Bus Drivers’ Exposure To Mechanical Shocks Due To Speed Bumps

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ABSTRACT

Many bus drivers are exposed to health risks, due to repeated exposure of mechanical shocks when frequently riding over traffic speed bumps. This paper presents recent results from an investigation of vibrations imposed on the driver from some twenty speed bumps in the Stockholm area (Sweden). The vibrations have been evaluated in accordance with the new standard ISO 2631-5. It defines a method of quantifying whole-body vibration containing multiple shocks (such as bumpy rides) in relation to human health. It uses peak vibration (shock) values to predict compression stress in the spine, and reports equivalent daily static compression dose, S_{ed}. The results show high S_{ed} -values with high health risks even at low speeds. This finding made the Swedish Work Environment Administration prohibit line bus traffic on the related streets until some speed bumps were altered. The health risk depends on the number of daily shock exposures. On the worst investigated road the speed limit is 50 kmph (30 mph), while the maximum acceptable speed was 10 km/h (6 mph) assuming 150 bumps per day.

INTRODUCTION

Back disorders are costly to society and are the main causes of sick leave in the working community. They cause great pain to those suffering, and are a significant economical burden to society. Professional bus drivers are one group of workers that have been found to be at high risk for back disorders, [1]. Numerous types of back disorders are caused by ride vibration. Many epidemiological studies have been made on the relationship between back disorders and vehicle operation with vibration exposure. The results show overwhelming evidence of a relationship that is consistent and strong, which increases with increasing exposure, and is biologically plausible. The risk is elevated in a broad range of driving occupations, including bus drivers. Vibration exposure data indicate that current buses are likely to expose drivers to vibration levels in excess of levels recommended in ISO standards, and that common control measures, such as seat suspension, are often ineffective. A causal link has been found between back disorders, driving occupation and whole body vibration. Numerous back disorders are involved, including lumbago, sciatica, generalized back pain, and intervertebral disc herniation and degeneration. Elevated risks are consistently observed after five years of exposure [2].

In Europe, the Health and Safety Directive on physical agent vibration (2002/44/EC), [3], demand employers to make organizational and/or technical measures to minimize the workers’ daily exposure to whole-body vibration, if it is higher than the Action Value A(8) = 0.5 m/s^2. Work tasks that bring exposures above the limit A(8) = 1.15 m/s^2 are prohibited by the Directive.

The vibration exposure of professional drivers has been correlated with road roughness, vehicle type and condition, as well as with driving behavior such as speed. Among the conclusions were that many heavy vehicle drivers are exposed to vibrations (shocks) above the Action Value A(8) = 0.5 m/s^2. Within reasonable ranges, road roughness was found to have a much larger impact than other factors [4]. In general, transient vibrations with multiple shocks are more hazardous than stationary vibration [5]. In practice, this means that bumpy rides typically are unhealthier than ride vibration, i.e. from a modestly wash-boarded gravel roads.

A method to quantify whole-body vibration containing multiple shocks in relation to human health was standardized in 2004. The ISO 2631-5 method uses peak vibration values to predict compression stress in the spine, and reports equivalent daily static compression dose, S_{ed}. An S_{ed} -value above 0.8 MPa reflects a high health risk due to transient mechanical shocks. In contrast, an S_{ed} -value below 0.5 MPa corresponds to a non-significant risk. For workers exposed to repeated mechanical shock, such as when driving on bumpy roads, EU Directive 2002/44/EC demands the employer to perform a risk assessment. In Sweden, such assessments are made in accordance with ISO 2631-5 (2004), [6].

A draft version of the ISO 2631-5 method was applied on Italian bus drivers, while driving a wide range of buses on smooth to rough surfaces [7]. The authors concluded that "*Frequent road resurfacing has been found to be most effective in reducing the risk. Careful identification (and removal) of occasional highly vibrating vehicles is also recommended, while the impact of a faster vehicle replacement rate is more moderate. Other factors (e.g. age, daily driving time, total number of years of exposure) have very limited effect.*" This study did not include driving over speed bumps. Still, it emphasizes the importance of a smooth road surface to keep health risks low.

From the above it is clear, that it is adequate to raise a question concerning health risks among bus drivers, when frequently passing speed bumps and thus being exposed to repeated mechanical shocks. The objective of the work reported in this paper was to compare a sample of different speed bump designs with respect to health risks, in terms of back disorders related to transient ride vibration, for professional bus drivers.

METHOD

The study combined laser scanning of road surface geometry with vibration measurements using standard seat pads. It is a long term objective to find a way to predict vibrations directly from the road (or bump) geometry, as will be discussed later. For car traffic, a model to predict vibration and shock levels from road surface data is already developed [4].

MEASURING BUMP GEOMETRIES AND BUS RIDES

Approximately twenty bumps in the Täby area, some 25 km N E of Stockholm (Sweden), were tested. The bumps were of four types and in different condition. Some were tested in two traffic directions. The tested bump types are presented in Table I.

#	Type	# of Individual Bumps
1	"Shock-free" wave-shaped Gunnar Prefab, partly made of precasted Portland Cement Concrete (PCC).	6
2	Bus pillows, precasted in PCC	2
3	Flat top asphalt bumps with cobble stone ramps.	16
4	Round top bump in asphalt.	1

Table I. List of the investigated speed bumps.

The 3-D geometry of each speed bump was scanned, using a laser/inertial Profilograph as shown in Figure 1. This type of Profilograph, equipped with a ramp of lasers scanning the road surface, is routinely used for surveying of the condition of paved public roads in Sweden. The resolution is 0.1 mm, while accuracy (precision and trueness) are within fractions of a millimeter under normal operation conditions. The Profilograph allows accurate measurements while driving at speeds up to 165 kmph, while 15 to 90 kmph are normally used.

Figure 1. Profiling a flat top bump with cobble stone with the Profilograph.

MEASURING BUS RIDE VIBRATION

Transient vibration was measured in two different buses while driving at various speeds. Most measurements were made in a long articulated low entrance bus for urban traffic, seen in Figure 2. Some measurements were also made in a short bus, designed for rural traffic.

Figure 2. Long articulated low entrance bus.

Vibration was recorded on the bus driver's seat, using a triaxial seat pad complying with ISO 8041, as seen in Figure 3. The vibration measurements were made with a system that fulfils the accuracy demands in standard ISO 8041. The seat was of a non-suspended type; the type of seat normally being used in urban buses in Sweden. The bus driver's weight was 90 kg.

Figure 3. Triaxial seat pad mounted on the bus driver’s seat.

CALCULATION OF EQUIVALENT DAILY STATIC COMPRESSION DOSIS, S_{ed}

When evaluating mechanical shocks from buses driving over speed bumps, the normal five step procedure [8] can be simplified into:

1. Recording of accelerations from seat pad, while driving at various speeds over each bump;
2. Evaluation of representative peak vibration at highest legal bus driving speed;
3. Calculation of the equivalent daily static compression dosis, S_{ed}, for a relevant number of bumps/day.

In the first step, it is important that the duration of the measurement is sufficient to ensure that the multiple shocks are typical of the exposures that are being assessed [6]. In the current case study, the precision was monitored by taking repeated measurements, as well as reproduced measurements at various speeds.

In the second step, the spinal compression response was calculated. This was done in MATLAB using the VibraTools Suite™ from Axiom EduTech, which includes functionality to perform all necessary data processing for compliance with ISO 2631-5. After identification of the most harmful shock events, the damage effect is calculated with Miner-Palmgren´s theory on mechanical fatigue. These procedures are all specified by ISO 2631-5. The specified risk assessment is based on ultimate strength of the lumbar spine, verified by in-vitro studies. The results from this third step are presented as equivalent static compression dosis, S_{ed}. Standard 2631-5 defines these criteria and limit values:

- Low risk for back disorders: $S_{ed} < 0.5$ MPa.
- High risk for back disorders: $S_{ed} > 0.8$ MPa.

In the present study, the results were compared to the limit $S_{ed} = 0.5$ MPa in order to meet the criteria “Low risk for back disorders”. It should be noted that in seated position without vibration, the spinal static compression level is about 0.25 MPa. The S_{ed} -value refers to additional stress from transient vibration, not including the static 0.25 MPa.

RESULTS AND DISCUSSION

The results show unacceptable S_{ed} -values even at low speeds; thereby health risk is high. This finding made the Swedish Work Environment Administration prohibit line bus traffic on a handful of the related streets after April 30 2007, at a fine of 1 MSEK (approx. $150,000).

Some flat top bumps showed extremely high shock levels. The graph in Figure 4 shows results from a street with five "very aggressive" flat top bumps. The resulting graph shows that the driver seat transient vibration caused an S_{ed} value exceeding the limit of 0.5 MPa (low health risk) already at one trip per day, while the High health risk limit of 0.8 MPa was passed at three trips daily. Unfortunately no measurement were planned or executed on passenger seats. Assuming that passengers are exposed to somewhat similar shock levels as the bus driver, these data raise concerns for health risks also for commuting passengers.

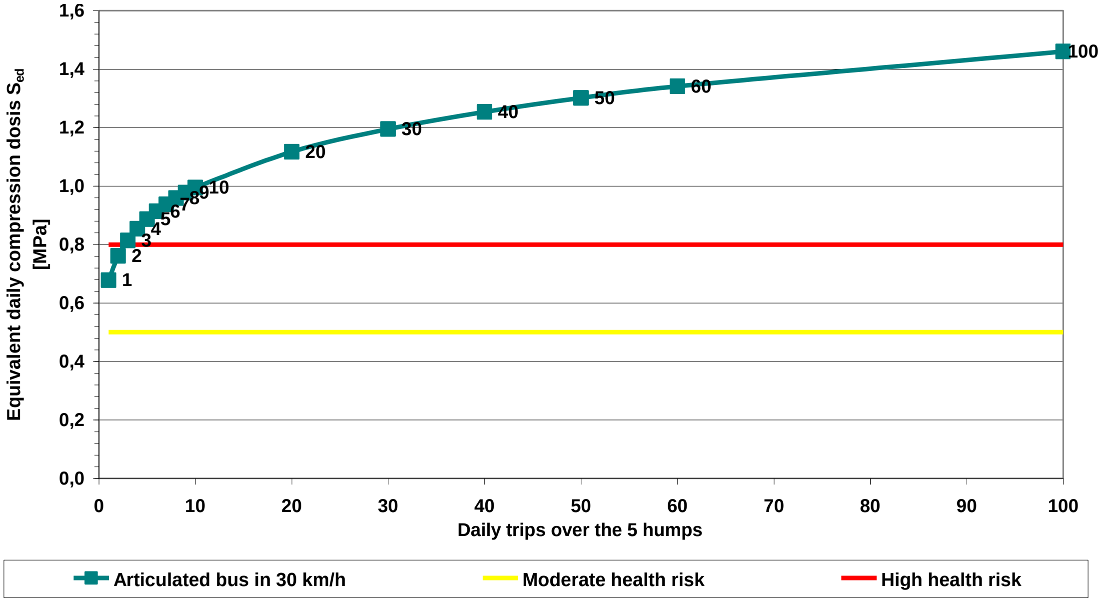

Figure 4. Health risk vs. number of daily trips per day (flat top bumps). Bus having nominal speed, 30 kmph.

The health risk increases with increased number of bumps per day, see Figure 4. These data are the results from an articulated bus driving at 30 kmph (approx. 20 mph), assuming from 1 to 100 daily trips. An increase from one to two daily trips over the streets five bumps will increase the S_{ed} -value by 12 %. An increase from nine to ten trips daily will increase S_{ed} by 2 %. An increase from 99 to 100 trips daily will increase S_{ed} by only 0.2 %. The alarming fact is, that even after as few as three daily trips on this stretch, the health risk is high. Some bus drivers frequents this stretch tenfolds per day, which results in very severe health risks. It should be noted, however, that the results in Figure 4 assume a driving speed at the regulated speed of 30 kmph which causes great uncomfort, making some drivers drive slower than 30 kmph when passing the bumps. This is further discussed below.

HEALTH RISK VERSUS SPEED

Reproduced measurements at various nominal speeds show that the S_{ed} -value (and thereby the health risk) increase with increased speed, see Figure 5.

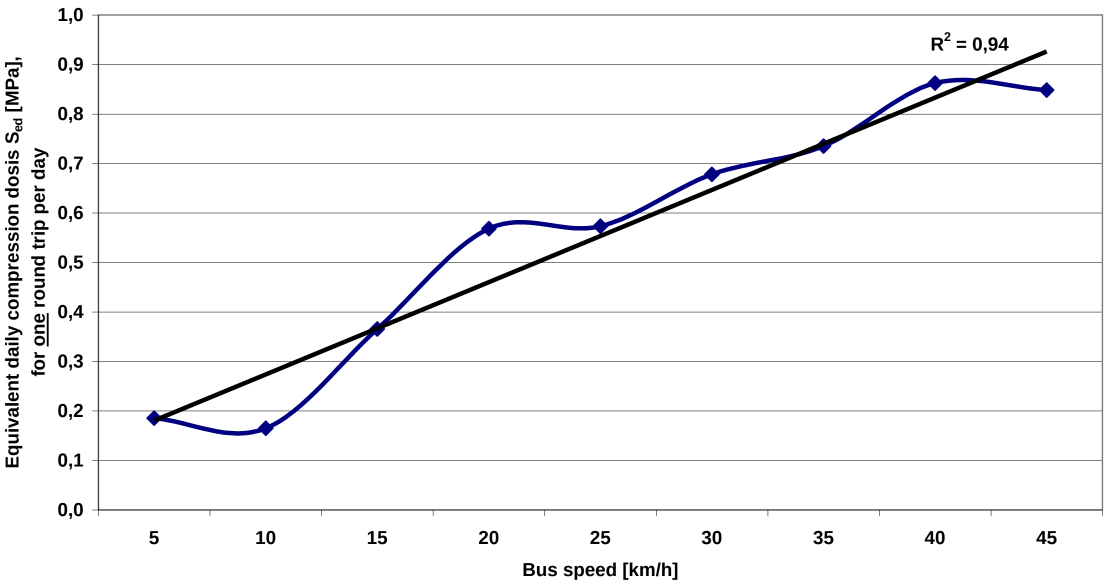

Figure 5. Health risk increases with speed; data from an articulated bus on flat top bumps.

From Figure 5 it is clear that the static compression dose is not following a linear relationship with speed, as can be seen between 10 and 20 kmph. This can be partly explained by the fact that the frequency content of the shock changes with speed, and thus the relationship between the speed and S_{ed} will be a rather complicated relationship. Furthermore, the S_{ed} model itself is nonlinear. It is still apparent from Figure 5 that the static compression dose generally is increasing with speed.

The speed where the limit value S_{ed} = 0.5 MPa is reached, varies with the number of bumps per day. The highest acceptable speed over the same road as presented in Figures 4 and 5 is presented in Figure 6 as a function of the number of daily trips over the 5 bumps on this street. Drivers who make some 30 trips daily (30 * 5 = 150 bumps/day) on this road, cannot drive more than 10 km/h before the limit value is exceeded. Since the drivers also drive over other bumps, S_{ed} will be higher in practice. This reduces the maximum acceptable speed further.

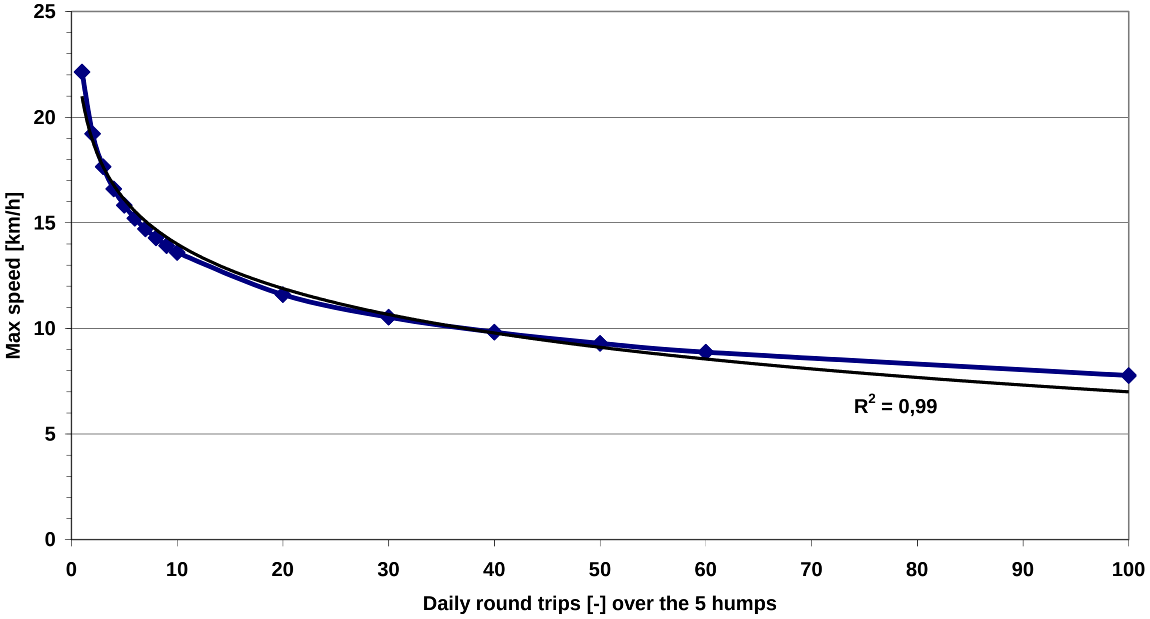

Figure 6. Max speed without exceeding the limit S_{ed} = 0.5 MPa.

LARGE VARIANCE BETWEEN BUMP DESIGNS

The project objective was to investigate several different speed bump designs with respect to health risk. Measurements of different speed bumps using the same driver, and bus, and constant nominal speed showed a very large variance in S_{ed} -values, and thus also in health risk. Figure 7 shows that the bus driver was exposed to some 1.6 MPa over the flat top bumps at the Airport Rd, which is about 170 % more than the 0.6 MPa achieved over the flat top bumps at the Viking Rd. The variance was large also among the other tested bumps. This indicates that the status of current speed bumps is so poorly standardized (design, construction variance as well as wear and tear conditions), that each bump should be regarded as an individual. Overall, some bump types are still consistently showing lower static compression than other types.

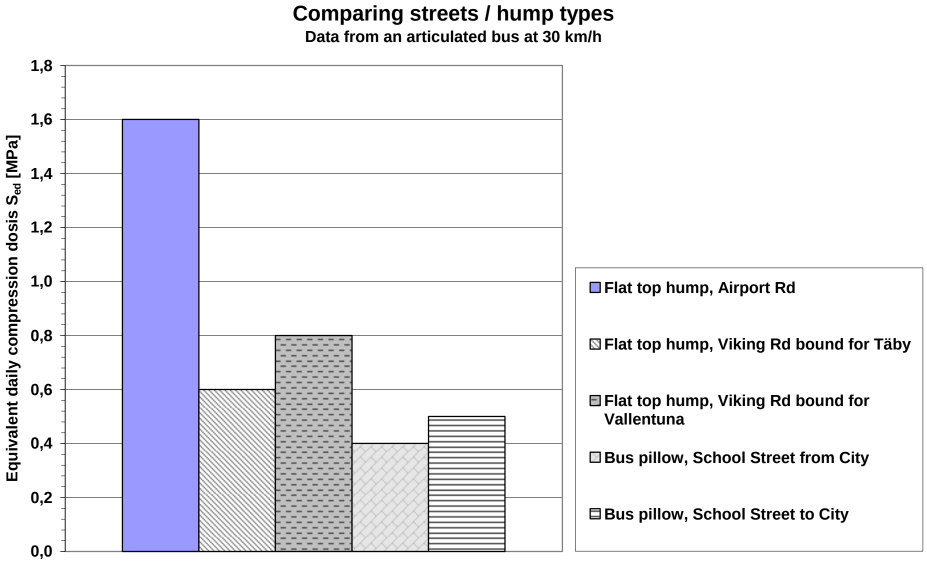

Figure 7. Health risk per street (rather: per group of bumps)

The Profilograph inertially compensated laser scans showed that many bumps were deformed compared with their nominal geometry. An example was the cobble stone ramps at some of the flat top bumps, an example of which is shown in Figure 8. These ramps were also found to generate much traffic noise.

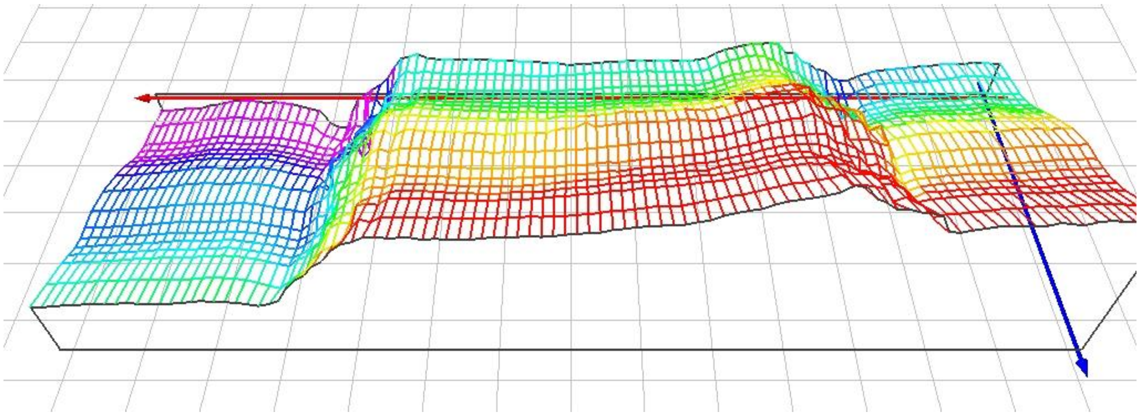

Figure 8. 3D geometry of one of the bumps at the Viking Rd

CONCLUSIONS AND RECOMMENDATIONS

Many bus drivers are at risk for back diseases due to repeated shock exposure during their daily trips over traffic calming speed bumps. Some twenty bumps in the Täby area were tested. These bumps are a sample of the types used in Sweden. The bus driver seat vibrations were evaluated in accordance with the ISO standards 2631-1 and 2631-5. Many of the exposures were very uncomfortable at 15 km/h and extremely uncomfortable at 30 km/h, as per the 2631-1 evaluation. ISO 2631-5 defines a method to quantify whole-body vibration containing multiple shocks in relation to human health. It uses peak vibration values to predict compression stress in the spine, and computes equivalent daily static compression dose, S_{ed}. The results show high S_{ed} values even at low speeds; thus the health risk is high.

The only bump type that gave acceptable spinal compression stress was the Bus pillow. However, Bus pillows yield other kinds of problems for traffic with articulated buses, so a recent trend is actually to remove them. All other bump types gave unacceptably high vibration and shock on the bus driver seat. Results from the flat top bumps were so high that they bring a concern for possible adverse health effects also for bus commuters. The round top bump at was almost as aggressive, when tested with a less shock sensitive bus/seat system designed for rural operations. The flat top bumps with ramps of asphalt, performed best of the non-acceptable bumps (however also these were tested with the less shock sensitive bus/seat system). The variance in results within each family of bumps is so large, that a more detailed ranking is without meaning. This indicates that speed bumps should be more rigidly standardized, both in terms of shape and long term shape preservation. It is strongly suggested that suitable bump shapes should be investigated, that make passages uncomfortable without producing harmful spinal compression.

Drivers performing some 30 trips daily over bumps corresponding to the 5 tested flat top bumps at the example road presented in this paper, cannot exceed 10 kmph without exceeding the limit of $S_{ed} = 0.5$ MPa.

The obtained high spinal compression levels on the driver could seemingly be reduced by better seat design. However, measurement results in [9] showed that an advanced seat didn't significantly reduce the shocks at bumps, although it significantly improved the ride quality between bumps. Furthermore, there is a high likelihood that the passengers will also be exposed to high spinal compressions, and it is likely unrealistic to make passenger seats with as high damping as is necessary to yield acceptable spinal compression levels.

Buses with low entrance/floor have short suspension stroke, such that their suspension easily bottoms out at high bumps and the ride becomes very bumpy. Therefore, streets with aggressive bumps should preferably be operated by buses of other types. However, this is in conflict with passenger capacity and concern for disabled passengers.

Mathematically, the S_{ed} value is related to peak vibration to the power of 6. A practical outcome of this is that for low numbers of daily bump exposures, an additional daily bump increases the S_{ed} -result significantly. This results in a high variability in S_{ed} -results. However, many bus drivers are exposed to up to some 300 bumps per day. At this number of daily bumps, the S_{ed} -results are quite consistent also for rather large variance in the number of daily bumps. For reference purpose, each bump should be evaluated for a high reference exposure of 300 runs daily. This can be reflected by using an index suffix; $S_{ed,\ 300}$.

MEASURE ACTUAL SPEED TO IMPROVE PRECISION

The bus actual speed may differ from the desired nominal speed. Obstructions from fellow road users may cause the bus driver to temporarily reduce speed by some ten – fifteen km/h. If such data aren't discarded, the result from reproduced measurements at various speeds may be unnecessary noisy. Later measurements have proved precision to improve, by monitoring actual speed and plotting S_{ed} versus the recorded speed.

The ”shock-free” Gunnar Prefab bump [10] may be shock-free in cars and small trucks, but excite significant shocks in the tested bus. This may partly depend on on-site construction variance, wear and tear. Laser scanning confirms a well conserved shape of the pre-casted ramp also after several years in service [9]. However, the driver seat in the bus show much higher shock levels, than in the cab of the small truck which was used when initially testing the GP-bump. Maybe the wave-shaped ramp is somewhat to short and the plateau somewhat to short in order to spare bus drivers. An observed large reduction in wheel axle hop and associated noise motivate modification and further testing of the GP-bump.

Parallel research [11] show how road profile data can be used to accurately compute ride vibration in a simulated passenger car driving over speed bumps. With appropriate computerized bus models, it would be possible to simulate vibration measurements in various buses, with various speeds, lateral positions etc., using a surface geometry profile obtained by a laser/inertial Profilograph. However, creating an accurate model of an articulated bus is a rather complex task.

In 1999, ride vibration was recorded on the driver seat in heavy timber logging trucks, riding on a frost damaged road in northern Sweden [4]. The present results in buses riding at 30 kmph over speed bumps show higher overall vibration than in this previous study. In 1999, there was no method available to quantify health risks from transient vibration. Therefore no S_{ed}–values were reported for the truck drivers. A subjective comparison between the present seat vibrations in buses with the seat vibrations of the trucks in the 1999 study, gives reason to believe that also drivers of heavy trucks on rough paved roads could be exposed to harmful spinal compression levels. There are thousands of km paved public roads in similar poor condition in the European Northern Periphery. This has called for a similar investigation on S_{ed}–values in heavy trucks riding on these roads. Such a study has been performed parallel to this bus study, in the Roadex III research project funded by the EU [12].

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REFERENCES

[1] Okunribido, O. O., Shimbles, S. J., Magnusson, M. & Pope, M. (2007). “City bus driving and low back pain: A study of the exposures to posture demands, manual materials handling and whole-body vibration,” Applied Ergonomics 38, pp 29 – 38.

[2] Teschke, K., Nicol, A-M., Davies, H. & Ju, S. (1999). “Whole Body Vibration and Back Disorders Among Motor Vehicle Drivers and Heavy Equipment Operators: A Review of the Scientific Evidence,” Report to Workers' Compensation Board of British Columbia.

[3] Directive 2002/44/EC on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration) (sixteenth individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC). The European Parliament and the Council, 2002, Article 3:2.

[4] Ahlin, K., Granlund, J. & Lundström, R. (2000). ”Whole-body Vibration When Riding on Rough Roads – A shocking Study,” Swedish National Road Administration, Vol. 31E.

Internet 2007-10-02: http://www.vv.se/filer/skakstudie.pdf.

[5] Sandover, J. (1998). “High acceleration events: An introduction and review of expert opinion,” Journal of Sound and Vibration 215(4), p 927 – 945.

[6] Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration – Part 5: Method for evaluation of vibration containing multiple shocks. International standard, ISO 2631-5 (2004).

[7] Lenzuni, P. & Pieroni, A. (2003). “Lifetime exposure of bus drivers to shocks and impulsive acceleration,” 10th Int. Congress on Sound and Vibration, Stockholm, Sweden.

[8] Mechanical vibration - Measurement and calculation of occupational exposure to whole-body vibration with reference to health – Practical guidance. European standard, EN 14253.

[9] Granlund, J. (2007). “Färdvibration från vägbulor (Ride vibration caused by speed bumps),” Report from Swedish Road Administration Consulting Services to Luleå University of Technology, for inclusion in a main report: “Förhöjda övergångsställen för alla trafikanter” (Raised junctions for all road users) made by Rosander, P., Johansson, C & Lyckman, M.

Internet 2007-10-02: http://epubl.ltu.se/1402-1536/2007/08/LTU-TR-0708-SE.pdf

[10] Granlund, J. & Lindström, F. (2003). “Design of a shock-free speed control bump,” 10´th Int Congress on Sound and Vibration, Stockholm, Sweden.

[11] Granlund, J., Kristiansen, E. & Lindström, F. (Unpublished). ”Measuring reference ride vibration over traffic calming speed bumps,” Paper submitted to World Road Associations 6’th Symposium on Pavement Surface Characteristics, to be held in Slovenia 2008.

[12] Roadex III on Health Issues Related to Poorly Maintained Road Networks.

Internet 2007-10-02: http://www.roadex.org/ROADEX%20III/RIII-task-b3.htm.