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Research Article

Comparative Analysis of Two Different Light Rail Superstructures in Istanbul Traffic in Terms of Vibration

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ABSTRACT

Railway-induced vibrations are one of the major problems that need to be suppressed for the passengers or people who are living around the railway. It is essential that the vibrations are first tried to be suppressed on the source, railway. Thus, the railway superstructure components contain various elastic elements used in vibration insulation, such as rail pads. In this study, two different railway superstructures used in Istanbul railway traffic were tested while passing the railway vehicle at various speeds, and the vibrations generated by the wheel-rail interaction were compared regarding passenger comfort and the environment in compliance with the relevant standards. Used railway superstructures to compare the propagated vibrations are constructions with single and double elastomeric layers installed on the same line, sequentially. In this experimental benchmarking study which contains some evaluations according to standards, the behaviour of these two railway superstructure types in terms of vibration insulation in light metro lines is revealed using measurement results. Consequently, when the double-layered elastomer is used instead of a single-layered in the superstructure, the comfort level of the people living around the line is improved as up to 64% and the comfort level of the passengers is improved as up to 54%. In addition, in terms of the safety investigations of the buildings around the line, a meaningful decrease in vibrations greater than 70 Hz is observed and it is concluded that residential buildings could be built up to 5 m distance.

Keywords: *Railway, Superstructure, Rail pad, Vibration analysis, Vibration Insulation*

İstanbul Trafiğinde Bulunan İki Farklı Hafif Metro Üstyapısının Titreşim Bakımından Karşılaştırmalı Analizi

ÖZET

Demiryoluna bağlı titreşimler, yolcuların veya demiryolunun çevresinde yaşayan insanlar için bastırılması gereken en önemli sorunlardan biridir. Titreşimlerin öncelikle kaynakta, yani demiryolu üzerinde bastırılmaya çalışılması esastır. Bu nedenle, demiryolu üst yapı bileşenleri, titreşim yalıtımında kullanılan ray pedleri gibi çeşitli elastik elemanlar içerir. Bu çalışmada, İstanbul demiryolu trafiğinde kullanılan iki farklı demiryolu üst yapısı, demiryolu aracı çeşitli hızlarda geçerken test edildi ve tekerlek-ray etkileşiminin oluşturduğu titreşimler, yolcu konforu ve çevre ile ilgili standartlara uygun olarak karşılaştırıldı. Yayılan titreşimleri karşılaştırmak için aynı hat üzerinde yerleştirilmiş tek ve çift elastomerik tabakalara sahip demiryolu üstyapıları kullanılmıştır. Standartlara göre bazı değerlendirmeler içeren bu deneysel kıyaslama çalışmasında, bu iki demiryolu üst yapı tipinin hafif metro hatlarında titreşim yalıtımı açısından davranışları ölçüm sonuçları kullanılarak ortaya konmuştur. Sonuç olarak, üstyapıda tek katman yerine çift katmanlı elastomer kullanıldığında, hat çevresinde yaşayan insanların konfor seviyelerinde %64'e, araç içerisinde bulunan yolcuların konfor seviyelerinde ise %54 varan iyileşme gerçekleşmiştir. Ayrıca, hat çevresinde bulunan binaların güvenliği bakımından yapılan araştırmada 70 HZ'den büyük titreşimlerde anlamlı bir azalma gözlenmiş ve hatta en az 5 m mesafeye kadar konut amaçlı bina yapılabileceği sonucuna ulaşılmıştır.

Anahtar Kelimeler: *Demiryolu, Üstyapı, Ray pedi, Titreşim analizi, Titreşim izolasyonu*

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I. INTRODUCTION

Nowadays, more than 1.8 million people per day use railway transportations in Istanbul [1]. Increasing the ratio of railways in urban transportation brings solutions to several problems, such as traffic and CO_2 emissions, however, at the same time, it causes different problems. Near environment of the railway lines and passengers may highly be affected by railway-induced vibrations [2]. Mitigation of railway-induced vibrations is a meaningful requirement to passengers, environmental buildings and people who live near the railway lines. Thus, it is extremely important to provide solutions to vibration and noise problems in the construction phase. Taking basic precautions in the construction phase could increase the comfort level of passengers and people who live in buildings near the railway line. To reduce the vibration effects, different superstructure types are developed such as single (just rail pads) or double layered pads (rail pads with baseplate pads) [3-5], mass-spring systems [6], floating slabs [3, 7, 8], under ballast mats [9, 10].

The vibrations due to wheel-rail interaction in railways occur at 0-20 Hz on vehicles, 0-500 Hz on the track and 0-1500 Hz on the track components like rail pads and sleepers [11]. The vibrations below 100 Hz are important when the effects of railway vibrations on the comfort of passengers and people who live in the environment, and robustness of the environmental buildings are examined [12-15]. Taking this information into consideration, research and vibration measurement implementations were carried out on the railway and its environment [7, 16-19]. In addition, several theoretical and analytical studies have been conducted to reduce the effects of railway-induced vibrations since Bata's study of the effects of transport vibrations on buildings [3-6, 8-11, 20-24]. These insightful studies sometimes introduce novel techniques for implementation; they sometimes shed lights into the effects of material technology developments [9, 10, 25, 26].

Even though much theoretical research has been carried out on the subject in the past, the number of experimental studies that investigate the effects of railway-induced vibrations is under researched. The effectiveness of floating slab track (FST) system in Konya Light Rail was investigated by Dere [7]. In Dere’s study, above 50 Hz vertical vibrations were suppressed successfully, contrary to below 1 Hz vibrations using FST. Also, using the receptance function method, Cui shows that FST system reduces ground vibrations greater than 15 Hz theoretically [21]. Kouroussis [16] evaluated the ground-borne induced vibrations on buildings and inhabitant, by comparing many kinds of standards. This study is not concerned with the source of vibration and only compares the evaluation methods. A field test was performed to investigate the frequency-domain characteristics of ground vibrations generated by high-speed trains traveling on non-ballasted track situated at an embankment on the line between Beijing and Shanghai in China, by Wang et al. [17]. Frequency-weighted ground acceleration levels were calculated using the method in ISO2631-1-1997 to investigate the potential effects of ground vibrations. Moreover, Gong and Griffin [18] carried out an experimental study on passenger comfort. They exhibited a novel method related to the transmission of vibration throughout the seats of railway vehicles. Some measurements were carried out to investigate the effects of subway-induced vibration and noise on the ground and inside a 3-story building in a metro depot, by Zou et al [19]. In this study, although the effects of railway-induced vibrations on building inhabitants were examined, they were not focused on the railway superstructure.

Obviously, there are a large number of papers that have considered the effects of the railway-induced vibrations on near buildings or inhabitants. However, there are differences on ground velocities and accelerations with different superstructure conditions. In these conditions, wheel-rail dynamic interactions are inevitably different along a railway. Thus, we should note that it is necessary to analyze the characteristics of railway-induced vibrations from different test sections which consist of different superstructures.

For the above-mentioned purposes, in this study, a field test was performed to investigate the environmental effects of vibrations generated by light rail metro traveling on slab track superstructures situated at two different embankments on the line in Istanbul. Two test sections with a certain distance were used to acquire the vertical, transversal and longitudinal ground vibrations in this measurement. In the process of data collection, vibration velocity and acceleration were obtained using two similar experimental conditions at three different vehicle speeds. To investigate the similarities and differences in their ride and environmental effects, the measured vibration velocity and acceleration data from the similar tests were considered. Compared measurements were evaluated by the DIN 4150-2, DIN 4150-3 and ISO 6231 standards for the safety of structures near the railway field and passenger comfort. This comprehensive study could provide valuable insights into understanding the effects of different railway superstructures on the interior and environmental vibrations for the urban rail lines.

II. METHODOLOGY

This part presents the main standards related to the comfort of the inhabitants (DIN 4150-2), the safety of the buildings regarding vibration (DIN 4150-3) and the passenger comfort (ISO 2631). The aim is not describing the details of the associated methods but emphasizing their main logics.

When evaluating according to DIN 4150 standard, vibrations between 1-100 Hz are considered given that high-frequency vibrations are assumed to have small effects due to soil damping. On the other hand, vibrations from 0.4 to 80 Hz are examined when evaluating indoor comfort degree according to ISO 2631.

A. DIN 4150-2 STANDARD

Railway-induced vibrations are transmitted underground at 3 directions. Vibrations may affect the structure of the building and its inhabitants. To determine the comfort level of a human who lives in the vibrated buildings, DIN 4150-2 German standard is usually used. This standard aims the use of a running root-mean-square applied to the velocity signal. The vibration evaluation process according to the standard is explained below.

Using Eq. 1, $KB_F(t)$ is a weighted time-averaging signal which calculated from measured vibration velocities at 3 directions (x, y, and z). Then, if it is necessary, doze vibration value KB_{FTR} is calculated. Afterward, the results could be compared with Table 1. If the maximum value of $KB_F(t)$ which called KB_{Fmax} is smaller than three guideline limits called A_u, A_o and A_r for associated structure, the necessity of standard is applied for daytime or night.

$$KB_F(t) = \sqrt{\frac{1}{\tau}\int_0^t KB^2(\xi) e^{-(t-\xi)/\tau} d\xi} \quad (1)$$

where, the weighted velocity signal $KB_F(t)$ is achieved by the original velocity signal using the high pass filter.

When the vibrations are evaluated according to the standard, the KB_{Fmax} value is compared with the A_u value given in Table 1 for the appropriate structure type. If $KB_{Fmax} \leq A_u$, the standard is satisfied. If $KB_{Fmax} > A_u$, it should be checked whether $KB_{Fmax} \leq A_o$ this time. If this is not provided, the vibrations are above the reference values of the standard. Otherwise, the KB_{FTr} value is found, and the comparison is made for the A_r value. To be able to satisfy the standard, $KB_{FTr} \leq A_r$ must be confirmed. In this case, it can be said that the vibration effects are rare. If this condition is not fulfilled, it means that the vibrations affect the comfort of inhabitants negatively according to standard. The flow diagram for the evaluation method is given in the relevant standard [12]. According to DIN 4150-2, for the vibrations caused by rail traffic, A_u and A_r limit values are used. This is based on 1.5 times the values specified by the standard for close-range public transport. For the five different construction types, the smallest of the boundary A_u values given in the standard is for particularly vulnerable affected places with a value of 0.15 (building type 5). On the other hand, the maximum A_u limit value for building type 1 in the standard is

0.6. The A_r limit values for these structures are 0.075 and 0.3, respectively. For other structures specified in the standard, the limit values are within the limit values mentioned for the first and fifth type of structure here.

Table 1. *DIN 4150-2 Reference Values* [12]

No	Affected Places	Day			Night		
		A_u	A_o	A_r	A_u	A_o	A_r
1	Affected places, in their environment only commercial facilities and, exceptionally, apartments for owners and managers of companies and for supervisory authorities and on-call persons are accommodated	0.4	5	0.2	0.3	0.6	0.15
2	Affected places, in the vicinity predominantly commercial facilities are housed	0.3	6	0.15	0.2	0.4	0.1
3	Affected places, in the area neither predominantly commercial facilities are still predominantly apartments housed	0.2	5	0.1	0.15	0.3	0.07
4	Affected places, in the environment predominantly or only flats are housed	0.15	3	0.07	0.1	0.2	0.05
5	Particularly vulnerable affected places, eg. in hospitals, rehabilitation clinics, as far as they are in designated special areas	0.1	3	0.05	0.1	0.15	0.05

B. DIN 4150-3 STANDARD

The vibrations generated by the rail systems used in the urban transportation cause various effects, such as damages on the surrounding buildings. Hence, vibrations that occur in vibration-sensitive structures, such as hospitals, schools, and historical buildings, need to be analyzed. In the evaluation of the measurements performed for this purpose, the DIN 4150-3 1999-03 (Vibration in buildings-Part 3: Effects on Structures) standard is used [13]. This standard is used to detect and evaluate the effects measured in the structural systems due to vibrations.

To assess in accordance with this standard, $v_{i,max}$ that is the maximum value in three directions ($i = x, y, z$) of the vibration velocity of the time ($v_i(t)$) are considered. This value is simplified and defined by v_i. In Table 2 and Figure 1, reference values are given for v_i in the base and uppermost ceiling plane in various building types [13].

Table 2. DIN 4150-3 Reference Values [13]

No	Type of Structures	Vibration peak particle Velocity *(mm/s)*			
		Foundation Frequency			Plane of Floor of Uppermost Storey
		1-10 *(Hz)*	**10-50** *(Hz)*	**50-100** *(Hz*)*	**Frequency Mixture**
1	Buildings used for commercial purposes, industrial buildings and buildings of similar design	20	20 to 40	40 to 50	40
2	Dwellings and buildings of similar design and/or use	5	5 to 15	15 to 20	15
3	Structures that, because of their sensitivity to vibration, do not correspond to those listed in lines 1 and 2 and are of great intrinsic value (eg. buildings that are under a preservation order)	3	3 to 8	8 to 10	8

(*) For frequencies above 100Hz, at least the values specified in this column shall be applied

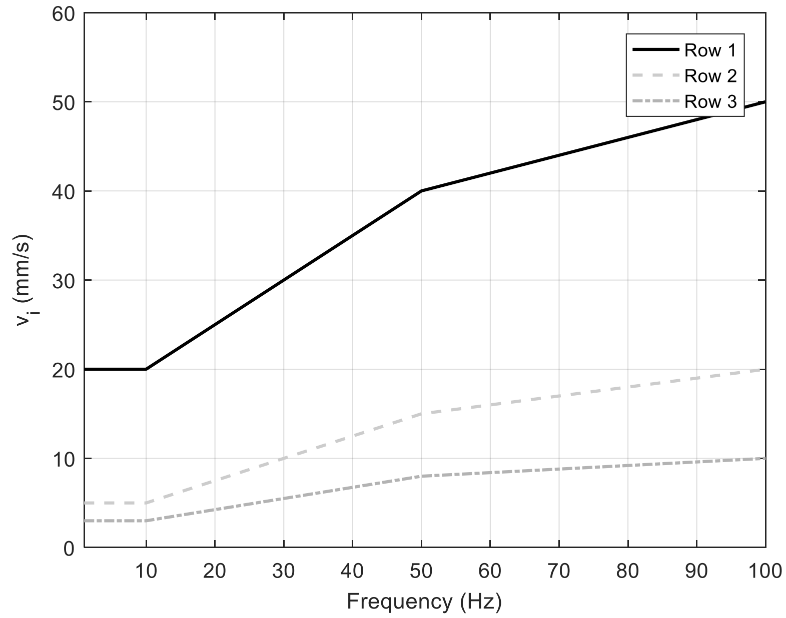

Figure 1. *DIN 4150-3 Reference curve for different building types* [13]

C. ISO 2631 STANDARD

The International Organization for Standardization gives general advice about the evaluation of human exposure to whole-body vibrations [14, 15]. The safety of driving depends on displacement responses and comfort level also depends on acceleration responses. The magnitude of three directions of vibration is evaluated frequency-dependent filters. The data measured according to the standard are processed between 0.4-80 Hz frequency and 1/3 octave band. Weighted acceleration data are calculated using Eq. 2 to 4. As a result of the evaluation, the comfort level is graded considering the total vibration value a_v as Table 3.

Table 3. *Comfort graduation according to ISO 2631* [15]

The total vibration value (a_v) *(m/s^2)*	**Graduation**
Less than 0.315	Not uncomfortable (NU)
0.315-0.63	A little uncomfortable (LU)
0.5-1.0	Fairly uncomfortable (FU)
0.8-1.6	Uncomfortable (U)
1.25-2.5	Very uncomfortable (VU)
Greater than 2	Extremely uncomfortable (EU)

The various frequency weighting filters (W_d, W_k, W_c) described in the relevant standards (ISO 2631-1 and ISO 2631-4) are implemented to the measured acceleration values. These filters are called W_d in the longitudinal (x) and lateral (y) vibrations of the vehicle and W_k in the vertical (z) vibrations. W_c is the filter used for passenger backrest position. The frequency-dependent variations of these filter gains are shown in Figure 2.

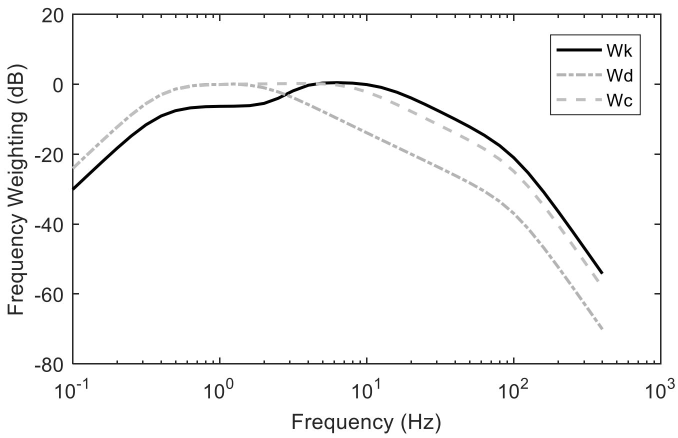

Figure 2. *Frequency weighting curves according to ISO 2631*

A root-mean-square (RMS) value which describes the smoothed vibration amplitude by supposing that the human body responds to average vibration amplitude during a record time $0 \le t \le T$ is calculated as follows:

$$a_w = \sqrt{\frac{1}{T}\int_0^T a_w^{\,2}(t)dt} \tag{2}$$

For the conversion of one-third octave band data, the weighting factors given in standard are used. The overall weighted acceleration is determined in accordance with the following equation [14, 15]:

$$a_w = \sqrt{\sum_i (W_i a_i)^2} \tag{3}$$

where; a_w is the weighted total acceleration value, Wi is the i^{th} band weighting factor in the 1/3 octave band and a_i represents the RMS value of acceleration in the 1/3 octave band.

$$a_v = \sqrt{k_x^2.a_{wx}^2 + k_y^2.a_{wy}^2 + k_z^2.a_{wz}^2} \quad (4)$$

where; a_v is the total vibration value of the weighted accelerations, k_x, k_y and k_z represent the multiplication factors, and a_{wx}, a_{wy} and a_{wz} represent the RMS values of the weighted total accelerations for the x, y and z axes. For seated and standing passengers; k_x, k_y and k_z are accepted equal to 1.

III. IMPLEMENTATION OF THE MEASUREMENT TEST

A. INTRODUCING THE LIGHT RAIL-LINE SPECIFICATIONS

Measurement field is located at Esenler Metro Station between Yenikapı and Kirazlı light rail metro line represented in Figure 3. Six axels light rail vehicle was used for the measurements (ABB-525).

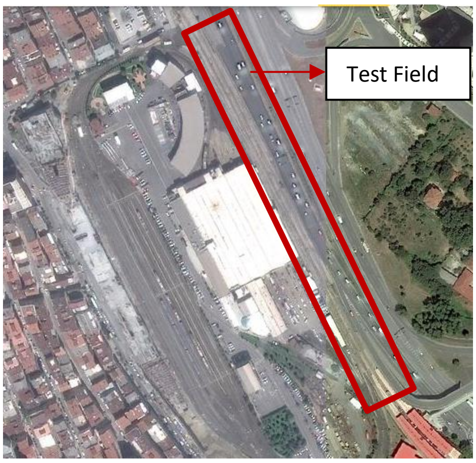

Figure 3. *Measurement field (coordinates: 41.038684"N, 28.887408"E)*

As reported above, there are two different railway superstructures on the measurement field;

- Half of the test area has a single elastomeric layered track (Fig. 4.a), composed of rail, rail pad and rail pad bed ("Vossloh DFF 21" type rail fastening system).
- The rest of the test area has a double elastomeric layered track (Fig. 4.b), composed of rail, rail pad, base plate, base plate pad and base plate bed ("Vossloh System 336" type rail fastening system).

The test line is a straight (no curve) line, has welded rail, and has no significant rail irregularities, also wheels of the railway vehicle had newly turned and its kilometer is below 50 km. The weather is clear, cloudless and rainless and the temperature is between 24.3°C and 23.8°C on the test day.

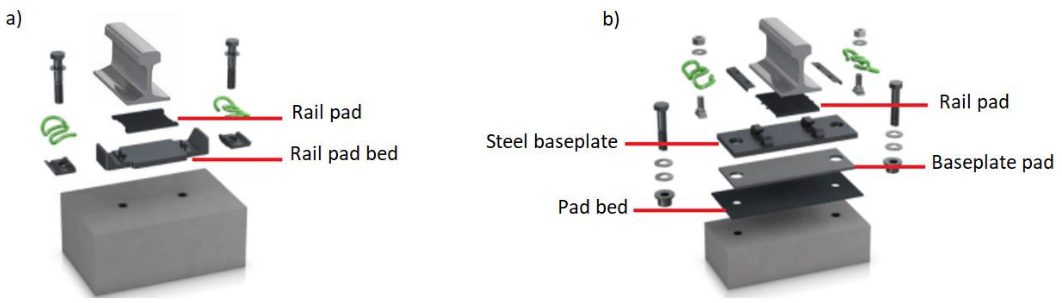

Figure 4. *The composition of tested track types:* ***a)*** *Single layered fastening system, Vossloh DFF 21 [27]*
b) *Double layered fastening system, Vossloh System 336 [28]*

B. CONFIGURATION AND SETUP OF THE MEASUREMENTS

In the test field, two kinds of measurements occurred as outdoor and indoor cases for three different vehicle speeds, 10 km/h, 30 km/h and 50km/h.

In the case of outdoor measurements, vibrations were measured at a distance of 1.5 m and 5 m from the rail at three (*x*, *y*, and *z*) and one direction (*z*), respectively. In outdoor measurements, DIN 4150-2 and DIN 4150-3 standards were considered. The measurement area is shown in Figure 5. In Figure 5, *x*, *y* and *z* directions represent the longitudinal, lateral and vertical directions, respectively. Figure 6 shows the top view of the outdoor measurement setup.

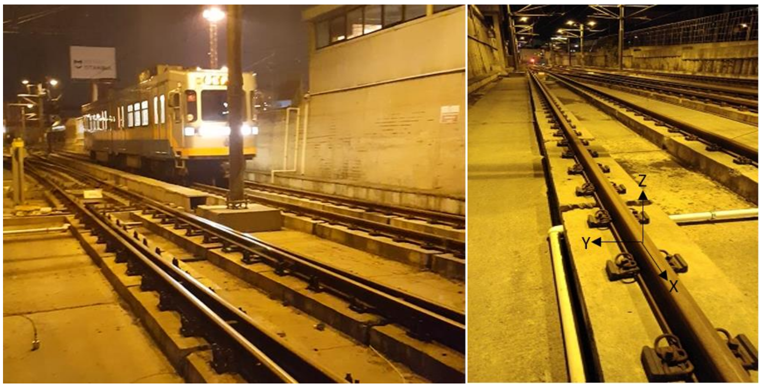

Figure 5. *Outdoor measurement area and axis directions*

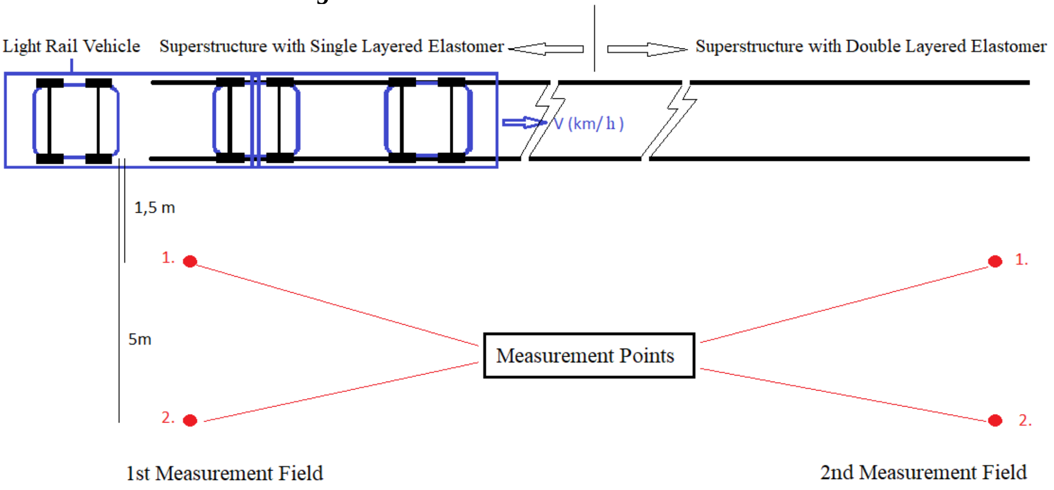

Figure 6. *Top view of outdoor measurement setup*

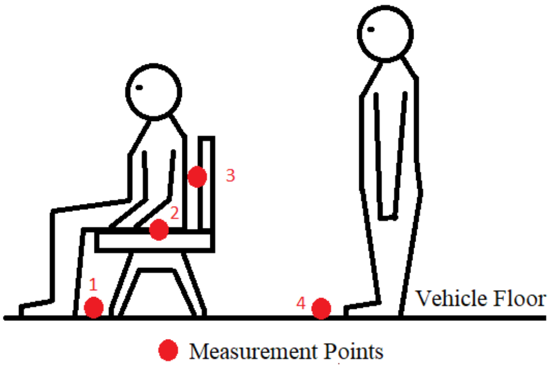

Figure 7. *Indoor measurement setup*

Figure 8. *Measurement equipment on the indoor test (Dewesoft Sirius Data Acquisition System)*

Indoor measurements were based on the ISO 2631 standard, where vibrations were measured from the backrest and sitting place of the passenger, and also from the two points of floor of the vehicle for seating and standing passengers in three directions (*x*, *y*, and *z*), (Fig. 7 and Fig. 8).

Accelerometers used in outdoor and indoor measurements are listed in Table 4 and 5, respectively. Vibrations were collected and analyzed using Dewesoft Sirius Data Acquisition System are shown in Figure 8.

Table 4. *Technical specifications of accelerometers in outdoor measurements*

Measurement Points	**1**	**2**
Type	Accelerometer	Accelerometer
Trademark/Model	Kistler 8688A10	Brüel&Kjaer 8340
Sensitivity *(mV/g)*	500	10000
Frequency Range *(Hz)*	0.5-3000	0.1-1500
Measurement Range *(g)*	±10	±0.5
Axis Type	3 (x, y, z)	1 (z)

Table 5. *Technical specifications of accelerometers in indoor measurements*

Measurement Points	**1**	**2**	**3**	**4**
Type	Accelerometer	Accelerometer	Accelerometer	Accelerometer
Trademark/Model	Kistler 8688A10	Brüel&Kjaer 4515B	Brüel&Kjaer 4515B	Dytran 3093B1
Sensitivity *(mV/g)*	500	100	100	100
Frequency Range *(Hz)*	0.5-3000	0.25 - 900	0.25 - 900	2-5000
Measurement Range *(g)*	±10	±50	±50	±50
Axis Type	3 (x, y, z)	3 (x, y, z)	3 (x, y, z)	3 (x, y, z)

IV. MEASUREMENT RESULTS

To summarize, vibrations that were measured on the close environment of the line and in the vehicle were comparatively evaluated within the framework of the relevant standards for two different superstructure systems. As a result, comparative data on vibration insulation performances of these two different superstructure types were obtained for both cases.

A. EXPERIMENTAL BENCHMARKING OF SUPERSTRUCTURES BY THE USE OF RELEVANT STANDARDS

To determine the comfort level of a human who lives in the buildings that excited by railway system effects, DIN 4150-2 German standard was used as a result of outdoor measurements in the first step. In the second step, the environmental effects of the vibrations of the railway system were evaluated for the structural safety using DIN 4150-3 standard. As a result, our findings show which railway superstructure provides more comfort and safety for the people who are living in the surrounding buildings.

A.1. Comparison According to the DIN 4150-2 Standard

The measured vibration velocities from two points at the ground near the railway where two different superstructures are used while the light rail vehicle is moving at three different speeds (10 km/h, 30 km/h, and 50 km/h) are given comparatively in Figure 9.

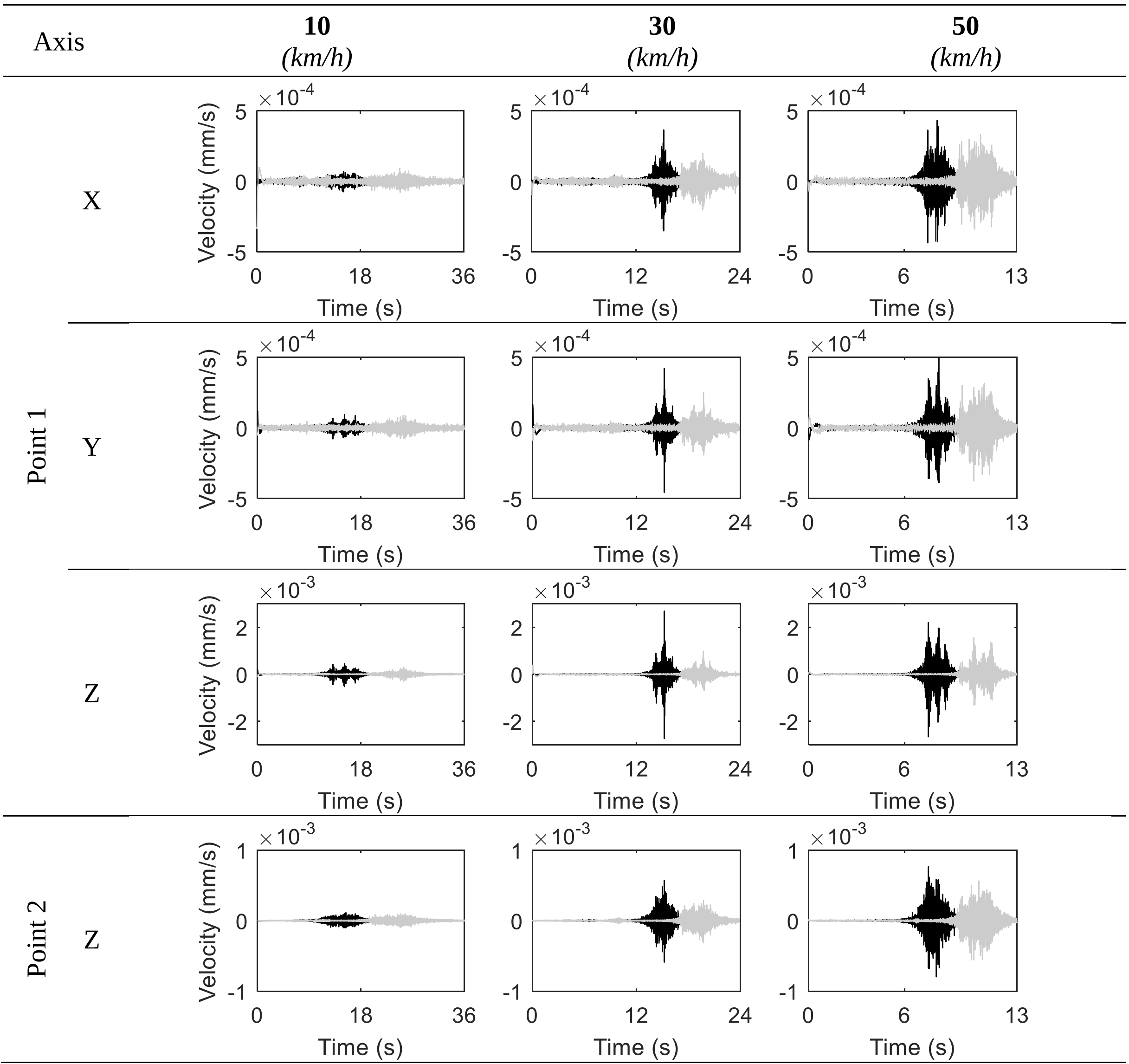

Figure 9. *Velocity-time results of vibrations measured at points 1 and 2 at different speeds ('Dark Line' 1st Measurement Field, 'Soft Line' 2nd Measurement Field)*

The first and second measurement points are 1.5 and 5 meters away from the track for both measurement areas, respectively. The measurement points represent the building grounds which may be close to the urban railway lines considering the worst case scenario.

In Figures 9 and 10, the dark line shows the vibrations measured from the 1st measurement field where the single elastomer layer is used, while the soft line represents the vibrations measured from the 2nd measurement field where the double elastomer layer is used. Figure 10 shows the time-dependent variation of the KB_F values of vibrations obtained using the DIN 4150-2 standard.

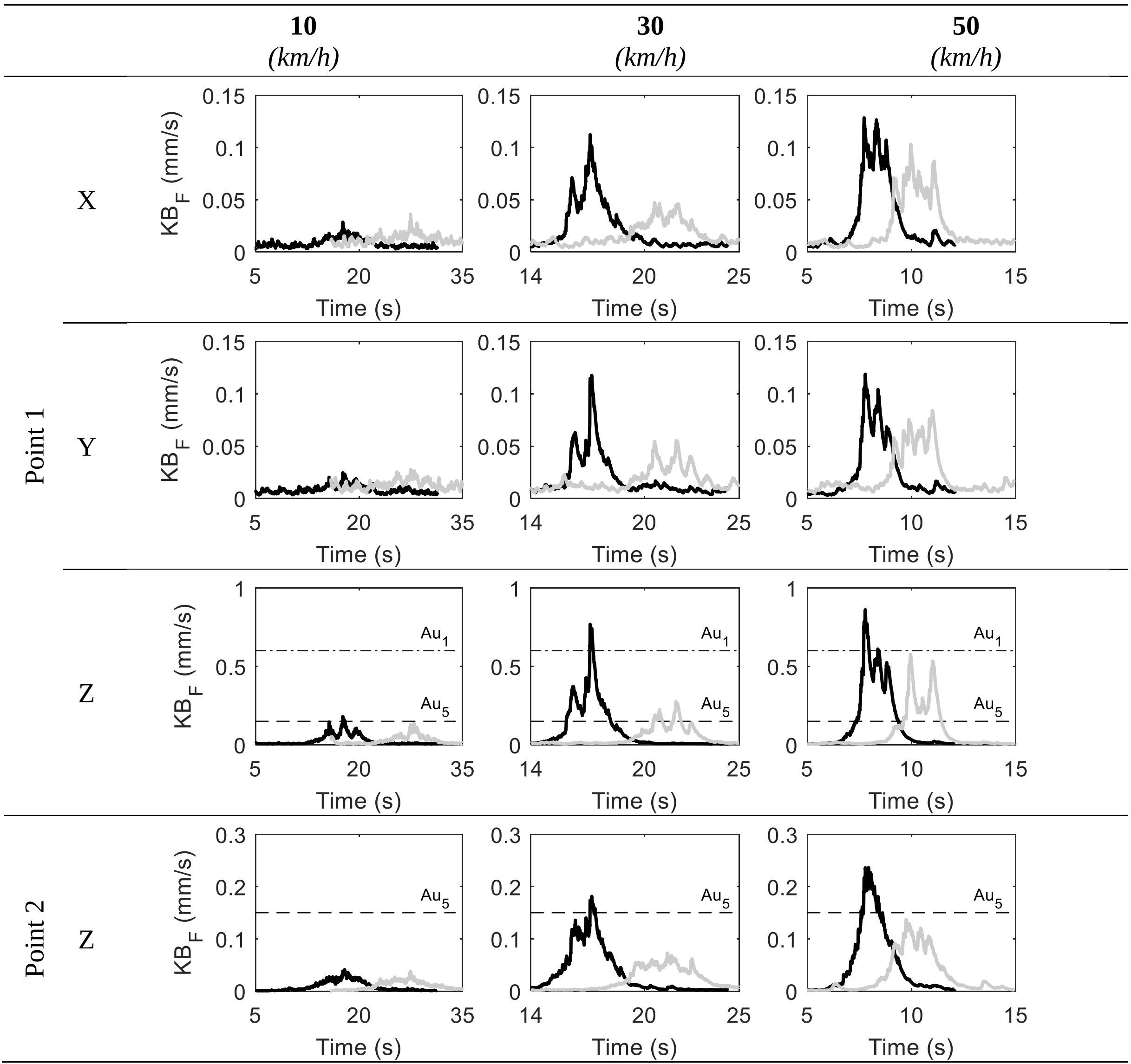

Figure 10. *Time-dependent variation of the $KB_{F(t)}$ values of vibrations ('Dark Line' 1st Measurement Field, 'Soft Line' 2nd Measurement Field)*

The comfort is evaluated by comparing the maximum rating KB_{Fmax} with the three guideline limits known as A_u, A_o, and A_r, for an overall evaluation and the short-term frequency vibrations as well as [12]. Table 6 represents the KB_{Fmax} values of all measurements.

Although the location of the measurement was similar to the 1st, 2nd or 3rd structures type according to the standard, the results were examined regarding all building types. When the KB_{Fmax} values in Figure 10 and Table 6 are examined, the standard is provided in all type of buildings, in both types of superstructures at *x* and *y* axes at all speeds. On the other hand, it can be said that large amplitudes occur in the *z*-direction and the vertical axis is dominant. When the results are analyzed on the *z*-axis for the 2nd measurement point, the standard limit values (A_u) are exceeded according to the standard in the superstructure with single layer elastomer structure at vehicle speeds of 30 km/h and 50 km/h. In the superstructure with double layer elastomer, although the limit value is exceeded for the buildings in the 5th group, the standard is provided for the buildings in the 1st group. Figure 10 and Table 6 show that the superstructure with double-layer elastomer suppresses the vibrations significantly compared to the other one-layered superstructure. Also, they present the superiority of double-layered superstructure according to the DIN 4150-2 standard. The results show that in all buildings except for Group 1, the buildings should be constructed at least 5 m away from the railway so that the vibrations in the *z*-axis remain below the standard.

Table 6. *KB_{Fmax} values of all measurements*

Field 1	**10** *(km/h)*			**30** *(km/h)*			**50** *(km/h)*		
	X *(mm/s)*	**Y** *(mm/s)*	**Z** *(mm/s)*	**X** *(mm/s)*	**Y** *(mm/s)*	**Z** *(mm/s)*	**X** *(mm/s)*	**Y** *(mm/s)*	**Z** *(mm/s)*
1	0.0277	0.0246	0.18	0.1123	0.1178	0.7686	0.1284	0.1189	0.8616
2			0.0413			0.1815			0.2366
Field 2	**10** *(km/h)*			**30** *(km/h)*			**50** *(km/h)*		
	X *(mm/s)*	**Y** *(mm/s)*	**Z** *(mm/s)*	**X** *(mm/s)*	**Y** *(mm/s)*	**Z** *(mm/s)*	**X** *(mm/s)*	**Y** *(mm/s)*	**Z** *(mm/s)*
1	0.0362	0.0277	0.1359	0.0472	0.0546	0.2754	0.1030	0.0833	0.5727
2			0.0381			0.0728			0.1372
Improvement *(%)*	**10** *(km/h)*			**30** *(km/h)*			**50** *(km/h)*		
	X *(mm/s)*	**Y** *(mm/s)*	**Z** *(mm/s)*	**X** *(mm/s)*	**Y** *(mm/s)*	**Z** *(mm/s)*	**X** *(mm/s)*	**Y** *(mm/s)*	**Z** *(mm/s)*
1	-30.69	-12.60	24.50	57.97	53.65	64.17	19.78	29.87	33.53
2			7.75			39.47			42.01

A.2. Comparison According to the DIN 4150-3 Standard

This standard was used to determine the effects of the measured vibrations on the structures and to assess whether they have damaged the structures. In this section, the vibrations which are shown in the time domain the previous section were evaluated in the frequency domain according to DIN 4150-3 standard.

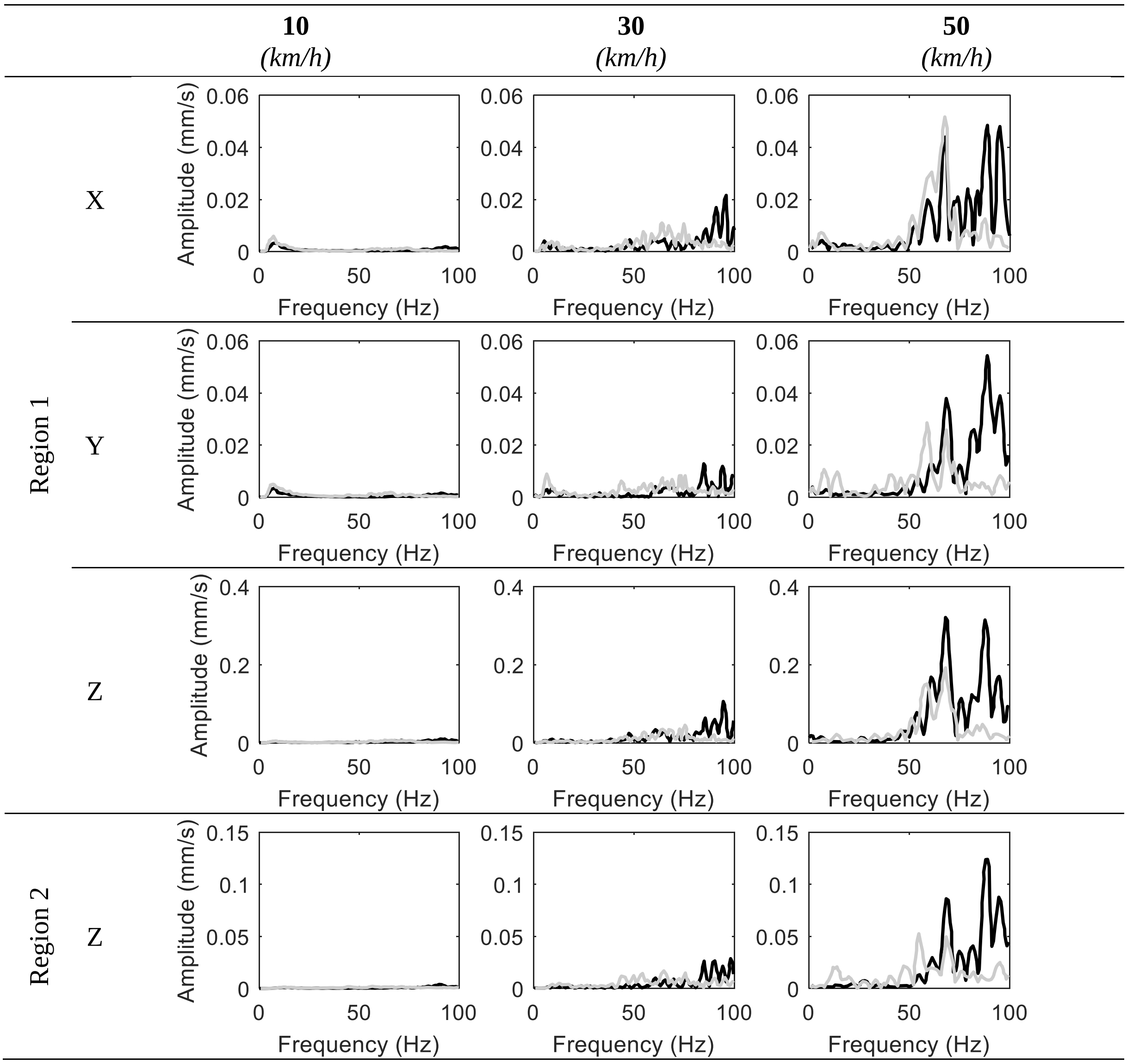

Figure 11. *Velocity-frequency results of vibrations measured at points 1 and 2 at different speeds ('Dark Line' 1st Measurement Field, 'Soft Line' 2nd Measurement Field)*

Figures 9 and 11 show the time and frequency domain results of the velocities measured in two regions, respectively. The results in the frequency domain in Figure 11 suggest that the *z*-axis vibrations are more dominant than the other axis vibrations. When the two superstructures are examined comparatively, it is seen that the superstructure with double layer elastomer structure produces more successful results, especially over 70 Hz.

When an evaluation according to DIN 4150-3 is made for both types of used superstructures, all frequency values between 1-100 Hz have vibration velocities below the limit values specified in Figure 1. As a result, it can be said that the buildings that will be constructed at 1.5m or 5m distance to the railway will not be damaged by railway vibrations according to the standard. In addition, it is seen that buildings will be affected much less when double layered superstructure is used.

A.2. Comparison According to the ISO 2631 Standard

In addition to the environmental effects of rail-borne vibrations, the two different superstructures were evaluated comparatively using the ISO 2631 standard for the effects on the travel comfort of the passengers in the vehicle. The most important expectation after the transportation safety of passengers who travel for a long time by train is the ride comfort. The most important parameter that affects the driving comfort is the in-car vibrations caused by wheel-rail interaction and road irregularities. To evaluate the effects of indoor vibrations on passenger comfort according to ISO 2631 standard, the acceleration values of the vibrations between 0.4-80 Hz were examined for two different superstructures and three different vehicle speeds. Raw vibration results obtained from four different points of the vehicle are given in Figures 12-14 in 1/3 octave band, and the weighted acceleration values for *x*, *y* and *z*-axes are given in Table 7. The results of total acceleration values (a_v) given in Table 7 are evaluated according to ISO 2631 standard (Table 3). Figures 15-17 shows the total acceleration (comfort) values of 4 different points in the vehicle, while the rail vehicle passes through single and double layered superstructures, respectively, at speeds of 10, 30 and 50 km/h. In these graphs, 1-4 measurement points represent the sitting passenger foot point, a point on the seat surface, sitting passenger backrest point and standing passenger foot point, respectively.

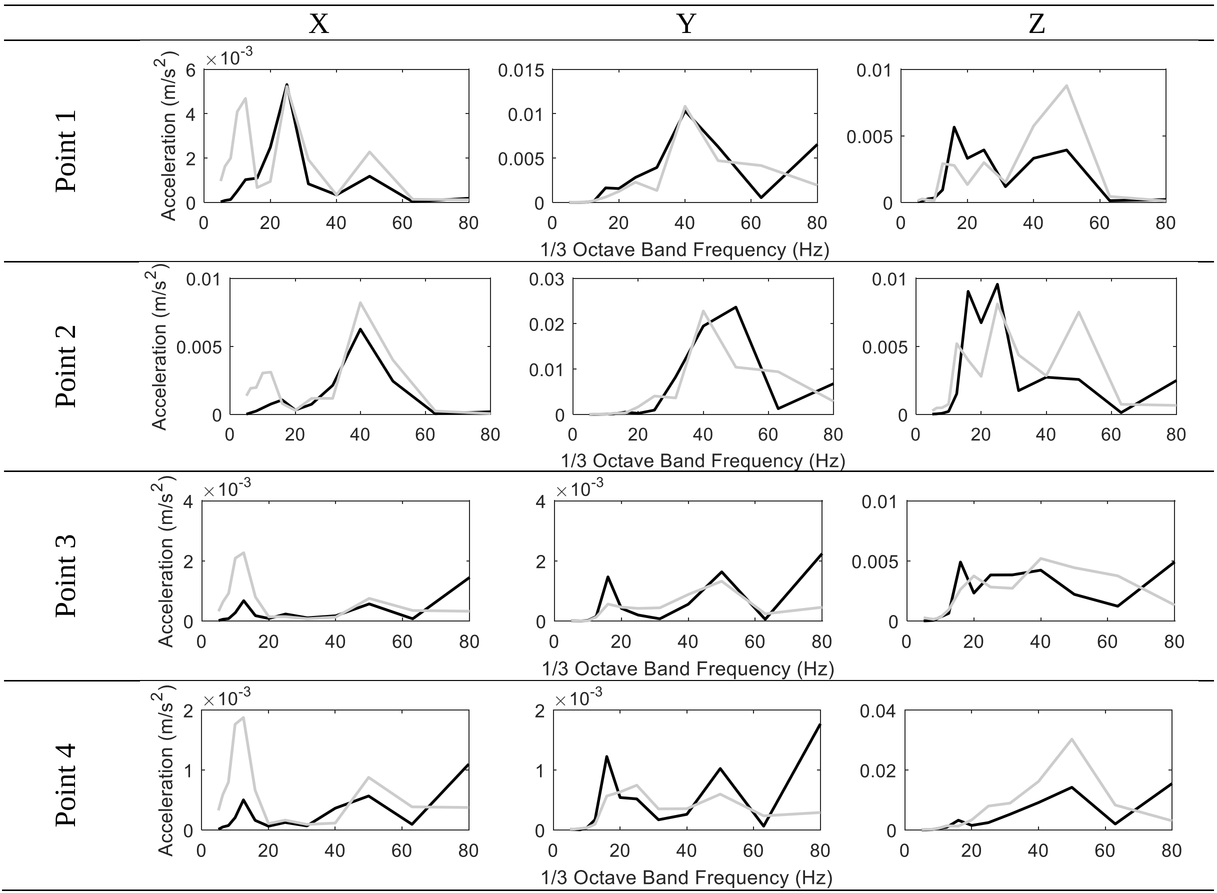

Figure 12. *Frequency-acceleration data for a vehicle speed of 10 km/h in 1/3 octave band ('Dark Line' 1st Measurement Field, 'Soft Line' 2nd Measurement Field)*

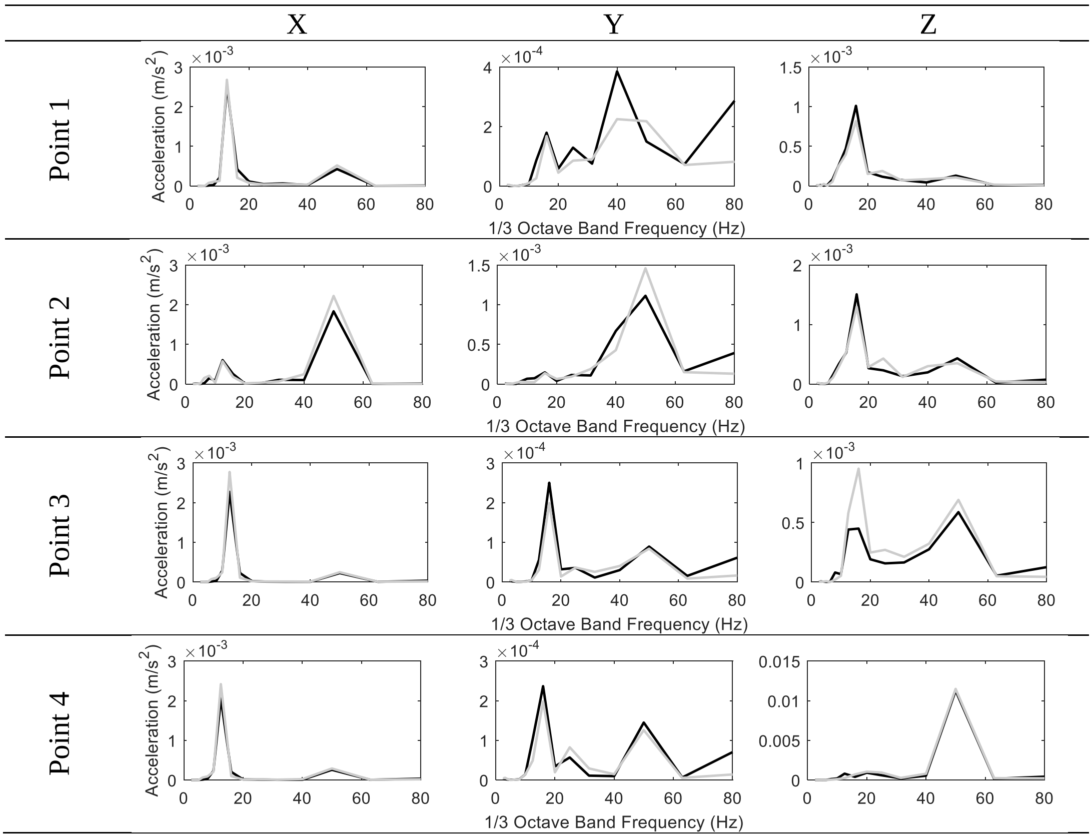

Figure 13. *Frequency-acceleration data for a vehicle speed of 30 km/h in 1/3 octave band ('Dark Line' 1st Measurement Field, 'Soft Line' 2nd Measurement Field)*

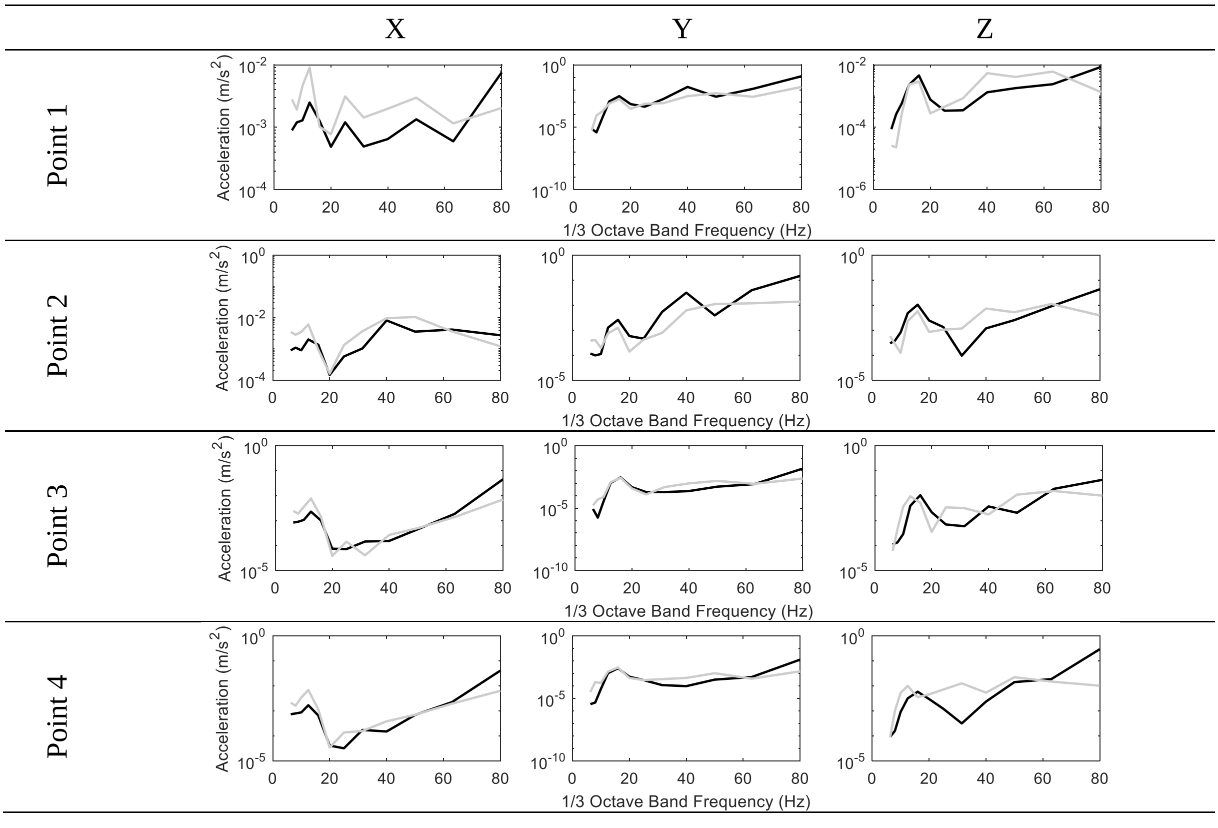

Figure 14. *Frequency-acceleration data for a vehicle speed of 50 km/h in 1/3 octave band ('Dark Line' 1st Measurement Field, 'Soft Line' 2nd Measurement Field)*

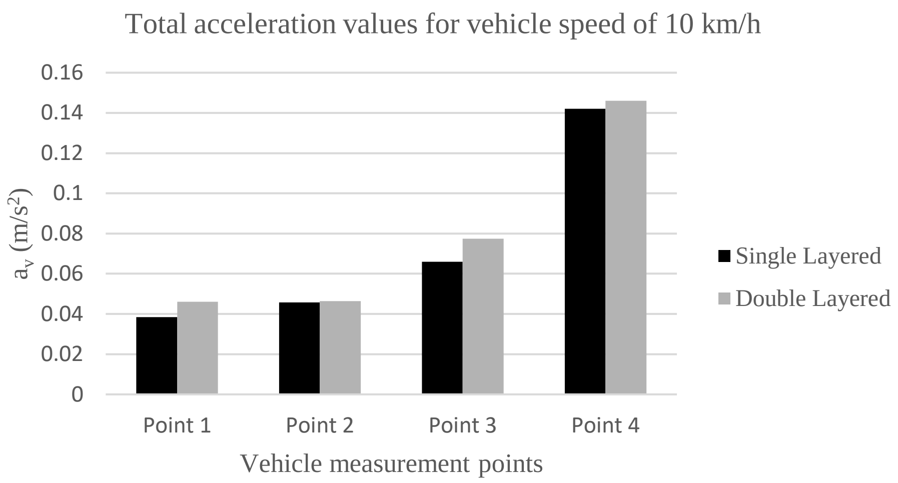

Figure 15. *Total acceleration values for a vehicle speed of 10 km/h*

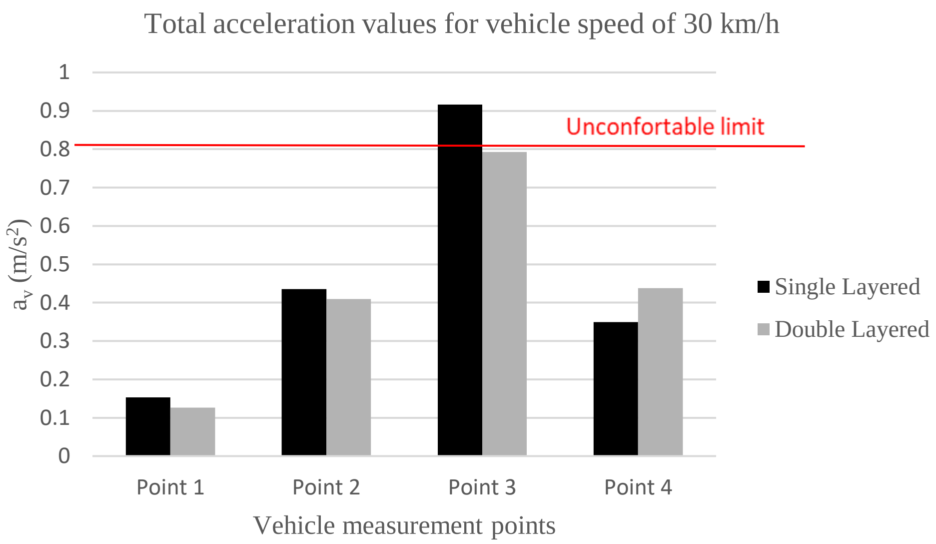

Figure 16. *Total acceleration values for a vehicle speed of 30 km/h*

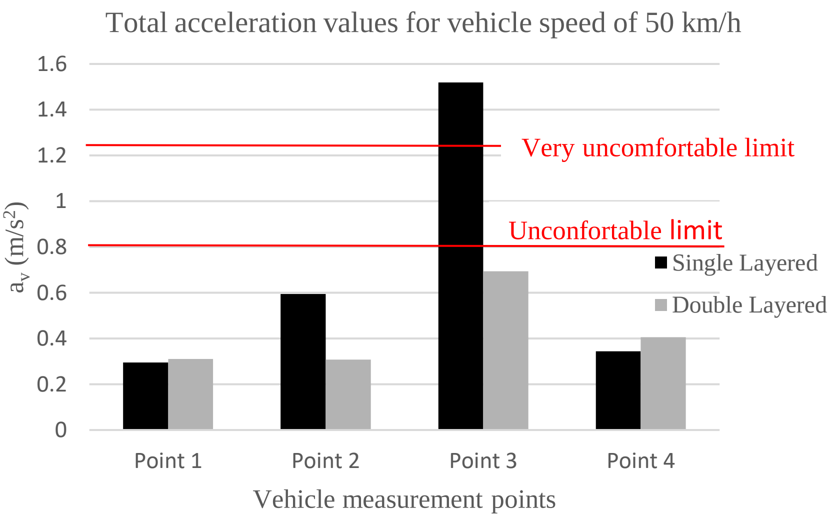

Figure 17. *Total acceleration values for a vehicle speed of 50 km/h*

When Figures 15-17 are examined at the vehicle speed of 10 km/h, measured vibration values at all points in the vehicle is evaluated as quite comfortable for passengers. From this, it can be concluded that single or double layered superstructure at low speeds does not affect indoor comfort. When evaluating the single layered superstructure at a speed of 30 km/h, the total acceleration values of all points increase, while the total acceleration value of backrest point of the sitting passenger exceeds the limit value of the uncomfortable situation. On the other hand, when the vehicle passed on the double layered superstructure, the same value is below the uncomfortable situation limit. When the vehicle passed from a single-layered superstructure at a speed of 50 km/h, the comfort is evaluated according to Figure 17, where the situation is very uncomfortable for the in-vehicle measuring point 3. However, the total acceleration values for all points are below the uncomfortable limit when the vehicle passed from the double-layered superstructure at the same speed. As a result, as the vehicle speed increases, it is seen that the double layer superstructure has a positive effect also on passenger comfort in urban rail transportation.

V. CONCLUSION

In this study, the effects of rail-borne vibrations on the passenger and the environment were investigated for two different superstructures. Two different superstructures with single and double layer elastomer structure were used in this investigation. While the vehicle passes between these two superstructures at speeds of 10, 30 and 50 km/h, the vibrations occurring at a distance of 1.5 m and 5 m from the rail were evaluated according to DIN 4150-2 and DIN 4150-3 standards. In addition, the comfort of passengers traveling in the rail vehicle under the same conditions was evaluated according to the ISO 2631 standard. In these comparative evaluations, the superiorities of the superstructures with single and double elastomer layers against each other were demonstrated. For these studies, vibrations were measured from various points using a real vehicle and railway used in Istanbul traffic.

As a result of the studies and evaluations, with the increase of vehicle speed, the vibrations that affect the environment and passengers have increased, which affects the people living in the surrounding buildings and the passengers traveling in the rail vehicle negatively. At the same time, the vibration values have increased regarding the safety of the buildings. In addition, the following findings were reached.

If the superstructure with a double-layer elastomer is used instead of a single-layer elastomer:

- Up to 64% improvement in the comfort of people living in the vicinity
- More successful results for the safety of surrounding buildings, especially for over 70 Hz vibrations
- Ability to the construction of buildings for residential aim at a closer distance to the railway (about 5 m)
- 54% more comfortable travel in the passenger's back for over 30km/h vehicle speed

Consequently, the superiority of the superstructure having double layer elastomer according to the single layer is demonstrated by measurement studies. Although it is expensive and difficult to maintain compared to the other, it is concluded that the superstructure with double layer elastomer can be used effectively in railway lines where the environmental vibration problems may occur.

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