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Minimum Sound Testing of Medium- and Heavy-Duty Electric Vehicles

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Abstract

The acoustic performance of seven vehicles was evaluated according to Canadian Motor Vehicle Safety Standard 141 (CMVSS 141), which governs minimum required sound levels for hybrid and electric vehicles with a gross vehicle weight rating (GVWR) of 4536 kg (10,000 lb) or less. To better understand the sound profiles of medium-duty electric vehicles (MDEVs) and heavy-duty electric vehicles (HDEVs), the sound emissions of two light-duty electric vehicles (LDEVs), one MDEV, three HDEVs, including an electric transit bus, and one heavy-duty internal combustion engine (HD ICE) vehicle were compared. The sound emissions of the MDEV and HDEVs were quieter than the HD ICE vehicle and comparable to that of the LDEVs equipped with auxiliary speakers. The MDEV with its auxiliary speaker turned off and all three HDEVs without auxiliary speakers met CMVSS 141 requirements in reverse gear and at speeds of 20 km/h and 30 km/h. The MDEV, though not subject to CMVSS 141, failed to meet the minimum sound requirement at stationary when its auxiliary speaker was deactivated. Similarly, the electric transit bus did not meet sound requirements at stationary and 10 km/h, highlighting the potential of acoustic vehicle alert systems (AVAS) in enhancing the detectability of quiet vehicles.

Keywords

Minimum sound testing, Medium- and heavy-duty electric vehicles, MDEV, HDEV, CMVSS 141, FMVSS 141, UN ECE R138

Introduction

The transition to electric vehicles (EVs) marks a significant shift in the automotive industry, driven by the need for a reduction in air pollutants and greenhouse gas emissions (GHGs). In Canada, medium- and heavy-duty vehicles (MHDVs) have historically been a major source of GHG emissions, accounting for 27% of Canada's transportation emissions and 6% of total emissions [1].

To reduce emissions, including those from the transportation sector, Canada introduced the 2030 Emissions Reduction Plan (ERP) in March 2022. The ERP outlines ambitious climate objectives, including a target for 100% of MHDV sales to be zero-emission vehicles by 2040, where feasible [2].

MHDVs pose risks to vulnerable road users (VRUs) due to their size, weight, blind spots, and large turning radius. Research conducted by Transport Canada indicates that interactions between VRUs and heavy-duty vehicles in urban environments present a risk of death and serious injury, particularly at intersections where turning maneuvers occur. These risks are attributed to the inability of heavy-duty vehicle drivers to detect VRUs, as well as VRUs' lack of awareness regarding the movements of these vehicles [3].

Transport Canada's National Collision Database contains data on all reported motor vehicle collisions that the provinces and territories provide each year. On average, between 2018 and 2022, VRUs, including pedestrians and cyclists, accounted for 16% of fatalities in commercial vehicle collisions [4]. Of the fatal collisions involving heavy-duty vehicles with pedestrians and cyclists, 83% were collisions with pedestrians, and 17% with cyclists [4]. When combining existing risks to VRUs from MHDVs with the quiet operation of emerging electric powertrains, medium-duty electric vehicles (MDEVs) and heavy-duty electric vehicles (HDEVs) may present a unique risk.

A study by the National Highway Traffic Safety Administration (NHTSA) found that overall sound levels for light-duty hybrid EVs (HEVs) were lower than their internal combustion engine (ICE) equivalents. In two instances, the HEVs were too quiet to be recorded when stationary under ambient conditions [5]. Another NHTSA study revealed that light-duty HEVs had higher rates of pedestrian and cyclist crashes than ICE vehicles during certain maneuvers [6].

In response to these safety concerns, the governments of the European Union, the United States, and Canada introduced minimum sound regulations for EVs and HEVs. Canadian and U.S. regulations apply to vehicles with a gross vehicle weight rating (GVWR) of 4536 kg (10,000 lb) or less, with the standards being Canadian Motor Vehicle Safety Standard 141 (CMVSS 141) and Federal Motor Vehicle Safety Standards 141 (FMVSS 141), respectively [7, 8]. In contrast, the European regulation, United Nations Economic Commission for Europe Regulation 138 (UN ECE R138), applies to light-, medium-, and heavy-duty electric vehicles [9].

During NHTSA's rulemaking process for light-duty vehicles, a test on an electric heavy vehicle (Navistar eStar two-axle delivery van) was conducted on an ISO 10844:1994 surface suitable for heavy vehicles. Without sound enhancements, the vehicle met FMVSS 141 requirements at standard ambient levels during tested pass-by speeds and when stationary [10]. Additionally, screening data for four hybrid and electric heavy-duty vehicles was collected, indicating that some of these vehicles may already produce sufficient sound to be detected by pedestrians [11].

However, the screening data were limited, and the test procedure did not fully comply with established standards (e.g., SAE J2889). Variations in acoustic environments, operational conditions, test surfaces, and microphone placements indicated the need for further assessment. While the data offered insights into the sound levels of hybrid and electric MHDVs, they were not conclusive. As a result, NHTSA did not include MHDVs in the final rule [10, 11].

Recent testing on the Freightliner eCascadia, a Class 8 electric truck, revealed that without an acoustic vehicle alert system (AVAS), it fails to meet FMVSS 141 sound level requirements [12], potentially increasing collision risks for VRUs and workers in industrial and urban environments.

The increasing number of medium- and heavy-duty zero-emission vehicle models (66 to 90 models in Canada and the U.S. from 2021 to 2024) and projected sales (1.75 M units globally by 2044) signal their rapid adoption [2, 13]. This study provides sound characteristic data to help inform approaches for their safe deployment.

Method

Seven vehicles were tested following CMVSS 141 at the Transportation Research Center (TRC) in East Liberty, Ohio. TRC has over 45 years of mobility testing experience and is in a region that has suitable temperature and wind speed ranges required by FMVSS 141 and UN ECE R138 [14]. Although both UN ECE R138 and FMVSS 141 require an ISO 10844 surface, the limited availability of such surfaces for heavy vehicles in North America required substitution of a Jennite surface for testing purposes. Note, all vehicles including the light-duty electric vehicles (LDEVs) were tested on the Jennite surface. Ambient sound levels ranged from 28.8 to 42.8 A-weighted decibels (dBA), averaging 38 dBA. One-third octave band sound pressure levels (SPLs) were corrected in line with FMVSS 141 and UN ECE R138 requirements.

To evaluate the potential dBA impact of using the Jennite surface, END_T measurements were taken. END_T measures the difference in dBA due to surface texture by comparing a test track to a reference track with a standard texture. A positive END_T value indicates the test track is noisier than the reference track, while a negative value means it is quieter. The ISO 10844 surface at TRC has an average END_T of 0.33 dBA, and the Jennite surface has an average END_T of 0.35 dBA, indicating that the Jennite surface texture has minimal impact on the recorded SPLs relative to an ISO 10844 surface. For additional context, the surface design given in ISO 10844 is consistent with road-building practice.

There is currently only a limited selection of HDEVs in Canada; therefore, vehicles were selected based on availability. An urban transit bus was included due to its frequent interactions with pedestrians and its significance in Canada's transit electrification efforts.

Details regarding the test vehicles' class, model year, vehicle type, GVWR, propulsion system, and tire and cab details are provided in Table 1. Note, only vehicles with a GVWR of 4536 kg (10,000 lb) or less are required to comply with CMVSS 141. Therefore, LDEV 1 and LDEV 2 are the only vehicles in Table 1 that are subject to CMVSS 141.

The MDEV and HDEVs (class 6 and 8) were tested in a "bobtail" configuration (i.e., without a trailer) as FMVSS 141 does not apply to vehicles with a GVWR over 4536 kg (10,000 lb), and UN ECE R138 states that measurements should be taken without a trailer, except for non-separable vehicles [9]. It is important to note that the MDEV is typically a straight box truck; however, the vehicle used in this testing was acquired without a box and tested as such. The MDEV was also the only vehicle equipped with an

TABLE 1 Test vehicles' details (class, year, vehicle type, GVWR, propulsion system, and tire and cab style).

Label	Class, model year and vehicle type	GVWR kg (lb)	Propulsion system	Tires (F/R) and cab style (if applicable)
LDEV 1	Class 1 2023 light-duty passenger SUV	2270 (5004)	77 kWh, 225 hp, single electric motor	235/55R19 235/55R19
LDEV 2	Class 2 2023 light-duty pickup truck	3742 (8250)	98 kWh, 450 hp, dual electric motors	275/65R18 275/65R18
MDEV	Class 6 2023 medium-duty delivery truck	11,793 (26,000)	168 kWh, 220 hp, electric motor	295/75R22.5 295/75R22.5 straight truck, no box
HDEV 1	Class 8 2020 heavy-duty transit bus	19,875 (43,820)	388 kWh, 240 hp, electric motor	305/70R22.5 305/70R22.5
HDEV 2	Class 8 2024 heavy-duty 6 × 4 tractor	24,132 (53,202)	396 kWh, 536 hp, eAxle electric motor	11R22.5 11R22.5 day cab
HDEV 3	Class 8 2023 heavy-duty 4 × 2 tractor	29,000 (63,934)	340 kWh, 455 hp, electric motor	295/75R22.5 295/75R22.5
HD ICE	Class 8 2012 heavy-duty 6 × 4 tractor	26,308 (58,000)	425 hp, 6-cylinder, 12.8 L, In-line diesel engine	295/75R22 275/80R22.5 day cab

auxiliary speaker (Figure 1) to provide supplemental sound during its operation. For this reason, the MDEV was tested in two configurations: speaker ON and speaker OFF.

CMVSS 141 allows for compliance with either UN ECE R138 or FMVSS 141; however, there are differences between the two test procedures. These differences are summarized in Table 2, covering specific tests, testing options, and speed ranges for acceleration simulation. In this study, the third option for the reverse test under UN ECE R138 was used.

FMVSS 141 allows options for 2-band or 4-band compliance, while UN ECE R138 only permits 2-band compliance. In this study, results were analyzed using both methodologies.

Finally, TRC uses NHTSA's MATLAB-based "Quiet Vehicle Compliance Tool" for data processing and analysis.

FIGURE 1 AVAS mounted on the MDEV.

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TABLE 2 FMVSS 141 versus UN ECE R138—test scenarios and requirements.

Tests	FMVSS 141	UN ECE R138
Sound at stationary	Mandatory 1. Vehicle detection and 2. Vehicle directivity	Optional
Reverse	Mandatory Vehicle is stationary.	Mandatory Vehicle can be: 1. In motion; 2. In a motion-simulated environment; or 3. Stationary but in reverse gear with the parking brake released.
Constant speed 1	11 km/h (±1 km/h)	10 km/h (±2 km/h)
Constant speed 2	21 km/h (±1 km/h)	20 km/h (±1 km/h)
Constant speed 3	31 km/h (±1 km/h)	N/A
Acceleration simulation	Relative volume increase of 3 dBA between the following speed ranges: 1. Stationary to 10 km/h 2. 10 km/h to 20 km/h 3. 20 km/h to 30 km/h	Frequency shift of 0.8% per km/h between the following speeds: 1. 5 km/h (±2 km/h) 2. 10 km/h (±1 km/h) 3. 15 km/h (±1 km/h) 4. 20 km/h (±1 km/h)

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Results and Discussion

Figures 2–6 show the measured one-third octave band SPLs across different test procedures, including reverse, stationary, and speeds of 10 km/h, 20 km/h, and 30 km/h. The plots represent the quieter side of each vehicle, which varied between the passenger and driver side.

In Figure 2, showing vehicles operating in reverse gear, the MDEV shows the highest one-third octave band SPL at 3150 Hz and HDEV 1, HDEV 2, and HDEV 3 peak

FIGURE 2 Reverse one-third octave band SPLs vs frequency for all test vehicles.

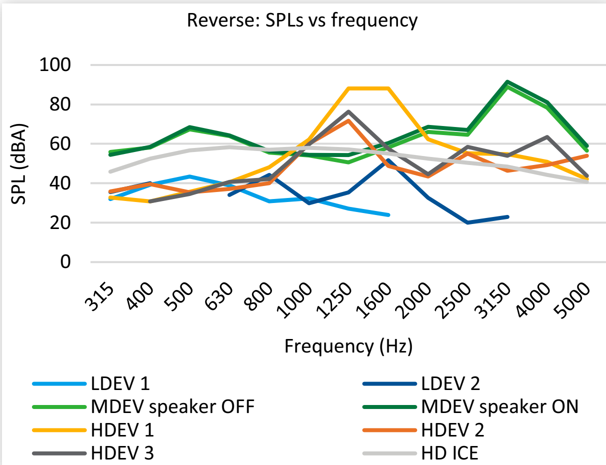


FIGURE 3 Stationary one-third octave band SPLs vs frequency for all test vehicles.

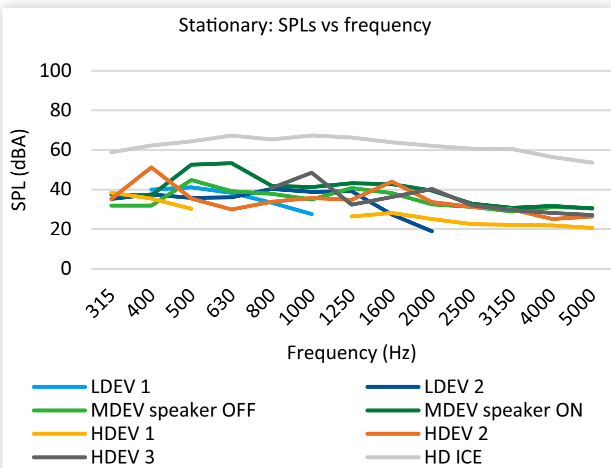


FIGURE 4 Pass by one-third octave band SPLs vs frequency at 10 km/h for all test vehicles.

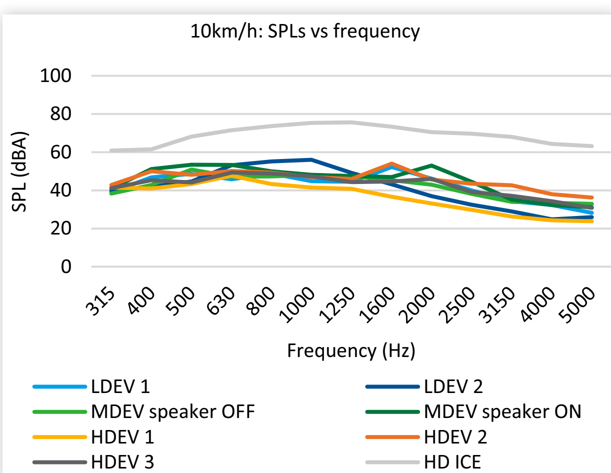


FIGURE 5 Pass by one-third octave band SPLs vs frequency at 20 km/h for all test vehicles.

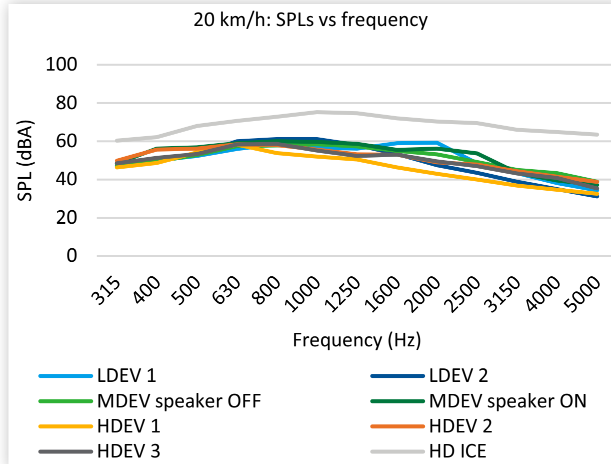
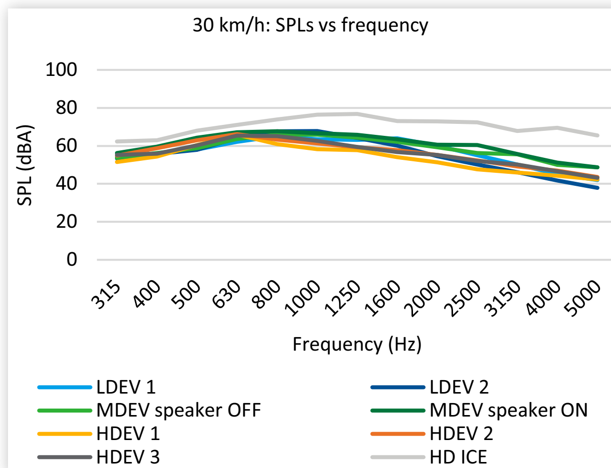


FIGURE 6 Pass by one-third octave band SPLs vs frequency at 30 km/h for all test vehicles.

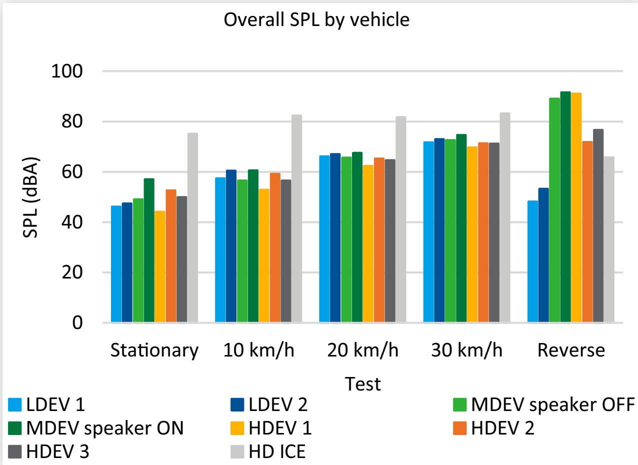


in the 1250 Hz–1600 Hz range. This is due to the primary frequencies observed in each of the vehicles' backup alerts. These alerts are mandated in Europe under UN ECE R165 for vehicles with a GVWR over 3500 kg but are not required by federal regulation in Canada or the United States [15].

The one-third octave band SPLs are not shown in Figures 2 and 3 when the difference between vehicle and ambient one-third octave band levels are less than or equal to 3 dBA [8], an occurrence at TRC, which is a relatively quiet environment. In contrast, urban environments like New York City, with an average street noise level of 73 dBA [16], may present a greater challenge for AVAS to stand out amid the louder background noise.

Simply increasing the volume of the AVAS may not be an effective solution as it would contribute to noise pollution. Instead, frequency shifting could improve detectability in a greater number of ambient conditions, and especially for vehicle operations at standstill and low

FIGURE 7 Overall SPLs by test for all test vehicles.



speeds up to 10 km/h, where volume changes of less than 3 dBA would be difficult to detect [17] (Figure 7).

Figures 4–6 clearly show that one-third octave band SPLs increase with vehicle speed. The heavy-duty ICE (HD ICE) vehicle consistently produced the highest sound levels when moving in a forward direction, despite not having the greatest GVWR among the Class 8 vehicles. This indicates that factors such as engine noise, mechanical vibrations, and the exhaust system contribute significantly to the vehicle's overall sound profile.

As the speed increases, the sound profiles of all EVs begin to converge. This suggests that air resistance and tire noise from the MDEVs and HDEVs become more prominent, causing the sound levels to become more uniform across the vehicles.

The MDEVs and HDEVs are 18 dBA–31 dBA quieter than the HD ICE at stationary, and 22 dBA–30 dBA quieter at 10 km/h. Though the MDEVs and HDEVs approach the sound levels of the HD ICE vehicle at higher speeds, they remain quieter than or in line with the LDEVs, and approximately 10 dBA–12 dBA quieter than the HD ICE vehicle at 30 km/h (Figure 7).

It is also important to note that the MDEV with its speaker ON was louder than all three HDEVs in every test condition but remained quieter than the HD ICE vehicle in all test conditions aside from the reverse test.

Comparison with FMVSS 141 and UN ECE R138 Standards

Since CMVSS 141 allows for compliance through either FMVSS 141 or UN ECE R138, there are separate tables for each scenario: Table 3 for the FMVSS 141 4-band results, Table 4 for the FMVSS 141 2-band results, and Table 5 for the UN ECE R138 2-band results. The key distinction between the 2-band assessments is that FMVSS 141 requires the sum of two non-adjacent bands to meet the minimum required band sum SPL, where one of the two bands must be the highest one-third octave band SPL from the 315 Hz to 800 Hz range and the other must be the highest one-third octave band SPL from the 1000 Hz to 3150 Hz range. In comparison, UN ECE R138 requires each of the two one-third octave bands to meet the minimum SPL, with one of the bands needing to be at or below 1600 Hz. However, if a vehicle without an AVAS fulfills the overall SPLs with a margin of +3 dBA, the requirement for one-third octave bands and frequency shift do not apply [9].

Each table displays vehicle ID and its pass/fail status (if applicable). Table 4 displays band sum SPLs and Table 5 displays overall SPLs; however, if a minimum of two bands did not meet the requirements of FMVSS 141, a "N/A" (not applicable) is shown. Note, the MDEVs, HDEVs, and HD ICE are not required to comply with CMVSS 141. In this study, CMVSS 141 is applied to these vehicles as a

TABLE 3 FMVSS 141 4-band results—pass/fail status for test vehicles.

Test/vehicle ID	LDEV 1	LDEV 2	MDEV speaker ON	MDEV speaker OFF	HDEV 1	HDEV 2	HDEV 3	HD ICE
Stationary	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Pass
10 km/h	Fail	Fail	Pass	Fail	Fail	Pass	Fail	Pass
20 km/h	Fail	Fail	Pass	Fail	Fail	Fail	Fail	Pass
30 km/h	Pass	Fail	Pass	Pass	Fail	Fail	Fail	Pass
Reverse	Fail	Fail	Pass	Pass	Pass	Fail	Fail	Pass

TABLE 4 FMVSS 141 2-band results—band sum SPL (dBA) and pass/fail status for test vehicles.

Test/vehicle ID	LDEV 1	LDEV 2	MDEV speaker ON	MDEV speaker OFF	HDEV 1	HDEV 2	HDEV 3	HD ICE
Stationary	N/A (Fail)	N/A (Fail)	53.7 (Pass)	N/A (Fail)	N/A (Fail)	52.0 (Pass)	N/A (Fail)	70.3 (Pass)
10 km/h	53.8 (Pass)	56.1 (Pass)	56.2 (Pass)	52.7 (Pass)	N/A (Fail)	55.5 (Pass)	51.4 (Pass)	77.8 (Pass)
20 km/h	61.8 (Pass)	63.6 (Pass)	62.4 (Pass)	61.0 (Pass)	59.1 (Pass)	60.2 (Pass)	60.0 (Pass)	76.9 (Pass)
30 km/h	67.6 (Pass)	69.3 (Pass)	69.9 (Pass)	68.2 (Pass)	66.6 (Pass)	67.4 (Pass)	67.2 (Pass)	78.6 (Pass)
Reverse	N/A (Fail)	52.4 (Pass)	91.5 (Pass)	88.9 (Pass)	88.1 (Pass)	71.7 (Pass)	76.3 (Pass)	61.2 (Pass)

TABLE 5 UN ECE R138 2-band results—test vehicles' overall SPL (dBA) and two-band pass/fail status.

Test/vehicle ID	LDEV 1	LDEV 2	MDEV speaker ON	MDEV speaker OFF	HDEV 1	HDEV 2	HDEV 3	HD ICE
Stationary	Not applicable							
10 km/h	57.4 (Pass)	60.5 (Pass)	61 (Pass)	56.6 (Pass)	52.9 (Fail)	56.6 (Pass)	59.2 (Pass)	82.3 (Pass)
20 km/h	66.1 (Pass)	67.0 (Pass)	68 (Pass)	65.6 (Pass)	62.4 (Pass)	64.7 (Pass)	65.3 (Pass)	81.7 (Pass)
30 km/h	Not applicable							
Reverse	48.2 (Pass)	53.3 (Pass)	92 (Pass)	89.1 (Pass)	91.1 (Pass)	76.7 (Pass)	71.9 (Pass)	65.8 (Pass)

benchmark for comparison to the minimum sound standards applicable to other vehicles.

Results from Tables 3 and 4 show that all EVs observe a higher failure rate under FMVSS 141's 4-band requirement than its 2-band requirement. For example, LDEV 2, HDEV 2, and HDEV 3 pass four or more 2-band tests but fail four or more 4-band tests. The MDEV equipped with a supplemental speaker provides an interesting case. When the speaker was on, the vehicle was 4 dBA louder on average and met the 4-band sound requirements more consistently compared to when the speaker was off. The MDEV also failed the 2-band sound requirement at stationary when the speaker was off. These results showcase the effectiveness of an AVAS in enhancing vehicle sound to meet regulatory requirements.

HDEV 1 (electric transit bus) failed the 2- and 4-band sound requirements at stationary and 10 km/h. In this case, an AVAS may be particularly useful to enhance VRU safety as transit buses typically operate in more densely populated urban settings and frequently maneuver between low speeds and stationary at bus stops where VRUs may be present.

Overall, the MDEV with its auxiliary speaker turned off and all three HDEVs without auxiliary speakers met FMVSS 141 requirements in reverse gear and at speeds of 20 km/h and 30 km/h. The variability between the band results suggests that, without an AVAS, the 2-band sound requirement is more achievable for the MDEVs and HDEVs compared to the 4-band requirement.

Utilization of a 4-band capable AVAS is worth considering for several reasons. For example, content in multiple one-third octave bands could increase the time-to-vehicle arrival since multiple band content can more easily be detected due to overall strength and/or because there is a greater probability that at least one band will be detected [8]. NHTSA's analysis showcased that detecting at least one band of content increased with the increasing number of components. For example, signals with content in 1, 2, 3, 4, 5, 6, and 7 one-third octave bands had probabilities of 55%, 81%, 93%, 97%, 98%, 100%, and 100%, respectively [8]. However, it is important to note that the detectability did not significantly increase above content in 4 bands [8].

Results from Table 5 show that all vehicles met the overall SPL criteria for each test. Many vehicles without an AVAS, namely, the MDEV with its speaker off, HDEV 2, HDEV 3 and the HD ICE, fulfilled overall SPL requirements with a margin of +3 dBA. As such, these vehicles were not subject to the one-third octave band and frequency shift requirements. However, the electric transit bus at 10 km/h, which met the overall SPL requirement, did not meet the 2-band requirement. The absence of a requirement to emit sound at stationary and at a pass-by speed of 30 km/h does not offer a comparator to FMVSS 141.

Acceleration Simulation

According to FMVSS 141, the normalized band sum SPL must increase by at least 3 dBA between speed intervals to simulate acceleration [8]. In contrast, UN ECE R138 mandates that the frequency of the AVAS should increase by an average of at least 0.8%/1 km/h within the speed range of 5 km/h to 20 km/h when driving forward [9]. As previously mentioned, if a vehicle without an AVAS fulfills the overall SPLs with a margin of +3 dBA, the requirement for one-third octave bands and frequency shift does not apply [9]. For this reason, a "N/A" (not applicable) is shown in Table 6.

The requirement of FMVSS 141 for a 3 dBA minimum increase between speed intervals was met by all EVs. Notably, the MDEV with its auxiliary speaker turned off and all three HDEVs without auxiliary speakers met the relative volume change requirement, demonstrating their ability to generate sufficient sound to simulate acceleration. However, a key consideration is that louder sound does not necessarily lead to better detectability [12].

NHTSA considered frequency shifting useful for enhanced detectability and recognizability; however, FMVSS 141's volume-based test procedure was deemed more feasible due to the impracticality of identifying and

TABLE 6 Pass/fail status of test vehicles for acceleration simulation.

Test/vehicle ID	LDEV 1	LDEV 2	MDEV speaker ON	MDEV speaker OFF	HDEV 1	HDEV 2	HDEV 3	HD ICE
Relative volume change test status	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Fail
Frequency shift test status	Pass	Fail	Pass	N/A	Fail	N/A	N/A	N/A

verifying tones without prior knowledge of the expected frequency shift [8].

In comparison, the frequency shift test required by UN ECE R138 proved challenging for some vehicles. Notably, LDEV 2, which is certified to FMVSS 141 and HDEV 1 (the electric transit bus), did not meet this requirement. The vehicles without an AVAS, namely, HDEV 2, HDEV 3, HD ICE, and the MDEV with its speaker off, fulfilled an overall SPL requirement with a margin of +3 dBA in each of their constant speed tests and were not subject to the frequency shift requirement.

It is possible that a relative volume change combined with frequency shifting could further enhance VRU safety by making vehicle movements easier to detect compared to just increasing SPLs [8, 12]. Testing to evaluate VRU perceptions would be needed to confirm this hypothesis.

Limitations of the Study and Future Work

This study's scope was limited to a specific set of vehicles and test procedures, which may not fully represent all vehicle types or real-world scenarios. Future research could evaluate a broader range of vehicle types, powertrains (e.g., fuel cell EVs), different driving conditions, and additional environmental settings to provide a more comprehensive understanding of MDEV and HDEV sound levels. To connect sound levels to VRU safety, future research could evaluate sound level perception and how this may vary with different types of ambient noise, and constructive/destructive interference when multiple AVAS are present. Additionally, the time of perception relative to time of collision could be evaluated when MDEVs and HDEVs are accelerating and with various AVAS and engine/motor locations (front versus back) on longer vehicles such as electric transit buses. Additionally, the test methodology could be enhanced using a multiple microphone array to more accurately capture sound energy.

Conclusions

In this article, seven vehicles were evaluated following CMVSS 141, including two LDEVs, one MDEV with an auxiliary speaker, three HDEVs, including an electric transit bus, and one HD ICE vehicle. The main conclusions are the following:

- The MDEV and HDEVs are 18 dBA–31 dBA quieter than the HD ICE vehicle at stationary, and 22 dBA–30 dBA quieter at 10 km/h. MDEV and HDEV sound levels rise with increasing speed but remain 10 dBA–12 dBA less than the HD ICE vehicle at the highest tested speed of 30 km/h. This illustrates the quieter operation of the MDEV and HDEVs compared to ICE equivalents, even at 30 km/h.
- The MDEV with its speaker off and all three HDEVs without auxiliary speakers met CMVSS 141 requirements in reverse gear and at speeds of 20 km/h and 30 km/h.
- All vehicles passed the FMVSS 141 2-band requirement at 20 km/h and 30 km/h. Three of the MDEV and HDEVs did not meet the 2-band requirement at stationary and/or 10 km/h. The MDEV equipped with an auxiliary speaker failed the 2-band sound requirement at stationary when the speaker was off but met the requirement when the speaker was on. This showcases the effectiveness of an AVAS in enhancing MDEV sound profiles. The detectability of the sound is enhanced with a 4-band–compliant AVAS; however, all vehicles observed a higher failure rate under FMVSS 141's 4-band analysis than its 2-band analysis.
- HDEV 1 (electric transit bus) failed the 2- and 4-band sound requirements under FMVSS 141 at stationary and 10 km/h. In this case, an AVAS may be particularly useful to enhance VRU safety as transit buses typically operate in more densely populated urban settings and frequently maneuver between low speeds and stationary at bus stops where VRUs may be present.
- All vehicles met the overall SPL and/or 2-band criteria under UN ECE R138 except for the electric transit bus at 10 km/h. The electric transit bus met the overall SPL requirement but did not meet the minimum 2-band requirement. Additionally, LDEV 2 and HDEV 1 did not meet the frequency shift requirement for acceleration simulation.

This study shows that there could be an opportunity to enhance VRU safety around MDEVs and HDEVs by adding an AVAS, particularly when vehicles are operating at low speeds (10 km/h) or stationary. VRU safety around MDEVs and HDEVs could also be enhanced by equipping vehicles with a 4-band–compliant AVAS and/or an AVAS that employs frequency shifting between speed intervals.

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Acronyms

AVAS - acoustic vehicle alert system

CMVSS 141 - Canadian Motor Vehicle Safety Standard 141

dBA - A-weighted decibel

ERP - emissions reduction plan

EV - electric vehicle

FMVSS 141 - Federal Motor Vehicle Safety Standard 141

GHG - greenhouse gas

GVWR - gross vehicle weight rating

HDEV - heavy-duty electric vehicle

HD ICE - heavy-duty internal combustion engine

HEV - hybrid electric vehicle

ICE - internal combustion engine

ISO - International Organization for Standardization

LDEV - light-duty electric vehicle

MHDV - medium- and heavy-duty vehicle

MDEV - medium-duty electric vehicle

NHTSA - National Highway Traffic Safety Administration

SAE - SAE International

SPL - sound pressure level

TRC - Transportation Research Center

UN ECE R138 - United Nations Economic Commission for Europe Regulation 138

VRU - vulnerable road user

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