

Article

Experimental Analysis of the Adequacy of Speed Bumps in Terms of Driving Comfort

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Abstract

Speed bumps are commonly used as traffic calming devices to reduce vehicle speeds on urban road sections. However, their geometric design and implementation quality are critical not only for traffic safety but also for vehicle occupants' comfort. If speed bumps are not designed in accordance with relevant standards, they may generate excessive vibration and negatively affect driver and passenger comfort. This study investigates the compliance of 10 different speed bumps with design standards and evaluates their effects on driver and passenger comfort. Field experiments were conducted using triaxial accelerometers at different vehicle speeds under two- and four-passenger loading conditions. The measured vibration data were evaluated using vertical acceleration and Overall Vibration Total Value (OVTV)-based comfort criteria. The results showed that only one of the examined speed bumps fully complied with the relevant design standards. The statistical results indicated that vehicle speed, speed bump type, passenger loading condition, and passenger position significantly influenced OVTVs. Overall, the study demonstrates that improperly designed or constructed speed bumps can substantially reduce vehicle occupant comfort. The proposed field-based evaluation approach can be used to assess existing speed bumps and support the design of safer and more ergonomic traffic calming devices.

Keywords: speed bumps; traffic accident; driving comfort

1. Introduction

With the increasing population around the world, the number of vehicles is increasing day by day. The increasing number of vehicles can cause various problems in traffic. In order to prevent these problems, various measures are taken by policy practitioners. Especially since the traffic density is high in the city centers, there are more precautions in these places. Many of the measures taken aim to prevent problems that may occur by reducing the speed of the vehicles. By reducing the speed of the vehicles, the number of accidents or the severity of the accidents can be lessened. Traffic accidents are one of the most important causes of death. More than half of these deaths involve vulnerable road users (pedestrians, cyclists and motorcyclists). Thanks to speed-limiting measures, it is possible to significantly reduce the accidents that may occur, and thus the loss of life and property.

One of the methods used to reduce the speed of vehicles in traffic is speed bumps. These bumps are among the most effective traffic calming tools that prevent urban traffic accidents by forcing drivers to reduce their speed, causing them to drive at more moderate



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vehicle speeds [1–6]. If the drivers do not reduce their speed in accordance with the speed bumps determined by the local authorities when they encounter the speed bumps, the driving safety and the level of driving comfort perceived by the driver will decrease. For this reason, speed bumps play a deterrent role in the driver's thought of accelerating [7].

There are different types of speed bumps in terms of size, material used and location. One of them, the raised pedestrian crossing, is a speed bump with large width and a pedestrian path built on it. This type of platform is usually produced from asphalt or concrete-containing material. Another type of speed bump is the rubber speed bump. In this type, the width of the mound is smaller than that of the raised pedestrian crossing. It is only used to reduce vehicle speed. It is applied by mounting profiles with rubber material to the road [8]. Another type of speed bump is a speed hump. Speed bumps are similar to the raised pedestrian crossing in terms of size and material used, but there is no pedestrian crossing on them. Rubber provides a more comfortable passage compared to speed bumps [9–15].

2. Related Work

In the literature, there are various studies examining speed bumps. These studies reveal important results. However, thanks to the development of technology and analysis methods, it is possible to examine speed bumps in more detail by using various devices and methods. Gedik et al. [16] investigated the effect of parabolic speed bump profiles on driving comfort and safety at variable vehicle speeds. For this purpose, in situ and simulation tests were performed in which root-mean-square values were evaluated. Loprencipe et al. [17] examined the geometric and functional properties of raised pedestrian crossings. Accordingly, they determined that there are serious differences between the designed and implemented raised pedestrian crossings. Kırbaş and Karaşahin [18] investigated the vibration effects of a vehicle passing over road structures on the passenger seat of the vehicle. In the study, they determined the comfort threshold values at 20, 30, 40 and 50 km/h driving speeds. Lan et al. [19] calculated the vertical accelerations on the bumps of different heights and widths by simulating the passage of vehicles over the bumps. As a result of this investigation, they determined the most ideal speed limits on the bumps.

With well-designed deceleration platforms, vehicle speeds can be reduced by keeping driving safety and comfort high [20]. However, due to the wrong design or positioning of these platforms, the necessary conditions may not be met [21]. Many countries around the world have determined various criteria for speed bumps in terms of passenger safety and comfort. These criteria aim to keep the width, height, material type and color of the platforms within certain limits. Especially the platform width and height are very important from an ergonomic point of view [22–27].

Stan and Oprea [28] presented a comprehensive review of WBV assessment methods, highlighting that although frequency-weighted indices such as weighted RMS acceleration, vibration dose value (VDV), and Overall Vibration Total Value (OVTV) are recommended by ISO 2631-1, their application in practical vehicle engineering studies remains limited. The authors also emphasized the need for integrated and application-oriented approaches that combine field measurements with standardized vibration assessment methods to improve the reliability of ride comfort evaluation [29].

Beyond vehicle comfort assessment, WBV has recently been incorporated into infrastructure management. Dutta et al. [30] proposed a road-user-centric pavement management framework in which whole-body vibration exposure was used as an indicator of pavement condition. Their study demonstrated that vibration-based performance measures can provide a practical and cost-effective means of prioritizing maintenance activities while better reflecting the actual experience of road users than conventional pavement evaluation methods.

Similarly, Konieczny et al. [31] investigated driver exposure to both whole-body and hand–arm vibrations under real driving conditions using measurements conducted in accordance with ISO 2631-1 and ISO 5349. Their findings highlighted the importance of frequency-dependent vibration analysis for accurately evaluating ride comfort, identifying resonance effects, and reducing long-term health risks associated with vehicle vibration exposure [32].

In developed countries, the use of speed bumps has evolved from extensive research and testing that has been appropriately designed and standardized [33,34]. However, research on speed bump design and standardization in developing countries such as Turkey is currently insufficient. In addition, although there has been a great deal of research on traffic calming in Europe and the USA, research examining the effects of certain features of speed bumps is largely lacking [35]. This justifies the need for research. A holistic approach combining field and simulation testing is essential to better understand the impact of traffic calming devices on driving comfort and driving safety. Therefore, the study takes a holistic approach to evaluate the effects of different parabolic-shaped speed bumps, especially in residential areas.

Unlike previous studies that mainly evaluated speed bumps using conventional acceleration metrics, this study integrates geometric compliance assessment with ISO 2631-1 frequency-weighted comfort evaluation under different operating conditions. The proposed methodology evaluates driver and passenger comfort using both conventional vertical acceleration and Overall Vibration Total Value (OVTV) under different vehicle speeds, passenger loading conditions, and seat positions. Therefore, the proposed field-based framework provides a practical tool for assessing existing speed bumps and identifying those requiring geometric or operational improvement.

3. Materials and Methods

3.1. Study Area

In the study, a total of 10 speed bumps were used, including 2 raised pedestrian crossings, 3 rubber speed bumps and 5 speed humps located at different points in Erzurum. Six of the selected speed bumps are in Atatürk and Erzurum Technical Universities, and the other 4 are located on the main streets in various parts of the city. The locations of these speed bumps in the city are shown in Figure 1 and Table 1.

Table 1. Types and locations of speed bumps.

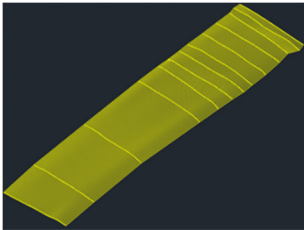
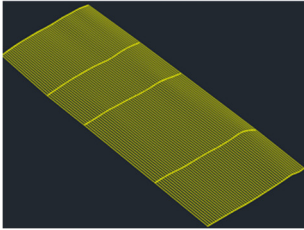
Speed Bump Number	Type	Location	3D Profile
1	Raised Pedestrian Crossing-1	Faculty of Agriculture, Ataturk University	
2	Raised Pedestrian Crossing-2	Hospital, Atatürk University	

Table 1. Cont.

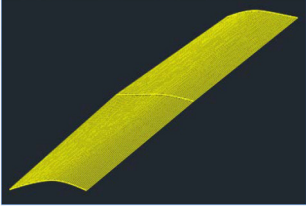
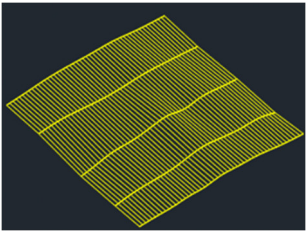
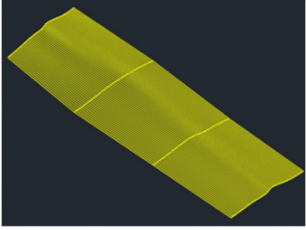
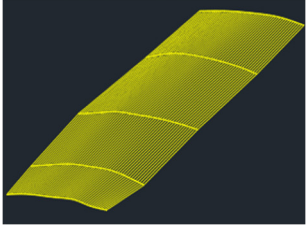
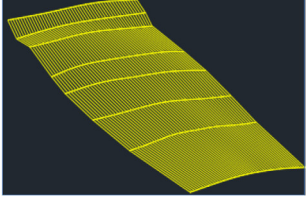
Speed Bump Number	Type	Location	3D Profile
3	Rubber Speed Bump-1	Faculty of Theology, Atatürk University	
4	Rubber Speed Bump-2	Application and Research Center, Atatürk University	
5	Rubber Speed Bump-3	Erzurum Technical University	
6	Speed Hump-1	Rectorate, Atatürk University	
7	Speed Hump-2	Dadaşkent-1	
8	Speed Hump-3	Dadaşkent-2	
9	Speed Hump-4	Şükrüpaşa-1	

Table 1. Cont.

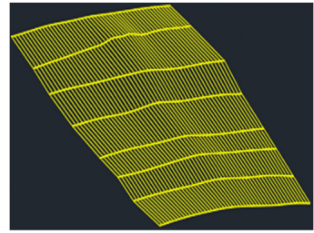
Speed Bump Number	Type	Location	3D Profile
10	Speed Hump-5	Şükrüpaşa-2	

**Figure 1.** The locations of speed bumps (Source: Google Earth).

Raised pedestrian crossings in the city are generally preferred in places where pedestrian traffic is heavy and road width is large. These are located on the roads in front of the Research Hospital and Faculty of Agriculture at Atatürk University. In addition, rubber speed bumps are also used to prevent the speed limit from being exceeded in places where the speed limit is low. These speed bumps are also located within the campus areas of Atatürk and Erzurum Technical Universities. Speed humps are applied in order to reduce the speed of the drivers a little, instead of reducing the speed to very low levels at various points of the city. These are often located near intersection grades and school districts.

3.2. Method

In the study, the coordinates of each speed bump were determined with the Cross-Origin Resource Sharing device and 3D surface profiles were obtained. The real surface shapes of the speed bumps were drawn with the help of the AUTOCAD 2024 software. As a result of the physical measurements, it was determined whether the dimensions of the speed bumps, the sections of which were determined, were in accordance with the legislation. Both raised pedestrian crossings and speed humps have been evaluated for compliance with the Institute of Transportation Engineers (ITE) and Federal Highway Administration (FHWA) design standard. An evaluation was made according to the options

specified in the MUTCD and General Directorate of Highways (KGM) traffic sign handbook (Uniform Traffic Control Devices Handbook) for markings to be made at raised pedestrian crossings and speed humps. Turkish Standard Institute (TSE) K 16 standard was used to investigate the suitability of rubber speed bumps [36–38].

Before starting the acceleration measurements, 1 Testbox Data Logger, 4 Sensebox 70 × 3 triaxial accelerometers and 1 laptop computer were calibrated in the laboratory as shown in Figure 2. The device was set to record 200 data per second. The accelerometers were numbered from 1 to 4 as shown and placed in the vehicle as shown in the figure. The person who used accelerometer number 2 also kept a record of the data transferred to the laptop and processed it into the tables.

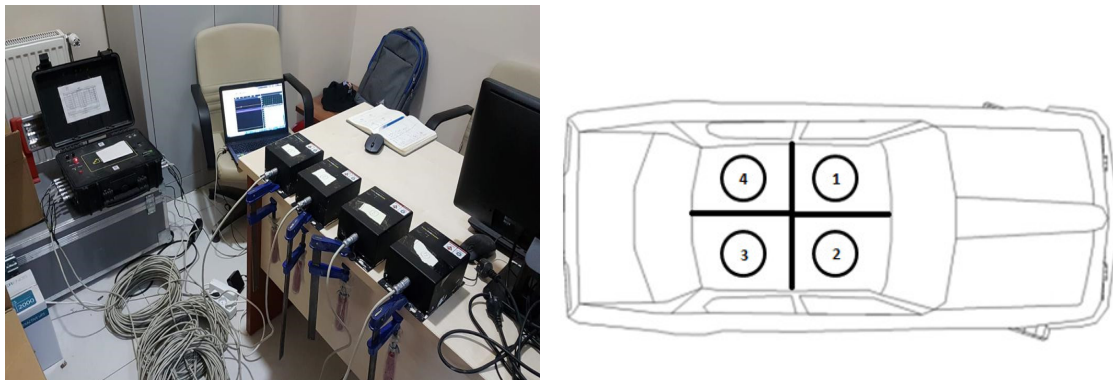


Figure 2. The accelerometers used in the study and their positions in the vehicle.

The data recorder used in acceleration measurements and the uninterruptible power supplies that provide energy to the system were placed in the trunk of the vehicle. The data logger was placed in the luggage compartment to prevent data loss in the cables going from the device to the accelerometer. The flow diagram of the acceleration transmitted to the driver/passengers in the vehicle shows the path from the speed bump to the vehicle wheels, from the wheels to the shock absorbers, from the shock absorbers to the seat, under the seat to the seat surface, and from the seat surface to the driver/passengers. A certain amount of vibration in each layer was damped by the spring systems and the flexible materials on the seat. For these reasons, accelerometers were placed in a region between the seat surface and the driver/passenger, where the vibration was last transmitted to the driver/passenger, rather than under the seat and under the vehicle. In the ISO 2631-1 standard, it is stated that the accelerometers used to measure the vibration of the driver/passenger sitting in the seat should be between the endpoint (seat surface) and the body surface where the vibration is transmitted to the body. It is stated that these surfaces in the human body should be measured from the heel of the foot, where the vibration is felt most, the calf and the middle of the back where the spinal cord in the back is supported [39].

The vibration assessment inside the vehicle should be done separately for each individual because of each individual's weight, age, sitting style, etc. The vibration value that will be felt due to the situations will not be the same. For this reason, acceleration measurements were made separately for each seat surface. The results obtained were compared according to the comfort lower limit values. The acceleration intervals used in this study were established based on the comfort categories specified in ISO 2631-1 (Table 2). These internationally recognized thresholds provide the reference framework for classifying the measured weighted accelerations into different passenger comfort levels.

Table 2. Comfort categories of accelerations according to ISO 2631-1 standard.

a_w (m/s ²) Range	Level of Comfort
<0.315	Not uncomfortable
0.315–0.500	A Little Uncomfortable
0.500–0.800	Fairly Uncomfortable
0.800–1.250	Uncomfortable
1.250–2.000	Very Uncomfortable
2.000<	Extremely Uncomfortable

3.3. Statistical Analysis

In addition to descriptive comfort classification, statistical analyses were performed to evaluate the effects of vehicle speed, speed bump type, passenger loading condition, and passenger position on vibration exposure. OVTV was used as the primary dependent variable because it represents the frequency-weighted multi-axis vibration exposure recommended by ISO 2631-1. The normality of OVTVs was evaluated using the Shapiro–Wilk test. Since normality was not satisfied, non-parametric tests were used. Vehicle speed, speed bump type, loading condition, and passenger position were considered as explanatory variables. The relationship between vehicle speed and OVTV was examined using Spearman correlation analysis. Differences in OVTVs among speed bump types were evaluated using the Kruskal–Wallis test. The effect of passenger loading was examined by comparing the two-passenger and four-passenger test conditions. Passenger position effects were evaluated using the OVTVs obtained from the four-passenger tests. The significance level was set at $p < 0.05$.

4. Results and Discussion

4.1. Comfort Evaluation of Speed Bumps

The most dominant vibration axis determining the comfort degree of the individuals sitting in the seat is defined by vertical acceleration along with the forward–backward (x-direction) accelerations coming from the back of the seat. In the ISO 2631-1 standard, if the lateral accelerations on the back of the seat cannot be measured, it is requested to obtain the lateral acceleration by multiplying the acceleration magnitudes here by 1.4. In the study, a comfort evaluation was made according to the vertical acceleration values of 15, 20, 25, 30 and 35 km/h speeds over a total of 10 speed bumps of three different types.

Most previous studies evaluating the ride comfort of speed bumps have primarily relied on peak or unweighted vertical acceleration values, or on conventional RMS acceleration, to assess passenger discomfort. Although ISO 2631-1 has long recommended the use of frequency-weighted vibration indices for evaluating whole-body vibration, this recommendation has rarely been incorporated into field-based evaluations of speed bumps. Consequently, the comfort classifications reported in previous studies may not fully represent the vibration actually perceived by vehicle occupants, since the human body exhibits different sensitivities to different vibration frequencies and attenuates certain frequency components.

To address this gap, the present study evaluates ride comfort using the Overall Vibration Total Value (OVTV), which is calculated from frequency-weighted RMS accelerations in accordance with ISO 2631-1. Rather than merely applying an existing standard, this study investigates whether comfort assessments based on conventional vertical acceleration differ from those obtained using the ISO-recommended frequency-weighted approach under real driving conditions. The comparison is performed using field measurements collected from

ten speed bumps representing three commonly used geometric designs at five operating speeds (15, 20, 25, 30, and 35 km/h).

Therefore, the main scientific contribution of this study is not the application of ISO 2631-1 itself, but the systematic comparison of conventional acceleration-based assessments and frequency-weighted OVTV-based evaluations for a diverse set of real-world speed bump geometries. This comparison demonstrates the extent to which conventional methods may overestimate or underestimate passenger discomfort and provides practical evidence supporting the use of frequency-weighted vibration indices for more realistic ride comfort assessment and speed bump design evaluation.

4.2. Comfort Evaluation According to Vertical Acceleration Values

Paddan and Griffin, Song et al., and Bilgin et al. [3,19,38] made a comfort assessment by taking into account the vertical acceleration values, which they stated as the most dominant axis in their studies. Therefore, in the study, firstly, the comfort evaluation was made by taking the vertical acceleration values as a reference.

4.2.1. Comfort Evaluation for Two-Passenger Tests

The comfort levels determined according to the vertical acceleration values as a result of the two-person tests are shown in Figure 3 for the first passenger and in Figure 4 for the second passenger.

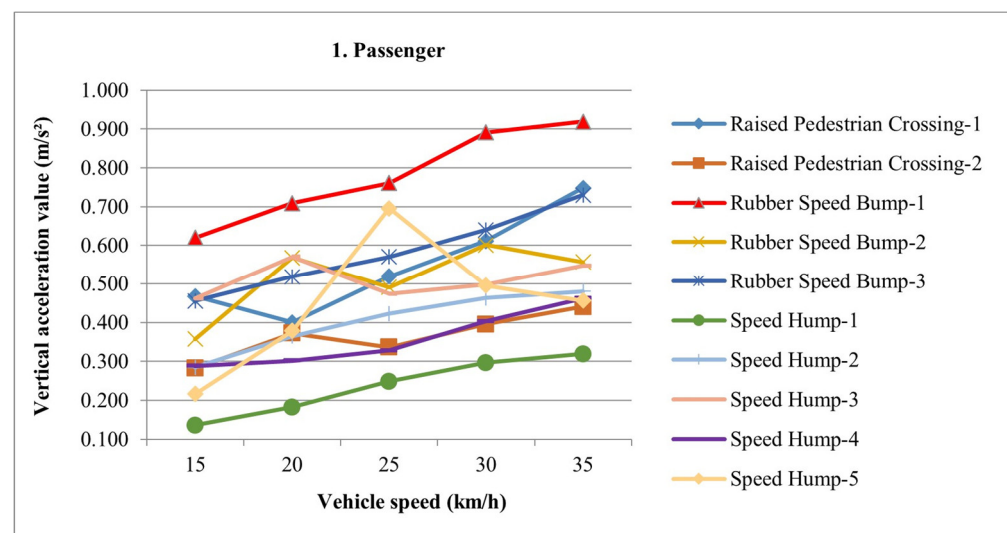


Figure 3. The comfort levels determined according to the vertical acceleration values for the first passenger.

When the values for the first passenger were examined, the comfort level of the Speed Hump-1 at 30 and 35 km/h speeds was “uncomfortable”. The comfort level of other speed bumps at different passengers and speeds were in the categories of “a little uncomfortable” and “fairly uncomfortable”. As a result, 41 of the 50 comfort values, i.e., 82%, were found in the uncomfortable categories.

When the values for the second passenger were examined, the comfort level of Rubber Speed Bump-1 at speeds of 25, 30, and 35 km/h was found to be “very uncomfortable”. The comfort level of Rubber Speed Bump-1 at 15 and 20 km/h, Raised Pedestrian Crossing-1 and Rubber Speed Bump-3 at speeds of 30 and 35 km/h, and Raised Pedestrian Crossing-2 at a speed of 35 km/h was found to be “uncomfortable”. The comfort level of other speed bumps is in the categories of “a little uncomfortable” and “fairly uncomfortable”. As a result, in the two-passenger tests, 44 of the total 50 vertical acceleration values, i.e., 88%, at

10 different speed bumps and five different speeds, were found to be uncomfortable for the second passenger.

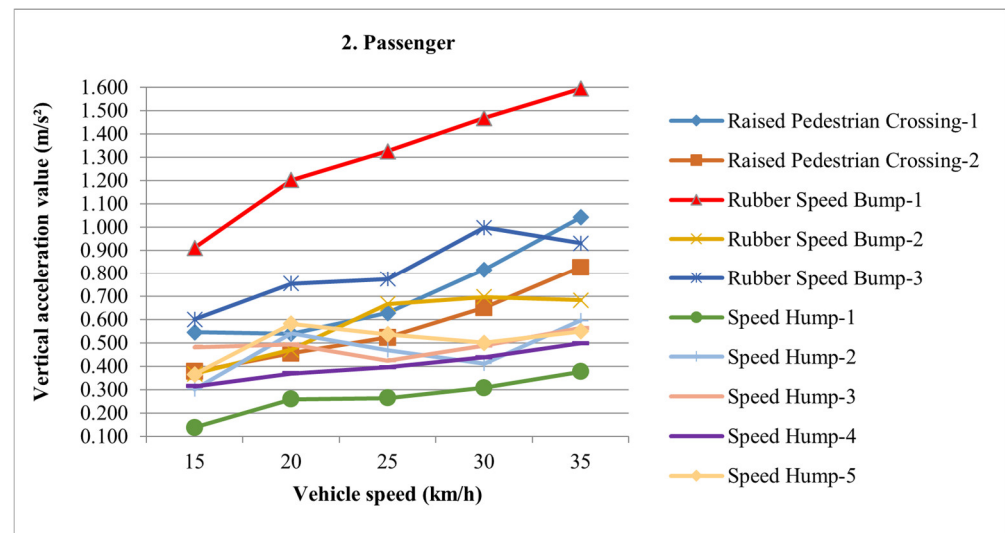


Figure 4. The comfort levels determined according to the vertical acceleration values for the second passenger.

4.2.2. Vertical Acceleration Value for Four-Passenger Tests Comfort Evaluation

The comfort levels determined according to the vertical acceleration values for the first passenger in the four-passenger tests are shown in Figure 5.

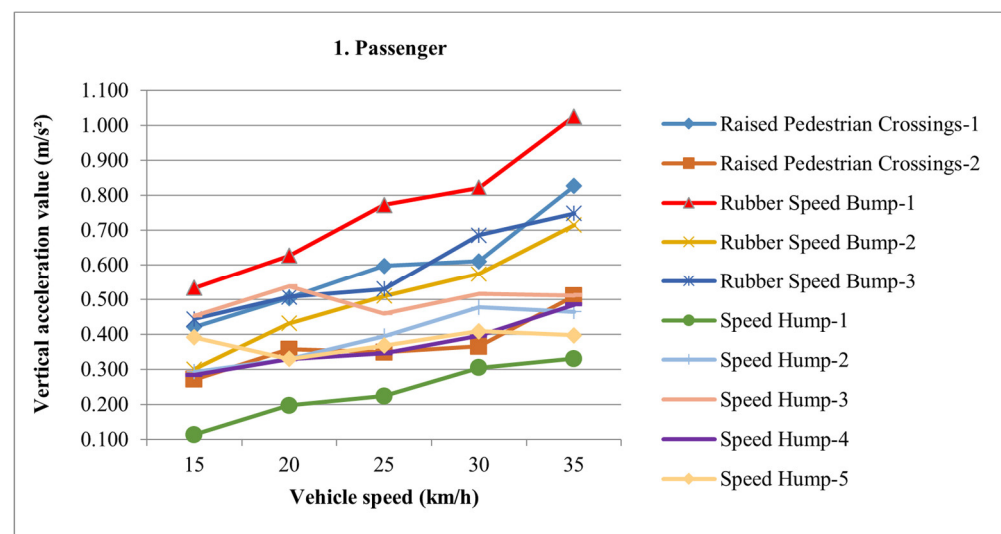


Figure 5. The comfort levels determined according to the vertical acceleration values for the first passenger.

The comfort level of the Raised Pedestrian Crossing-1 at speeds of 30 and 35 km/h was found to be “uncomfortable”. The comfort level of other speed bumps was in the categories of “a little uncomfortable” and “fairly uncomfortable”.

In the four-passenger tests, a total of 50 vertical acceleration values were obtained for the first passenger, considering 10 different speed bumps and five vehicle speeds. Of these values, 42 were classified as uncomfortable, corresponding to 84% of the first-passenger test results.

The comfort levels determined as a result of the evaluations made for the second passenger in the four-passenger tests are shown in Figure 6.

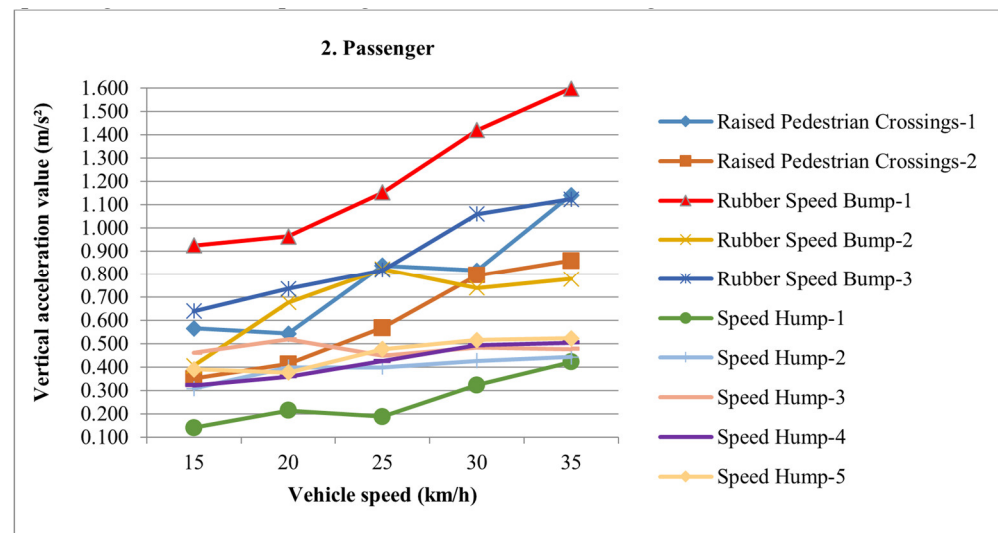


Figure 6. The comfort levels determined according to the vertical acceleration values for the second passenger.

The comfort levels of Rubber Speed Bump-1 at 15 and 20 km/h; Raised Pedestrian Crossing-1, Rubber Speed Bump-1, Rubber Speed Bump-2, and Rubber Speed Bump-3 at a speed of 25 km/h; Raised Pedestrian Crossing-1 and Rubber Speed Bump-3 at a speed of 30 km/h; and Raised Pedestrian Crossing-1, Raised Pedestrian Crossing-2, and Rubber Speed Bump-3 at a speed of 35 km/h were found to be “uncomfortable”. In addition, the comfort level of Rubber Speed Bump-1 at 30 and 35 km/h was found to be “very uncomfortable”. The comfort level of other speed bumps was in the categories of “a little uncomfortable” and “fairly uncomfortable”. In the four-passenger tests, a total of 50 vertical acceleration values were found for the second passenger at 10 different speed bumps and five different speeds, and 46 of them were found to be uncomfortable. This value constitutes 92% of the tests for the second passenger from the four-passenger tests.

The comfort levels determined as a result of the evaluations made for the third passenger in the four-passenger tests are shown in Figure 7.

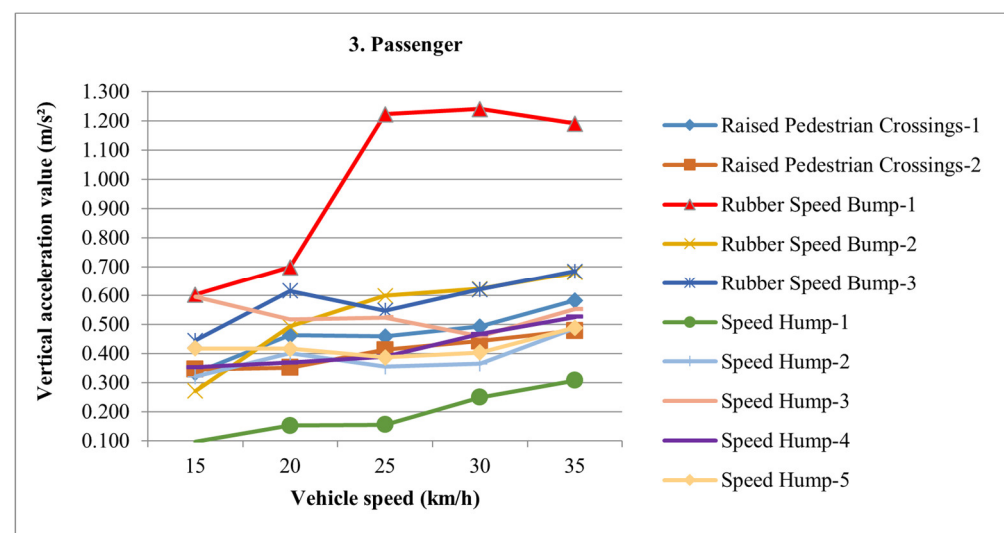


Figure 7. The comfort levels determined according to the vertical acceleration values for the third passenger.

At speeds of 25, 30, 35 km/h, the comfort level of Rubber Speed Bump-1 became “uncomfortable”. The comfort level of other speed bumps was in the categories of “a

little uncomfortable” and “fairly uncomfortable”. In the four-passenger tests, a total of 50 vertical acceleration values were found for the third passenger at 10 different speed bumps and five different speeds, and 44 of them were found to be uncomfortable. This value constitutes 88% of the tests for the third passenger from the four-passenger tests.

The comfort levels determined as a result of the evaluations made for the fourth passenger in the four-passenger tests are shown in Figure 8.

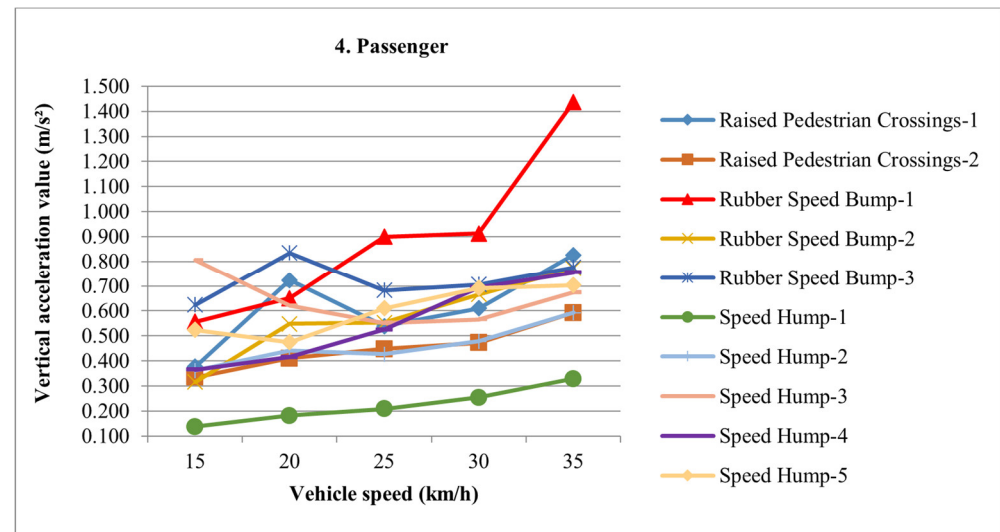


Figure 8. The comfort levels determined according to the vertical acceleration values for the fourth passenger.

The comfort levels of Speed Hump-3 at 15 km/h, Rubber Speed Bump-3 at 20 km/h, Rubber Speed Bump-1 at 25 and 30 km/h, and Raised Pedestrian Crossing-1 at 35 km/h were classified as “uncomfortable”. At 35 km/h, Rubber Speed Bump-1 was classified as “very uncomfortable”, representing the highest vertical acceleration value for the fourth passenger. The remaining speed bump–vehicle speed combinations were classified within the “not uncomfortable”, “a little uncomfortable”, or “fairly uncomfortable” categories. In the four-passenger tests, a total of 50 vertical acceleration values were obtained for the fourth passenger, considering 10 different speed bumps and five vehicle speeds. Of these values, 46 were classified as uncomfortable, corresponding to 92% of the fourth-passenger test results.

According to the general comfort evaluations made by considering the vertical acceleration values in the four-passenger tests, the majority of the raised pedestrian crossings, speed bumps and speed humps except Speed Hump-1 were found to be at an uncomfortable level. On the other hand, the level of the speed bumps that were found to be uncomfortable remained in the categories of “a little uncomfortable, fairly uncomfortable, uncomfortable, very uncomfortable”. No traffic calming devices were found at the level of “extremely uncomfortable”. In the four-passenger tests, a total of 200 vertical acceleration values at 10 different speed bumps and five different speeds were found for the first, second, third and fourth passengers, and 178 of them were found to be uncomfortable. This value accounts for 89% of all four-passenger tests.

According to the comfort evaluations made by considering the vertical acceleration values obtained in the two and four passenger tests, it was observed that the level of discomfort increased as the vertical acceleration value increased. In the two-passenger tests, a total of 300 vertical acceleration values were found for the first and second passengers, and for the first, second, third and fourth passengers in the four-passenger tests, at 10 different speed bumps and five different speeds, and 263 of them were found to be uncomfortable.

This value constitutes 87.67% of all comfort evaluations made by considering the vertical acceleration values.

4.3. Evaluation of Driving Comfort According to OVTV

In the study, the most decisive axis in the comfort values is in the vertical direction, and vibration measurements were made in which the x direction is also decisive. For this reason, it was concluded that it would not be correct to evaluate the comfort by always taking the vertical acceleration value as a reference. In addition, frequency weighting should be applied because a part of each acceleration value is damped by the human body. In order to reach the OVTV, a three-axis measurement was made and the effect of vibrations transmitted from the back of the seat was also reflected in the calculation as a coefficient. As a result of these calculations, OVTV and comfort levels were determined separately for each speed bump, passenger and speed. The OVTV obtained in this section will help determine the real comfort levels of the passengers.

4.3.1. OVTV for Two-Passenger Tests of Comfort Evaluation

The data on the comfort levels determined according to the OVTV obtained as a result of the evaluations made for the first passenger from the two-passenger tests are shown in Figure 9.

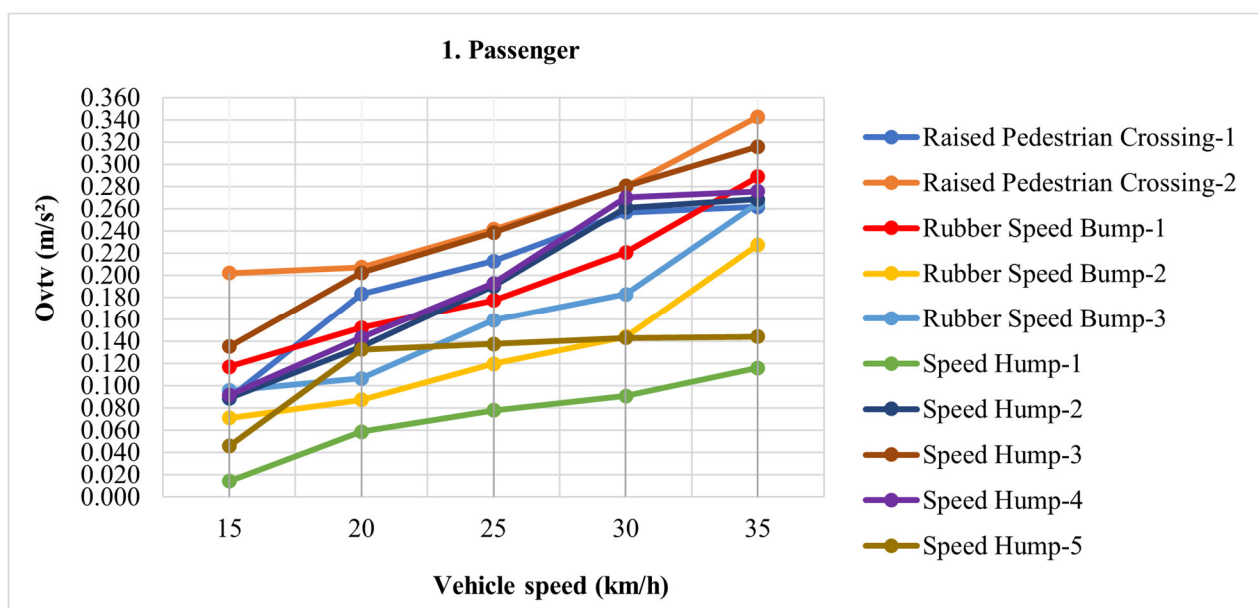


Figure 9. The comfort levels determined according to the OVTV for the first passenger.

According to the results of the comfort assessment at 35 km/h, it was determined that the Raised Pedestrian Crossing-2 and the Speed Hump-3 were in the “a little uncomfortable” category. All of the other speed bumps were at the “comfortable” level at different speeds for passengers. In the two-passenger tests, a total of 50 OVTV were found for the first passenger, with 10 different traffic calming devices and five different speeds, and two of them were found to be uncomfortable. This value constitutes 4% of the tests made for the first passenger from the two-passenger tests.

The data on the comfort levels determined according to the OVTV obtained as a result of the calculations for the second passenger in the two-passenger tests are given in Figure 10.

For the second passenger in the two-passenger tests, Rubber Speed Bump-1 at 30 km/h and Raised Pedestrian Crossing-2, Rubber Speed Bump-1, Rubber Speed Bump-3, and

Speed Hump-3 at 35 km/h were classified as “a little uncomfortable”. The remaining OVTVs for the other speed bumps and vehicle speeds were within the comfortable range. In total, 50 OVTVs were obtained for the second passenger in two-passenger tests, and five values were classified as uncomfortable. This corresponds to 10% of the tests for the second passenger.

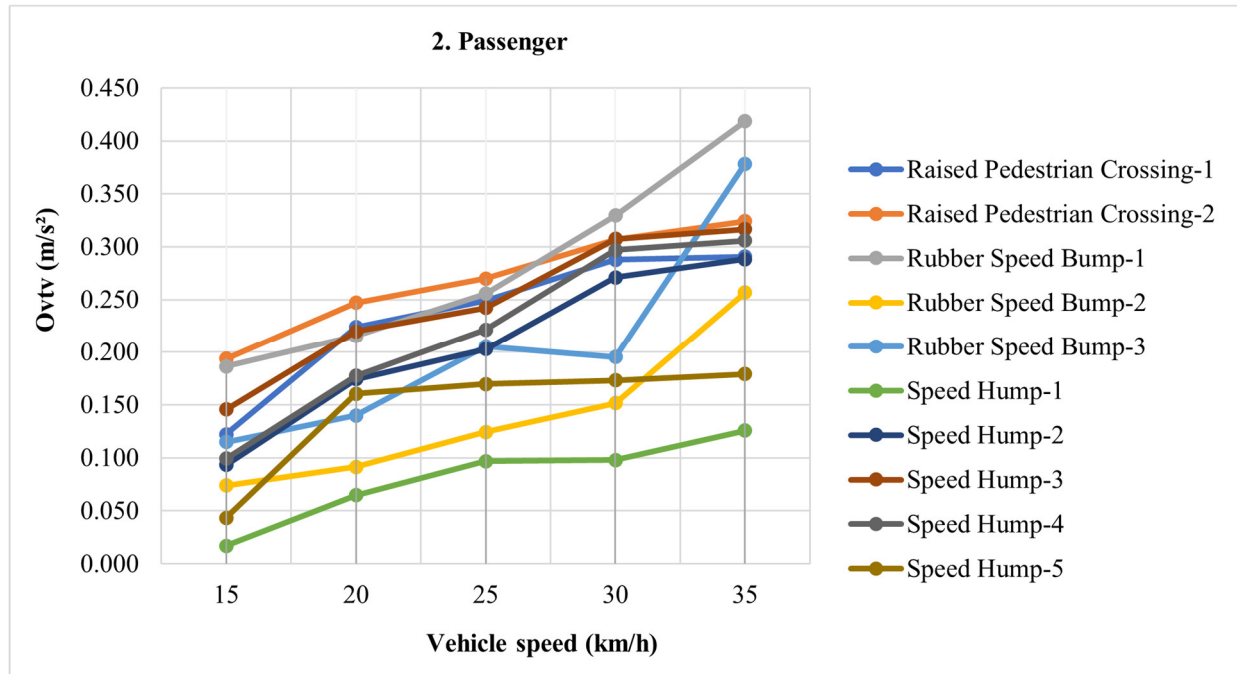


Figure 10. The comfort levels determined according to the OVTV for the second passenger.

4.3.2. OVTV for Four-Passenger Tests of Comfort Evaluation

The data on the comfort levels determined according to the OVTV obtained as a result of the calculations for the first passenger in the four-passenger tests are given in Figure 11.

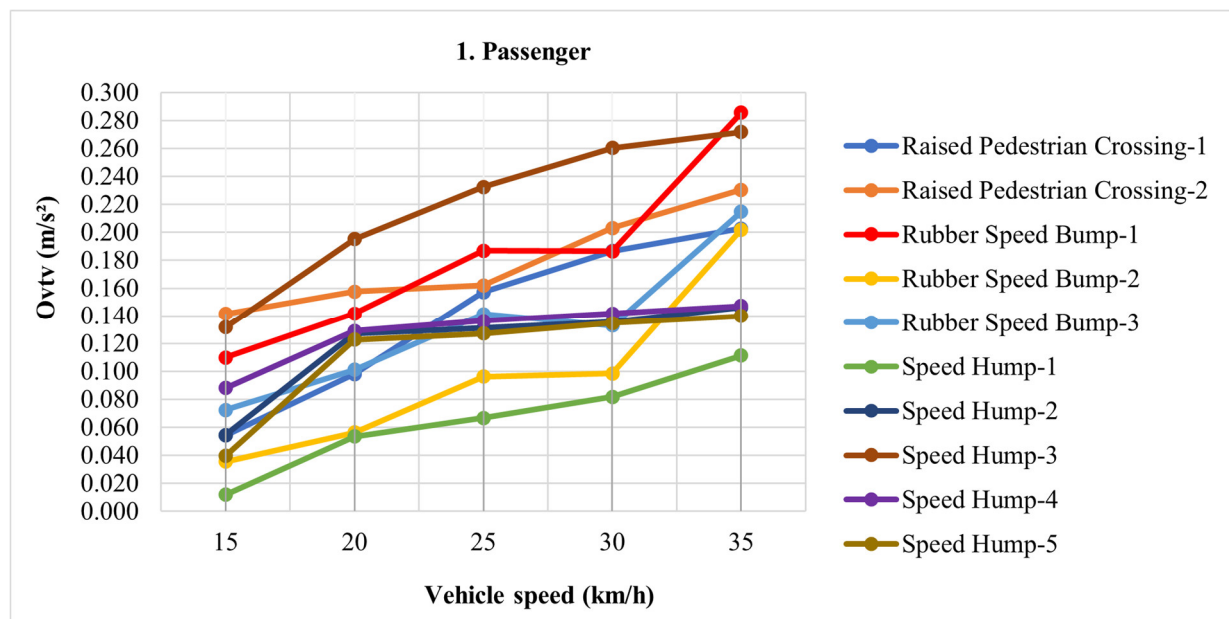


Figure 11. The comfort levels determined according to the OVTV for the first passenger.

The comfort level of the first passenger was found to be “comfortable” at all speed bumps and at different speeds. In other words, no speed bump was in the uncomfortable category for the first passenger.

The results of the comfort levels determined according to the OVTVs for the second passenger in the four-passenger tests are shown in Figure 12.

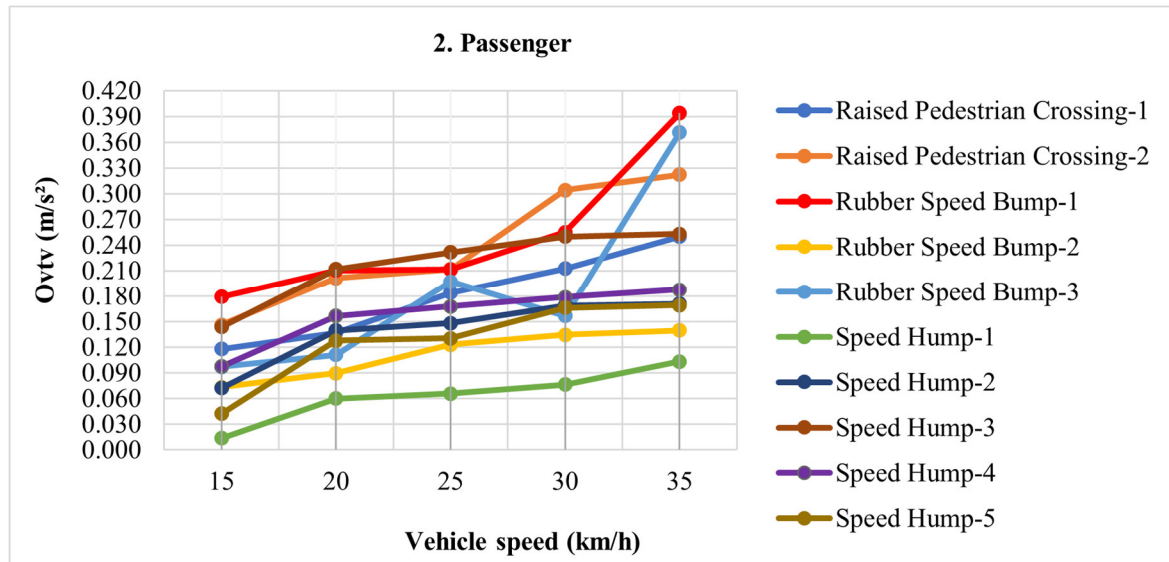


Figure 12. The comfort levels determined according to the OVTV for the second passenger.

For the second passenger in the four-passenger tests, the OVTVs generally increased with vehicle speed, with the highest values observed at 35 km/h. According to the ISO 2631-1 comfort threshold, values exceeding 0.315 m/s^2 were classified as “a little uncomfortable”, while the remaining values were within the “not uncomfortable” comfort category. The highest OVTVs were observed particularly for Rubber Speed Bump-1 and Rubber Speed Bump-3 at 35 km/h. Overall, the results indicate that the second passenger was mostly within the “not uncomfortable” comfort category, except for the speed bump–speed combinations exceeding the ISO comfort threshold.

The comfort levels determined according to the OVTVs for the third passenger in the four-passenger tests are shown in Figure 13.

For the third passenger, only the OVTV for Speed Hump-3 at 35 km/h was classified as “a little uncomfortable”. The remaining OVTVs for the other speed bumps and vehicle speeds were within the comfortable range. In total, 50 OVTVs were obtained for the third passenger in the four-passenger tests, and only one value was classified as uncomfortable, corresponding to 2% of the tests.

The comfort levels determined according to the OVTVs for the fourth passenger in the four-passenger tests are shown in Figure 14.

For the fourth passenger, only the OVTV for Speed Hump-3 at 35 km/h was classified as “a little uncomfortable”. The remaining OVTVs for the other speed bumps and vehicle speeds were within the comfortable range. In total, 50 OVTVs were obtained for the fourth passenger in the four-passenger tests, and only one value was classified as uncomfortable. This corresponds to 2% of the tests for the fourth passenger.

Based on the OVTV-based comfort evaluation of the two- and four-passenger tests, all uncomfortable cases were classified only within the “a little uncomfortable” category. No OVTV was classified under higher discomfort levels. The results also showed that discomfort levels tended to increase as OVTVs increased. Overall, 300 OVTVs were obtained from the two- and four-passenger tests, considering 10 speed bumps, five vehicle

speeds, and different passenger positions. Among these values, 12 were classified as uncomfortable, corresponding to 4% of all OVTv-based comfort evaluations. A speed-based summary of the OVTv comfort classification is presented in Table 3.

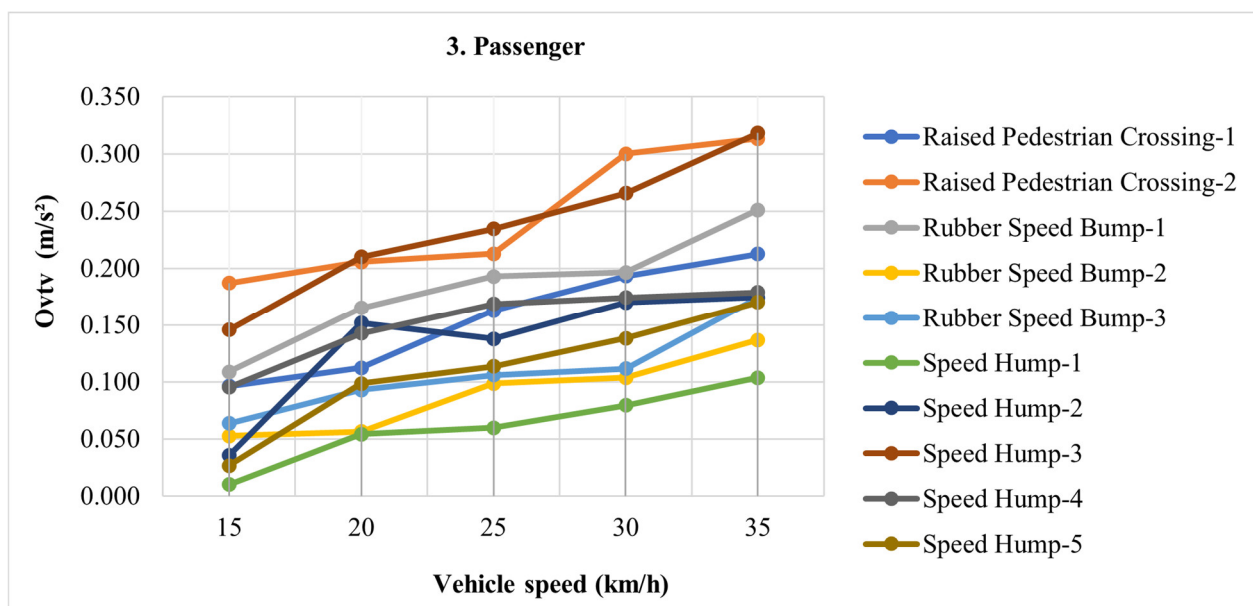


Figure 13. The comfort levels determined according to the OVTv for the third passenger.

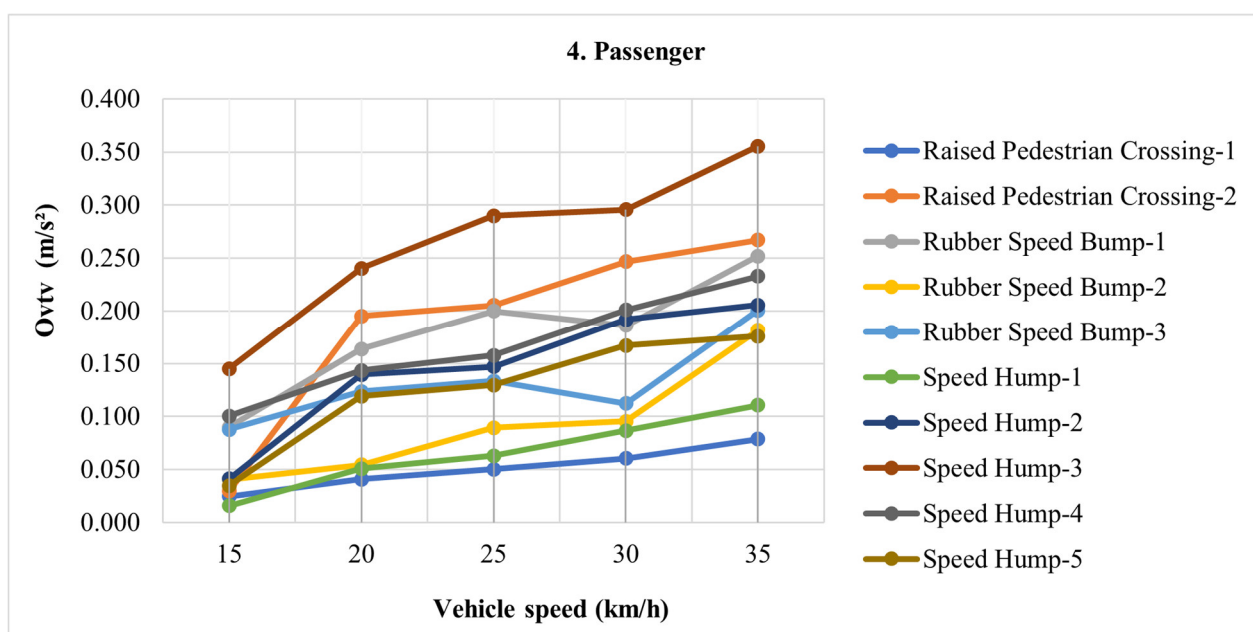


Figure 14. The comfort levels determined according to the OVTv for the fourth passenger.

To further support the descriptive comfort classification, statistical analyses were performed using the OVTv dataset. Since the OVTv did not follow a normal distribution according to the Shapiro–Wilk test, non-parametric statistical methods were used. The relationship between vehicle speed and OVTv was examined using Spearman correlation analysis. Differences in OVTv among speed bump types were evaluated using the Kruskal–Wallis test. The effect of passenger loading was examined by comparing corresponding seat positions under two- and four-passenger conditions using the Wilcoxon signed-rank test. Passenger position effects were evaluated using the Friedman test based on the four-passenger test data. In addition, the association between vehicle speed and comfort

classification was evaluated using the chi-square test. The statistical analysis results are summarized in Table 4.

Table 3. Summary of OVTV-based comfort classification by vehicle speed.

Vehicle Speed	Total OVTVs	Mean OVTV (m/s ²)	Median OVTV (m/s ²)	Uncomfortable Values	Uncomfortable Percentage
15 km/h	60	0.0865	0.0890	0	0.00%
20 km/h	60	0.1383	0.1390	0	0.00%
25 km/h	60	0.1643	0.1625	0	0.00%
30 km/h	60	0.1898	0.1845	1	1.67%
35 km/h	60	0.2300	0.2285	11	18.33%
Total	300	0.1618	0.1495	12	4.00%

Table 4. Statistical analysis results for OVTVs.

Analysis Objective	Statistical Test	Variables/Groups	Test Statistic	p-Value	Interpretation
Normality check of OVTVs	Shapiro–Wilk test	OVTVs	W = 0.981	0.0006	OVTVs were not normally distributed; therefore, non-parametric tests were preferred.
Effect of vehicle speed on OVTV	Spearman correlation	Vehicle speed vs. OVTV	rho = 0.582	<0.001	A significant positive relationship was found; OVTV increased as vehicle speed increased.
Difference among speed bump types	Kruskal–Wallis test	Raised pedestrian crossing, rubber speed bump, speed hump	H (2) = 15.078	0.0005	OVTVs differed significantly among speed bump types.
Effect of passenger loading condition	Wilcoxon signed-rank test	Corresponding first and second passenger positions under two- and four-passenger conditions	W = 36.5	<0.001	Passenger loading condition had a significant effect on OVTVs.
Effect of passenger position	Friedman test	Passenger positions in four-passenger tests	chi-square (3) = 28.335	<0.001	OVTVs differed significantly among passenger positions.
Association between speed and comfort classification	Chi-square test	Vehicle speed vs. comfort-able/uncomfortable classification	chi-square (4) = 40.451	<0.001	The proportion of uncomfortable cases increased significantly with vehicle speed.

The statistical findings support the descriptive results. Vehicle speed had a significant positive association with OVTV, confirming that vibration exposure increased as vehicle speed increased. The significant difference among speed bump types indicates that the geometric and material characteristics of the traffic calming devices influenced passenger comfort. The passenger loading and passenger position results also show that vibration exposure varied depending on the seating and loading conditions. In addition, the chi-square test confirmed that uncomfortable OVTV classifications were concentrated at higher vehicle speeds, especially at 35 km/h.

4.4. Comparison of Driving Comfort According to Vertical Acceleration and OVTV

According to the evaluations made with vertical acceleration values, the comfort levels of 85% of passengers in the two-passenger tests, 89% in the four-passenger tests and 87.67% in total speed bumps were found to be uncomfortable. The reason for this situation is the high acceleration values. However, some of the acceleration caused by vibration is damped by our body. For this reason, it is stated that frequency weighting should be done for different people and situations when evaluating according to the ISO 2631-1 standard. In the evaluations made according to frequency weighting, it was seen that the comfort level of 7% of the two-passenger tests, 2.5% of the four-passenger tests and 4% of the total speed bumps were classified as uncomfortable.

In other words, there are a total of 30 comfort values for a speed bump. Since we have 10 speed bumps, this value means a total of 300 comfort values. According to the evaluations made considering the vertical accelerations, the comfort level of 37 values was found to be comfortable. This constitutes 12.33% of the total value. According to the evaluations made considering the OVTV, 288 out of 300 comfort values were found to be comfortable. This constitutes 96% of the total value. According to these results, it has been seen that the number of values in the comfortable category, as a result of the evaluations made by taking into account the OVTV, is approximately eight times higher than the number of values determined by considering the vertical acceleration value and the comfort level.

As stated in the ISO 2631-1 standard, vibration causes different effects and discomfort on each individual. For this reason, comfort evaluations based only on vertical acceleration values may not fully represent the actual comfort perception of seated vehicle occupants. In the results, it has been shown that many speed bumps, which are uncomfortable according to the vertical acceleration values, are comfortable as a result of the evaluations made by considering the OVTV.

Although this study provides a field-based comfort evaluation using triaxial acceleration measurements and OVTV-based criteria, it has some limitations. The study was conducted using a single passenger car and selected speed bumps in one city. Detailed vehicle suspension dynamics, spring–damper parameters, and gross vehicle weight variations were not mathematically modeled. Therefore, the findings should be interpreted as field-based comfort assessment results rather than a full vehicle dynamics simulation. Future studies should include different vehicle types, repeated measurements, and integrated vehicle suspension models to improve the generalizability of the findings.

5. Conclusions

In this study, the compliance of 10 speed bumps in Erzurum with the standards was investigated. The three-dimensional shapes of the speed bumps examined in the experiment were modeled in detail. Then, a comfort evaluation was made according to the vertical acceleration and OVTV data at 15, 20, 25, 30 and 35 km/h speeds with accelerometers placed in different parts of the vehicle. It has been observed that among the speed bumps, except for Rubber Speed Bump-2, other speed bumps do not meet the desired criteria, both in terms of geometry and surface shapes. In addition, the data obtained showed that as the vertical acceleration value increases, the discomfort also increases. According to the vertical acceleration-based evaluation, 87.67% of the comfort values were classified within the uncomfortable categories. In contrast, according to the OVTV-based evaluation, 96% of the comfort values were classified within the comfortable category. However, it has been revealed that it would be more beneficial to examine both vertical acceleration and OVTV data together. The combined use of vertical acceleration and OVTV provides a more comprehensive basis for evaluating speed bump comfort performance. For this reason,

it has been determined that all speed bumps except for Rubber Speed Bump-2 should be reviewed and built in accordance with the design standards and the necessary markings should be made on them to make them easier to notice by the drivers. For this, it would be more appropriate to make the most optimum design by considering the criteria specified in the design standards.

The statistical analysis also supported the descriptive findings by showing that vehicle speed, speed bump type, passenger loading condition, and passenger position influenced OVTVs. In particular, the increase in uncomfortable OVTV classifications at higher speeds indicates that speed control and geometric design should be considered together when evaluating the comfort performance of speed bumps.

The findings emphasize the importance of designing and implementing speed bumps in accordance with relevant standards by local authorities. In addition, the study suggested that acceleration values should not be taken from only one point in the vehicle in order to obtain results with sufficient accuracy in the studies planned to be carried out in this field in the future.

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