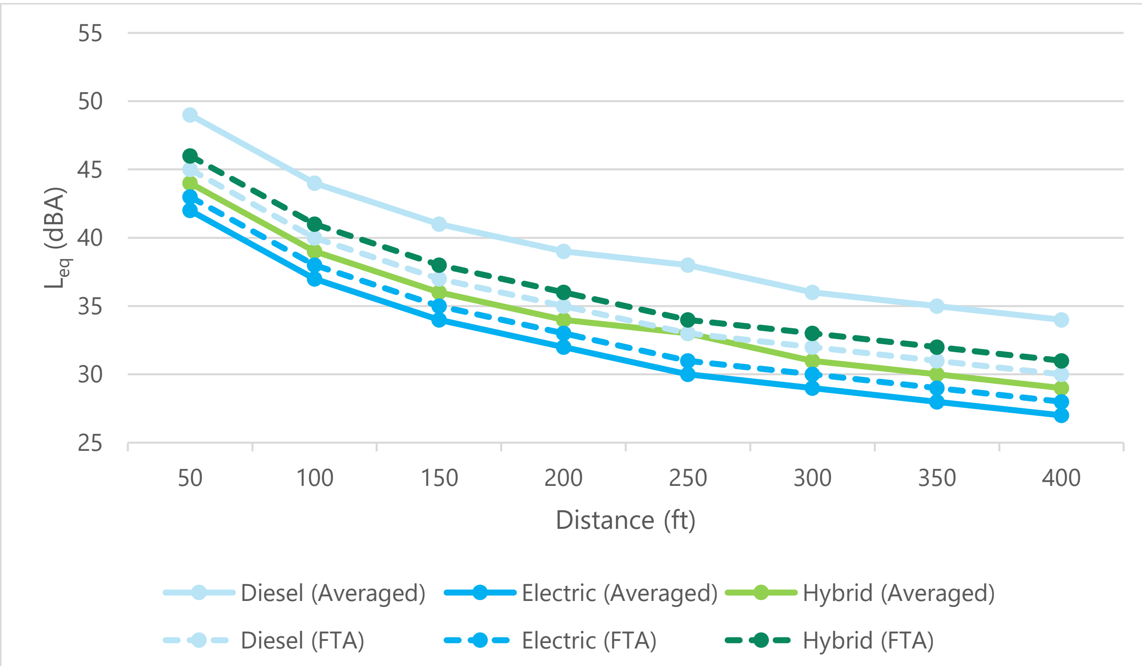
Figure 10. Bus Noise vs. Distance at 50 mph over Acoustically Reflective Ground



Source: FTA, 2018

This graph of sound level vs. distance shows that at 50 mph (80 kmh) the averaged diesel bus is loudest, the averaged electric bus is quietest, and the averaged hybrid bus is roughly in the middle of the other two. Bus noise levels based on FTA SEL values range between the averaged values. Figure 11 shows similar data for attenuation over acoustically absorptive ground.

Figure 11. Bus Noise vs. Distance at 50 mph over Acoustically Absorptive Ground



Source: FTA, 2018

This graph shows the same relationship between bus types as the previous, but with additional attenuation applied due to ground absorption. These simple propagation calculations do not account for the shielding effects of buildings located close to the alignment which interrupt sound propagation and reduce noise levels behind the buildings.

6 FINDINGS

Noise from electric buses varies with speed more than from diesel buses at speeds at or below 30 kmh. There is closer agreement, but still a moderate difference in noise from electric and diesel buses between 30 kmh and 40 kmh. For hybrid buses, there is a substantial difference in noise from diesel for speeds at and below 10 kmh, and a moderate difference for speeds between 10 kmh and 20 kmh. There is merit in identifying speed regimes on bus routes that have residences and other noise-sensitive parcels adjacent to the alignments, and selecting the bus type that will be quietest for most of the route.

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