Sound power level of electric vehicles running in steady low speed

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1. Introduction

Electric vehicles (EV) and hybrid electric vehicles (HEV) are becoming popular, and the number of production is rapidly increasing. The other type of electric vehicles, such as fuel cell electric vehicle (FCV), has also been introduced in the market. These vehicles are generally quieter than the internal combustion engine vehicles (ICEV) particularly when they are travelling at lower speed. It is highly demanded to predict and evaluate of the environmental noise reduction effect by the growth of their population.

In Japan, the ASJ RTN-Model 2013 [1] is widely used for the prediction and evaluation of road traffic noise. In the model, A-weighted equivalent continuous sound level (L_{Aeq}) at the prediction point is calculated from the A-weighted sound power level (L_{WA}) of the passing vehicles on the target road. The L_{WA} is given as a function of running speed for each type of vehicle and running condition.

In order to predict the noise reduction effect of electric vehicles, it is necessary to understand their L_{WA} . Some studies on the sound power level of EV/HEVs [2,3] have reported that the L_{WA} of EV/HEVs was 1 to 2 dB lower than ICEVs while they were driven at steady speed of 50 km/h. However, there is little knowledge about that in lower speed. Our research goal is to clarify the L_{WA} of electric vehicles running in lower speed.

On the other hand, the quietness of electric vehicles has also been regarded as a matter of concern, because they are potentially dangerous to pedestrians when the approach of them becomes inaudible under urban noise. Hence, the devices to enhance pedestrians' awareness using acoustic vehicle alerting system (AVAS) has been introduced. The device creates artificial noise in the speed range from 0 to 20 km/h. The UN-Regulation [4] introduces the minimum sound level, spectral characteristics, and frequency shift depending on the vehicle's speed. However, there are few studies to examine the effect of AVAS on the environmental noise. The effect on the sound power level was measured and examined in this report.

2. Measurement

The measurements were conducted on flat straight section of private roads in four universities. Seven measurement campaigns, four times in the site A and once each in the

others, conducted from 2016 to 2018. Table 1 shows the measurement environment. All measurement sites were paved with dense asphalt concrete. The background noise levels were measured when the other specific noises were not observed. The background noise levels in the Table were averaged value among several times during each measurement. Test vehicles were seven kind of passenger vehicles those have been available in the market. The specifications of test vehicles are shown in Table 2. All of the test HEVs could be driven by their electric motors with or without running the internal combustion engine. In the measurements in this report, only the data being driven solely by electric motors were employed.

The measuring microphone was set at 1.2 m height and 2.0 or 7.5 m away from the center of the lane. The orthogonal line from the microphone to the lane was defined as the PP' line, and 10 m distance before and after the PP' line were defined as AA' and BB' line, respectively. The vehicle was driven to run at steady speed during the testing distance, from AA' line to BB' line, as shown in Fig. 1. The running speed from crossing AA' to BB' lines were continuously observed by the speed gun.

The L_{WA} of passing-by vehicle is usually calculated from the obtained A-weighted sound pressure level at the microphone d [m] away. Usually the distance d is 7.5 m to ensure the assumption that the test vehicle is an omnidirectional point sound source in hemi-free field. It is necessary, however, to shorten the distance d in consideration of avoiding the influence of background noise, because the noise emitted from the test electric vehicles are low compared to conventional vehicles.

The shorter distance makes difficult to consider a test vehicle as an omnidirectional point sound source. The measurement value may be influenced by interference of rolling noise from each tire. According to the literature [5], which examine similar problem with the larger vehicle whose length were comparable with horizontal distance to the microphone, the dispersion of L_{WA} prediction due to wheel-base length of larger vehicles could be reduced by using the square integration method [6].

Then, the L_{WA} were calculated by the square integral method. The energy average levels $\bar{L}$ of the sound pressure level while the vehicle passes through both sides l [m] of the PP' line were obtained. Then the L_{WA} were calculated by the formula (1).

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Table 1 Measurement environment.

	Site A	Site B	Site C	Site D
Location	Kyushu Univ., Ito Campus (Fukuoka, Japan)	Kyushu Univ., Chikushi Campus (Fukuoka, Japan)	Nihon Univ., Funabashi Campus (Funabashi, Japan)	Univ. Miguel Hernandez. (Elche, Spain)
Background noise level [$L_{Aeq,10s}$]	38.2–53.8 dB	46.1 dB	41.4 dB	44.3 dB

Table 2 Specifications of the test vehicles.

Test vehicle	EV1	HEV1	HEV2	HEV3	HEV4	FCV1	ICEV1
Weight [kg]	1,430	1,360*	1,610	1,100	1,400	1,850	1,650
Wheelbase [mm]	2,700	2,700	2,850	2,550	2,600	2,780	2,890
Tire size	205/55R16	195/65R15*	195/65R15	185/60R15	225/45R17	215/55R17	205/60R16
Site	A	A, C, D	A	A	D	A	B

*Same model but with 1,370 kg weight and 215/45R17 tire was used in the test at UMH.

Fig. 1 Measurement set-up.

$$L_{WA} = \bar{L} + 20 \log_{10} d + 8 + 10 \log_{10} \left(\frac{\kappa}{\tan^{-1} \kappa} \right) \quad (1)$$

Where $\kappa = l/d$. The length l was the testing distance 20 m, from AA' line to BB' line, in this study. Only the measurement data that exceed the sound pressure level of 10 dB higher than the background noise level during testing distance were employed in the following analysis.

3. Results

3.1. Comparison of measurement methods

The L_{WA} was calculated using the square integral method using the microphone in short distance. To confirm the method, the measurements were conducted using two microphone set at $d = 2.0$ and $d = 7.5$ simultaneously for the test vehicles HEV2, HEV3 and FCV1 in the test site A. Then, the differences by the measurement distance, calculated by the formula (2), were examined.

$$\Delta L_{WAe} = L_{WAe,2.0m} - L_{WAe,7.5m} \quad (2)$$

Where $L_{WAe,2.0m}$ is power level calculated by the measured sound pressure level at 2.0 m away from the vehicle, and $L_{WAe,7.5m}$ is that at 7.5 m. The average and the standard deviation of the difference between the length for each test vehicle are shown in Table 3. The number of measured data-pairs for each test vehicle are also shown in the Table. The calculated level from the measurement at $d = 2.0$ were slightly underestimated. However, the deviations were not too large. Vehicle noise has comprehensive spatial directivity

Table 3 Level difference between the measurement distance (ΔL_{WAe}).

	Average	S.D.
HEV1 ($N = 9$)	−1.55	0.32
HEV2 ($N = 25$)	−2.71	0.49
FCV1 ($N = 21$)	−2.57	0.47

because the noise generated from each tier is influenced by the body shape. Due to the perpendicular directivity, it could be thought that the calculated L_{WA} were different among the measurement distance. Further examination on the directivity of vehicle noise is important for understanding the difference. Even though the systematic underestimation should be noted in the discussion, in this paper, the L_{WA} calculated by square integral method at 2.0 m position were employed for following analysis.

3.2. Speed dependence of L_{WA}

Figure 2 shows the speed dependence of the L_{WA} of passing-by test vehicles obtained by the square integral method using 2.0 m distance microphone. The dependence of a passenger car in steady traffic flow section in ASJ RTN-Model 2013 [1] and that of rolling noise contribution (L_{WR}) addressed in CNOSSOS-EU [7] are also shown in the Figures. With regard to the ASJ model, although the steady traffic flow section is defined at the speed of 40 km/h or higher, in this analysis that is extended to 15 km/h. In the CNOSSOS model, the coefficients are given for each 1/3 octave band. Here, equivalent equation was estimated by accumulating all bands and A-weighted correction.

The speed dependence of the L_{WA} of each test vehicle showed similar curve to the ASJ-steady and the rolling noise contribution of CNOSSOS-EU. The regression coefficients of test electric vehicles were ranged from 32.5 to 36.5, except the test vehicle HEV3 with small amount of samples, and close to each other among the test vehicles. Those were greater than that of ASJ ($= 30$), and similar to that of the

Fig. 2 Speed dependence of L_{WA} for each test vehicle running in slower speed.

rolling noise contribution of CNOSSOS ($= 32.7$). It is generally regarded that the propulsion noise of vehicles predominant in the accelerating condition, while the tier/road and aerodynamic noise are predominant in constant speed running. The aerodynamic noise depends on the vehicle speed, then the tire/road noise contribution is more dominant in the lower speed range. The results showed that the sound power level of electric passenger vehicles travelling slowly were similar to ASJ-steady and the rolling noise contribution of CNOSSOS. These suggest that the contribution of propulsion noise is negligibly small and the tire/road noise is dominant for the sound power level of electric passenger vehicles travelling slowly.

The L_{WA} obtained in the test site D (HEV1 and HEV4) were comparable with ICEV1. The possible effect of road surface was considered. The comparison of L_{WA} of the test vehicle HEV1 measured in three different test sites (site A, C, and D) shows that the result in site D was significantly higher but the regression coefficients were similar. As the possible reason, the difference of tire size and gross weight would be mentioned. However, the test vehicle FCV, which has the heaviest weight, didn't show particular increase among the results in test site A. This suggests the important role of road surfaces.

Based on the regression equation, the L_{WA} at 20 and 30 km/h was calculated for each test vehicle. The differences from the estimated L_{WA} of ICEV1 were ranged from -4.3 to $+1.1$ dB at 20 km/h and from -4.3 to $+1.8$ dB at 30 km/h. Those were from -4.3 to -1.6 dB at 20 km/h and 30 km/h if the results in site D were excluded. According to the previous reports [2,3], the difference was around 2 dB in 50 to 60 km/h range. The difference of sound power between electric and conventional vehicles are wider and noticeable in the speed range blow around 40 km/h.

3.3. Effect of AVAS on overall L_{WA}

The effect of AVAS on L_{WA} was examined by test vehicle EV1 and HEV3 in site A. The difference of L_{WA} with and without AVAS operation were calculated. The test vehicles,

Fig. 3 Relative band power levels of EV1 with or without AVAS operation.

EV1 and HEV3, with the AVAS designed under the previous guideline, which was published by Japanese ministry of land infrastructure and transportations in 2010, were used in this measurement. The L_{WA} was calculated and compared among with or without AVAS operation.

The differences of L_{WA} at 10 ± 2 km/h were 1.8 and 5.3 dB for EV1 and HEV3, respectively. The differences at 20 ± 2 km/h were less than 1 dB for both vehicles. The effect of AVAS on relative A-weighted sound power level in 1/3 octave bands are shown in Figs. 3 and 4. At 10 km/h, the effects of AVAS operation on the spectrum were significant for both test vehicles, particularly for HEV3. At 20 km/h, however, the differences were not significant.

4. Conclusions

In order to introduce electric vehicles into the noise prediction models, it is necessary to develop the model of the

Fig. 4 Relative band power levels of HEV3 with or without AVAS operation.

sound power level as the function of the vehicle speed. In this research, several measurements on sound power level (L_{WA}) were carried out on a dense asphalt pavement. The result showed that L_{WA} of test electric vehicles in 20 to 30 km/h speed range were 2 to 4 dB lower than the ICEV. Additionally, the comparison of L_{WA} and the frequency characteristics among with or without AVAS were examined. The effect of AVAS was not negligible particularly at very low speed.

It is still important to accumulate more measuring data of electric vehicles running in lower speed for further discussion. Moreover, the noise reduction effect of these vehicle can be expected in the vicinity of signalized intersections or expressway tollgates, where the vehicles are in accelerating and the

propulsion system plays important role on noise emission. The examination on the L_{WA} of electric vehicles in acceleration is also the future work.

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