IMPACT OF VERTICAL ROAD TRAFFIC-CALMING DEVICES ON SAFETY

Samo Zupan
Miha Ambrož
Gašper Šušteršič
Ivan Prebil
University of Ljubljana
Faculty of Mechanical Engineering
Chair of Modelling in Engineering Sciences and Medicine
Aškerčeva cesta 6, SI-1000 Ljubljana, Slovenia
samo.zupan@fs.uni-lj.si, miha.ambroz@fs.uni-lj.si,
gasper.sustersic@fs.uni-lj.si, ivan.prebil@fs.uni-lj.si

ABSTRACT

Vertical road traffic-calming devices are often used to calm the running velocity of road vehicles in urban areas all over the EU. The so-called “humps” made of the same material as the pavement are built into the pavement. There are three different forms of humps: trapezoidal and sinusoidal humps and trapezoidal table. The actual shape of constructed speed humps (sample measured in Slovenia) varies considerably and often deviates from specifications. Characteristics were determined through measurements of the longitudinal hump profile and certain vehicle dynamics parameters at hump negotiation. For existing humps, the evaluation of the quality of the construction geometry is presented.

Furthermore, a safe method was identified to determine the influence of different speed humps on vehicle ride dynamics and, consequently, on vehicle and passenger safety through computer simulation. A commercial simulation tool with a detailed measurement vehicle model was used for computer simulation of basic vehicle dynamics. A comparison between measurement and simulation results shows good agreement. Simulation was later on used to evaluate the impact of the hump geometry change on vehicle dynamics at hump negotiation in the event of different vehicle load conditions and velocities.

1 INTRODUCTION

At the Chair of Modelling in Engineering Sciences and Medicine (KmTM) at the Faculty of Mechanical Engineering (University of Ljubljana), a decision was made to commence research that would enable a better insight into traffic-calming devices and measures. One of the main goals was to do research on one of the strictest and least favoured road measures among drivers – permanent velocity-reducing features. Drivers have various experiences with such features, some of which include vehicle damage and decreased personal safety. Therefore, many complaints are made that velocity-reducing features are too high, poorly marked, lit and maintained as well as constructed in inappropriate or unnecessary places and have inappropriate profile or slope inclination while the front part is often reported as too short.

Road barriers or speed humps are traffic-calming devices and measures implemented at level crossroads without traffic lights on public roads and uncategorized roads used for public transport. The first goal of this research was to determine which standards and technical regulations are used by the road administration to build velocity-reducing features. Own developed measurement equipment was used to measure the longitudinal profile of several typical types of speed humps which were later compared to the prescribed ones. Dynamics of a vehicle driving over various speed humps was measured by means of a measurement vehicle.
Samo Zupan, Miha Ambrož, Gašper Šušteršič, Ivan Prebil
IMPACT OF VERTICAL ROAD TRAFFIC-CALMING DEVICES ON SAFETY

Figure 1: Examples of constructed permanent road barriers included in the research sample

Selected was a small but representative sample of constructed barriers (Ljubljana – a few examples, Figure 1) in order to determine the appropriateness and conformity of measured humps compared to the prescribed ones. Analysis of measurements and basic statistic evaluation was applied to determine the main errors in the construction of speed humps.

Driving over barriers with the measurement vehicle at higher velocities is certainly a safety risk for passengers, equipment and the vehicle itself. However, it would be interesting to find out whether driving over barriers with a prescribed maximum velocity is safe when barriers are correctly constructed and what driving over inappropriately constructed barriers might lead to. Another interesting question would be what are the maximum velocity limit exceedings that still do not endanger the safety or cause any permanent consequences while driving over barriers. It is for this purpose that a computer simulation of driving over geometrically ideal and measured real-life humps was applied and a comparison of measurements and simulations of the vehicle dynamics during target velocity driving was performed.

2 TECHNICAL SPECIFICATION OF ROAD BARRIERS OR SPEED HUMPS

Traffic-calming devices are physical, illuminated and other type devices and barriers which help reduce vehicle velocities in road traffic and draw drivers' attention to velocity limits on dangerous road sections. Preliminary research has shown that within European countries similar road barriers are being used with only minor differences [1].

In the Republic of Slovenia, the only official document regulating traffic-calming measures is the Technical specification for public roads TSC 03.800:2009 [2] issued in the Official Gazette of the Republic of Slovenia, No. 55/09 by the Slovene Roads Agency. The specification regulates technical conditions for traffic-technical device design and determination of traffic-calming measures on public and uncategorized roads where public transport is allowed. However, it does not specify removable physical barriers for traffic-calming which are laid down in the rules on traffic signs and traffic equipment on public roads. Experience has shown that removable barriers (sometimes referred to as »speed
humps) have a much smaller impact on vehicle behaviour than permanent barriers, which is why they were not included in this study. The most frequent and probably the most efficient and at the same time least favoured traffic-calming measure are humps and ramps which are included in this study.

Table 1: Main technical properties of humps and ramps [2]

<table>
<thead>
<tr>
<th>Speed interval of use – actual velocity $v_{85}$</th>
<th>Trapezoidal hump</th>
<th>Sinusoidal hump</th>
<th>Trapezoidal ramp</th>
</tr>
</thead>
<tbody>
<tr>
<td>$30 \text{ km/h} &lt; v_{85} &lt; 70 \text{ km/h}$</td>
<td>$30 \text{ km/h} &lt; v_{85} &lt; 50 \text{ km/h}$</td>
<td>$50 \text{ km/h} &lt; v_{85} &lt; 70 \text{ km/h}$</td>
<td></td>
</tr>
<tr>
<td>Pass-over or target velocity $v_{po}$, $v_{ti}$</td>
<td>$v_{po} = 30$, $40$, and $50 \text{ km/h}$</td>
<td>$v_{po} = 30 \text{ km/h}$</td>
<td>desired $v_{ti}$</td>
</tr>
<tr>
<td>Height $H$</td>
<td>$H = 0.12 \text{ m}$</td>
<td>$H = 0.12 \text{ m}$</td>
<td>$H = 0.12 \text{ m}$</td>
</tr>
<tr>
<td>Length $L$</td>
<td>$L_{2} = 2.40 \text{ m}$ (central part)</td>
<td>$L = 4.80 \text{ m}$ (overall)</td>
<td>$L_{2} = 3$ to $9 \text{ m}$ (central part)</td>
</tr>
<tr>
<td>Slope inclination $h$</td>
<td>$h = 2.5 %$, $5 %$, $10 %$</td>
<td>variable, max. $6 %$ (sinusoidal profile)</td>
<td></td>
</tr>
</tbody>
</table>

* both conditions applied simultaneously

** $k = \frac{19.2}{(47 - v_{po})}[\text{m}]$ **

$h = \frac{H(47 - v_{po})}{19.2}$

Figure 2: Theoretical shape of trapezoidal and sinusoidal humps as defined by TSC [2]

Humps and ramps (Table 1, Figure 2) are regarded as one of the strictest measures the purpose of which is to force drivers to slow down. Their effect depends mostly on the shape or inclination of slopes as well as the distance between the individual barriers in the event of a sequence. The longitudinal inclination of slopes is subject to the highest possible vertical acceleration of $0.7 \text{ g}$. However, the specification does not provide appropriate interpretation of this definition. It is not specified whether it refers to the acceleration of sprung (presumably, and also confirmed through experiments performed) or unsprung vehicle masses, nor does it explain the manner in which the acceleration is to be calculated or measured.

The regulation determines the conditions of use (volumes of traffic, the width, the steepest inclination, etc.) the most significant one of which specifies that on road sections where barriers are to be constructed, vehicles reach a velocity $v_{85}$ within a limited interval. The actual velocity $v_{85}$ is the velocity provided by technical elements of a designed or existing road prior to the installation of traffic-calming devices. This is the velocity in a free flow of
traffic on a clean and wet roadway reached by 85% of vehicles. After the installation of the devices the velocity decreases (label $v_{85}$). The pass-over velocity $v_{po}$ at the device location is smaller than the velocity $v_{85}$ and is defined by the device geometry and the distance between successive devices. Target velocity $v_t$ is the velocity which is to be reached by means of the measure.

Barriers designed for various pass-over velocities (Figure 2) differ mainly in inclinations and thereby the length of entry and exit slopes. With trapezoidal barriers, the central part should always be the same (length 2.4 m), the difference between a trapezoidal barrier and a ramp is mainly in the length of the central part which in the event of a ramp can be appropriately adjusted (zebra crossing, crossroads). Ramps are usually constructed in pedestrian areas with crossings and low velocity limits (below 30 km/h, usually even less). Ramp inclinations are calculated in accordance with the target velocity. The height of all barriers should not exceed 120 mm. Deviations usually occur in ramps the height of which is adjusted to the the height of curbs, which, however, is not especially specified by TSC.

3 MEASUREMENTS OF BARRIER GEOMETRY AND RESULTS

Geometry measurements of the humps were performed in Ljubljana. The test sample was chosen on the basis of preliminary visual inspection of humps around the city in order to establish a representative sample of well and poorly constructed humps. Measurements were performed by means of classic measurement tools: linear measuring tools, digital protractor (Mitutoyo Digital Protractor Pro 360) and a purpose-designed measurement system for measuring the longitudinal profile of a barrier (Figure 3).

![Profilograph carriage with sensors](image)

![Horizontal profilograph track](image)

![Profile measurement](image)

**Figure 3: Preparation of profilograph for measuring the longitudinal profile of road velocity-reducing features**

The measurement profilograph (Figure 3:) consists of the elements of Lego Mindstorms NXT kit that were used to build profilograph carriage with sensors. For the purpose of measuring the longitudinal profile coordinate, a rotary encoder with a resolution of 1° was installed in the device, as well as an ultrasonic sensor with a resolution of 1 mm in order to perform vertical coordinate measurements. The device is placed on a straight sloted Al alloy profile which is placed horizontally across the velocity-reducing barrier by means of adjustable stands. The developed software in the device enables movement of carriage over a barrier, whereby data on longitudinal and vertical coordinate is captured and stored into a database in pre-determined time intervals. The database is then processed, which results in a digital (tabular) description of a longitudinal hump profile. The profile then enables calculation of comparable geometrical parameters of a barrier, graphical presententation thereof (Figure 4) and computer simulations of driving over existing real barriers [3, 5, 6].

The study included six trapezoidal barriers, whereby on each barrier two measurements were performed – one on the entry to a barrier and one on the exit of a barrier, which equals in a total of 12 measurements of slope inclinations. The mean value of slope inclination
measurements is equal to 13.33 %, the median is equal to 13.4 %, standard deviation 2.35 %, minimum value 9.93 %, and maximum value 18.67 %. The theoretical slope inclination indicated by TSC for a trapezoidal barrier with a velocity limit of 30 km/h is equal to 10 %, which is also the maximum barrier inclination possible.

Based on the comparison between a theoretical slope inclination according to TSC and statistical estimators of slope inclination measurements, it is evident that most inclinations of constructed barriers are too big and that these deviations may vary significantly. Therefore, a conclusion can be made that the slope inclination of trapezoidal barriers is in general too big, which is also confirmed by a probability graph (Figure 5). The graph shows that with most (approx. 90 %) constructed barriers the inclinations are steeper than allowed and in the event of poor-quality barriers exceed the maximum inclination limit by a factor of 2.

The study also included five sinusoidal barriers. Two measurements were performed on each barrier – one on the entry to a barrier and one on the exit of a barrier, which equals in a total of 10 measurements of slope inclinations. The mean value of slope inclination measurements is equal to 8.05 %, the median is equal to 6.68 %, standard deviation 5.01 %, minimum value 3.00 %, and maximum value 17.10 %. The theoretical slope inclination indicated by TSC for a sinusoidal barrier with a velocity limit of 30 km/h is equal to 6 %. In accordance with TSC, sinusoidal barriers are intended only for a velocity limit of 30 km/h. However, they are sometimes without any prior modification used for higher velocity limits.

Based on the comparison between a theoretical slope inclination according to TSC and statistical estimators of measurements, it is evident that most inclinations of constructed barriers are steeper than allowed. However, the deviations are not as significant as in the event of trapezoidal barriers. The probability graph (Figure 6) shows that with most (approx. 70 %)
constructed barriers the inclinations are steeper and in the event of poor-quality barriers exceed the maximum inclination limit by a factor of 3. The extreme sinusoidal barriers are poorly constructed, whereas the entry and exit profile is incorrect (too steep) and the middle part too long. Consequently, they resemble trapezoidal barriers (Figure 4).

4  MEASUREMENTS AND SIMULATIONS OF DRIVING OVER ROAD VELOCITY-REDUCING BARRIERS

The dynamics of driving over the selected barriers was measured by a specially equipped measurement vehicle Opel Zafira 2.0 DTI (Figure 7). The vehicle velocity was measured with a contactless distance and velocity sensor (Corrsys Datron S-400). Vertical accelerations and movement of the front left wheel (unsprung mass) were measured by means of a wire displacement transducer SpaceAge Control 161-1915, whereas vertical accelerations of the vehicle and the unsprung part of the front left suspension were measured by two triaxial accelerometers Silicon Designs SD-2422-025, of which one is placed in the gravity centre of the vehicle so that measurement axes were in accordance with the longitudinal, transverse and vertical axis of the vehicle reference frame, and the other approximately in the centre of the left front wheel. The experiments were video recorded with a digital camera Prosilica EC 1020C (in direction of driving). The vehicle was also equipped with a measurement computer with the National Instruments (NI) hardware for digitalisation and measurement processing. The developed software application based on NI Labview enables the measured data to be captured, digitalised, converted and stored in an ASCII measurement file as time series of values (Figure 8).

![Figure 7: Measurement equipment of the measurement vehicle](image)

During the measurement vehicle drive over velocity-reducing barriers, the following quantities were acquired, measured and stored:
- video signal from digital camera in the vehicle (recording in the direction of driving),
- longitudinal vehicle velocity \( v \),
- travelled distance \( s \),
- acceleration components in the vehicle gravity centre \( a_x, a_y \) and \( a_z \),
- acceleration components on the axis of the front left wheel \( a_{1Lx}, a_{1Ly} \) and \( a_{1Lz} \),
- vertical displacement of the suspension of the front left wheel \( z_{1L} \).
Figure 8: Measurement database of time measurements

Detailed (RD geometrical) models were developed for the purpose of measuring the ride dynamics of significant parts or assemblies of the measurement vehicle or the entire vehicle (Figure 9). For the purpose of simulations, the models with characteristic parameters were applied into the MSC Adams software environment for simulation of multi-body systems.

Figure 9: Modelling of the measurement vehicle for simulations

Detailed geometrical models of significant vehicle assemblies for detailed simulations of the vehicle ride enable quality measurements similar to real-life values of the vehicle response for an individual ride protocol. Unfortunately, all key data on the vehicle which are necessary for the simulation of the ride dynamics are not available and could not be obtained from the manufacturer. This mostly applies to data on spring-damping characteristics of the undercarriage and inertia characteristics of the entire vehicle. Therefore, for the purpose of simulations, values were calculated from other sources and/or obtained from some less complex measurements the performance of which was possible. In order to perform more detailed measurements of the aforementioned characteristics, performance of appropriate preparations and measurements are needed, all of which is currently taking place.

One of the main goals of the study was to determine the level of agreement between the simulations of driving over road barriers (with theoretical or measured profiles) and typical measured values. For this purpose, simulations and comparisons of all barriers measured were performed (example – Figure 10, Table 2).
First measurements show a relatively good agreement between the results despite the fact that in some time intervals absolute and relative deviations of some measured and simulated values can be quite significant. However, dynamic transient phenomena should always be observed in a longer time period. Deviations among current oscillation amplitudes occur also due to time lag among simulated curves which result mostly from the fact that spring and damping characteristics of the undercarriage and other vehicle systems are not determined in as much detail as necessary. Furthermore, this also impacts maximum amplitude values of individual simulated oscillation.

An overview of all measurements performed at velocities of 20 to 33 km/h (decreased velocities in the event of seemingly poor-quality and dangerous barriers) and simulations shows (Table 3) that the acceleration of the vehicle centre of gravity is significantly smaller than the allowed value (0.7 g) determined by the TSC definition of the barrier geometry. Most measured barriers had a velocity limit sign of 30 km/h. Even though inappropriately constructed barriers were driven over at a relatively low velocity, the impact of wheels on overly steep slopes was perceived by the passengers as unpleasant.

Acceleration measurements of the vehicle centre of gravity barely exceeded 50 % of the acceleration limit. Two barriers (a trapezoidal and a sinusoidal one) have a velocity limit sign
of 40 km/h. In accordance with the specification, sinusoidal barriers are intended only for the velocity of 30 km/h, while the geometry of the constructed trapezoidal barrier was in accordance with the specification for the velocity limit of 30 km/h. However, none of the barriers were driven over by a measurement vehicle at a velocity of 40 km/h.

Table 3: Extreme acceleration values obtained from a sample of barriers at velocities of 20 to 33 km/h

<table>
<thead>
<tr>
<th></th>
<th>Measurement</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoG acceleration [g]</td>
<td>max. 0.20 ↔ 0.40</td>
<td>0.30 ↔ 0.70</td>
</tr>
<tr>
<td></td>
<td>min. -0.25 ↔ -0.45</td>
<td>-0.20 ↔ -0.60</td>
</tr>
<tr>
<td>FL wheel acceleration [g]</td>
<td>max. 0.95 ↔ 2.05</td>
<td>1.20 ↔ 2.65</td>
</tr>
<tr>
<td></td>
<td>min. -0.55 ↔ -1.20</td>
<td>-1.20 ↔ -2.45</td>
</tr>
</tbody>
</table>

Comparisons between measurements and simulations performed have shown the following extremes: the maximum vertical acceleration of the centre of gravity obtained from the simulation is by 100% bigger than the vertical acceleration of the centre of gravity obtained from the same measurement, whereas the minimum vertical acceleration of the centre of gravity obtained from the simulation is equal to the one obtained from the measurement (which is mostly due to “damped free fall” of the vehicle). The simulated maximum vertical acceleration of the front left wheel is bigger than the measured one by 29%, whereas the simulated minimum vertical acceleration of the front left wheel is bigger than the measured one by 87%.

Table 4: Example – results of kinematical quantities in the event of simulation at the Koseze

<table>
<thead>
<tr>
<th>Vehicle velocity 40 km/h, speed limit (hump) 30 km/h</th>
<th>Simulation</th>
<th>Permissible values [g]</th>
<th>Difference between simulated and permissible value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoG acceleration [g]</td>
<td>max. 1.00</td>
<td>0.7</td>
<td>42% &gt; than allowed</td>
</tr>
<tr>
<td></td>
<td>min. -0.93</td>
<td>-0.7</td>
<td>32% &gt; than allowed</td>
</tr>
<tr>
<td>FL wheel acceleration [g]</td>
<td>max. 2.35</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>min. -2.95</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Also performed was a simulation of driving over barriers while exceeding the velocity limit of 30 km/h. Due to the evaluated spring-damping characteristics, the agreement between measurement and simulation results is not excellent. However, simulations performed have confirmed that accelerations progressively increase as the velocity increases. In the event of poorly-constructed barriers, simulations have shown that accelerations of the vehicle centre of gravity exceed the permissible limit (example - Table 4).

5 CONCLUSION

The geometry measurements of permanent velocity-reducing road barriers show that some parameters deviate significantly from the prescribed ones. This mostly applies to the inclinations of entry and exit slopes, which are usually too big in regard to the velocity limit, as well as the length and height of barriers. The height of barriers seldom exceeds the prescribed limit of 120 mm and is usually even lower, except in the event of trapezoidal barriers (zebra crossings, crossroads). However, these deviations have a lesser impact on the dynamics of driving over barriers, which was also confirmed by the results of measurements and simulations of the ride dynamics of the vehicle driving over barriers. Most critical are inclinations of constructed entry and exit slopes which are too big.

The measurements of the dynamics of driving over barriers have shown that in the event of low velocities accelerations of the vehicle centre of gravity are well below the value
(usually below 50 %) determined as permissible by the technical specification – i. e. 0.7 g. This is also true in cases where subjective feelings at crossing the barrier were really bad and the wheel impact against too-steep slopes of poorly-constructed barriers is big (wheel accelerations). Therefore, it remains to be answered whether the limit of 0.7 g is appropriate and whether other parameters of driving over barriers are also to be taken into account, instead of just the acceleration of the vehicle centre of gravity.

Despite a relatively detailed vehicle model, ride simulations show significant yet stable deviations among extreme values of kinematical parameters (accelerations). The reason for this lies behind insufficient knowledge on spring and damping characteristics of the measurement vehicle. Upon the completion of all necessary measurements of these characteristics, less deviation among simulation and measurement results is expected. Only then shall this tool become a quality tool for evaluation of the safety of various barriers (theoretical and constructed ones) and the maximum velocity which is still safe and does not pose a threat of potential vehicle damages and injuries to vehicle occupants. Current simulations and experience show that many poorly-constructed barriers pose a significant threat to drivers’ safety even in the event of minor exceedings of the velocity limit.

REFERENCES

2. TSC 03.800 : 2009: Naprave in ukrepi za umirjanje prometa, Tehnična specifikacija za ceste, Direkcija RS za ceste, Ministrstvo za promet, Ur. l. RS, št. 55/09
5. ZUPAN, Samo, AMBROŢ, Miha, ŠUŠTERŠIČ, Gašper, PREBIL, Ivan: Dinamika vozila pri vožnji prek ovire za umirjanje prometa, Innovative Automotive Technology – IAT 09, April 2009