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Measurement of whole-body vibration exposure from speed control humps

E. Khorshid[a,*], F. Alkalby[b], H. Kamal[c]

[a]Mechanical Engineering Department, Kuwait University, P.O. Box 5969 Safat, Kuwait
[b]Industrial Training Institute, P.O. Box 1236 Sabah Alsalem, Kuwait
[c]Electrical Engineering Department, Kuwait University, P.O. Box 5969 Safat, Kuwait

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Abstract

The main objective of speed control humps is to introduce shocks and high vibration levels when a car passes over them if its speed is higher than the allowable limit. Hump geometry is a major factor in altering the level of these shocks and specifying the speed limit. However, there is no study of the relationship between whole body vibration due to passing over a speed control hump and lower back pain or occupational diseases. In this study, an experimental investigation is conducted to evaluate health risks associated with different geometry speed control humps. Vibration levels and shocks are measured by a seat pad accelerometer placed under the driver's seat to evaluate hazard risks on the human body's lower back. The assessment is based on two standard methods of measuring whole body vibration: the British standard BS 6841 and the new ISO/DIS standard 2631-5. These methods are used to assess the effects of vehicle type, passenger location in the vehicle, vehicle speed, and speed control hump geometry. It was found that circular speed control humps currently installed on many public roads should be modified in order to eliminate hazards. Two newly designed speed humps were proved to be less hazardous than circular speed control humps.

1. Introduction

Accident rates in Kuwait, like other countries, are high due to the violation of speed limits and a shortage of traffic forces. Therefore, speed humps are a very efficient way of slowing down cars, and, especially in residential areas, may help reduce accidents [1]. Based upon the study by Saadoon [2], speed control humps (SCHs), which are 4 m wide and 10 cm high, are replacing 1 m wide and 15 cm high humps on many residential roads. This is because the second speed bumps are found to be ineffective in controlling speed limits at the desired value, according to Saadoon [2].

A speed hump is a local elevation of the road surface of limited height, usually 0.1–0.15 m, in order to decrease driving speeds to an acceptable limit known as the critical speed (CS). A speed hump works by transmitting an upward force to a vehicle, and its occupants, as it traverses the hump. The force induces

*Corresponding author.
E-mail address: khorshid@kuc01.kuniv.edu.kw (E. Khorshid).

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Nomenclature

A_{ik}	acceleration value of peak number i of the response acceleration, m/s^2
a_w	weight filtered acceleration, m/s^2
CC	comfort criteria in terms of g ($g = 9.81\,\mathrm{m/s^2}$), m/s^2
CS	critical speed, km/h
CS_f	factor of the critical speed CS
D_k	acceleration dose in the k direction, m/s^2
g	gravitational acceleration, 9.81 m/s^2
k	direction of the measured acceleration response
m_k	constant in the k direction
N	number of periods under testing condition
$N_{0.8}$	number of hump crossing to reach the 0.8 S_{ed}
N_{15}	number of hump crossing to reach the 15 m/s$^{1.75}$ VDV_t
$\underline{S_e}$	lower limit value according to the ISO/DIS 2631-5 standard, 0.5 MPa
$\overline{S_e}$	upper limit value according to the ISO/DIS 2631-5 standard, 0.8 MPa
S_e	equivalent static compression stress, MPa
S_{ed}	daily dose of equivalent static compressive stress, MPa
VDV	vibration dose value, m/s$^{1.75}$
$\overline{\mathrm{VDV}}$	limit zone of vibration dose value equal to 15 m/s$^{1.75}$, m/s$^{1.75}$
VDV_t	total vibration dose value, m/s$^{1.75}$
VDV_x	vibration dose value in the x-axis, m/s$^{1.75}$
VDV_z	vibration dose value in the z-axis, m/s$^{1.75}$

Subscripts

H	hump type
LBP	lower back problems
SCH	speed control hump
TCD	test condition with N number hump crossing for daily dose
TCS	test condition with single hump crossing
V	measurement condition

a front-to-back pitching acceleration that increases as the vehicle travels faster. Watts [3] stated that the ideal SCH should be crossed without damage to load or vehicle, loss of control, or driver discomfort, which means (ideally) zero vertical acceleration, as shown in Fig. 1. If the SCH is crossed with a speed that is above the CS, the driver should suffer some discomfort without damaging the load or vehicle or risking loss of control.

Occupants in vehicles are exposed to whole body mechanical vibration during their daily ride. Whole body vibrations (WBVs) originate from two different types of force. A random and sudden forces designated as a *shock* [4]. When the tires hit a bump or sink into a pothole, shock occurs. If this shock is strong enough, it can cause severe spinal injury (discussed in the book by Dupuis and Zerlett [5]), as reported in case studies by Bowrey et al. [6].

The reported research by Rosegger and Rosegger in Ref. [7] claimed that shaking and jolting may lead to macro and micro-trauma to the vertebrae. The work by Troup [8] argued that transmitted road-shock is a source of back problems. More recent studies focused on the effect of vibration on health. Johanning et al. [9], Sandover [10], Paddan and Griffin [11], Lings and Leboeuf-Yde [12], and Teschke and Nicol [13] all came to the conclusion that drivers of certain vehicles are at risk for lower back problems (LBPs). Unfortunately, no one appears to have carried out an epidemiological study where the prevalence of high acceleration was considered. However, in the review study on the effect of long-term exposure to WBV by Wikström et al. [14], it was concluded that many repeated shocks with a sufficient level and duration might lead to back problems. In addition, the study by Cross and Walters [15] concluded that "jarring" was considered a cause of 36% of back injuries by mobile equipment operators. The experimental work by Granlund and Lindströms [16] demonstrated that high level of shocks are introduced to vehicle occupants while crossing SCHs. Shock can also cause severe spinal injury [5]. There are several reported Scandinavian injury cases from riding in buses over traffic calming road humps. Some injuries may occur to seated as well as standing people in vehicles. Short-term injury may be the fracture of vertebrae, while a long term one may result in back pain, which may have a direct relation to SCH devices as opposed to road roughness. As an example of a crash fracture of vertebrae, a 49-year-old female traveling on a double decker public transport was jolted upward as the vehicle traversed a road hump and then on landing back on her seat, experienced acute low back pain. The injury was in the form of a fracture of the third lumber vertebrae, and she continued to suffer chronic lower back pain.

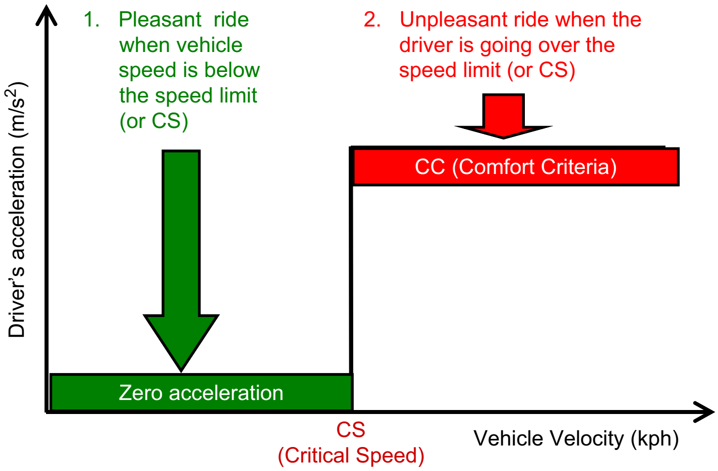


Fig. 1. Response of the driver's acceleration as a function of velocity for an ideal SCH.

Bowrey et al. [6] reported that a 34-year-old female suffered a similar problem when crossing a SCH, but this injury was to the spine tissue and neck.

Health risks to vehicle occupants from SCH shocks, were analyzed using two standards: the British standard BS 6841 [17] and the new ISO/DIS 2631-5 standard [18]. A SCH experiment entails a variety of testing conditions: different hump profiles and dimensions, different vehicle speeds, and various seat locations within the vehicle. These conditions cause various types of repeated shocks to the vehicle's occupants and the driver. To date there has been no published research on WBV of SCHs and their possible hazard on human health.

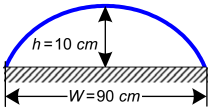
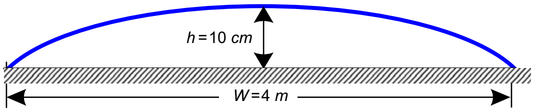
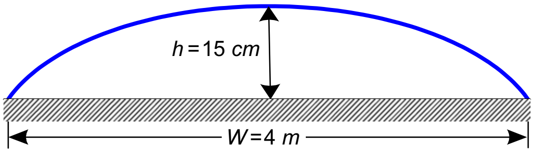
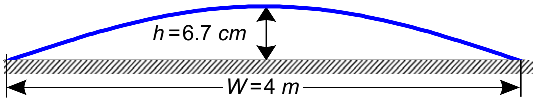
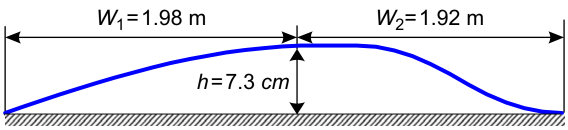
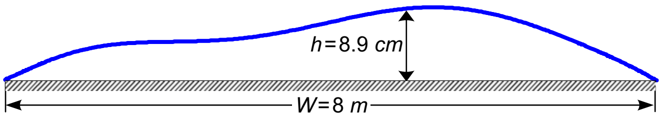
The present study investigates the relationship between induced vibration levels due to hump crossing and vehicle seat positions for various vehicle models and sizes. The effect of the number of hump crossings per day, hump geometry, and vehicle speed were examined experimentally in order to minimize possible health hazards, according to the two standards, and useful recommendations for crossing SCHs are suggested.

2. Experimental methods

2.1. Speed control hump geometry

Table 1 shows seven types of SCHs that were used for experimental testing, in order to study vibration and shock in different vehicles. Hump1 is, in fact, a speed control bump with a 10 cm height and a 90 cm width. It is used to control traffic at the speed limit, the CS, of 30 km/h. Another parameter used to assess SCHs is the comfort criteria (CC), which is defined as the maximum value of shocks passed to the driver's seat when the vehicle crosses the SCH at a speed equal to or exceeding the CS [19]. Refer to Fig. 1 for more clarification on both CS and CC terms. For Hump1, the CC is equal 0.6 g. Hump2 is a circular hump designed for a CS between 45 and 60 km/h with a CC equal to 0.6 g. Hump2 is becoming popular and is starting to replace Hump1 due to its effectiveness in controlling vehicle speed and public acceptance due to minimized discomfort. Both Hump1 and Hump2 are currently being installed on residential roads. Hump3 is a circular hump that has similar geometries to Hump2, but with an exact circular profile, which was made according to the recommended specifications of Chadda and Cross [20]. This hump is used for off-road testing. Hump4, which is 15 cm high, is usually used to measure the effect of hump height variation on vehicle shocks. Hump5 has a sinusoidal profile and is designed for a CC of 0.6 g. It is designed for roads with CSs between 35 and 60 km/h and is currently installed in many European countries [21]. It has great dynamics due to its smooth profile, which minimizes the amount of shocks at initial contact between the vehicle front tires and the hump surface. Great hump dynamics, or an efficient hump, means that the hump introduces vibration to the vehicle driver similar to the ideal hump response discussed above and presented in Fig. 1. Hump6 and Hump7 are

Table 1
Speed control humps used in the study

H (km/h)	Name	Hump geometry	CC (g)	CS (km/h)
1	Hump1	 Short bump	0.6	⩽35
2,3	Hump2 Hump3	 Long circular hump (on and off road humps)	0.6	45⩽CS⩽60
4	Hump4	 Long circular hump with large height	1.3	35⩽CS⩽60
5	Hump5	 Sinusoidal–sinusoidal hump	0.6	35⩽CS⩽60
6	Hump6	 Optimal sinusoidal–cycloidal hump	0.6	35
7	Hump7	 Optimal polynomial hump of degree-7	0.6	60

both obtained based on the numerical optimization method given in the study by Khorshid and Alfares [19]. Both humps were designed to minimize the amount of shocks on the driver's head using numerical optimization methods. It is important to point out that the design criteria for these SCHs was not to minimize the amount of shocks on the transmitted acceleration (force) from the driver's seat to the human body, but to reduce the amount of driver head acceleration while crossing the SCH. Hump6 was designed for a CC of 0.6 g and a CS of 30 km/h, where the upper bound on the total hump width is constrained to 4 m. Hump7 was designed for a CS of 60 km/h and the same CC as Hump6. Also, the limited total width was set to be 8 m with a polynomial profile instead of a fixed specified function like that of Hump6. Note that both longer humps and a polynomial profile increase the hump efficiency.

2.2. Experimental procedure

Four different measurement conditions were selected, as shown in Table 2, to cover a wide range of actual road conditions. Three of these measurements were used for different vehicle types to test driver's response. The last measurement was used for the rear-seated passenger in a long sport utility vehicle. For the calculation of the total daily dose, the testing condition is symbolized as $\mathrm{TCD}_{H,V}$ where H represents the hump type in Table 1 and V represents the measurement conditions of Table 2. Running speeds varied between 10 and 80 km/h, which are typical daily speeds. Sample runs for the un-weighted driver seat acceleration in the x

Table 2
Vibration measurement for all speed humps

V	Vehicle type and measurement locations
1	Small passenger car, driver's seat
2	Medium passenger car, driver's seat
3	Sport utility vehicle, driver's seat
4	Sport utility vehicle, rear back seat (refer to Fig. 8 for seat position)

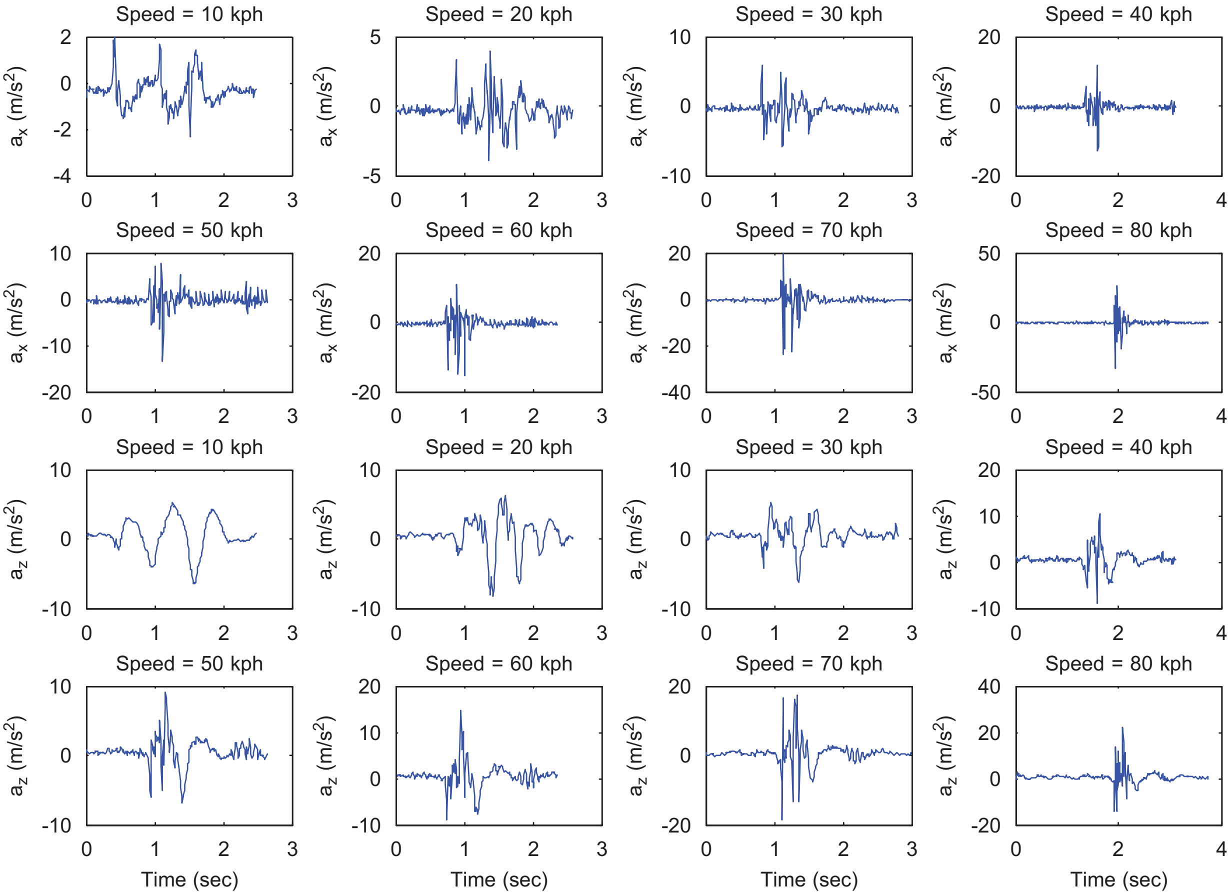


Fig. 2. The un-weighted driver seat acceleration in the x (for-aft) and z (vertical) directions of the small passenger vehicle when crossing Hump1 at different driving speeds.

(for-aft) and z (vertical) directions of the small passenger vehicle, when crossing Hump1 at different driving speeds, is shown in Fig. 2. Only one occupant (the driver) participated in this study for testing conditions related to the front-seated driver. He was 26 years old, 165 cm tall and weighted 80 kg. Another testing object participated for the rear-seated passenger testing condition. He was 24 years old, 172 cm tall and weighted 85 kg. In fact, using a single testing object has some limitations. The expected values of the vibration for different seat occupants will change since the apparent mass will change (refer to the ISO 5982 [22]). However, the amount of change is not clear unless a mathematical model is used. Mansfield and Maeda [23] observed that there will not be a great effect on the vibration level transmitted to the human body system at low frequencies, i.e. the frequency content of the measured signal has little energy above 80 Hz. This condition occurs in the present study for seated driver passing over a SCH as shown in Fig. 3, where the frequency

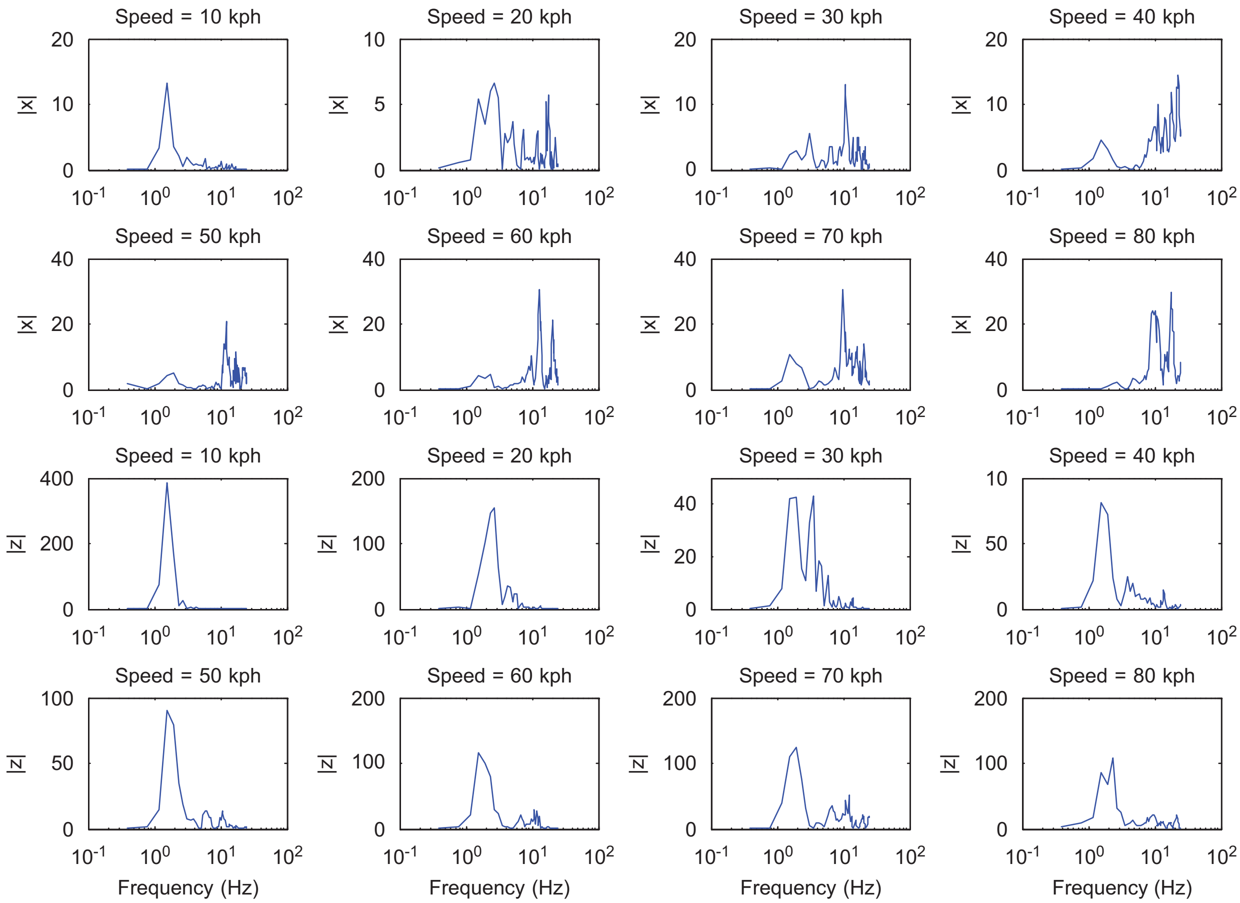


Fig. 3. The un-weighted power spectral densities of both signals in the x and z directions for the driver's seat for the small passenger vehicle crossing Hump1 (the x-axis is a log scale).

contents of the signals in z direction for the small passenger vehicle crossing Hump1 are shown.The WBV for different testing conditions of the vehicles while crossing the SCHs was measured at the driver/seat interface for the x-, and z-axis. These two axes have most of the impact and shocks from crossing the SCH and, therefore, are selected to conduct the experimental measurements. Note that the signal in the y-axis is very small compared to the other axes and consequently was ignored.

2.3. Measurement procedure

Two methods for evaluating the effect of repeated mechanical shocks on the human body are available from the literature: the British standard BS 6481 [17] and the new ISO/DIS 2631-5 [18]. These methods include the required experimental measurements, assessment on possible hazards, analysis of experimental results, and calculation of number of humps to reach these hazard limits. They are utilized for evaluating the health hazard on drivers when crossing SCHs. Both of these methods provide a means to identify motions that are potentially injurious, but the relationship between the action levels and the occurrence of injuries is not proven. The actual point at which injury occurs will also be dependant on other factors such as posture. The BS 6841 [17] was selected, because it is easy to use. This standard fits our proposed study [24]. The new ISO/DIS 2631-5 [18], on the other hand, is also suitable for the proposed study since it predicts possible hazards on the human lower back as a result of repeated shocks on vehicle occupants when crossing a SCH. Note that the this standard was not judged of a sufficient quality to become a full standard. Therefore it is still a draft international standard (DIS) [18].

2.4. Equipment

WBV was measured at the driver's (or passenger) seat interface by using a triaxial seat pad accelerometer (model 4322) made by Bruel and Kjaer®. Vibrations were measured using LabView software with a National Instruments data acquisition card. Two acceleration signals for each test were recorded on a digital computer for 4 s at 499 samples/s. Acceleration signals were low pass filtered with the cut-off frequency set at 100 Hz. Frequency weighted accelerations were calculated using the weighting factors suggested by BS 6841 [17]. For the ISO/DIS 2631-5 [18], no weighting of the signals was needed. All calculations were carried out using MATLAB software [25].

3. Data analysis

Vibration measurements were analyzed using the procedure described in both the British Standard BS 6841 [17] and the International Standard ISO/DIS 2631-5 [18]. International Standard ISO 2631-1 [26] is a more recent standard than BS 6841 that provides similar (but not identical) procedures for evaluation of vibration and shock. The differences between the ISO 2631-1 [26] and BS 6841 are due to variations in the shapes of the frequency weightings, the phase responses of the frequency weighting filters, the method of combining multiaxis vibration, and the assessment method [24].

For the British Standard BS 6841, the analysis includes the application of frequency weightings, the use of multiplying factors in different axes, and the calculation of vibration dose values (VDVs). For the International Standard ISO/DIS 2631-5 [18], the analysis includes the use of multiplication factors in different axes. Both the equivalent static compressive stress S_e and the summation of the daily dose of equivalent static compressive stress S_{ed} over the different axes were calculated as outlined in the next sections.

3.1. British standard BS 6841

3.1.1. Vibration dose values

According to the British Standard BS 6841 [17], the VDV is defined as the cumulative vibration and shock measures that a person is exposed to during a given period of time. The VDV reflects the magnitude, frequency and duration of the total exposure to vibration. The VDV is described by the following equation:

$$\mathrm{VDV} = \sqrt[4]{\int_{t_1}^{t_2} a_w(t)^4 \, \mathrm{d}t}, \tag{1}$$

where $a_w(t)$ is the weighted filtered signal, and t_1 and t_2 are the initial and final times of the calculation period, respectively. Note that $a_w(t)$ is converted back to the time domain so as to calculate the VDV from Eq. (1), since this calculation is possible only in the time domain.

In the case of SCHs, there exist N periods with different signals for repeated daily shocks. The fourth root of the sum of the fourth powers of the VDVs in each axis is determined for calculating the total vibration dose values VDV_t as follows:

$$\mathrm{VDV}_t = \left(\sum_{n=1}^{n=N} \mathrm{VDV}_n^4 \right)^{1/4}, \tag{2}$$

where VDV_n is the VDV in the n period. The VDV_t of multi axes is calculated from

$$\mathrm{VDV}_t = \left(\mathrm{VDV}_x^4 + \mathrm{VDV}_z^4 \right)^{1/4}, \tag{3}$$

where VDV_x and VDV_z are the VDV along the x- and the z-axis, respectively.

The number of periods, N, was assumed to be 32, which is a typical average number of humps (fixing hump type) per day for normal driving conditions. However, the assumed number of daily humps to be crossed may be slightly higher as in the case reported in Ref. [27], where the total number of humps was as high as 264 humps per day.

The British Standard BS 6841 [17] offers an interpretation of VDVs which amounts to the definition of an action level: "Sufficiently high vibration dose values will cause severe discomfort, pain and injury. ... Vibration dose values in the region of $15\,\mathrm{m/s^{1.75}}$ will usually cause severe discomfort ... increased exposure to vibration will be same by increased risk of injury." The guidance in British Standard BS 6841 [17] is expressed in terms of VDVs. The text of the standard states that "it is not possible to specify with any precision either the type or the probability of any injury that may occur due to excessive vibration exposures". However, a note states that epidemiological studies suggest that back complaints are associated with exposure to prolonged periods of vibration and repeated shock. The standard states that the value of $15\,\mathrm{m/s^{1.75}}$ is not a limit but a consensus of opinion on methods of assessing vibration and shock, which was influenced by biodynamic and subjective data obtained in laboratories and by data from field studies.

3.2. *ISO/DIS 2631-5*

ISO/DIS 2631-5 [18] has been prepared by a group of experts in order to provide a method of assessing the adverse health effects from vibration containing multiple shocks, which are measured at an occupant seat pad. This standard is still a DIS. Vehicles crossing over SCHs mostly produce these types of vibrations and shocks, especially at high speeds or with a *badly designed* hump.

3.2.1. *Spine response acceleration*

The most common adverse health effect from whole-body vibration is the degeneration of the lumbar spine. Sandover [28] used experimental data and a simple mathematical model to prove that repeated loading could lead to damaging the vertebral endplates. Therefore, the aim of this study is to assess the effect of compressive stresses on the human discs.

The spine response acceleration was calculated based on a simple linear mass–spring system in the horizontal x direction with a natural frequency of 2.125 Hz and a critical damping ratio of 0.22. For the vertical z direction, a more complex, nonlinear model was used. The model assumes that the occupant who is subjected to vibration is in the upright position and adheres to his/her seat. Different postures can result in different responses of the spine. The acceleration in the k direction is defined as

$$D_k = \left[\sum_i A_{ik}^6\right]^{1/6}, \tag{4}$$

where A_{ik} is the acceleration of peak number i, and k is equal to x or z directions. Note that the peak is defined as the maximum absolute value of the response acceleration between two consecutive zero crossings. In the x direction, peaks in the positive and negative directions were considered. In the z direction, *only* positive peaks were considered (compression of the spine). The MATLAB PostPeak subroutine was used to find these positive and positive-negative peaks for the experimental data.

3.2.2. *Static compressive stress, S_e*

Annex A (informative) of the ISO/DIS 2631-5 [18] was used to calculate the equivalent static compressive stress S_e using the following equation:

$$S_e = \left[\sum_{k=x,z} (m_k D_k)^6\right]^{1/6}. \tag{5}$$

Recommended values of m_k in MPa/(m/s^2) are: $m_x = 0.015$ and $m_z = 0.032$. If D_k is calculated as the daily acceleration dose, then S_e becomes the daily static compression dose (S_{ed}). Annex A states that $S_{\mathrm{ed}} \leqslant 0.5\,\mathrm{MPa}$ indicates a low probability and $S_{\mathrm{ed}} \geqslant 0.8\,\mathrm{MPa}$ indicates a high probability of a health hazard. Moreover, it is assumed that the total working days per year are 240 days of vibration exposure.

4. Results and discussions

The effects of hump type, seating position, vehicle type, and evaluation method on the shock amount introduced in a vehicle are discussed in some detail. As a sample run, the original un-weighted signals of the seat acceleration in the *x*- and *z* directions are shown in Fig. 2 for a small passenger vehicle (testing condition $TCS_{1,1}$) crossing over a short bump (Hump1) at different speeds. It is clear that high-level shocks are introduced to the driver for this testing condition, especially for increased vehicle speed. For example, for the test condition at 80 km/h, the absolute peak signal in the vertical direction is equal to $22\,m/s^2$. Conversely, for the test condition at 10 km/h, the absolute peak signal in the vertical direction is only $7\,m/s^2$. It is worth noting from Fig. 2 that the absolute peak signal in the vertical direction is higher than that in the for-aft direction at low speed, and both signals have similar absolute peaks in the vertical direction at higher speeds (above 30 km/h).

The un-weighted power spectral densities for these testing conditions in Fig. 2 are shown in Fig. 3, which indicates that the frequency spectra demonstrate peaks at 2, 4 and 12 Hz in the *z* direction depending on the speed. For the *x* direction, the peaks occur at 4 Hz in addition to other peaks at higher frequencies above 10 Hz, depending on the vehicle's speed. The amplitudes of the peaks in the *z* direction are higher than that of the *x* direction by more than 500%.

4.1. Effect of hump type

This section discusses the effect of hump type on the amount of shocks introduced in a vehicle. To do so, the vehicle type and seat position are fixed, and the vibration data is recorded while crossing the seven types of SCHs listed in Table 1. The amount of vibration at different speeds is related to the hump geometry (hump profile, width and height). This was clearly demonstrated in the theoretical study by Khorshid and Alfares [19]. In this study, a mathematical model for simulating a seated human body with the vehicle dynamics was used to study the influence of several hump geometries on human comfort. Moreover, the authors used an optimization method to design an efficient hump to meet the ideal hump described in Fig. 1.

The recorded signals, in the *x* and *z* directions, are used to calculate the VDV_t value for a single run using Eq. (3), according to the BS 6841 [17]. This VDV_t is increased as the number of crossed humps in the driving routes is increased. If the number of speed humps per day is assumed to be 32, then the VDV_t values are plotted in Fig. 4 for testing conditions $TCD_{H,1}$. The first observation from the figure is that the action limit of $15\,m/s^{1.75}$ is not exceeded for vehicle speeds equal to and less than 30 km/h. However, crossing Hump1 at speeds equal to 50 km/h and more introduce VDV_t that exceeds $15\,m/s^{1.75}$. Moreover, Hump4 has the most severe effect on human health because of the hump height (15 cm), which introduces a large amount of shocks to the driver. The maximum VDV_t when crossing Hump4 at a speed equal to 80 km/h is $38\,m/s^{1.75}$. This value, which is almost 250% of the $15\,m/s^{1.75}$ action limit, increases the possible risk of injury.

The efficiency of the hump depends on both the CS and the comfort level above the CS (see Fig. 1). If not specified, the standard comfort level, CC, is assumed to be in the range of 0.4–0.9 g according to many references (Ref. [29]). Note that, in the proposed study, the CC values are 0.6 g for all humps except that of Hump4, which is 1.3 g. In fact, reducing the VDV values might suggest that the ride is more comfortable "and perhaps less likely to deter speeding drivers". However, for the optimal designs of SCH's (Hump6 and Hump7 in Table 1), if the drivers were speeding up, the amount of shock introduced while crossing the speed hump will be high enough to force them to reduce their speeds. A full study conducted on the efficiency of these humps to meet both of these contradicting criteria is described in the work by Khorshid and Alfares [19]. If it is assumed that the efficient hump should have a CS equal to 40 km/h and the comfort level is 0.6 g, then the efficiency of all tested humps in Fig. 4 can

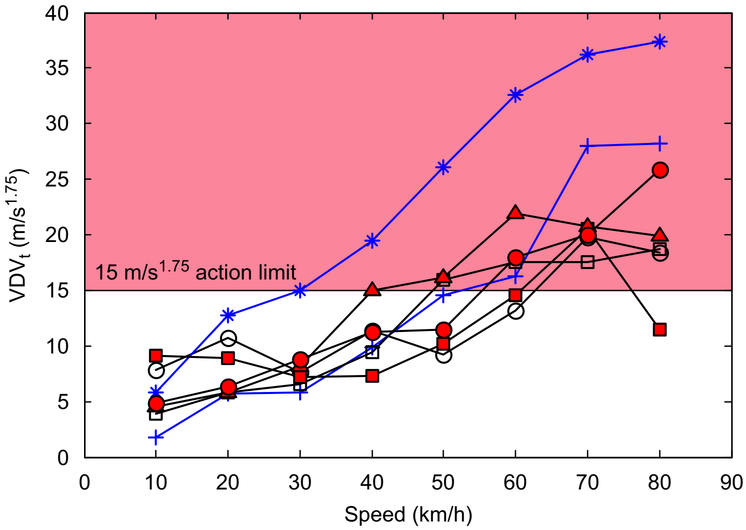


Fig. 4. Comparison of VDV_t at the driver's seat for the small passenger vehicle while crossing different SCHs according to BS 6841 [17] for 32 humps/day. –○– Hump1, –+– Hump2, –■– Hump3, –*– Hump4, –□– Hump5, –▲– Hump6, –●– Hump7.

be calculated as follows:

$$f_e = \frac{\sqrt{\sum_{i=1}^{n_1}\left(\frac{\mathrm{VDV}_i - 0}{n_1}\right)^2 + \sum_{i=1}^{n_2}\left(\frac{\mathrm{VDV}_i - \mathrm{CC}}{n_2}\right)^2}}{32}, \tag{6}$$

where n_1 is the number of tests below the CC and n_2 is the number of tests above the CC.

Fig. 5 shows the static stresses on the spine (S_{ed}) when analyzing the data for $TCD_{H,1}$ according to the ISO/DIS 2631-5 standard. It is clear that most of the SCHs will have large values of S_{ed} on the lower back at speeds above 40 km/h. Also, Hump7 has the least amount of S_{ed} for $TCD_{H,1}$ among all the tested humps (average values over the whole speed range). On the other hand, when a small passenger vehicle crosses Hump4 32 times a day, it introduces stresses higher than the $\underline{S_e}$ limit at speeds equal to or greater than 15 km/h, as shown in Fig. 5. This speed is lower than the specified CS of Hump4, which is equal to 35 km/h (Table 1). Therefore, these experimental results show that even though the vehicle crosses this hump within the assigned speed limit 32 times a day, the driver will have a possible health problem according to the ISO/DIS 2631-5 standard. Finally, for Hump4 ($TCD_{4,1}$), the calculated S_{ed} values exceeds $\overline{S}_e$ limit at a speed of 20 km/h.

From this observation, it is important to take great precautions in the construction of SCHs that do not exceed the specified hump height of 10 cm, as recommended by the traffic transportation authorities [2]. Note that the experimental work by Khorshid and Elkalby [30] where field measurements for some of the SCHs currently installed in Kuwait were conducted, found that the 15 cm height humps do exist in actual residential roads and result in high shock levels that might create LBPs for the seated driver, even with a single pass, as discussed later.

4.2. Effect of vehicle type

Different vehicles vary in their suspension system, seat characteristics, tire properties, and vehicle dimensions. These variations affect the amount of shock transmitted to the driver and, therefore, change the assessment results of SCHs for possible health risks to vehicle occupants. Toward this goal, the test is conducted on three different categories of vehicles: small passenger, medium passenger and sport utility. Figs. 6 and 7 show the VDV_t and S_{ed} for the testing condition of $TCD_{H,V}$ (for 32 hump crossing per day) where $H = \{4, 6, 7\}$ from Table 1 and $V = \{1, 2, 3\}$ from Table 2.

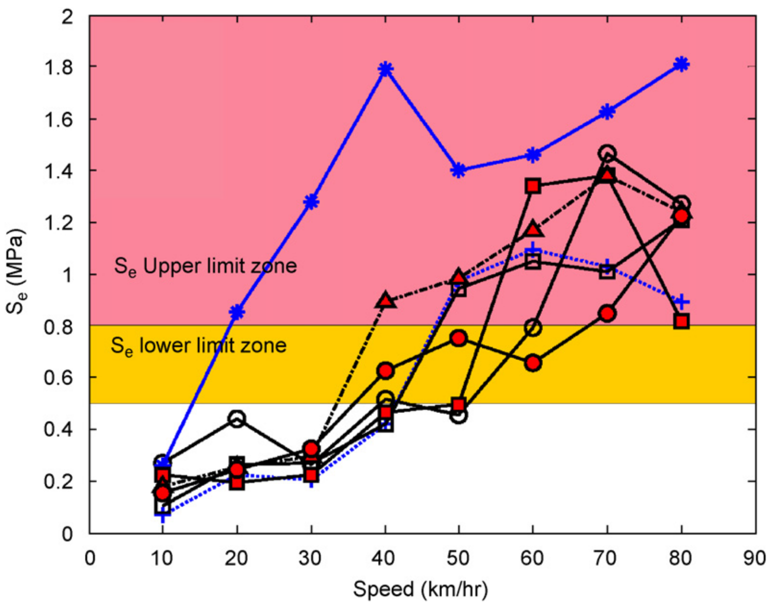


Fig. 5. Comparison of S_e at the driver's seat for the small passenger vehicle while crossing different SCHs according to ISO/DIS 2631-5 [18] for 32 humps/day. –○– Hump1, –+– Hump2, –□– Hump3, –*– Hump4, –■– Hump5, –▲– Hump6, –●– Hump7.

Fig. 6 shows the VDV_t for different vehicles if the daily number of hump crossings is assumed to be 32 humps/day. For all these SCHs, in both the cases of the medium passenger and the sport utility vehicles, the VDV_t values will not pass the $\overline{VDV}$ limit when crossing these SCHs in all speed ranges from 10 to 80 km/h according to the BS 6841 [17]. On the other hand, the equivalent static compression stress values of the small passenger vehicle will be more than the 15 $m/s^{1.75}$ limit for the following cases: (1) Hump4: at 30 km/h and faster; (2) Hump6: at 60 km/h and faster; and (3) Hump7: at 55 km/h and faster. For $TCD_{H,2}$ and $TCD_{H,3}$, for seated driver in the medium passenger and sport utility vehicles, the VDV_t exceeds the $\overline{VDV}$ for the following: (1) Hump4: at speeds equal to and more than 50 km/h; (2) Hump6: at speed equal to and more than 55 km/h; and (3) Hump7: the VDV_t values do not exceed the $\overline{VDV}$ for all tested speeds.

Analysis of the data according to ISO/DIS 2631-5 [18] for different vehicle categories with different humps is shown in Fig. 7 for 32 hump crossings per day. For $TCD_{4,1}$, the small passenger vehicle surpasses the $\underline{S_e}$ lower limit zone at 15 km/h and the $\overline{S_e}$ at 32 km/h. For the other two vehicles, their S_e are higher than the $\underline{S_e}$ limit at speeds equal to 38 and 42 km/h for $TCD_{4,2}$ and $TCD_{4,3}$. Moreover, both vehicles have S_e values exceeding the $\overline{S_e}$ at speeds equal to 43 and 45 km/h. This means that the driver of a small passenger vehicle will have a great health risk to his/her lumber spine under these driving conditions compared to the drivers for the other vehicles.

Fig. 7 illustrates the effect of vehicle variation with Hump6 on the daily static stress S_{ed}. These testing conditions are $TCD_{6,1}$, $TCD_{6,2}$, and $TCD_{6,3}$ (seated driver). For all tested vehicles, there is a large health risk possibility for the driver at speeds above 50 km/h. Moreover, Fig. 7 shows the S_{ed} values on the driver's lower back with Hump7 for three different vehicle categories: $TCD_{7,1}$, $TCD_{7,2}$, and $TCD_{7,3}$. It is clear that this hump has the least effect among all the humps in terms of its effect on health. Only small passenger vehicles ($TCD_{7,1}$) exceed the $\underline{S_e}$ limit at speeds above 35 km/h and the $\overline{S_e}$ limit at speeds above 70 km/h. Meanwhile, for the sport utility and the medium passenger vehicles ($TCD_{7,3}$ and $TCD_{7,4}$), the stresses S_{ed} exceed the $\underline{S_e}$ at speeds above 60 km/h and the $\overline{S_e}$ at speeds above 70 km/h.

In summary, Figs. 6 and 7 show that the drivers for both sport utility and medium passenger vehicles have lower chances of having a health problem, such as LBP, compared to the drivers of small utility vehicles. This is due to the ability of the suspension system and the seat cushion in both vehicles to absorb shocks. Finally, it is shown that, based on either the BS 6841 [17] or the ISO/DIS 2631-5 [18] standards, for all three different vehicles, Hump4 has the most severe effect on human health, while Hump7 has the least effect.

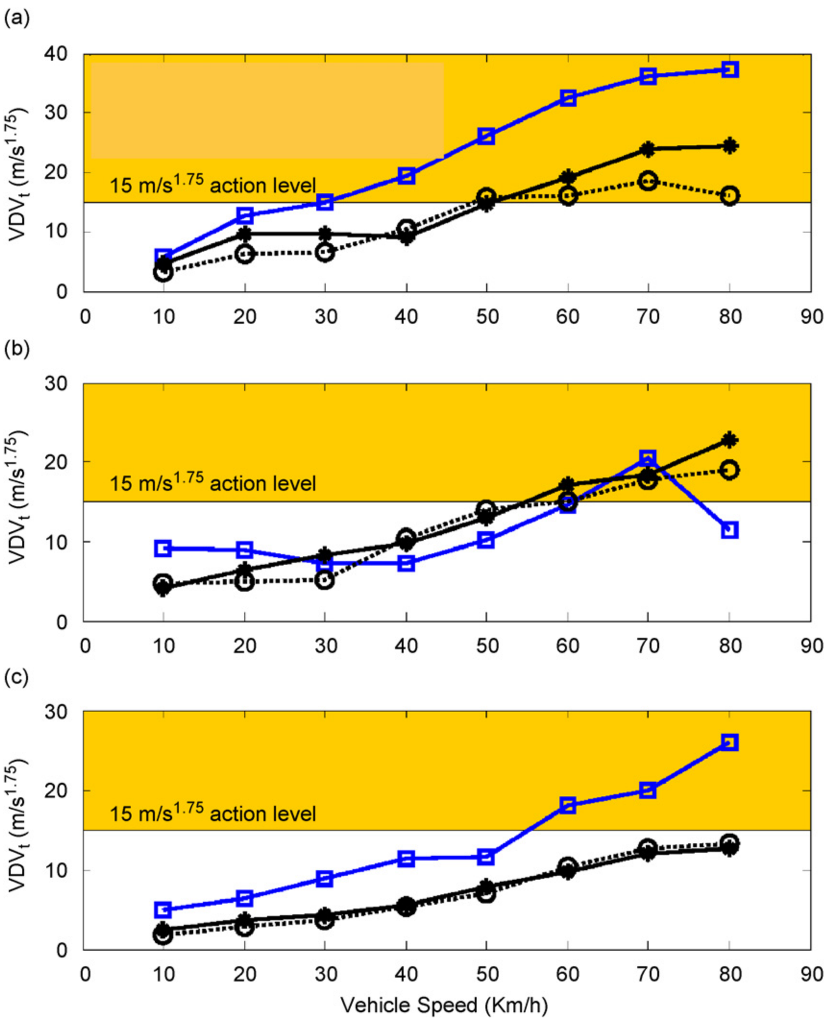


Fig. 6. Comparison of VDV_t at the driver's seat for different types of vehicles according to BS 6841 [17] for 32 humps/day while crossing different SCHs. (a) Hump4, (b) Hump6, (d) Hump7. –□– Small passenger vehicle, –○– sport utility vehicle, –*– medium passenger vehicle.

4.3. Effect of seat location

Seat location plays a critical role in the amount of shocks introduced to vehicle occupants. This happens due to the rotational motion of the vehicle when crossing the speed hump, which increases the amount of shocks to the rear passenger compared to the front seated one (see the Hanbook by Cebon [31]). For people riding public buses, Weber and Braaksma [29] suggested that it is important to consider the rear-seated passenger in the design of SCHs. Also, another study by Giacomin [32] showed the measurements of the vibration level in the child seat at different vehicle positions (front and rear seats). He observed that the vibration level measured at the interface between the children and their rear seats are higher than the vibration level of the front seat. Therefore, it is concluded from both studies that seat location will affect the amount of mechanical shocks level while crossing SCHs. The sport utility vehicle will be used for testing since it has a long base (from the front to the rear tires) and can clearly show the effect of seat position on the amount of the shocks introduced while crossing SCHs. Fig. 8 illustrates the top view of the location of the rear and front seats in the sport utility vehicle. Note that according to Table 2, the front seat is represented by measurement condition 3 and the rear seat is represented by measurement condition 4.

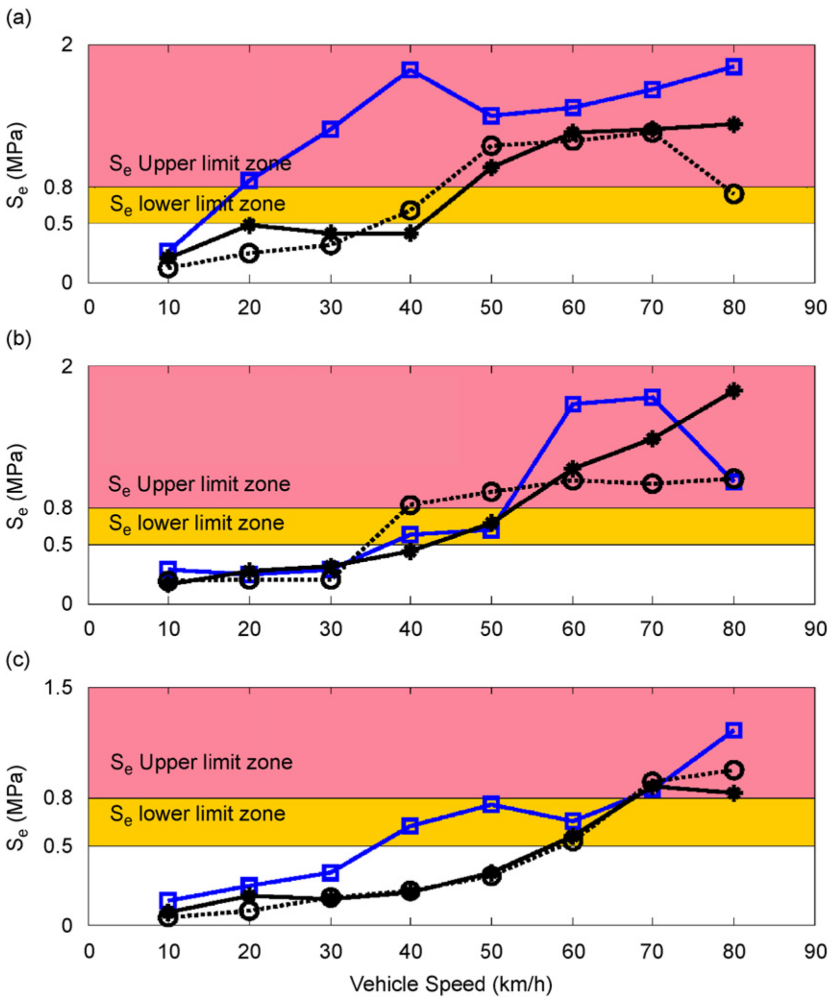


Fig. 7. Comparison of S_e at the driver's seat for different types of vehicles according to the ISO/DIS 2631-5 [18] for 32 humps/day while crossing different SCHs. (a) Hump4, (b) Hump6, (d) Hump7. –□– Small passenger vehicle, –○– sport utility vehicle, –*– medium passenger vehicle.

Fig. 9 shows the effect of seat position with different types of SCHs at different speeds for 32 hump crossings per day. The testing conditions for this figure are represented by $TCD_{H,V}$ where $H = \{4, 6, 7\}$ and $V = \{3, 4\}$. For Hump4 in Fig. 9, the VDV_t values for the rear-seated passenger exceed the $15\,m/s^{1.75}$ action level at speeds equal to and greater than 30 km/h. For example, the VDV_t at 40 km/h for the rear-seated passenger is equal to $90\,m/s^{1.75}$, which means that there is a high risk of harming the lower back of the passengers. In contrast, the front-seated driver will have a low probability of having a LBP for this testing condition. Moreover, the VDV_t for the front seated passenger surpasses the $\overline{VDV}$ at 60 km/h for Hump4. The same discussion is applied for Hump6 with $TCD_{6,4}$, as shown in Fig. 9. Also, for Hump7, the VDV_t values recorded at the rear seat exceed the $15\,m/s^{1.75}$ action limit at speeds above 60 km/h. In conclusion, Hump7 has the least probability of causing a LBP for both front and rear seated passenger according to the BS 6481 standard.

Fig. 10 shows the analysis of the experimental data based on the ISO/DIS 2631-5 [18] for 32 humps crossings per day. This figure illustrates that when crossing Hump4, the amount of static stress S_e exceeds the $\underline{S_e}$ at 25 km/h and the $\overline{S_e}$ at 32 km/h for the rear seated passenger. In addition, the amount of S_e reaches very high values, such as in the case of the 50 km/h test where the static stress is equal to 4.5 MPa for Hump4. This high stress on the lumber spine demonstrates the increased possibility of hazards on human health. For the

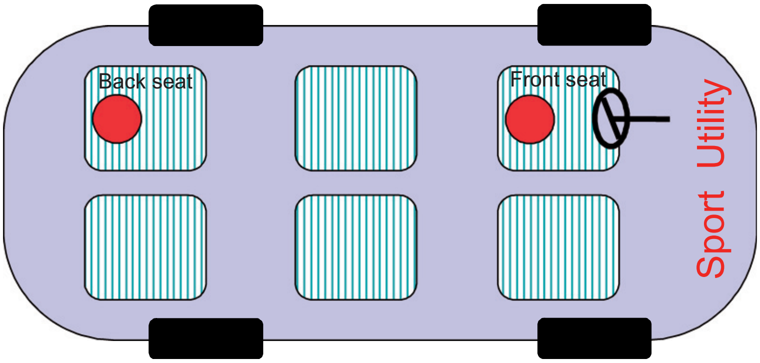


Fig. 8. Top view for different seat positions in the sport utility vehicle.

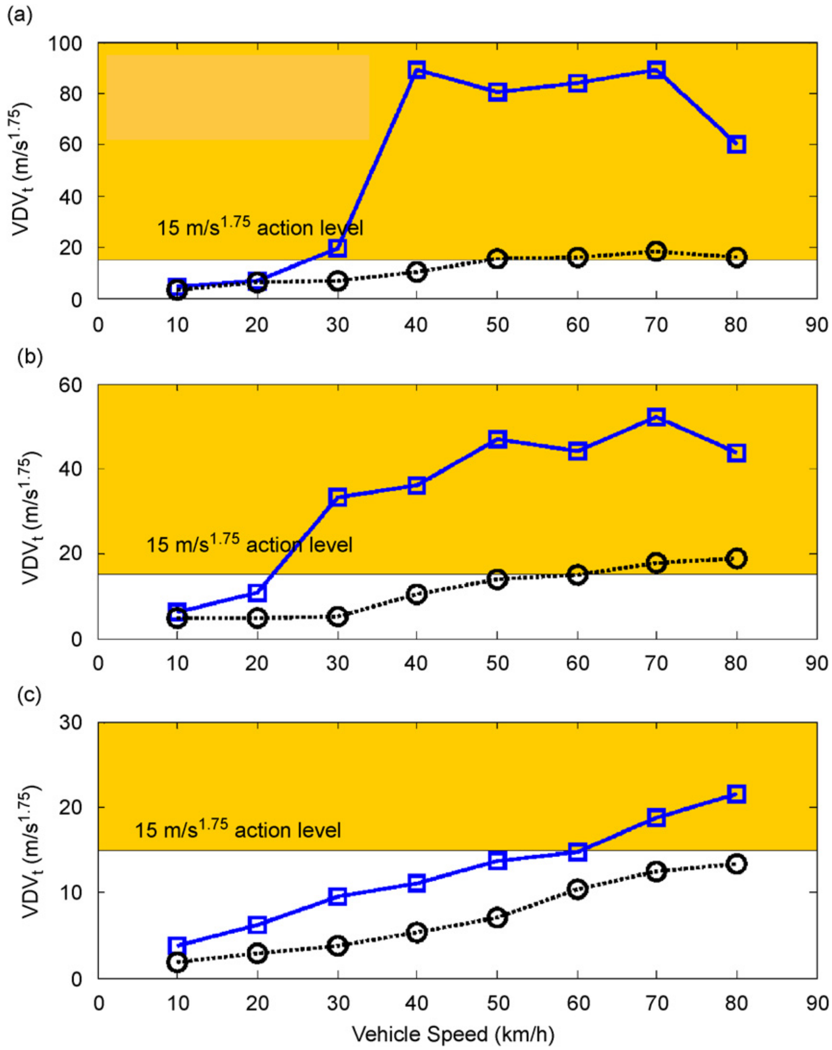


Fig. 9. Comparison of VDV$_t$ at different seat positions for the sport utility vehicle according to BS 6841 [17] for 32 humps/day while crossing different SCHs. (a) Hump4, (b) Hump6, (d) Hump7. –□– Back seat, –○–front seat.

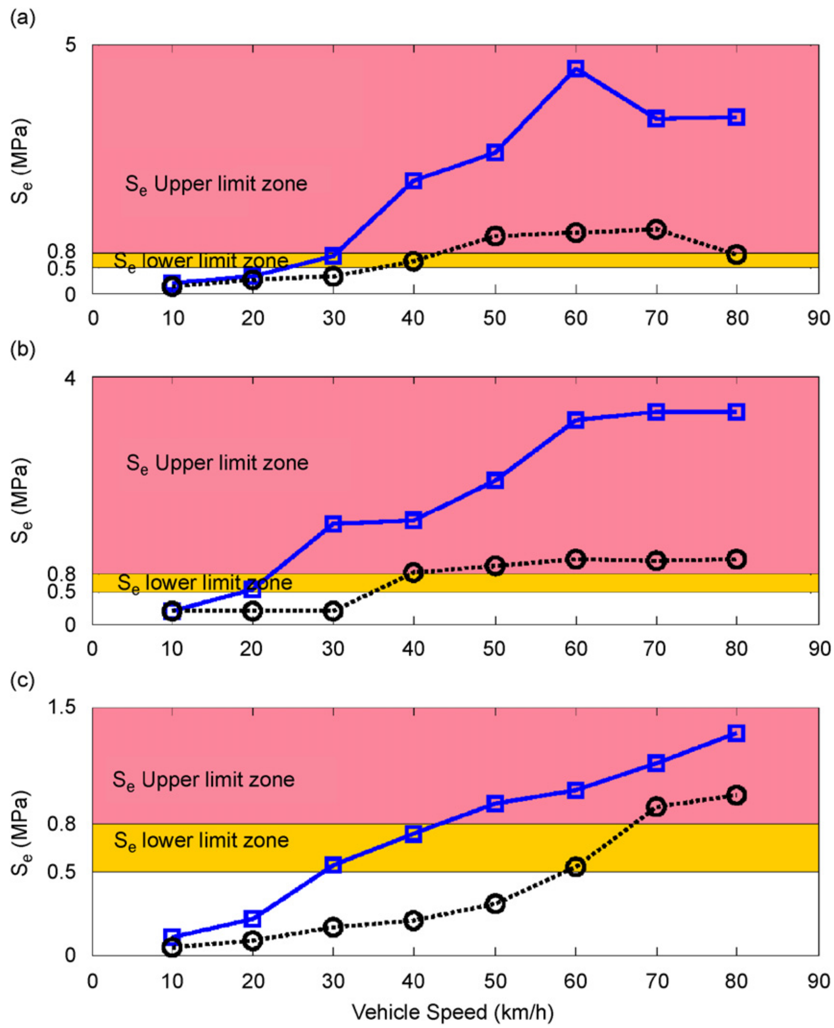


Fig. 10. Comparison of VDV_r at different seat positions for the sport utility vehicle according to ISO/DIS 2631-5 [18] for 32 humps/day while crossing different SCHs. (a) Hump4, (b) Hump6, (d) Hump7. –□– Back seat, –○–front seat.

driver seat, the S_e values will pass the $\underline{S_e}$ at 40 km/h and surpass the $\overline{S_e}$ at 45 km/h for Hump4. Moreover, Fig. 10 shows that Hump7 has great performance for reducing possible health risks on the rear seated passenger, since the S_e values will exceed the $\underline{S_e}$ limit at 60 km/h and the $\overline{S_e}$ at 70 km/h. Therefore, both standards demonstrate that Hump7 has great performance in minimizing the health risk on the rear seated passenger, which is usually at a higher health risk than the front seated passenger. A coincidental finding indicates that a low possibility of a health risk will occur at speeds close to 60 km/h, the same speed as the design criteria for the CC that was used in the work by Khorshid and Alfares [19] to find the optimal geometric design of this hump.

4.4. Predicting the number of shocks for possible health risks

It is important to find the number of crossed humps per day (N) that might cause health risks to vehicles' occupants. The procedure for finding these numbers starts by fixing the vehicle speed, hump type, vehicle type and seat location. Then, the number of humps to reach the "action level" of 15 m/s$^{1.75}$, as specified in BS 6841

[17], can be calculated as

$$N_{15} = \left(\frac{15}{\mathrm{VDV}_t}\right)^4, \tag{7}$$

where N_{15} is the number of humps to reach a VDV of $15\,\mathrm{m/s^{1.75}}$ and VDV_t is the total VDV measured for a specific test condition.

Furthermore, the number of crossed humps required to reach the upper stress limit zone of 0.8 MPa, as specified in the ISO/DIS 2631-5 [18], can be calculated as

$$N_{0.8} = \left(\frac{0.8}{S_e}\right)^6, \tag{8}$$

where $N_{0.8}$ is the number of humps required to reach a static stress of 0.8 MPa and S_e is the equivalent static compression stress calculated from the measured values. The reason for selecting the upper limit zone ($\overline{S_e}$) is because it represents a high probability of an adverse health effect from shock exposure introduced by crossing SCHs.

4.4.1. *Effect of vehicle speed*

The calculated values of N_{15} and $N_{0.8}$ using both standards are listed in Table 3 for different test conditions at different speeds. From this table, it is clear that as the vehicle speed increases, the number of hump crossings to reach the risk zone decreases. In general, this fact applies for all humps and all vehicle categories with a slight variation due to experimental errors. For example, consider a driver seated in small passenger vehicle crossing Hump7 at 20 km/h; according to the BS 6841, 1003 crossings are required to have a possible risk on the driver's health. On the other hand, with the same conditions but increasing the speed to 70 km/h, it takes 10 humps crossings to have a possible risk on the driver's health.

4.4.2. *Effect of hump type*

In this section, the discussion is based on the effect of the SCH type on the value of N, according to both evaluation standards. As shown in Table 3, for drivers using either the medium passenger or the sport utility vehicles, Hump4 has the least N_{15} and $N_{0.8}$ values compared to the other humps. This reflects the finding that SCHs with high raised profiles (or height), equal to 15 cm in this case, will introduce a large amount of shocks, which might put the driver's health at risk according to both BS 6841 [17] and ISO/DIS 2631-5 [18] standards. On the other hand, Hump7 has the largest numbers for N_{15} and $N_{0.8}$ which demonstrate that this hump has the least harmful effect on human health.

4.4.3. *Effect of vehicle type*

According to Table 3, the effect of different vehicle variations (driver's seats) on the predicted values of N_{15} and $N_{0.8}$ is demonstrated. The sport utility vehicle has the highest numbers for N_{15} and $N_{0.8}$, compared to medium and small passenger vehicles. This happens mainly due to the ability of both the seat and suspension systems to absorb shocks from SCHs. On the other hand, the small passenger vehicle has the lowest numbers because of the poor performance of both the seat and the suspension systems in absorbing shocks from SCHs.

4.4.4. *Effect of seat position*

For the sport utility vehicle, the effect of seat position on the values of N_{15} and $N_{0.8}$ is shown in the last four rows of Table 3. For all three humps and both evaluation standards, it is clear that the rear seats have much lower values of N_{15} and $N_{0.8}$ than the front seats. This means that the rear seated passenger has a greater health risk compared to the front seated driver. At velocities equal to 40 km/h and above, only one hump crossing can introduce shocks to the rear seated person which could present possible health risks. Therefore, people with LBPs should avoid the rear seats as much as they can in order to avoid worsening their LBP.

Table 3
Number of hump crossing per day to reach the action limit of 15 m/s$^{1.75}$ in the BS 6841 [17] standard and of an S_e equivalent to 0.8 MPa in the ISO/DIS 2631-5 [18] standard

Vehicle type	Standard method	Hump type	Vehicle speed (km/h)							
			10	20	30	40	50	60	70	80
Small passenger (driver's seat)	BS 6841	Hump4	1396	61	32	11	4	1	1	1
		Hump6	241	257	608	568	149	36	9	91
		Hump7	2794	1003	271	98	94	15	10	4
	ISO/DIS 2631-5	Hump4	29157	22	2	1	1	1	1	1
		Hump6	16759	40782	18114	218	154	1	1	8
		Hump7	630170	38120	7026	141	46	108	22	2
Medium passenger (driver's seat)	BS 6841	Hump4	3659	196	179	248	34	12	5	4
		Hump6	5681	941	338	174	58	19	14	6
		Hump7	47670	8310	5370	1711	458	187	77	66
	ISO/DIS 2631-5	Hump4	126583	677	1686	1818	10	2	2	2
		Hump6	452601	21853	8023	1197	89	4	1	1
		Hump7	49856 707	236927	407799	108715	6270	294	19	26
Sport utility (driver's seat)	BS 6841	Hump4	18020	1033	801	139	27	24	14	24
		Hump6	3380	2931	2361	137	42	32	16	13
		Hump7	137995	25447	8385	1988	661	140	66	52
	ISO/DIS 2631-5	Hump4	2559 784	43113	8104	165	4	3	2	49
		Hump6	161571	133524	103780	28	13	7	8	6
		Hump7	619 493 202	20905 362	375176	93721	10160	389	16	10
Sport utility (rear seat)	BS 6841	Hump4	4046	794	11	1	1	1	1	1
		Hump6	1137	128	1	1	1	1	1	1
		Hump7	8863	1166	195	107	46	34	13	8
	ISO/DIS 2631-5	Hump4	144786	6230	58	1	1	1	1	1
		Hump6	125246	304	1	1	1	1	1	1
		Hump7	5293 028	72112	322	55	14	8	3	1

4.4.5. Effect of evaluation methods

Table 3 shows that using two different methods will yield two different values for the number of hump crossings that may cause a health risk. In general, most of the test conditions in Table 3 show that $N_{0.8}$ is higher than N_{15}. This means that the ISO/DIS 2631-5 [18] is less conservative than the BS 6841 [17] in predicting possible health risks. For example, comparing both evaluation methods for the driver of the sport utility vehicle at all speed ranges from 10 to 80 km/h shows that the ISO/DIS 2631-5 has a larger N than the BS 6841.

Fig. 11 presents the effects of vehicle type, seat position, hump type (Humps 4, 6 and 7) and evaluation method as a function of the CS. It is evident that the CS of Hump4 is 45 km/h, the CS of Hump6 is 35 km/h, and the CS of Hump7 is 60 km/h. The y-axis represents the limiting number of humps for a possible health risk. According to Fig. 11, above a unit factor of the CS (CS$_f$), the number of hump crossings is decreased for all humps. Moreover, a front seated passenger in small vehicle and rear seated passenger in sport utility vehicle are both exposed to a high risk when crossing the speed hump above the speed limit, i.e. at values higher than a CS$_f$ of 1. For the front seated passenger or driver, Fig. 11 shows that above a CS$_f$ of one, there are still several hump crossings required before risking the passenger's health. In fact, this is needed for any speed hump design. In addition, all the cases in Fig. 11 below the unity CS$_f$ require a large number of hump crossings per day before causing a possible health risk. The only exception is the rear-seated passenger in the sport utility vehicle when crossing Hump4. Finally, Fig. 11 can be used to demonstrate when drivers or passengers may have valid complaints against the public authority that the speed hump did cause severe pain or damage to their lower backs. It is clear that introducing a possible health risk while crossing a speed hump depends on many factors such as car type, seat position, hump geometry, speed, number of hump crossings per day, and the evaluation method.

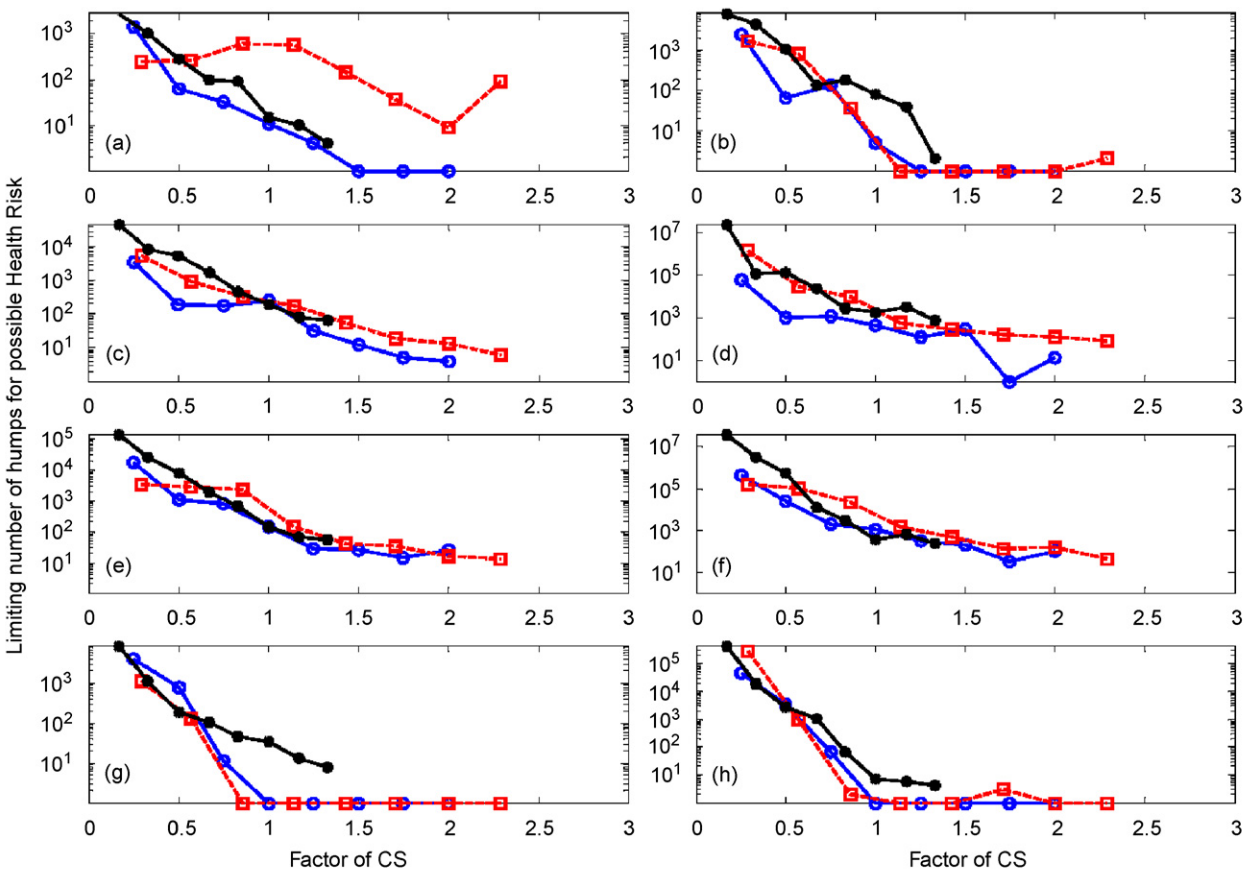


Fig. 11. The relation between the multiplications of the designed CS versus the limiting number of humps for: (a) small passenger vehicle with BS 6841; (b) small passenger vehicle with ISO/DIS 2631-5; (c) medium passenger vehicle with BS 6841; (d) medium passenger vehicle with ISO/DIS 2631-5; (e) sport utility (Front passenger) vehicle with BS 6841; (f) sport utility vehicle (front passenger) with ISO/DIS 2631-5; (g) sport utility (rear passenger) vehicle with BS 6841; (h) SPORT utility vehicle (rear passenger) with ISO/DIS 2631-5. –○– Hump4, –□– Hump6, –*– Hump7.

5. Conclusions

This study was performed to evaluate the ergonomic hazards associated with crossing different geometry SCHs. Whole-body vibration measurements and health risk assessments were carried out using the measurements and health risk procedures outlined in the BS 6841 [17] and the ISO/DIS 2631-5 [18] standards. The following conclusions were drawn from the study:

- The amount of shock that might harm the health of vehicle occupants depends on the vehicle speed, hump geometry, vehicle type, position of occupants in the vehicles, and evaluation method. The whole-body vibration of the driver's seat for three vehicle categories is affected greatly by hump geometry, especially the hump height. As the height increases, the health risk increases. The rear-seated passenger is also at high health risk, compared to the front-seated driver. Vehicles with good suspension-seat systems can reduce possible health risks when crossing SCHs.
- Some of the tested SCHs introduced mechanical shocks to vehicle occupants beyond the health-risk zone at speeds below the specified speed limit, or CS. This means that even though the driver obeys the speed limit, there is a probability of health risks for the vehicle's occupants. Further experimental investigations are needed to confirm these findings.

- It is clear that vehicle occupants are exposed to serious shock magnitudes when crossing SCHs at high speeds. Therefore, a new awareness campaign should be launched by the public authority to demonstrate the health risks that vehicle occupants might be exposed to by these repetitive hazardous situations (when violating speed limits while crossing SCHs).
- Construction companies or the public authority that are responsible for installing these humps on roads should follow the recommended dimensions precisely.
- The current study is directed towards future research in redesigning, and perhaps even removing, old SCH designs. Also, it is important to include human factors in the design of any new SCHs.
- The polynomial hump type (Hump7) can be labeled as an *Ergonomic* hump since it produces low levels of shocks to the driver, and therefore has the minimum health risk according to the BS 6841 standard. This observation is also true according to most of the test conditions which were analyzed based on the ISO/DIS 2631-5 standard. In addition to the case of the seated driver, Hump7 introduces the lowest shock to the rear-seated occupant among all the tested humps.
- Some agreement between both standards for predicting the number of humps that must be crossed to cause possible health risks was found. On the other hand, there was a significant variation in predicting these numbers for other test conditions. In summary, the ISO/DIS 2631-5 provides a lower assessment of the amount of shocks harmful to human health compared to the BS 6841.

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