Comparison of Speed Control Bumps and Humps according to Whole-Body Vibration Exposure

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Abstract: One of the easiest and most efficient ways to control vehicle speeds is to create undulations perpendicular to the axis of the road. The types of undulations especially used for speed management on urban road networks are called speed control bumps (SCBs) and speed control humps (SCHs) according to their width. In general, the undulation geometry is a very important factor in changing the shock levels to which passing vehicles are exposed, and accordingly, in reducing the vehicle speeds. This study compares SCBs and SCHs with regard to human health risks using the whole-body vibration (WBV) components (VDV, S_e, and R) to which vehicle drivers are exposed while passing over the undulations. Because SCBs and SCHs are usually preferred for use in urban road networks, experimental vibration measurements are conducted at 20, 30, 40, and 50 km/h vehicle speeds. In order to demonstrate the effects of different vehicle types, vibration measurements are repeated in the same driver and undulation geometries with sedan, hatchback, and station wagon vehicles for each measurement speed. The evaluations use standard evaluation methods which are frequently preferred in the world in WBV analysis. Using these methods, vehicle type and vehicle speed effects are reciprocally evaluated considering SCB and SCH geometries with equal heights. Use of the SCHs appears to be more suitable for human health in traffic speed management. **DOI: 10.1061/JTEPBS.0000177.** *© 2018 American Society of Civil Engineers.*

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Introduction

Speed is the cause of about one of three fatal accidents and also is an important factor determining the severity of all accidents. Whereas the mortality risk of pedestrians in accidents at 50 km/h is 80%, it is 10% at 30 km/h, according to the World Health Organization (WHO) (OECD 2006). Over the years, a variety of techniques has been developed by traffic engineers to mitigate the undesirable consequences of speed, particularly on urban roads. Some of these methods are warning and stop signs, traffic or vehicle restrictions, diagonal diverters, lane channelization, road chokers, traffic control with electronic detectors, rumble strips, and speed control undulations (SCUs). These methods have unique benefits such as diversion of traffic, increasing driving safety, and enabling pedestrian access while reducing the traffic speed.

SCUs are often preferred by local authorities because they are both economical and highly effective in reducing speed with respect to traffic calming. SCUs are called speed control bumps (SCBs), speed control humps (SCHs), speed control tables (SCTs), and speed control cushions (SCCs) depending on their size and section geometries. SCTs and SCCs are types of SCHs that are designed in unstable sections to fulfill special purposes such as maintaining traffic lane tracking and enabling pedestrian access. Frequently preferred in traffic management, SCBs and SCHs are designed to have constant cross sections along the platform width of the road. Despite the changed height, SCBs are narrow and somewhat abrupt (0.30–1-m base width), whereas SCHs are wide and relatively gradual (over 1-m base width) and have a sinusoidal, circular, or parabolic vertical profile in the direction of driving (Chadda and Cross 1985; Cottrell et al. 2006; Parkhill et al. 2007).

Particularly in countries in which the legal framework for implementing technical specifications is not strong, SCUs preferred for traffic calming by local authorities can be used without conducting any systematic analysis of their actual advantages and disadvantages. This causes erroneous and unnecessary uses. Widely used all around the world, this technique somehow is seen as a panacea that can be used in solving all speed-related problems (Pau and Angius 2001).

Although it is possible to avoid many of the drawbacks of SCU applications through proper site selection and appropriate traffic management projects, drivers and passengers are exposed to high amounts of vibration as they pass over SCUs. Whole-body vibration (WBV) exposure inside vehicles during transportation adversely affects drivers and passengers, particularly in terms of comfort, human health, and safety. Well-known adverse effects of WBV on the human body are gastrointestinal tract problems, spinal degeneration, lower-back pain, autonomic nervous system dysfunction, neck problems, and headaches (Eger et al. 2008). Twelve percent of transport, storage, and communication sectors and fourteen percent of wholesale and retail trade, repair of motor vehicles, motorcycles, and personal and household goods sectors are subject to a threat regarding the negative effects of vibration (Bovenzi 2005).

The vehicle and the driver (and passengers) are exposed to a front-to-back pitching acceleration that increases as the speed increases while passing over the SCUs. Employees of various professional groups (taxis, public transport, cargo couriers, and so on) are exposed to these whole-body mechanical vibrations and shocks quite often in vehicles during the day. In the literature, studies on human health considerations of high amounts of vibrations are quite limited. Watts (1973), the pioneer of SCU comparison, compared SCHs of different size, lengths, and heights in many respects. Watts evaluated comfort by measuring vibrations of vehicles exposures and by ride-evaluation questionnaires; feelings of discomfort started after a height of 5 cm for SCUs and a driving speed of

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24 km/h for passenger cars. Khorshid et al. (2007) conducted experimental research to evaluate the health risks associated with SCHs with different geometries. They found vibrations to which the driver was subjected when passing over SCUs of different geometries using passenger car–type vehicles. For vibration analysis to evaluate human health effects, they used the standards BS 6841 (BSI 1987) and ISO 2631-5. As a result of their study, they proposed an ergonomic SCH cross section. Bjarnason (2004) compared the vibrations to which the vehicle is exposed when passing over SCUs of different heights with smooth (SCT) and round (SCH) surfaces. The study determined that there was a sudden increase in vibrations when vehicles were driven at speeds above 30 km/h. Comparing SCTs and SCHs in terms of vibration exposures, SCTs were found to be more advantageous (Bjarnason 2004).

For different types of vehicles, comfort evaluations made on SCUs with different profiles show that after about 2 cm in height, the feeling of discomfort occurs (Watts 1973). Studies have shown that heavy vehicles are more adversely affected in terms of comfort than are passenger cars when passing over SCUs (Watts 1973; Weber and Braaksma 2000). As the size and weight of the traveling vehicle increases, the feeling of discomfort is much greater (Watts 1973). Particularly, articulated lorry vehicles are adversely affected by SCUs of almost every type and dimension (Watts 1973). On the other hand, Patel and Vasudevan (2016), evaluating SCUs for bicyclists (motorized and nonmotorized), found that passages over SCTs are significantly more comfortable than passages over SCHs. They suggested that SCHs should not be preferred when there are more bicycles than motorcycles in traffic.

The literature includes theoretical studies that optimize the SCU cross sections, assuming that the strength of the force exerted over the vehicle depends on the geometric designs and profile shapes of the SCUs. For optimization, vehicles often are modeled as quarter or half cars and the solutions use optimization (e.g., linear or sequential quadratic programming) or simulation techniques (e.g., simulink). Many studies have evaluated the dynamic response of vehicles by determining comfort criteria (CC) between 0.6 and 0.9g in polynomial or circular geometries (Aghazadeh et al. 2006; Fwa and Liaw 1992; Pedersen 1998; Khorshid and Alfares 2004; Salau et al. 2004; Ansari Ardeh et al. 2008; Kanjanavapastit and Thitinaruemit 2013; Molan and Kordani 2014). In general, it is understood that the SCH cross sections suggested by Watts fit the ergonomic constraints (Watts 1973).

According to Newton's law of motion, if the mass is assumed to be constant, the force acting on the mass increases as momentum increases. In this case, in a situation such as a vehicle passing over an SCU, a large amount of force is generated in mechanics as a result of instantaneous momentum, which is also called shock. The literature includes epidemiological studies investigating the effects of shocks on the human body. As a result of shock, lower back problems frequently occur in the human body. It is known that drivers or passengers often experience acute lower back problems that also lead to chronic back problems resulting from exposure to shocks while sitting or standing. In addition, in terms of severity, studies show that shock effects cause severe spinal injuries and also lesions in the form of fractures of vertebrae (Bowrey et al. 1996; Teschke et al. 1999; Turner and Griffin 1999; Zhao and Schindler 2014).

An 8-cm-high SCU was used for the first time in 1970 in Delft for the purpose of traffic calming (Cottrell et al. 2006). Ever since their first use, there have been ongoing investigation to determine to what extent SCUs reduce the speed of vehicles. Studies in the literature include before-and-after evaluations using the 85th percentile speed as a criterion to assess the efficiency of SCUs. In general, the studies show that as the height increases, the efficiency of traffic calming increases. Especially at heights over 5 cm, the speed has been found to decrease at a remarkable rate of 30% and above (Pau and Angius 2001; Pau 2002; Cottrell et al. 2006; Leden et al. 2006; Namee and Witchayangkoon 2011; Antić et al. 2013).

At the same time, speed is known to have adverse effects on the environment and energy consumption. There are also studies evaluating the benefits of energy efficiency and lessening of environmental problems resulting from SCU traffic calming through various strategies. In this context, among some of the issues evaluated are the effects of SCUs on traffic noise and the reduction of environmental damage with existing emission models. Contrary to general assumptions, studies have demonstrated that SCUs do not increase traffic noise during acceleration of vehicles (Abbott et al. 1995; Plowden and Hillman 1996; Kokowski and Makarewicz 2006; Ahn and Rakha 2009; Ventsislavova et al. 2016).

Intrinsically, SCBs cause security problems encountered during overspeed passages. It is known that higher SCBs are quite dangerous, especially during the passage of vehicles with low heights above ground. For this reason, higher SCBs are recommended for use only on private roads and in parking lots, where traffic speed is low and under control (Pau 2002; Parkhill et al. 2007). On the other hand, it is known that, especially in developing countries, SCBs are used incorrectly on streets, avenues, and even highways. It is unknown to what extent drivers and passengers are affected adversely by the vibrations to which they are exposed in vehicles due to the improper use of SCBs. This study comparatively evaluates SCBs and SCHs in terms of their harmful effects on human health and the body. Approximately 74% of all vehicles in the world are passenger cars (Statista 2017). Therefore, this study used passenger cars as the preferred type of vehicle for evaluation. Hence, a contribution is made to the existing literature in which only a limited number of studies on the subject exist.

Vibration Evaluation and Standard

While driving, drivers and passengers are exposed to vibrations at four different points: seat surface, seat back, knee–console space, and steering wheel. Numerous studies have been carried out on the subject in order to characterize or to specify a proper evaluation criterion regarding these vibrations (Kim et al. 2011). It is possible to consider human response to WBV involving five different effects: degraded comfort, interference with activities, impaired health, perception of low-magnitude vibration, and occurrence of motion sickness (Griffin 2012). WBVs are defined as the vibration perceived by an individual as a result of direct contact with vibrating surfaces. Therefore, in this study an accelerometer was placed in a rubber housing disc under the driver to make the most accurate quantitative measurement of whole-body vibrations on the human body, in accordance with ISO 2631 and EN ISO 8041 standards (ISO 2005). Measurements were conducted using a vibration measurement set comprising vertical accelerometers designed for the measurement of vibration (± 4 g, sensitivity 500 ± 15 mV/g), a GPS antenna (<15 m accuracy), and a data logger to record the vibration values in the vertical direction of the SCUs.

Vibration and shock measurements were analyzed in accordance with the procedures described in ISO 2631-1 and ISO 2631-5 (ISO 1997, 2004). These methods were used to evaluate the effects of SCU geometry, vehicle type, and vehicle speed.

ISO 2631-1 Standard

IS0 2631 (ISO 1997) defines crest factor as the modulus of the ratio of the maximum instantaneous peak value of the frequency-weighted acceleration signal to its root-mean square (RMS) value. If one crest factor value of vibration measurements is above 9, the

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fourth-power vibration dose method (VDV) should be considered when predicting health risks, particularly. The VDV is robust and takes into account the duration of the measurement period. It is sensitive to peaks in the vibration because human beings are very sensitive to the peaks (shocks) (Griffin 2007). VDV assessment is made on the fourth power of acceleration measurements instead of the second power at a given time interval. The unit of VDV component is $\mathrm{m/s^{1.75}}$, and is calculated as

$$\mathrm{VDV} = \left\{ \int_0^T [a_w(t)]^4 dt \right\}^{\frac{1}{4}} \tag{1}$$

where $a_w(t)$ = instantaneous frequency-weighted acceleration; and T = duration of measurement. When the vibration exposure consists of more than one time interval (i) of different magnitudes, the VDV for total exposure should be calculated as

$$\mathrm{VDV_{total}} = \left(\sum\nolimits_{\mathrm{i}} \mathrm{VDV_i^4}\right)^{\frac{1}{4}} \tag{2}$$

Table 1 lists ISO 2631-1 standard specifications of any time in the range of vibration exposure for which human health may be adversely affected (Bhattacharya and McGlothlin 1996).

ISO 2631-5 Standard

ISO 2631-1 addresses vibration analysis of persons on the vehicle seat subjected to mechanical shocks. Mechanical shocks cause adverse health effects in the lumbar spine. When calculating the lumbar spine response, this standard assumes that the person subjected to vibration is sitting upright and does not voluntarily rise from the seat during the exposure (ISO 2004). The spinal response is approximately linear in the x- and y-directions and nonlinear in the z-direction. In the z-direction, nonlinearity is expressed using a recurrent neural network model. The acceleration dose, D_k (in the k direction) that affects the spinal response is defined as

$$D_k = \left[\sum\nolimits_i A_{ik}^6\right]^{1/6} \tag{3}$$

where $A_{ik} = i$th peak of the response acceleration of k direction; and $k = x$-, y-, or z-direction. The acceleration peaks can be counted in the positive and negative directions in the x- and y-directions, but only in the positive direction in the z-direction because the compression of the spine is more concerned with the severity of exposure. The biomechanical model generated by the Palmgren-Miner approach has found that the factors affecting mechanical shock are the number and magnitudes of peak compression in the spine of a healthy person (ISO 2004). With these assumptions, an equivalent static compressive tension, S_e, is calculated as

$$S_e = \left[\sum\nolimits_{k=x,y,z} (m_k D_k)^6\right]^{1/6} \tag{4}$$

where D_k = dose of acceleration in the k direction. The recommended value of the m_k in the z-direction is $m_z = 0.032\ \mathrm{MPa/(m/s^2)}$. The daily equivalent static compression dose is S_{ed}, and D_k calculated as daily exposure is D_{kd}. According to the standard, $S_{ed} \leq 0.5$ MPa is a low probability, 0.5 MPa $< S_{ed} < 0.8$ MPa is a moderate probability, and $S_{ed} \geq 0.8$ is a high probability of an adverse health effect. It is assumed that S_{ed} is subject to vibration exposure for 240 days/year. The R factor is used to evaluate the human response dose of acceleration alongside the response of the spine

$$R = \left[\sum_{i=1}^{n} \left(\frac{S_{ed}.N^{1/6}}{S_{ui} - c}\right)^6\right]^{1/6}, \qquad S_{ui} = 6.75 - 0.066(b + i) \tag{5}$$

where N = number of exposure days per year; i = year; n = number of years of exposure; c = constant representing the static stress due to gravitational force; S_{ui} = ultimate strength of the lumbar spine for a person of age $(b + i)$ years; and b = age at which the exposure starts. According to the standard, $R \leq 0.8$ is a low probability, $0.8 < R < 1.2$ is a moderate probability, and $R \geq 1.2$ is a high probability of an adverse health effect (ISO 2004).

Table 1. Human health exposure limits

VDV ($\mathrm{m/s^{1.75}}$)	Description
<8.5	Health risks have not been objectively observed
8.5—17	Caution with respect to health risks is indicated
>17	Health risks are likely

Field and Application Experience

SCU Profiles

Figs. 1 and 2 show the schematic illustrations and photographs of SCU profiles used to evaluate the differences between SCBs and SCHs in terms of human health. The most important factors in an SCU affecting driving comfort are thought to be peak acceleration, cognitive stimuli, and rate of change of acceleration. Although the vertical vibration increases greatly with the increase of the SCU height and speed, this height is a significant distinction because it is not perceived much by the drivers at heights above 76 mm

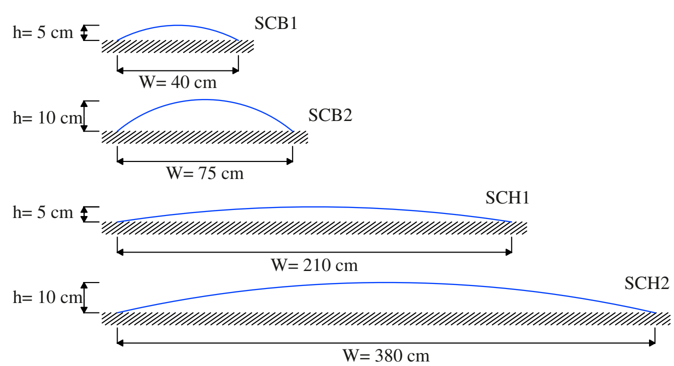

Fig. 1. Profiles of SCUs used.

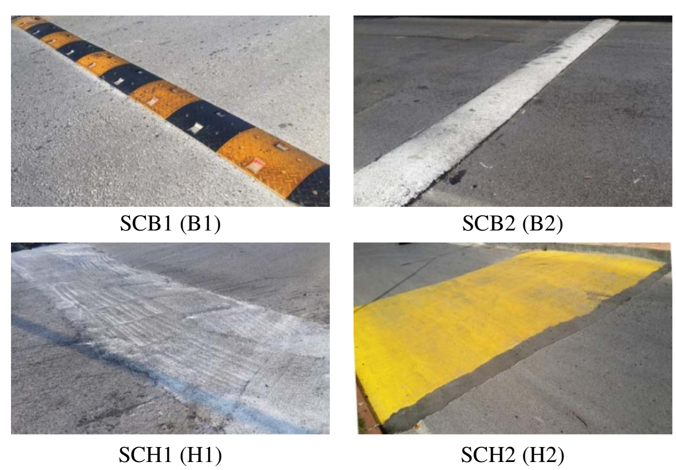

Fig. 2. Photos of SCUs used.

(Watts 1973). Therefore, heights of 5 and 10 cm were chosen to be above and below this value for measurements. Vibration measurements were repeated for both regions in order to evaluate the numerical balance of human relative comfort. All cross sections of the SCBs and SCHs used in this study were segments of a circle. Depending on this geometry, the widths of the SCUs used were different.

Studies show that in the selection of SCUs, two different parameters, CC and critical speed (CS), can be taken into consideration (Khorshid et al. 2007). The CS parameter indicates the acceptable speed limit at which the driver can pass over the SCU without losing control. The CC parameter indicates the maximum mechanical shock value to which the driver is exposed when passing over the SCU at a speed equal to or higher than CS. Experimental studies show that the acceptability value of CC for SCBs and SCHs is $0.6g$. Accordingly, CS is acceptable at ≤ 35 km/h for SCBs and 35 km/h $\leq$ CS $\leq$ 60 km/h for SCHs (Watts 1973; Khorshid et al. 2007). These criteria indicate that SCBs are not suitable for use in urban roads.

Experimental Procedure

This study identified the differences between SCBs and SCHs by assessing the effects of WBV on human health. The previous section explained the geometries of the SCUs selected for making that evaluation. After geometry, another important parameter is the speed of cars while passing over the SCU. In most countries, the speed limit is accepted as approximately 50 km/h in urban road networks for both security and efficient capacity use (OECD 2006). Experimental vibration measurements were made at vehicle speeds of 20, 30, 40, and 50 km/h, which drivers are assumed to use frequently during the day, because SCUs are preferred for use in urban road networks. Moreover, it was observed that during the fieldwork, the control of the vehicle was lost at speeds over 50 km/h with SCB2. Because the principle of evaluating all SCUs according to common vehicle types and speeds was taken into consideration, the other SCU sections were not measured at velocities above the measuring speed of 50 km/h. Studies show that drivers and passengers do not think differently about feeling the vibration (Watts 1973). Vibration measurements were made vertically on the driver's seat. The driver was 36 years old, 172 cm tall, and weighed 85 kg. All measurements were repeated with the same driver. Due attention was paid to ensure that the driver traveled as upright as possible, as recommended by the standards. On the other hand, the vehicle type is an important parameter that must be taken into account because the exposure to vibration during driving takes place in vehicles. In order to demonstrate the differences, the measurements were repeated with three different types of passenger cars: sedan (S), station wagon (SW), and hatchback (HB). It is known that the vibrations caused by the mechanical structure of vehicles have as strong an effect as road effects on the vibration exposure experienced in the vehicle. For this reason, care was taken to ensure that the vehicles used for measurement were well maintained and that their suspension systems had the same technology. Table 2 shows the factory technical specifications of the vehicles used for measurements.

Vibration data were collected for at least 3 s while passing over each SCU. Careful attention was paid to ensure that there were no obstacles to cause vibration of the vehicle in any way, apart from passing over the SCU.

Results and Discussions

For the four different SCUs with geometries explained in the previous section, vibration measurements on the driver's seat in the vertical direction were made with three different types of vehicles at speeds of 20, 30, 40, and 50 km/h, and the data were evaluated according to the ISO 2631 standard (ISO 1997, 2004). The effects of SCU geometry, vehicle type, and vibration evaluation method on the amount of mechanical shock encountered by the driver in the vehicle were considered comparatively. Actual vibration measurements were made at all speeds and all vehicle types over each SCU with different geometries. In other words, simulation techniques were not used to obtain vibration data. Measurements were repeated many times to eliminate factors indirectly affecting the vibration, such as the seating position of the driver (must be upright), the passage angle of the vehicle over the SCU (must be at a right angle), and so on. As evaluation data, the measurements closest to the ideal were used.

Table 2. Technical specifications of vehicles used

Vehicle	Weight (kg)	Axle distance (mm)	Length (mm)	Width (mm)
SW	950	2,441	4,388	1,636
S	1,096	2,625	4,480	1,715
HB	1,105	2,510	4,065	1,687

Relationships between SCU Profile, Vehicle Type, and Driving Speed

The effects of vibration on humans were evaluated using the VDV and S_e components described in the ISO 2631 standard, which is often used for this purpose. VDV and S_e components were obtained by reading the vibration data to which the drivers were exposed at different speeds of vehicles of different types over SCUs with 5- and 10-cm heights and circular geometry. Fig. 3 shows these components indicating the vibrations experienced by drivers in single passages of the vehicles over SCUs.

In general, the figure demonstrates that as the speed increased for each SCU geometry and type of vehicle, the vibration experienced by the driver increased. Even for a single pass over SCUs of the same height, the drivers were subjected to more vibrations from the SCBs than from the SCHs. There were small differences between values at the 5-cm height, but significant differences at the 10-cm height. Similar changes were seen in both components, S_e and VDV. According to ISO 2631, threshold values of 8.5 $m/s^{1.75}$ for VDV component and 0.5 MPa for S_e are accepted as having adverse effects on human health at moderate probability levels of vibration. It is understood that even at the highest acceptable speed, the driver sitting on the driver's seat is not exposed to any vibrations that could damage their body in any single pass over any SCU geometry with any vehicle type. On the other hand, it has been found during field research that as speed increases, control of vehicles is lost when passing over SCUs with a height of 10 cm, and that this case is much more evident in SCBs.

People traveling in vehicles on urban roads for home–work, home–school, and similar journeys have to cross over many SCUs during the day. This is a more serious case for the drivers of commercial taxis, public transport, cargo distributors, and so on. A similar comparison was made by calculating the vibration to which a human body would be exposed according to the approach of the ISO 2631 standard for 50 and 100 passes over SCUs during the day. In this case, the vibration components indicating daily exposure of the person were called S_{ed} and VDV_d. Fig. 4 shows the parametric representations of the vibrations to which the human body is exposed for 50 daily SCU passages. Although the threshold values were not attained for the SCBs or the SCHs at the 5-cm

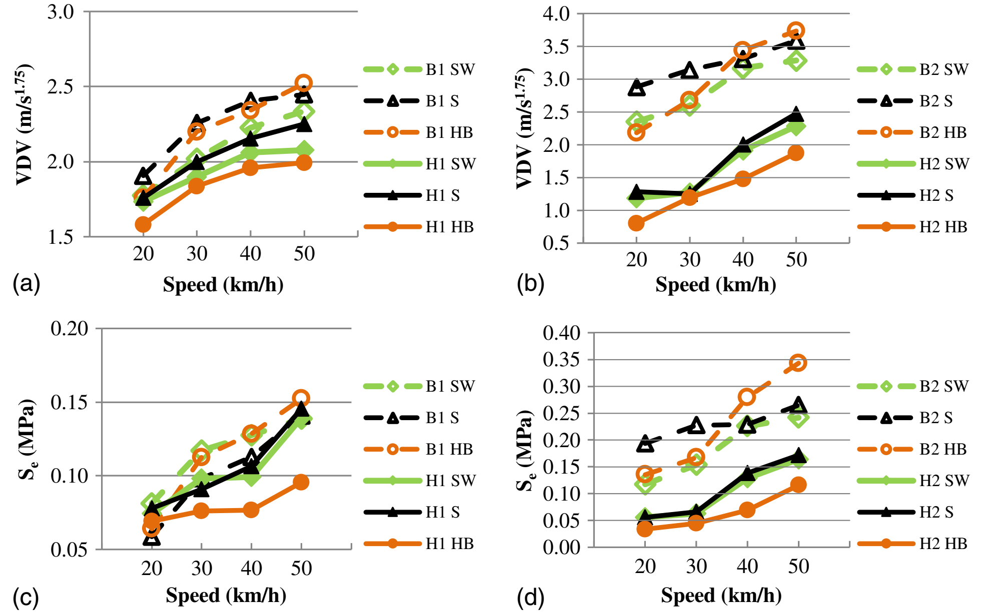

Fig. 3. Vibrations to which drivers are exposed in single pass of vehicles: (a and b) VDV for different vehicle types; and (c and d) S_e for different vehicle types.

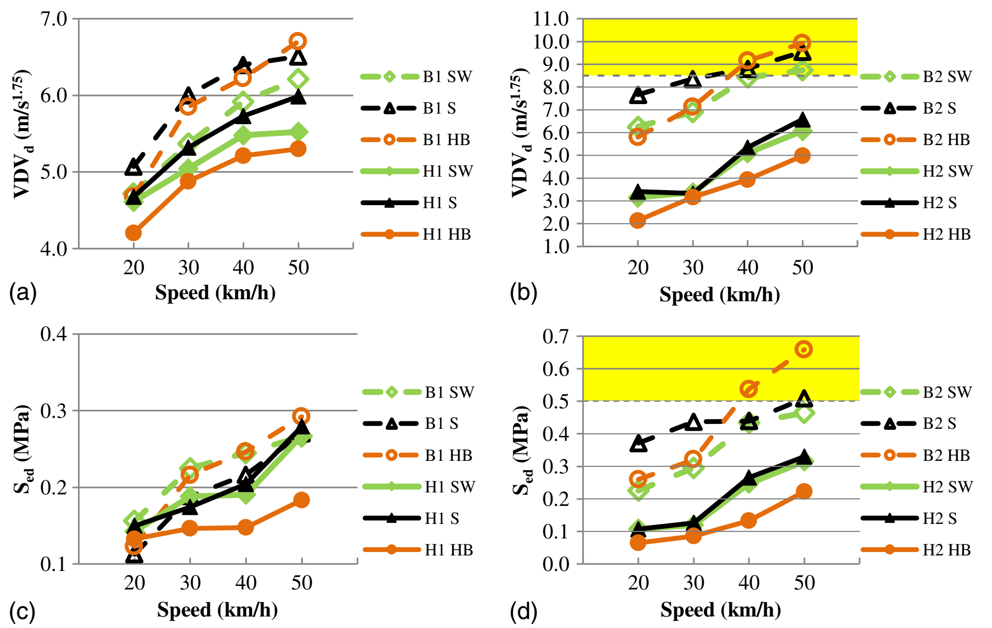

Fig. 4. Comparison for different type vehicles while crossing 50 SCUs/day of: (a and b) VDV$_d$; and (c and d) S_{ed}.

height, they were attained in all vehicle types at speeds of approximately 40 km/h and above for the SCsB at the 10-cm height for the VDV$_d$ component. The threshold values of the S_{ed} component were attained only with the HB-type vehicle. The S_{ed} component, which represents pressure strain on the spinal cord, is more conservative than the VDV$_d$ component, which can better indicate the shock effects to which the body is exposed.

Fig. 5 shows the components showing the vibration exposure of the human body at a 100 SCU/day passage of a vehicle. Similar to the 50 SCU/day passage, the thresholds were not attained with either SCBs or SCHs at the 5-cm height. At the 10-cm height, the threshold values were once more not attained with SCHs, but with SCBs significant thresholds were exceeded. The threshold value of the VDV$_d$ component was attained at all speeds with the S-type vehicle, and at speeds of approximately 30 km/h and above with other vehicles. The threshold value of the S_{ed} component was attained with all vehicles at speeds of approximately 40 km/h and above. As the number of daily passages increased, the adverse effects of vibration on the human body increased significantly.

According to the ISO 2631 standard, the adverse effects of vibration on human health can also be evaluated by the R factor, which provides annual analysis by taking human age into account. Fig. 6 shows with the R factor the vibration to which a person's body will be exposed with 50 and 100 SCUs passages per day,

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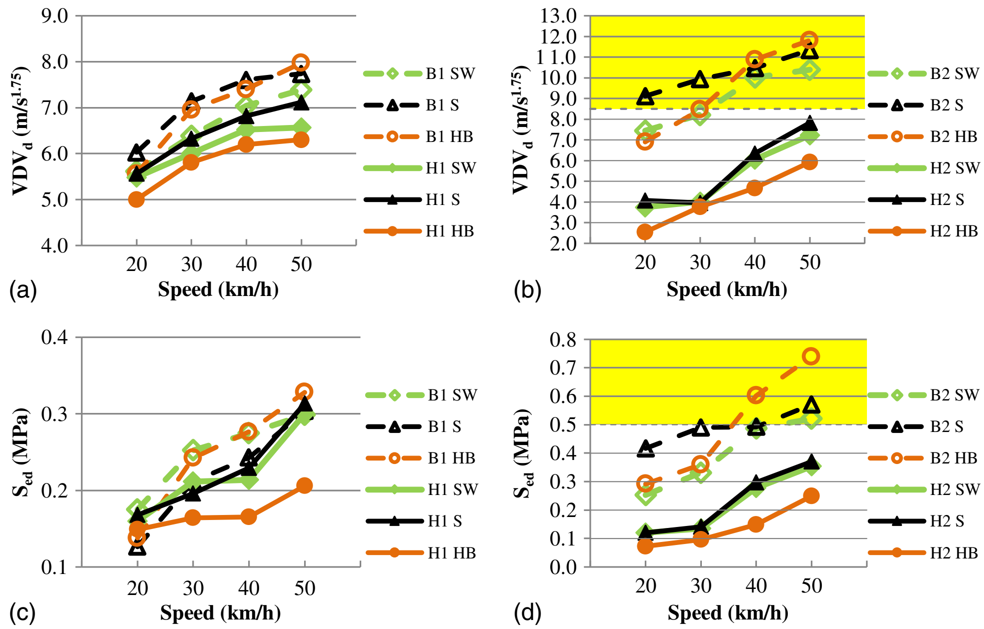

Fig. 5. Comparison for different type vehicles while crossing 100 SCUs/day of (a and b) VDV$_d$; and (c and d) S_{ed}.

assuming that an average person starts driving at the age of 20 and lives until the age of 65, which is accepted as an average human life span, and drives 240 days per year until the end of their life. Under the same conditions, R factor yielded results similar to the S_{ed} component.

In all evaluations, the vibration to which the driver is exposed to is directly related to the SCU geometry. The vibration experienced inside the vehicle increases with the increase of the SCU height. In addition, all assessments show that as the driving speed increases, the vibration in the vertical direction is increased. Examining all variations shows that SCBs have more vibration in the positive direction (S_e component) than do SCHs. Thus it is understood that SCBs are quite inconvenient designs for the human spine. Moreover, as the SCB height and driving speed increase, more adverse conditions occur in terms of human health. Furthermore, in SCBs and SCHs at low heights, instabilities occur especially at vibrations in the positive direction (S_e component) at different speeds.

The measurements were repeated with three types of passenger cars. Generally, with SCHs the vibration experienced by the driver increased with the increase of the vehicle length. In SCBs, although the weights of S-type and HB-type vehicles were almost the same, at higher driving speeds the driver was exposed to more vibration in the relatively shorter HB vehicles than in the S vehicles. Because the SW-type vehicle is long and light, more instability was observed during acceleration in the vertical direction than with the other types.

It is understood that vibration demonstrates its adverse effect on human health by reducing the S_e component relative to the VDV.

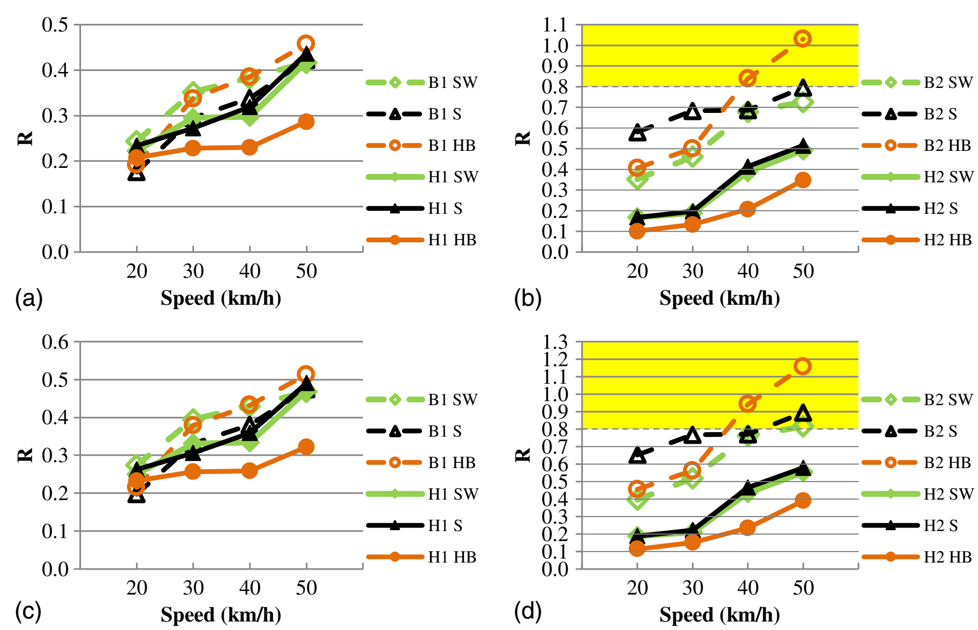

Fig. 6. Comparison of R factors for different type vehicles while crossing: (a and b) 50 SCUs/day; and (c and d) 100 SCUs/day.

For the SCU geometries and different vehicle types examined, multiple passages over SCBs caused the vibration to approach and occasionally surpass the threshold of moderate probability health risk. These evaluations clearly demonstrate that SCBs should not be preferred on urban roads where traffic volume is high. The use of SCHs instead of SCBs can reduce the wear on vehicles as well as reduce possible health problems due to vibration.

Crossing Thresholds for Human Health

In the light of these evaluations, it is important to know what number (N) of SCU passages may result in moderate probability of an adverse health effect. This information is found by determining at what number of passages the threshold values of the S_e and VDV components specified in the ISO 2631 standard are attained. N is derived from the approaches indicating the daily vibration exposure of the VDV and S_e components [Eqs. (2) and (4)], which express the adverse effects of vibration on human health (Khorshid et al. 2007). For this purpose, the maximum number of passages $N_{8.5}$ can be expressed as follows, according to the threshold value of the VDV_d component, which indicates a large number of daily passages (8.5 $\mathrm{m/s^{1.75}}$ in ISO 2631-1):

$$N_{8.5} = \left(\frac{8.5}{\mathrm{VDV}_d}\right)^4 \quad (6)$$

Similarly, the maximum number of passages $N_{0.5}$ can be expressed as follows, according to the threshold value of the S_{ed} component, expressing a large number of daily passages (0.5 MPa in ISO 2631-5):

$$N_{0.5} = \left(\frac{0.5}{S_{ed}}\right)^6 \quad (7)$$

For each of the SCU geometries examined in the study, Table 3 shows the passage numbers of the two components of the ISO 2631 standard, which indicate adverse effects of vibration, for moderate probability of an adverse health effect with different types of vehicles and at different driving speeds. In general, SCHs allowed for more passage than did SCBs with the same heights for both vibration components. This applies to all types of vehicles. In addition, with an increase in height, the difference between the number of passages over SCHs and SCBs also increased significantly.

The results show that the driving speed has a large effect on the number of passages at the limit of health risk. For example, for SCH1, which had the SCU geometry that can be considered the safest in terms of health risk for daily passage numbers, between driving speeds of 20 and 50 km/h in all types of vehicles there was about a 2–3 times difference in the VDV_d component. On the other hand, the same difference in SCH2 was as much as about 15–20 times. This suggests that the use of SCHs significantly reduces the adverse effect of vibration on human health when higher SCUs have to be built to reduce speed. However, for SCBs of different heights, the ratios were very close to each other.

It was generally observed that the change in the number of passages at different driving speeds for the S_{ed} component was greater than the same for the VDV_d component. For the S_{ed} component, which indicates the tension on the spinal cord, it is necessary to take into account the type of vehicle during the assessment. In terms of passage numbers, shorter length and more weight of the vehicle is very advantageous especially at high speeds. The main effect of SCHs is to cause a vehicle body deflection rather than a rapid deflection of tires and suspension (Watts 1973). Longer vehicles, even when the weight is the same, cause more tension on the spinal cord due to the rotational pitching effect during passage over the SCU. This has a greater effect especially in SCHs due to their longer geometric lengths. In SCBs, the length of the vehicle is advantageous in terms of vibration fading, and therefore of the vibration to which the driver is exposed.

Fig. 7 shows the numbers of passages from Table 3. Because the differences in the numbers of passages were very high, the vertical axis representing the passage numbers is logarithmically scaled at base 10.

Table 3. Number of crossings of SCUs/day to reach thresholds of moderate probability of adverse health effect in ISO 2631 standard

			Driving speed (km/h)			
Bump/hump type	Method	Vehicle type	20	30	40	50
SCB1	VDV_d	Station wagon	525	314	213	175
		Sedan	395	201	156	146
		Hatchback	544	223	174	129
	S_{ed}	Station wagon	54,303	6,051	3,634	2,195
		Sedan	384,076	17,482	7,613	1,999
		Hatchback	228,412	7,722	3,492	1,255
SCH1	VDV_d	Station wagon	577	402	289	281
		Sedan	546	326	242	203
		Hatchback	834	460	354	331
	S_{ed}	Station wagon	93,343	17,482	16,385	2,133
		Sedan	69,734	27,748	10,795	1,647
		Hatchback	143,543	79,703	76,660	20,543
SCB2	VDV_d	Station wagon	170	115	52	45
		Sedan	76	54	43	31
		Hatchback	230	101	37	27
	S_{ed}	Station wagon	5,960	1,181	118	78
		Sedan	298	112	109	45
		Hatchback	2,549	719	33	10
SCH2	VDV_d	Station wagon	2,640	1,994	387	192
		Sedan	1,908	2,129	322	139
		Hatchback	12,465	2,593	1,096	424
	S_{ed}	Station wagon	513,133	258,852	3,427	801
		Sedan	519,829	192,696	2,265	608
		Hatchback	10,585,442	1,977,678	141,265	6,512

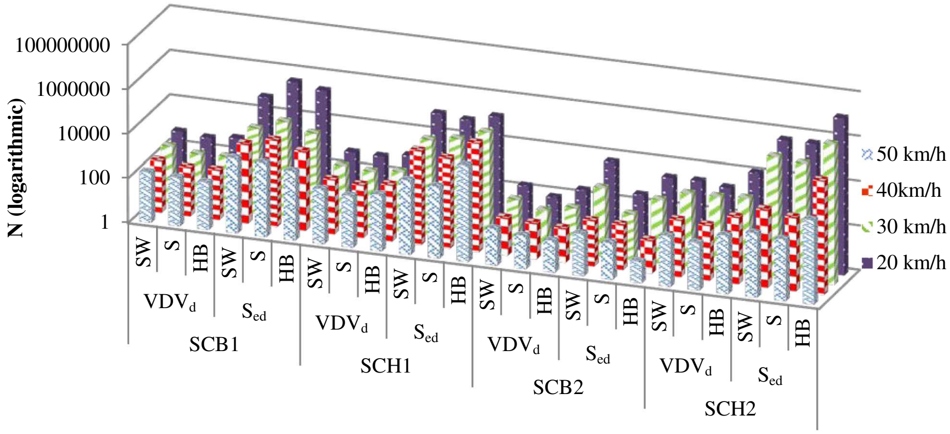

Fig. 7. Number of crossings of SCUs/day (the vertical axis is logarithmically scaled at base 10).

Conclusions

This study compared the risks of adverse effects on human health of the SCBs, which are frequently used in developing countries to reduce the traffic flow speed in urban roads, and of SCHs, which are recommended by internationally recognized standards. The 76-mm SCU height is an important distinction in terms of the sense of discomfort felt by drivers and passengers (Watts 1973). Two 5- and 10-cm-high SCBs and SCHs with circular geometry were reciprocally evaluated in terms of the vibration to which drivers were exposed when traveling in different vehicle types. The following findings were obtained:

- In all the evaluations, the vibration to which the driver is exposed was directly related to the SCU geometry, and for SCBs and SCHs the adverse effects of vibration in terms of comfort and human health became more evident as the height increased.
- For all SCU geometries, as the driving speed increased, the vibration in the vertical direction also increased.
- SCBs are quite inconvenient designs for the human spine, because they generally create more vibration in the positive direction (S_e component) than do SCHs.
- Repeated measurements with three different vehicle types showed that, due to the rotational pitching effect in the SCHs, as the vehicle length increases, the vibration experienced by the driver increases. In other words, in terms of vibration exposure, shorter vehicles provide advantages to drivers on passages over SCHs.
- However, for SCBs, in vehicles of approximately the same weight the driver is exposed to more vibrations, especially with short vehicles at high driving speeds. Long vehicles provide more comfort to drivers, especially at speeds of 40 km/h and faster on passages over SCBs. On the other hand, it seems that drivers of heavy vehicles are subjected to more vibration exposure than are those of light vehicles in SCB transitions.
- For high SCUs, especially SCHs, the moderate probability health risk is much greater at speeds of 40 km/h and faster than at lower speeds.
- For the SCU geometries evaluated, for multiple passages over SCBs, the vibration in several cases exceeded the moderate probability health risk threshold. Using SCHs instead of SCBs to reduce speed can reduce vehicle wear as well as possible health problems due to vibration.
- Vibration demonstrates its adverse effect on human health by reducing the S_e component relative to the VDV. This difference is evident when the predicted numbers of SCU passages (taking the average of all vehicles) reach the moderate probability health risk limit for the S_e and VDV components.
- Comparing the number of passages at health risk limits for VDV component, the ratio between SCB1 and SCH1 increased from 1.3 at a speed of 20 km/h to 1.8 at a speed of 50 km/h. When this was assessed between SCB2 and SCH2, the ratio decreased to 7 at a speed of 50 km/h from 36 at a speed of 20 km/h. This indicates that, in SCUs with 5-cm height, the passage numbers do not incur a large difference in accordance with ride speeds; nonetheless, in SCUs with a height of 10 cm, there were significant differences at low speeds in the number of passes, but this difference decreased as the speed increased.
- When this assessment was made according to the S_e component, the ratio between SCB1 and SCH1 increased from 0.5 at a speed of 20 km/h to 4.5 at a speed of 50 km/h. Between SCB2 and SCH2, this ratio decreased from 1,319 at a speed of 20 km/h to 60 at a speed of 50 km/h. Similar to the VDV component, together with increases in the ratio values, ride speed increases health risks significantly in passages over higher SCUs.
- For both vibration components (VDV and S_e), when SCUs were ranked from advantageous to disadvantageous in terms of the number of passages that reach health risk limits (in other words, in terms of vibration exposure), at 20 km/h the order is SCH2, SCH1, SCB1, and SCB2. This order changed to SCH1, SCH2, SCB1, and SCB2 for the speed of 50 km/h. By a very small margin, only the position of SCB1 and SCH1 are changed in the S_e component for the speed of 20 km/h. Similar results were obtained when SCUs were ranked according to health risks, although the evaluation principles of both components were different.

This study compared SCBs and SCHs according to different types of passenger cars. It would be useful to make similar evaluations for vehicles of different types, sizes, and weights as the next stage of the study. Because SCUs are often located in urban road networks, it is recommended that similar studies should be done for drivers and passengers (at different seating points) in bus and minibus types, especially for public transportation purposes.

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References

Abbott, P., J. Tyler, and R. Layfield. 1995. *Traffic calming: Vehicle noise emissions alongside speed control cushions and road humps*. Rep. No. TRL 180. Crowthorne, UK: Transport Research Laboratory.

Aghazadeh, B. S., K. Saeedi, and M. R. H. Yazdi. 2006. "Simulation of ride quality of vehicles crossing road humps." In *Proc., Int. Conf. on Modeling and Simulation*. Konya, Turkey: Selcuk Univ.

Ahn, K., and H. Rakha. 2009. "A field evaluation case study of the environmental and energy impacts of traffic calming." *Transp. Res. Part D Transp. Environ.* 14 (6): 411–424. https://doi.org/10.1016/j.trd.2009.01.007.

Ansari Ardeh, H., M. Shariatpanahi, and M. Nikkhah Bahrami. 2008. "Multiobjective shape optimization of speed humps." *Struct. Multidiscip. Optim.* 37 (2): 203–214. https://doi.org/10.1007/s00158-008-0226-7.

Antić, B., D. Pešić, M. Vujanić, and K. Lipovac. 2013. "The influence of speed bumps heights to the decrease of the vehicle speed—Belgrade experience." *Saf. Sci.* 57: 303–312. https://doi.org/10.1016/j.ssci.2013.03.008.

Bhattacharya, A., and J. D. McGlothlin. 1996. *Occupational ergonomics: Theory and applications*. Boca Raton, FL: CRC Press.

Bjarnason, S. 2004. *Round top and flat top humps: The influence of design on the effects*. Lund, SwedenLund Institute and Technology, Traffic Technology.

Bovenzi, M. 2005. "Health effects of mechanical vibration." *G Ital Med Lav Ergon.* 27 (1): 58–64.

Bowrey, D., R. Thomas, R. Evans, and P. Richmond. 1996. "Road humps: Accident prevention or hazard?" *J. Accid. Prev. Hazards* 13: 288–289.

BSI (British Standards Institution). 1987. *Guide to measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock*. BS 6841. London: BSI.

Chadda, H. S., and S. E. Cross. 1985. "Speed (road) bumps: Issues and opinions." *J. Transp. Eng.* 111 (4): 410–418. https://doi.org/10.1061/(ASCE)0733-947X(1985)111:4(410).

Cottrell, W. D., N. Kim, P. T. Martin, and H. J. Perrin Jr. 2006. "Effectiveness of traffic management in Salt Lake City, Utah." *J. Safety Res.* 37 (1): 27–41. https://doi.org/10.1016/j.jsr.2005.08.007.

Eger, T., J. Stevenson, P. É. Boileau, and A. Salmoni. 2008. "Predictions of health risks associated with the operation of load-haul-dump mining vehicles: Part 1—Analysis of whole-body vibration exposure using ISO 2631-1 and ISO-2631-5 standards." *Int. J. Ind. Ergon.* 38 (9–10): 726–738. https://doi.org/10.1016/j.ergon.2007.08.012.

Fwa, T. F., and C. Y. Liaw. 1992. "Rational approach for geometric design of speed-control road humps." *Transp. Res. Rec.* 1356: 66–72.

Griffin, M. J. 2007. "Discomfort from feeling vehicle vibration." *Veh. Syst. Dyn.* 45 (7–8): 679–698. https://doi.org/10.1080/00423110701422426.

Griffin, M. J. 2012. *Handbook of human vibration*. London: Academic.

ISO. 1997. *Mechanical vibration and shock—Evaluation of human exposure to whole-body vibration. Part 1: General requirement*. ISO 2631-1. Geneva: ISO.

ISO. 2004. *Mechanical vibration and shock—Evaluation of human exposure to whole-body vibration. Part 5: Method for evaluation of vibration containing multiple shocks*. ISO 2631-5. Geneva: ISO.

ISO. 2005. *Human response to vibration—Measuring instrumentation*. ISO BS EN 8041:2005. Geneva: ISO.

Kanjanavapastit, A., and A. Thitinaruemit. 2013. "Estimation of a speed hump profile using quarter car model." *Procedia–Soc. Behav. Sci.* 88: 265–273. https://doi.org/10.1016/j.sbspro.2013.08.505.

Khorshid, E., and M. Alfares. 2004. "A numerical study on the optimal geometric design of speed control humps." *Eng. Optim.* 36 (1): 77–100. https://doi.org/10.1080/03052150310001634871.

Khorshid, E., F. Alkalby, and H. Kamal. 2007. "Measurement of whole-body vibration exposure from speed control humps." *J. Sound Vib.* 304 (3–5): 640–659. https://doi.org/10.1016/j.jsv.2007.03.013.

Kim, M. S., K. W. Kim, and W. S. Yoo. 2011. "Method to objectively evaluate subjective ratings of ride comfort." *Int. J. Automot. Technol.* 12 (6): 831–837. https://doi.org/10.1007/s12239-011-0095-8.

Kokowski, P., and R. Makarewicz. 2006. "Predicted effects of a speed bump on light vehicle noise." *Appl. Acoust.* 67 (6): 570–579. https://doi.org/10.1016/j.apacoust.2005.10.001.

Leden, L., P. Gårder, and C. Johansson. 2006. "Safe pedestrian crossings for children and elderly." *Accid. Anal. Prev.* 38 (2): 289–294. https://doi.org/10.1016/j.aap.2005.09.012.

Molan, A. M., and A. A. Kordani. 2014. "Optimization of speed hump profiles based on vehicle dynamic performance modeling." *J. Transp. Eng.* 140 (8): 04014035. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000686.

Namee, S., and B. Witchayangkoon. 2011. "Crossroads vertical speed control devices: Suggestion from observation." *Int. Trans. J. Eng. Manage. Appl. Sci. Technol.* 2 (2): 161–171.

OECD (Organisation for Economic Co-operation and Development). 2006. *Speed management*. In *Proc., European Conf. of Ministers of Transport*, 286. Paris: OECD Publishing.

Parkhill, M., R. Sooklall, and G. Bahar. 2007. "Updated guidelines for the design and application of speed humps." In *ITE 2007 Annual Meeting and Exhibit*. Pittsburgh, PA: Institute of Transportation Engineers.

Patel, T., and V. Vasudevan. 2016. "Impact of speed humps of bicyclists." *Saf. Sci.* 89: 138–146. https://doi.org/10.1016/j.ssci.2016.06.012.

Pau, M. 2002. "Speed bumps may induce improper drivers' behavior: Case study in Italy." *J. Transp. Eng.* 128 (5): 472–478. https://doi.org/10.1061/(ASCE)0733-947X(2002)128:5(472).

Pau, M., and S. Angius. 2001. "Do speed bumps really decrease traffic speed? An Italian experience." *Accid. Anal. Prev.* 33 (5): 585–597. https://doi.org/10.1016/S0001-4575(00)00070-1.

Pedersen, N. L. 1998. "Shape optimization of a vehicle speed control bump." *Mech. Struct. Mach.* 26 (3): 319–342. https://doi.org/10.1080/08905459708945498.

Plowden, S., and M. Hillman. 1996. *Speed control and transport policy*. Bournemouth, UK: Policy Studies Institute, Bourne Press.

Salau, T. A. O., A. O. Adeyefa, and S. A. Oke. 2004. "Vehicle speed control using road bumps." *Transport* XIX (3): 130–136. https://doi.org/10.1080/16484142.2004.9637965.

Statista. 2017. "Number of vehicles in use worldwide 2006-2015." Accessed November 21, 2017. https://www.statista.com/statistics/281134/number-of-vehicles-in-use-worldwide/.

Teschke, K., A.-M. Nicol, H. Davies, and S. Ju. 1999. *Whole body vibration and back disorders among motor vehicle drivers and heavy equipment operators: A review of the scientific evidence*." Vancouver, Canada: Univ. of British Columbia Library.

Turner, M., and M. J. Griffin. 1999. "Motion sickness in public road transport: Passenger behavior and susceptibility." *Ergonomics* 42 (3): 444–461. https://doi.org/10.1080/001401399185586.

Ventsislavova, P., A. Gugliotta, E. Pena-Suarez, P. Garcia-Fernandez, E. Eisman, D. Crundall, and C. Castro. 2016. "What happens when drivers face hazards on the road?" *Accid. Anal. Prev.* 91: 43–54. https://doi.org/10.1016/j.aap.2016.02.013.

Watts, G. 1973. *Road humps for the control of vehicle speeds*. TRRL Rep. LR 597. Wokingham, UK: Transport and Road Research Laboratory.

Weber, P. A., and J. P. Braaksma. 2000. "Towards a North American geometric design standard for speed humps." *Inst. Transp. Eng. J.* 70 (1): 30–34.

Zhao, X., and C. Schindler. 2014. "Evaluation of whole-body vibration exposure experienced by operators of a compact wheel loader according to ISO 2631-1:1997 and ISO 2631-5:2004." *Int. J. Ind. Ergon.* 44 (6): 840–850. https://doi.org/10.1016/j.ergon.2014.09.006.