ICBEN
18 – 22 JUNE
ZURICH
2017

12th ICBEN Congress on
Noise as a Public Health Problem

Secondary analysis of social survey on community response to transportation vibration in Japan

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ABSTRACT

The Vibration Regulation Law in Japan has controlled vertical ground-borne vibrations caused by factories, construction work, and road traffic. In addition, ground-borne vibrations from the Shinkansen super-express railway have been controlled through an official recommendation. In the law and the recommendation, regulatory and guideline values are established, respectively. Law enforcement and recommendation has caused mitigation of ground-borne vibrations; however, most recent vibration-related complaints have been raised at sites below the values. This suggests that the established values are not sufficient criteria for preserving a living environment. To provide fundamental data for establishing vibration policies, we conducted a secondary analysis. In this study, we have analyzed the maximum-based energy-based vibration levels, which were considered as vibration exposure, and vibration perception and the rattling in terms of community response. The purpose of this study is to specify either a maximum-based or an energy-based index that more suitably corresponds to annoyance associated with ground-borne vibrations. In addition, we investigated the degree of the effect of noise exposure on vibration annoyance, and we compared vibration annoyance among certain transport facilities.

INTRODUCTION□

Ground-borne vibrations from transportation, vehicles, and railways are factors that disrupt the comfort of living environments and health. The Japanese government, for the purpose of preserving the living environment and of contributing to the protection of the health of the citizens, established the Vibration Regulation Law in 1976. The purpose of this law is to regulate the emission from the following ground-borne vibrations: specified factory vibrations, specified construction work vibrations, and road traffic vibrations. In addition, the recommendation "Measures for Vibration Caused by Shinkansen Trains Urgently Required to Preserve the Environment" was given to the Minister of Transportation by the Director of the Environmental Agency. The law and the recommendation pertain to only vertical vibrations on the ground surface. In the law, the regulatory standards for specified factory vibrations or specified construction work vibrations, and limits for road traffic vibrations have been established. In a similar manner, a guideline for countermeasures against the vibrations from the Shinkansen railway was stipulated as well. However, no regulation or standard on ground-borne vibrations from conventional railways has been covered by any statute.

The enforcement of the law and of the recommendation has contributed to the reduction in emissions of ground-borne vibrations. Although more than 40 years have passed since their enforcement, the law and the recommendation have never been revised. In recent years, most complaints against transportation-induced vibrations have been made at sites where measurement values are below the values of the regulatory standards, limits, or guideline. Particularly, we focused on horizontal vibrations in a two- or three-story detached house. Certain measurements reveal that a horizontal vibration level in the above mentioned detached house was 10 dB higher than that measured on the ground surface that is adjacent to the building. These facts suggest that the reality of complaints can't be caught sufficiently by present measurements and evaluations [1]. Therefore, the revision and the review of the regulatory standard and guideline values, including the evaluation of horizontal vibrations in buildings, should become the topic of new discussions.

To investigate the values that constitute the criteria for transportation-induced vibrations, the dose–response relationship for each vibration source should form the basis of the discussion. With regard to noise study, many socio-acoustic surveys on community responses to noise have been conducted in Japan. Accumulating micro data (exposures, community responses, demographic factors, etc.) that have been derived from the surveys, a sub-technical committee at the Institute of Noise Control Engineering/Japan has been managing the Socio-Acoustic Survey Data Archive (SASDA) since 2011 [2]. Using the SASDA, the committee has released dose–response relationships for transportation noises in Japan [3, 4]. However, micro data regarding vibration exposures and responses have not been managed in a unified manner for re-analysis. Thus, the accumulation and management is the first step toward preparing the aforementioned revision.

We compiled 14 datasets derived from twelve separate surveys, which had been conducted from 1995 to 2011, and had presented the relationships between the maximum-based exposure index and the annoyance associated with the following ground-borne vibrations: road traffic vibrations, conventional railway vibrations, and the Shinkansen railway (high-speed railway) vibrations [5]. Furthermore, we examined the effect of noise exposure on vibration annoyance. In this paper, by adding new datasets, we made efforts to conduct a secondary analysis of the exposure–response relationship for vibration. In the present work, using vibration exposures, the energy-based index, and the maximum-based index, we will first clarify the relationships between the exposure and the community response associated with ground-borne vibrations for each transportation facility. Next, focusing on annoyance, we will investigate either the maximum-based index or the energy-based index, whichever corresponds to annoyance most suitably. Finally, to examine the effect of noise exposure on vibration annoyance, we applied a logistic regression analysis to the datasets. Based on the results obtained, we compared the exposure–annoyance relationships among the sources.

METHOD

Dataset

Table 1 lists the outline of the 14 datasets that have been analyzed in this study. In the ID column, the prefixes denote road traffic (RT), conventional railway (CR), and the Shinkansen railway (SR) noise sources, respectively. The datasets were derived from 12 separate surveys, which were conducted in residential sites along the ground transportation. Certain surveys targeted inhabitants living in detached and apartment houses, which were mainly constructed with wood and reinforced concrete, respectively. In this study, we only addressed the case of detached houses.

The RT04 and CR04 datasets were derived from surveys that the Saitama University had conducted using a common questionnaire [6]. The survey mainly addressed the community response to ground-borne vibrations in a dense city. The CR03 and SR04 datasets were derived from surveys that had been conducted through collaborations among industries, educational institutions, and the administration in a manner of interview sessions [7]. The SR03 and SR05 datasets were derived from surveys that were conducted in the respective areas along the Sanyo and the Kyushu Shinkansen Line [8, 9]. The former survey compared the community responses to railway noise from the Shinkansen and from conventional railways; the latter compared community responses to railway noise and vibrations before and after the opening of the Kyushu Shinkansen Line. The SR05 dataset was derived from a survey that was conducted by the National Institute of Technology, Ishikawa College, in the areas along the Hokuriku Shinkansen Line before the opening of the new section. Other datasets were derived from surveys that were jointly conducted by the Yokohama National University and the Kanagawa Environmental Research Center. The RT01, CR01, and SR01 datasets were derived from surveys that compared the community response to noise and vibration among their sources [10]. The RT03 and CR03 datasets were originated from a survey that covered combined exposure to noise and vibrations induced by road traffic and conventional railways [11]. The SR02 dataset was derived from a survey that clarified combined annoyance due to noise and vibration from the Shinkansen trains [12].

As listed in Table 1, the wording of the questions and the annoyance descriptor differed among the datasets. The RT01, CR01, and SR01 datasets measured vibration annoyance based on a bearable–unbearable scale. The CR02 dataset used a satisfaction–dissatisfaction scale. Other datasets used a modifier similar to the International Commission on Biological Effects of Noise (ICBEN) verbal scale, although a descriptor of vibration annoyance, which was a response of “disturbed” or “bothered”, differed. In addition, it should be noted that the CR03 and SR04 datasets measured annoyance due to railway-induced vibrations, without specifying the Shinkansen super-express railway.

In the present work, in addition to annoyance, we examined responses of vibration perception and rattling. For vibration perception, the responses from the RT01, CR01, CR04, SR01, and SR03 datasets were clearly measured through the survey. Other datasets obtained the response based on vibration annoyance. More specifically, among five-point ratings, all rating categories except for the less rated category were considered indicative of vibration perception. The rattling from the KNG95 dataset was obtained in two formats, namely with a two-point scale (in 1995) and a five-point scale (in 1996). The five-point scale was based on the occurrence frequency of the event. On the other hand, the SR03, SR05, and SR06 datasets measured rattling with five-point occurrence strength. Other datasets used a two-point scale, in terms of presence or absence of rattling in the living environment. However, the RT03 and CR03 datasets measured rattling response.

Noise and vibration exposures

Exposures were estimated based on measurements of noise and ground-borne vibration, which were, in principle, obtained on a site-by-site basis for each survey. We measured the vertical vibration level (re 10^{-5} m/s^2) on the ground surface. In this work, we employed the maximum vibration level (L_{vmax}) and the equivalent continuous vibration level over 24 hours (L_{veq}) as vibration exposure. The estimation method is presented in Table 2.

Table 1: Outline of datasets and vibration annoyance

ID (Year)	Sample	Site location	Question on annoyance	Descriptor of annoyance
RT01 (1998)	353	Kanagawa Prefecture	Can you put up with vibrations from motor vehicles?	1. I don’t get disturbed by it 2. I can put up with it 3. If anything, I can put up with it 4. If anything, I can’t put up with it 5. I can’ t put up with it at all
RT02 (1999–2000)	657	Kanagawa Prefecture	We will ask you questions about the community or residence where you live. Are you satisfied or dissatisfied with vibrations from motor vehicles?	1. satisfied 2. somewhat satisfied 3. neither 4. somewhat dissatisfied 5. dissatisfied
RT03 (2004–2006)	640	Kanagawa Prefecture	When you are here, at home, are you bothered or not bothered by vibrations from motor vehicles?	1. not bothered at all 2. slightly bothered 3. moderately bothered 4. very bothered 5. extremely bothered
RT04 (2011)	205	Saitama City	Thinking about 1 year or so, when you are here, at home, how much are you bothered or annoyed by vibrations from motor vehicles?	1. not at all 2. slightly 3. moderately 4. very 5. extremely
CR01 (1997)	310	Kanagawa Prefecture	Can you put up with vibrations from motor vehicles?	1. I don’t get disturbed by it 2. I can put up with it 3. If anything, I can put up with it. 4. If anything, I can’t put up with it 5. I can’ t put up with it.
CR02 (2004–2006)	653	Kanagawa Prefecture	When you are here at home, are you bothered or not bothered by vibrations from trains?	1. not at all 2. slightly bothered 3. moderately bothered 4. very bothered 5. extremely bothered
CR03 (2006)	236	Nagoya City	How do you feel about house vibrations, except for earthquake when you are here, at home?	1. not disturbed at all 2. slightly disturbed 3. moderately disturbed 4. very disturbed 5. extremely disturbed
CR04 (2011)	171	Saitama City	Thinking about 1 year or so, when you are here, at home, how much are you bothered or annoyed by vibrations from passing trains?	1. not at all 2. slightly 3. moderately 4. very 5. extremely
SR01 (1995–1996)	709	Kanagawa Prefecture	When you are here, at home, how do you feel that the vibration from Shinkansen bullet train affects you?	1. I don’t disturb it. 2. I can put up with it. 3. if anything, I can put up with it 4. if anything, I can’t put up with it 5. I can’ t put up with it at all
SR02 (2001–2003)	872	Kanagawa Prefecture	When you are here, at home, are you bothered or not bothered by vibrations from the Shinkansen bullet trains?	1. not bothered at all 2. slightly bothered 3. moderately bothered 4. very bothered 5. extremely bothered
SR03 (2003)	358	Fukuoka Prefecture	There are many annoying factors regarding the passage of the Shinkansen bullet train in living environments. How much are you disturbed by house vibrations from the Shinkansen trains?	1. not at all 2. slightly 3. moderately 4. very 5. extremely
SR04 (2005)	175	Nagoya City	How do you feel about house vibrations, except for earthquake, when you are here, at home?	1. not at all 2. slightly 3. moderately 4. very 5. extremely
SR05 (2011–2012)	559	Kumamoto Prefecture	There are many annoying factors due to the passage of Shinkansen bullet train in living environments. How much are you disturbed by house vibrations from Shinkansen trains?	1. not at all 2. slightly 3. moderately 4. very 5. extremely
SR06 (2013)	294	Nagano Prefecture	There are many annoying factors regarding the passage of the Shinkansen bullet train in living environments. How much are you disturbed by house vibrations from the Shinkansen trains?	1. not at all 2. slightly 3. moderately 4. very 5. extremely

In a similar manner, the sound pressure level was measured at the same point where the vibration was measured; the equivalent continuous sound pressure level over 24 h (L_{Aeq}) was estimated as noise exposure mainly used in this study. For road traffic noise, the noise exposure was estimated based on measurements of short time intervals (from 10 min to approximately four hours). For the railway noises, the noise exposure was estimated based on the sound exposure level of the passing-by train and the frequency in operation. Certain railway datasets determine the L_{veq} values according to the maximum sound pressure level values of L_{Amax}, L_{Aeq}, and L_{vmax}.

Table 2: Methods for the calculation of vibration exposures

ID(Year)	Calculation for L_{vmax}	Calculation for L_{veq}
RT01 (1998)	Average of each maximum vibration level at intervals of 10 min (four times or more)	Energy mean value of each equivalent continuous vibration level at intervals of 10 min (four times or more)
RT02 (1999–2000)	Average of each maximum vibration level at intervals of 10 min (six times or more)	Energy mean value of each equivalent continuous vibration level at intervals of 10 min (six times or more)
RT03 (2004–2006)	Average of each maximum vibration level at intervals of 10 minutes (six times or more)	Equivalent continuous vibration level (six times or more)
RT04 (2011)	Average of maximum vibration levels of the top 10 vibration events (four h)	Equivalent continuous vibration level (four h)
CR01 (1997)	Average of maximum vibration levels of the upper half among 10 or more vibration events	Calculation based a maximum vibration level and duration of each event, and the frequency of train service
CR02 (2004–2006)	Average of maximum vibration levels of the top 10 among 20 vibration events	Calculation based energy sum of instantaneous vibration levels and duration of each event, and the frequency of train service
CR03 (2006)	Average of maximum vibration levels of the top 10 among 20 vibration events	Calculation based on energy sum of instantaneous vibration levels and duration of each event, and the frequency of train service
CR04 (2011)	Average of maximum vibration levels of the upper half vibration events induced by the closet line to measuring points	Equivalent continuous vibration level (four h)
SR01 (1995–1996)	Average of maximum vibration levels of the upper half among 10 or more vibration events	Calculation based on maximum vibration level and duration of each event, and the frequency of train service
SR02 (2001–2003)	Average of maximum vibration levels of the upper half among 10 or more vibration events	Calculation based on energy sum of instantaneous vibration levels and the duration of each event, and the frequency of train service
SR03 (2003)	Average of maximum vibration levels of the upper half among 10 or more vibration events	Estimation from the following equation: $L_{\text{veq}} = L_{\text{Aeq}} + L_{\text{vmax}} - L_{\text{Amax}}$
SR04 (2005)	Average of maximum vibration levels of the top 10 among 20 vibration events	Estimation from the following equation: $L_{\text{veq}} = L_{\text{Aeq}} + L_{\text{vmax}} - L_{\text{Amax}}$
SR05 (2011–2012)	Average of maximum vibration levels of the top 10 among measured vibration events	Estimation from the following equation: $L_{\text{veq}} = L_{\text{Aeq}} + L_{\text{vmax}} - L_{\text{Amax}}$
SR06 (2013)	Average of maximum vibration levels of the upper half around 10 vibration events	Estimation from the following equation: $L_{\text{veq}} = L_{\text{Aeq}} + L_{\text{vmax}} - L_{\text{Amax}}$

RESULTS AND DISCUSSION

Exposure–response relationship

To express the exposure–response relationships, we used the “highly annoyed” percentage of responses (%HA) as an annoyance index, namely the mean value of the percentage of “extremely annoyed” and “very annoyed” (%EA and %VA, respectively). Here, the responses of the top and any of the top two annoyance ratings stand for EA and VA, respectively. Figures 1 and 2 present the comparison of the L_{vmax}–%HA and the L_{veq}–%HA relationships, respectively, for every dataset of each source (left: Road traffic; center: Conventional Railway; right: Shinkansen Railway). Here, a given numerical value of the X axis represents the range of plus or minus 2 dB of the value. For example, an L_{vmax} of 48 dB means that the L_{vmax} lies within the range of 46–50 dB. For both figures, the %HA values are not plotted in the interval that contains less than 10 respondents. For road traffic vibration, the relationship of the RT02 dataset is extremely higher. This is attributed to the descriptor of dissatisfaction and that there is no modifier on the descriptor. Except for the RT02 dataset, we may observe that the difference among the relationships of the different datasets is small. Regarding conventional railway vibration, in the ranges of 51–55 dB or higher values, the %HA for the CR04 dataset abruptly increases and presents the highest values compared to the other datasets, followed by the CR02 dataset. In contrast, the %HA for the CR03 dataset presents considerably low values at higher ranges. Regarding the Shinkansen railway vibration, the %HA of the SR03 dataset rapidly rises, even in a low L_{veq} range of 26–30 dB, whereas the SR02 dataset gradually increases. Moreover, for every vibration, the “unbearable” modifier, which was used in the RT01, CR01, and SR01 datasets, indicates relatively small prevalence rates.

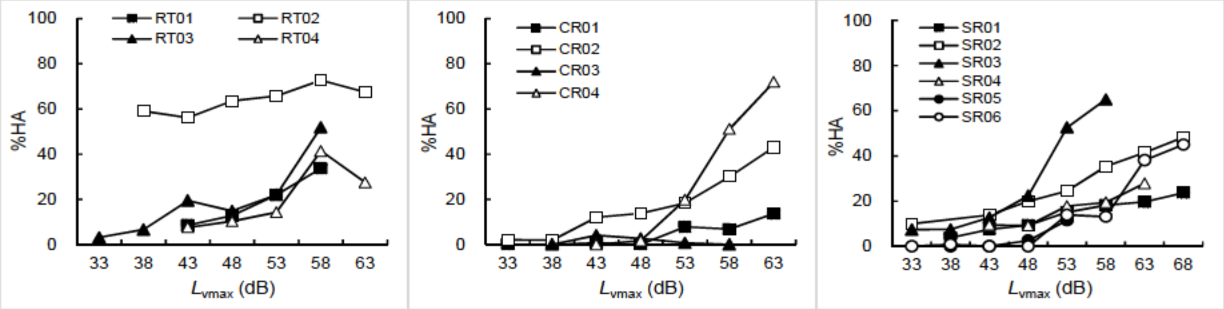

Figure 1: Comparison of L_{vmax}–%HA relationships of different datasets

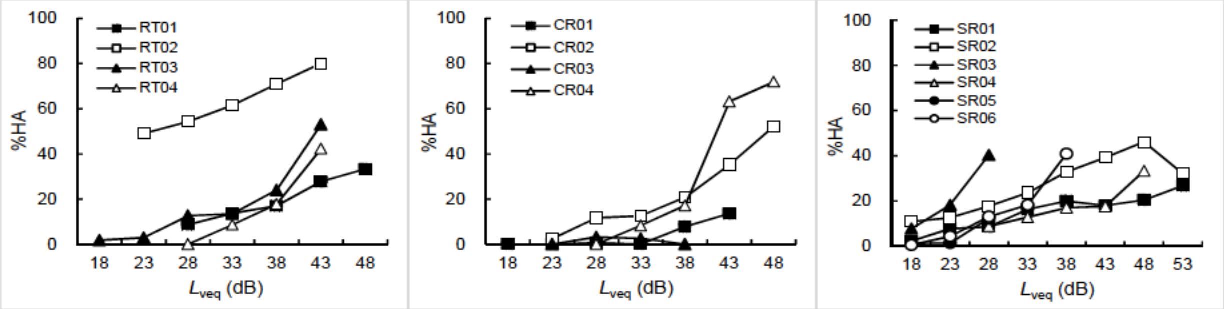

Figure 2: Comparison of L_{veq}–%HA relationships of different datasets

To examine responses of vibration perception and rattling, %P and %RT denote the rates of the perception and the prevalence of rattling, respectively. Figures 3 and 4 present the comparisons of the L_{vmax}–%P relationships and the L_{vmax}–%RT relationships, respectively. For the rattling where the five-point scale was used, the rate of answering any of the top two categories was calculated. The %P and %RT are not plotted in the interval that contains less than 10 respondents. Regarding road traffic, except for the RT02 dataset, the L_{vmax}–%P relationships are consistent among the datasets. The case of conventional railway presents greater variations in the L_{vmax}–%P and L_{vmax}–%RT relationships than those in the case of road traffic vibrations; however, it may be observed that the average slope of %RT is abrupt. The L_{vmax}–%P and L_{vmax}–%RT relationships for the Shinkansen railway are the highest; in particular, the SR01–SR03 datasets associated with the oldest line, namely the Tokaido Shinkansen line, present significantly higher values than the rest of the datasets. On the other hand, the relationship of the SR05 dataset that were derived from the new “Kyusyu Shinkansen line” presents low values. When the L_{veq} was substituted by L_{vmax} as vibration exposure, similar trends were observed for L_{vmax}. By comparing vibration indices, we found that the difference in the exposure–response relationships for energy-based exposure was almost the same as that for maximum-based exposure.

Then, focusing on annoyance responses, we compared the relationships between the maximum-based exposure and the annoyance that was associated with ground-borne vibration, according to the frequency of vibration events (including the duration). In this study, we used the difference between the L_{veq} and L_{vmax} values as an index of frequency (DL_v). Considering the average of the DL_v values for each vibration source, we divided the respondents into a high-frequency group (HF) and a low-frequency group (LF): the HF group receives values of $DL_v > -20$ dB and the LF group receives values of $DL_v \leq -20$ dB for road traffic and conventional railway vibrations; the HF group receives values of $DL_v > -15$ dB and the LF group receives values of $DL_v \leq -15$ dB for the Shinkansen railway vibration. Figure 5 presents the comparison of the L_{vmax}–%HA relationships between the high- and low-frequency groups for each vibration source. The RT02 dataset was excluded from further analysis.

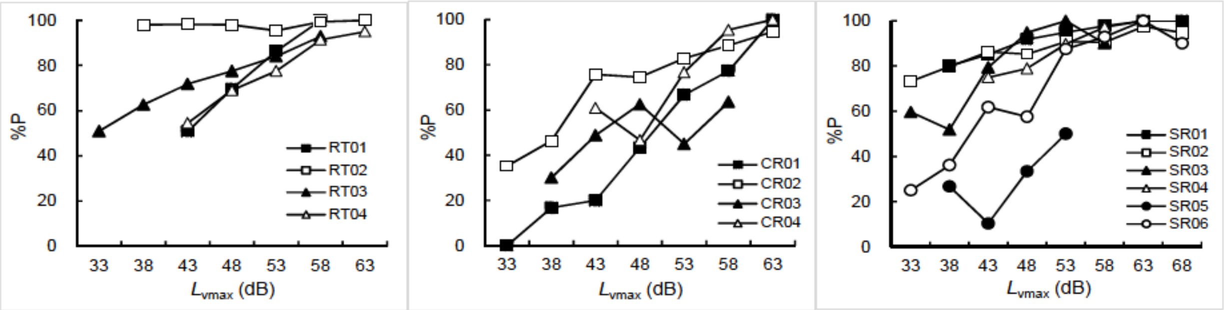

Figure 3: Comparison of the L_{vmax}–%P relationships among the dataset

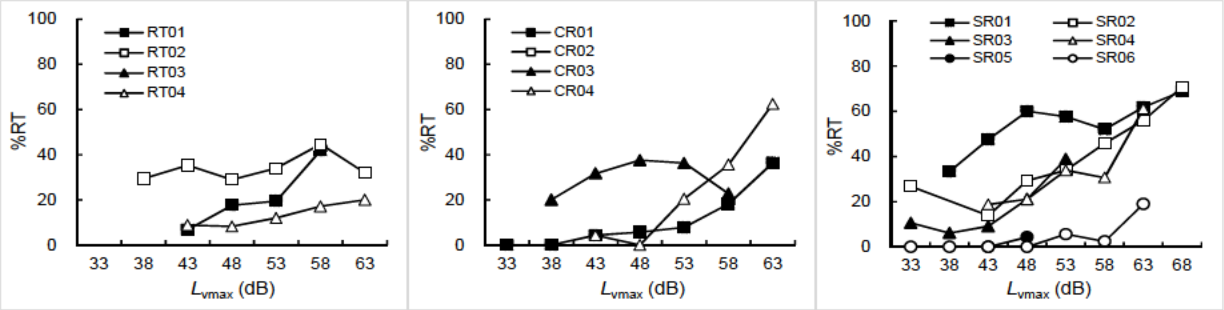

Figure 4: Comparison of the L_{vmax}–%RT relationships among the dataset

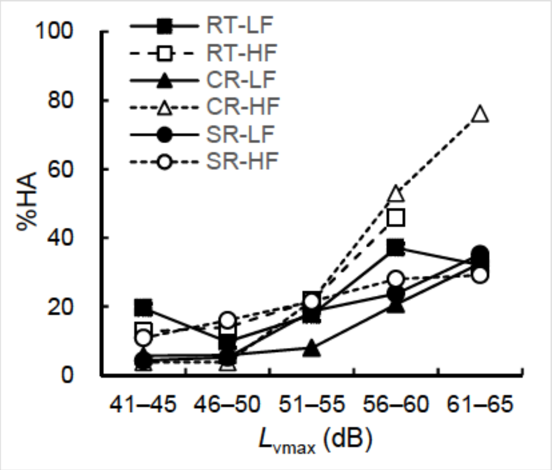

Figure 5: Comparison of the L_{vmax}–%HA relationships according to the frequency of vibration events

It may be observed that the prevalence rate for the high-frequency group is higher than that for the low-frequency group in certain exposure ranges; however, the difference depends on the vibration source. Regarding road traffic, in the three ranges from 46–50 dB to 56–60 dB, the differences in the %HA values between the RT–HF and the RT–LF groups are 4%, 4%, and 9%, respectively. For conventional railway, in the three ranges from 51–55 dB to 61–65 dB, the differences in the %HA values between the CR–HF and the CR–LF groups are 14%, 32%, and 43%, respectively. For the Shinkansen railway, within the ranges of 46–50 dB and 51–55 dB, the differences in the %HA values between the SR–HF and the SR–LF groups are 7% and 11%, respectively. From the above observations, the difference in the prevalence of annoyance according to the frequency of vibration events is substantial regarding conventional railway; however, the difference regarding road traffic and the Shinkansen railway is only slight.

Effect of noise on vibration annoyance

To reveal the effect of noise on vibration annoyance, we applied logistic regression analysis to the datasets. The analysis was applied to extremely and very annoyed responses due to ground vibrations as the dependent variable, while noise and vibration exposures, the annoyance descriptor, the sex, the age, and the housing structure were included as independent variables. For the vibration exposure, L_{veq} was used based on the abovementioned result that the frequency of the vibration events can affect the vibration annoyance. The analysis was applied with vibration and noise exposures, which were considered as category scales in 5- or 10-dB intervals, respectively.

Table 3: Parameter estimates of exposures for EA and VA due to road traffic vibration

Exposure	Range (dB)	EA			VA		
		Odds ratio	95% Lower CI	95% Upper CI	Odds ratio	95% lower CI	95% Upper CI
L_{veq}	26–30	6.5404	0.8373	51.0865	3.2817	1.2270	8.7771
	31–35	3.4494	0.4221	28.1905	2.9165	1.0805	7.8723
	36–40	6.3117	0.7994	49.8327	3.4461	1.2766	9.3025
	41–45	13.9366	1.7298	112.2853	8.8812	3.1721	24.8656
L_{Aeq}	41–50	0.3320	0.1090	1.0109	0.3479	0.1834	0.6600
	61–70	2.8094	1.5702	5.0268	1.9548	1.3276	2.8782

Table 4: Parameter estimates of exposures for EA and VA due to conventional railway vibration

Exposure	Range (dB)	EA			VA		
		Odds ratio	95% Lower CI	95% Upper CI	Odds ratio	95% Lower CI	95% Upper CI
L_{veq}	26–30	0.6839	0.1688	2.7706	2.3827	0.9352	6.0706
	31–35	1.4588	0.4323	4.9232	2.4108	0.9751	5.9605
	36–40	1.7449	0.5189	5.8673	4.6188	1.8939	11.2640
	41–45	5.6721	1.7071	18.8468	13.0883	5.1966	32.9645
	46–50	9.6222	2.5512	36.2917	10.5078	3.5908	30.7491
L_{Aeq}	31–40	0.0788	0.0100	0.6231	0.1810	0.0623	0.5262
	41–50	0.2052	0.0675	0.6244	0.3704	0.1932	0.7101
	61–70	1.7923	1.0156	3.1629	2.0431	1.2780	3.2664

Table 5: Parameter estimates of exposures for EA and VA due to the Shinkansen railway vibration

Exposure	Range (dB)	EA			VA		
		Odds ratio	95% Lower CI	95% Upper CI	Odds ratio	95% Lower CI	95% Upper CI
L_{veq}	26–30	4.0713	2.0372	8.1366	3.2443	2.1341	4.9322
	31–35	5.2602	2.7184	10.1787	4.2255	2.8354	6.2972
	36–40	9.3004	4.8711	17.7573	5.3982	3.6112	8.0693
	41–45	10.3016	5.2558	20.1915	5.7454	3.7420	8.8216
	46–50	8.4529	3.7804	18.9005	4.9724	2.8673	8.6230
L_{Aeq}	31–40	0.5120	0.2996	0.8750	0.5790	0.4158	0.8061
	51–60	1.5212	1.1062	2.0919	1.2783	0.9834	1.6617

Tables 3 through 5 list the parameter estimates of noise and vibration exposures for EA and VA due to each of ground-borne vibrations. The calculation of the odds ratio for the vibration annoyance was based on the following reference categories: 21–25 dB for the L_{Aeq}; 51–60 dB (road traffic and conventional railway) and 41–50 dB (Shinkansen railway) for the L_{veq}.

As listed in Tables 3 through 5, for both annoyance indices, the odds ratio of a smaller noise exposure category than the reference category of the L_{Aeq} is less than 1, with the exception of the L_{Aeq} range of 41–50 dB for EA due to road traffic vibration, where the upper limit of the 95% confidence interval is less than 1. In a similar manner, the odds ratio of a larger noise exposure category than the reference category of the L_{Aeq} is over the value of 1, with the exception of the L_{Aeq} range of 51–60 dB for VA due to the Shinkansen railway vibration, where the lower limit of the 95% confidence interval is over the value of 1. Among other factors, the sex and the descriptor significantly affected the %EA and %VA at the 5% level. Categories of female and bearable scale had lower prevalence rates than male and the ICBEN scale, respectively.

From the results listed in Tables 3 through 5, we established the L_{veq}–%HA relationships of different L_{Aeq} values (intervals of 10 dB). To determine each prevalence rate, we adjusted the sex and age according to the results of the national census in 2015, and we set the ICBEN verbal scale and wooden construction as the descriptor and housing structure items, respectively. The L_{veq}–%HA relationships for various L_{Aeq} values are presented in Figure 6. The %HA values are not plotted at the interval that involved less than 20 respondents.

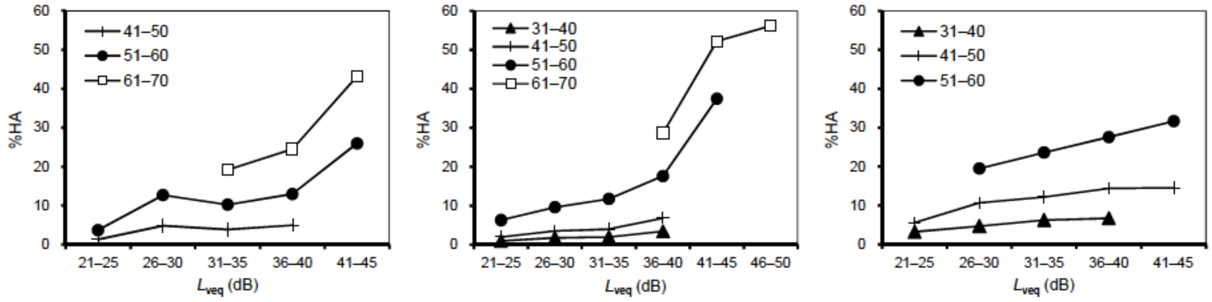

Figure 6: L_{veq}–%HA relationships for various L_{Aeq} values for each vibration source
(Left: Road traffic; Center: Conventional railway; Right: Shinkansen railway)

For road traffic and conventional railway, the L_{veq}–%HA relationships for L_{Aeq} ranges of 31–40 dB and 41–50 dB present extremely low values; in contrast, the %HA values for L_{Aeq} ranges of 51–60 dB and 61–70 dB abruptly increase as L_{veq} increases. For the Shinkansen railway, the %HA values for L_{Aeq} ranges of 41–50 dB and 51–60 dB gradually increase as L_{veq} increases.

We compared the %HA values of the same L_{Aeq} range, for all sources. In the L_{veq} range of 31–35 dB, the %HA values of the L_{Aeq} range of 41–50 dB are 4%, 4%, and 12% for road traffic, conventional railway, and the Shinkansen railway, respectively; the %HA values for the L_{Aeq} range of 51–60 dB are 10%, 12%, and 26%. In the L_{veq} range of 36–40 dB, the %HA values for the L_{Aeq} range of 41–50 dB are 6%, 7%, and 14% for road traffic, conventional railway, and the Shinkansen railway, respectively; the %HA values for the L_{Aeq} range of 51–60 dB are 13%, 17%, and 29%. In the L_{veq} range of 41–45 dB, the %HA values for the L_{Aeq} range of 51–60 dB are 26%, 38%, and 32% for road traffic, conventional railway, and the Shinkansen railway, respectively.

Discussion

From the results obtained using a logistic regression analysis, the increasing effect of noise exposure on vibration annoyance was confirmed. Focusing on the circumstances in which inhabitants were exposed to noise and vibration in detached houses, they were frequently exposed to simultaneously occurring noise and vibration over a long period of time [13, 14]. Under these circumstances, the inhabitants are forced to address the adverse effects from either vibration or noise from the source, particularly at high levels of noise and vibration exposures. On the other hand, at low levels of vibration exposure, the increase in noise annoyance with the increase in noise exposure can affect simultaneously occurring vibration annoyance. Based on the findings, it is likely that a synergetic effect of noise and vibration exposures on annoyance has occurred.

Comparing the exposure-–annoyance relationships, the prevalence rate of annoyance due to ground-borne vibrations from the Shinkansen railway presented higher values than other ground transportations. This is consistent with the comparison of the prevalence of noise annoyance [3]. The trend was observed at the medium level of noise and vibration exposures. It is assumed that the difference in noise annoyance may be attributed to vibration exposure. However, at the same level of vibration exposure, the noise exposure from the Shinkansen railway was lower than that of other means of transportation. Therefore, we addressed rattling, because the response due to the Shinkansen railway was higher than that due to other vibration sources. Additionally, Tamura reported that the Shinkansen railway noise was more negatively evaluated than conventional railway noise [15]. He also reported that inhabitants living in the areas along the Shinkansen railway were generally concerned with noise issues, and did not acknowledge the necessity of the Shinkansen railway. The negative opinion of the residents regarding the Shinkansen railway may promote great annoyances due to noise and ground-borne vibrations. In areas near the Shinkansen lines, ground-borne vibrations had greater impact on combined annoyance due to noise and ground-borne vibration [16]. Therefore, the vibration annoyance may be affected in a greater degree by negative opinions, rather than noise annoyance.

In this study, we estimated vibration exposure based on vertical measurements obtained on the ground surface. Even in the vertical direction, house vibration is different from ground vibration. Therefore, we could not precisely estimate values of vibration exposure for residents of detached houses. According to a recent study regarding the vibration amplitude in wooden- or steel-construction detached houses, there was no significant difference in the vertical vibration between the ground and the floors [17]. Therefore, on the average, the vertical vibration level in a detached house can be equivalent to measurements on ground surface. We expect that the averaged exposure–response relationships that have been presented in this study will be fully utilized.

CONCLUSION

We made a secondary analysis of 14 datasets derived from 12 separate surveys conducted in residential areas along the traffic facility for the past 20 years. In this study, we first investigated the relationships between exposures and community responses associated with ground-borne vibrations according to their source, using vibration exposures, the energy-based index, and the maximum-based index. Next, focusing on annoyance, we demonstrated that the maximum-based index corresponded in a more suitable manner than the energy-based index to annoyance. Finally, to clarify the effect of noise exposure on vibration annoyance, we applied a logistic regression analysis to the datasets. It was confirmed that noise exposure affected vibration annoyance. Based on the results, we established the exposure–annoyance relationships for each vibration source. By comparing the same exposure, the Shinkansen railway was found to be the most annoying vibration at a medium level of vibration exposure. In contrast, there was a slight difference in the prevalence of vibration annoyance among the vibration sources at a high level of vibration exposure.

Acknowledgments

The present study was supported by Grant-in-Aid for Scientific Research (C) of the Japan Society for the Promotion of Science (No.15K06341).

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