VERTICAL ACCELERATIONS OF THE BODY OF A MOTOR VEHICLE WHEN CROSSING A SPEED BUMP

ROBERT JANCZUR[1]

Cracow University of Technology

Summary

The article comprises results of determining the vertical accelerations of a selected point in the body of a VW Passat B5 passenger car when the car crossed a speed bump with various speeds. The measurements were carried out for two sets of shock absorbers, which differed from each other in vibration damping characteristics. The force-displacement and force-velocity (damping) characteristics of the shock absorbers having been removed from the motor vehicle were determined by rig testing. For comparison, the condition of the shock absorbers when installed in the vehicle was assessed by the EUSAMA diagnostic method. The speed bump had a trapezoidal profile and it was crossed by the vehicle with speeds of 20 km/h, 30 km/h, and 40 km/h. The accelerations were measured with the use of various measuring equipment, including Crossbow VG 440CA-200 and VBOX RLVBIMU03 measurement units and an HBM B12/200 acceleration sensor. The results have been presented in the form of time histories of the vertical acceleration of the car body, with highlighting the differences that occurred in the instrument readouts. Moreover, simulation tests were carried out with the use of the V-SIM program for the actual distribution of mass among individual vehicle wheels as well as stiffness and damping coefficients of the wheel suspension system determined on a test stand for both the shock absorber sets. The differences in the results obtained by individual test methods have been evaluated and the reasons that caused the differences to occur have been specified.

Key words: vertical acceleration of motorcar body, shock absorber characteristics, acceleration sensor

1. Introduction

The solutions used at present to reduce the traffic speed on specific road stretches, mostly at particularly dangerous spots, include "speed bumps", "speed humps", and "flat top humps", also referred to as "speed tables", i.e. raised pedestrian crossings. The solutions of this kind are to discipline vehicle drivers by significantly impairing the ride comfort when a vehicle is crossing such an "element of road infrastructure" with excessive speed.

The analysis of accelerations of selected points in the body of a motor vehicle when

[1] Cracow University of Technology, Institute of Automobiles and Internal Combustion Engines, Al. Jana Pawła II 37, 31- 864 Cracow, Poland, e-mail: robertj@mech.pk.edu.pl

crossing a speed bump and of the impact of the condition of shock absorbers and vehicle speed on the said accelerations was inspired by author's personal experience regarding this issue and a traffic incident with a Mercedes-Benz O 815 bus, the passengers of which incurred bodily injuries when the bus crossed a raised pedestrian crossing with an excessive speed. The circumstances of this incident indicated that the said bus, driven with a speed almost twice as high as the speed limit imposed on the road stretch under consideration and defined by a road sign B 33 as 30 km/h, was subjected to so high vertical accelerations that the occupants of the rearmost row of seats incurred bodily injuries in the form of compression traumas to the spinal column. Although it does not seem to be a very difficult task to identify the causes of the said incident from the factual point of view, a matter of special interest is an analysis of the impact of the speed with which a motor vehicle crosses such elements of road infrastructure as "speed bumps", "speed humps", or "raised pedestrian crossings" on vehicle body accelerations as well as the possibilities of determining, by measurements or simulation, the accelerations that occur in selected vehicle regions.

At present, many research centres and laboratories as well as schools of higher technical education have already been provided with appropriate research equipment, which offers inter alia a possibility of carrying out adequately accurate measurements of motor vehicle velocities and vertical accelerations of the vehicle body. This article includes a presentation of some equipment of this kind and the methods of using it at road testing of motor vehicles. This equipment, however, is in most cases unavailable for the forensic experts and specialists being called by courts for the needs of judgment of traffic incidents similar to the one with a bus as mentioned above. Therefore, such experts and specialists may use vehicle motion simulation programs as an aid to support their opinions. One of such programs is the one named V SIM, launched and being developed by CYBID sp.j., a company of Cracow. The CYBID test laboratory has at its disposal a Racelogic VBOX 3i measurement unit, which together with the test equipment possessed by the Motor Vehicle Construction Department of the Cracow University of Technology was used for the preparation of materials for this article [2, 3, i1–i4].

2. Measurements of accelerations of a selected point in the body of a motor vehicle when crossing a speed bump

2.1. Object of testing

To measure the accelerations of selected points in the vehicle body, a VW Passat Variant 1.9 TDI B5 passenger car manufactured in 2003 was used. During the tests, the car was provided with Goodyear 195/55 R16 tyres, inflated to pressures typical for partial vehicle loads, i.e. 2.3 bar and 2.1 bar for front and rear wheels, respectively. The road tests were carried out for two shock absorber sets, i.e. a standard set and a set of "sport" shock absorbers with higher damping forces. The test results obtained for the standard and "sport" shock absorber sets have been presented in a subsequent part of this article. The vertical vehicle body accelerations measured for the "sport" shock absorbers were higher than those measured for the standard set; therefore, the "sport" version was considered more interesting from the point of view of ride comfort and a risk of the vehicle occupant "health" limit being exceeded [4, 6].

A view of the test vehicle with the test equipment having been installed on it has been presented in Fig. 1. The force-displacement and force-velocity (damping) characteristics of the shock absorbers were determined on a POLMO-PIMOT AB 602 test stand installed at the Motor Vehicle Construction Department of the Institute of Automobiles and Internal Combustion Engines at the Cracow University of Technology. The test stand, provided with a slider-crank mechanism driven by an electric motor with controllable rotational speed, enabled stepless stroke adjustment of the shock absorber under test within a range from 1 mm to 100 mm. Fig. 3 shows a comparison of characteristics of the shock absorbers of the front wheel suspension system for a shock absorber stroke of 80 mm and for a selected example speed of the motor driving the test stand (the full-scope testing covered seven motor speeds for a stroke of 80 mm); the corresponding characteristics determined for the shock absorbers of the rear wheel suspension system can be seen in Fig. 4.

Fig. 1. A view of the VW Passat test vehicle

Fig. 2. A view of the VBOX and Crossbow measuring equipment installed in the vehicle interior

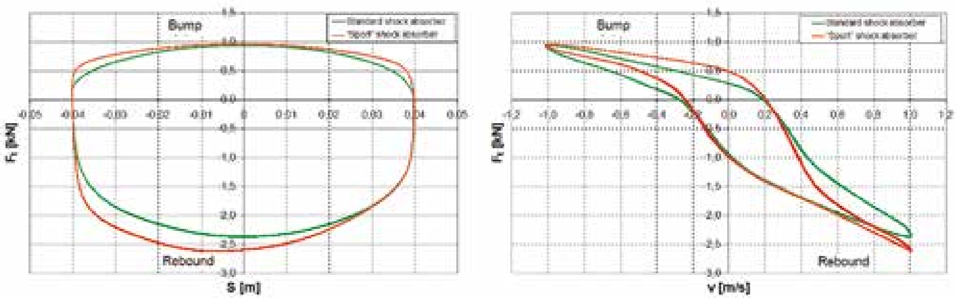

Fig. 3. Force-displacement P_t = f(s) and force-velocity P_t = f(v) (damping) characteristics of the standard and "sport" shock absorbers of the front wheel suspension system of the VW Passat test vehicle (green and red curves, respectively)

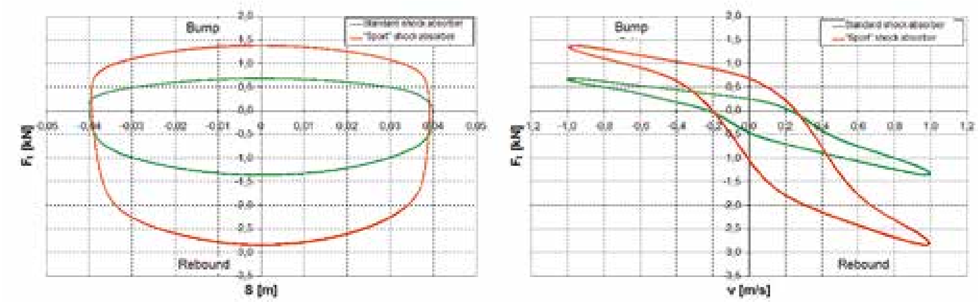

Fig. 4. Force-displacement $P_t = f(s)$ and force-velocity $P_t = f(v)$ (damping) characteristics of the standard and "sport" shock absorbers of the rear wheel suspension system of the VW Passat test vehicle (green and red curves, respectively)

Although the damping forces produced by the "sport" shock absorbers of the rear wheel suspension system were about twice as high as those of the corresponding standard shock absorbers (Fig. 4), the EUSAMA indicator values obtained from diagnostic tests carried out by the EUSAMA method for the standard and "sport" shock absorbers differed from each other by about 8–9 %. For obvious reasons the test results obtained with the use of the said test methods cannot be compared with each other but it is absolute certain that the actual damping forces of shock absorbers cannot be reliably estimated from the diagnostic tests. The differences in the EUSAMA values obtained for shock absorbers of the same vehicle axle were as follows:

- for standard shock absorbers, 5 % for the front wheels and 2 % for the rear wheels;
- for "sport" shock absorbers, 6 % for the front wheels and 3 % for the rear wheels.

During the road tests, the VW Passat test car was loaded with two occupants (a driver and a test equipment operator) and the test equipment. The distribution of masses among vehicle wheels, which was also adopted at the computer simulations of the speed bump crossing, has been presented in Table 1.

Table 1. Distribution of masses among vehicle wheels

	Mass accrued to the left wheel [kg]	**Mass accrued to the right wheel [kg]**
Front axle wheels	482	460
Rear axle wheels	331	341

2.2. Measuring equipment

At the road tests of the VW Passat car, two measuring channels, separate but synchronized with each other, were used. In the first measuring channel, cooperating with two HBM Spider 8 measurement amplifiers and provided with a computer data collection system based on the Catman program, the following sensors were used:

- Correvit Corrsys 8-CE measuring head for vehicle velocity measurements;

- 9-parameter measuring block Crossbow VG 440CA-200 (3 accelerations, 3 angular velocities, and 3 angles of rotation in relation to three mutually perpendicular axes) with an NAV-DAC 440 converter, to measure the roll, pitch and yaw of the vehicle body;
- HBM acceleration sensor B12/200, to measure the vertical acceleration of the car body.

The location of the sensor installation places, situated in the longitudinal vehicle symmetry plane and convenient for installation reasons, has been presented in Figs. 1, 2, and 5.

As the second measuring channel, a Racelogic VBOX 3i measurement unit was used, which was composed of the following modules:

- VBOX 3i RTK, marked with a symbol VB3iR10G10 and comprising a system to process signals received from GPS and peripheral devices, with a signal recording system, suitable for both analog signals (up to 4 channels with a 24-bit signal processing), and signals received from the CAN;
- IMU (Inertial Measurement Unit), marked with a symbol RLVBIMU03 and provided with 3 angular velocity sensors and 3 accelerometers based on the MEMS (Micro Electro-Mechanical Systems) technology, to measure these parameters in relation to three mutually perpendicular axes;
- CAN, marked with a symbol RLVBCAN02, i.e. a module to decode signals taken from the vehicle's CAN bus and to record the signals in up to 16 channels (records of the data received from the vehicle's CAN bus were not used at the tests described herein).

The location of the VBOX modules has been presented in Figs. 1, 2, and 5. Information about the measuring ranges of the instruments mentioned above and their accuracy in the ranges as used at the tests has been brought together in Table 2.

Table 2. Measuring ranges and accuracy of the measuring equipment [i1, i2, i3, i4]

Quantity measured	Symbol	Measuring instrument	Measuring range	Measuring accuracy
Longitudinal velocity of the vehicle	v_L	Correvit S-CE measuring head	0–350 km/h	0.1 km/h
Vertical acceleration of the vehicle body	a_{zC}	Crossbow measuring block	± 4 g	< 0.5 mg
Vehicle body pitch rate (angular velocity)	ω_{yC}	Crossbow measuring block	± 200 °/s	< 0.02 °/s
Vehicle body pitch angle	ϑ_C	Crossbow measuring block	± 180 °	< 0.2°
Vehicle driving speed	v	VBOX	0.1–1600 km/h	0.01 km/h
Vertical acceleration of the vehicle body	a_{zV}	VBOX	± 1.7 g	< 1 mg
Vehicle body pitch rate (angular velocity)	ω_{yV}	VBOX	± 150 °/s	nonlinearity 0.1 % resolution 0.01 °/s
Vertical acceleration of the vehicle body	a_{zH}	HBM	± 200 m/s^2	± 0.2%

The views of the Correvit measuring head, Crossbow measuring block (lower module, yellow, in Fig. 2), and IMU (Inertial Measurement Unit) of the VBOX system (upper module, blue, in Fig. 2) installed in the vehicle have been presented in photographs in Figs. 1 and 2. The approximate locations of the measuring instruments in the longitudinal symmetry plane of the VW Passat car has been shown in Fig. 5.

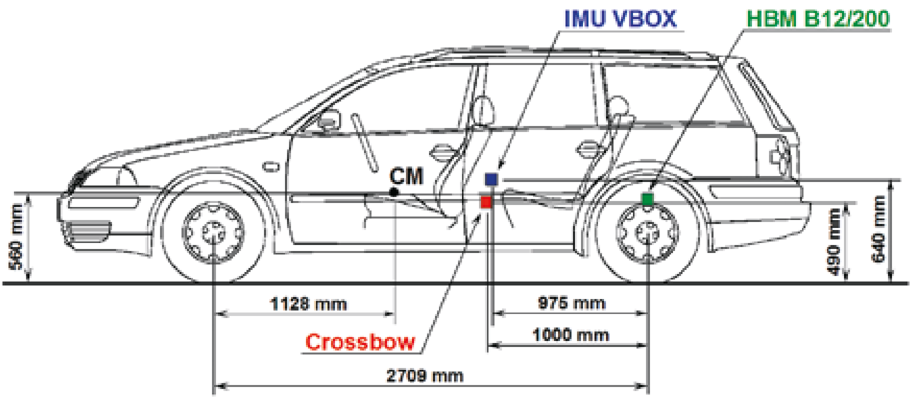

Fig. 5. Approximate locations of the Crossbow and VBOX inertial blocks and the HBM sensor: CM – centre of mass

2.3. Results of road tests of the vehicle

The vertical accelerations of selected points in the vehicle body were measured at three different speeds, i.e. about 20 km/h, 30 km/h, and 40 km/h, with which the vehicle crossed two successive speed bumps [1], such as those used in most cases on estate roads. The speed bump[2] profile used at the tests has been shown in Fig. 6. According to requirements [5], the designed limit speed of crossing a speed bump should be lower than, or equal to, 10–15 km/h. At the places where speed bumps are actually installed, a speed limit of 20 km/h is imposed. Consistently, so was on the road stretch where the tests were carried out.

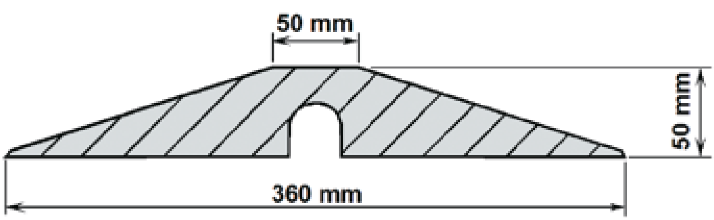

Fig. 6. Profile of the speed bump used at the road tests of the VW Passat car

[2] The limit speed of crossing a speed bump is the highest speed with which a medium-size passenger car (with a mass of 950–1050 kg) can cross the speed bump without considerable inconveniences in the car motion or a hazard to traffic safety [5].

Unfiltered time histories of the vertical vehicle body accelerations at the place of location of the Crossbow and VBOX IMU instruments, together with time histories of the vehicle body pitch rate, recorded for the vehicle with the "sport" set of shock absorbers, have been presented in Figs. 7, 8, and 9. Fig. 10 shows a comparison between the vertical acceleration vs. time curves recorded when the car with the "sport" shock absorbers crossed the first speed bump with speeds of 20 km/h, 30 km/h, and 40 km/h, with indicating the instants when the front and rear axle wheels run onto the speed bump.

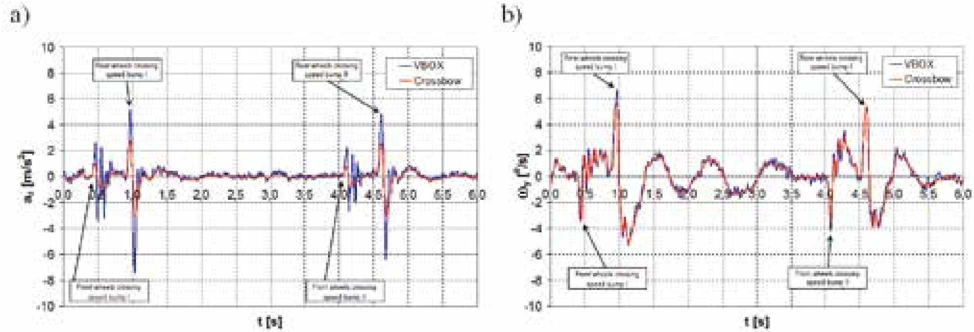

Fig. 7. Time histories of the vertical acceleration a_z and pitch rate ω_y measured with the use of the Crossbow and VBOX instruments for the vehicle crossing the speed bumps with a speed of 20 km/h

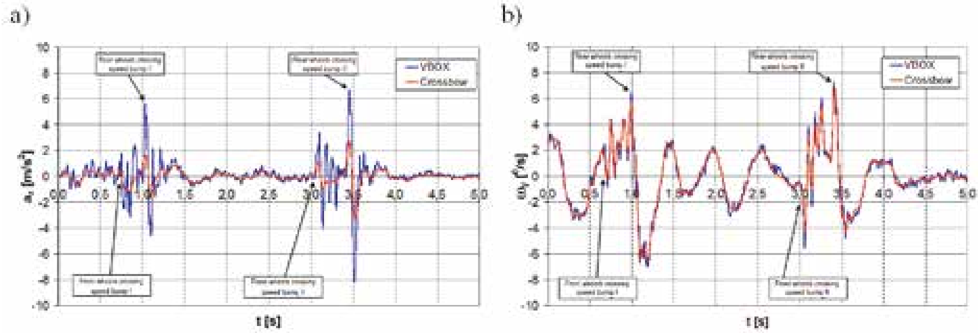

Fig. 8. Time histories of the vertical acceleration a_z and pitch rate ω_y measured with the use of the Crossbow and VBOX instruments for the vehicle crossing the speed bumps with a speed of 30 km/h

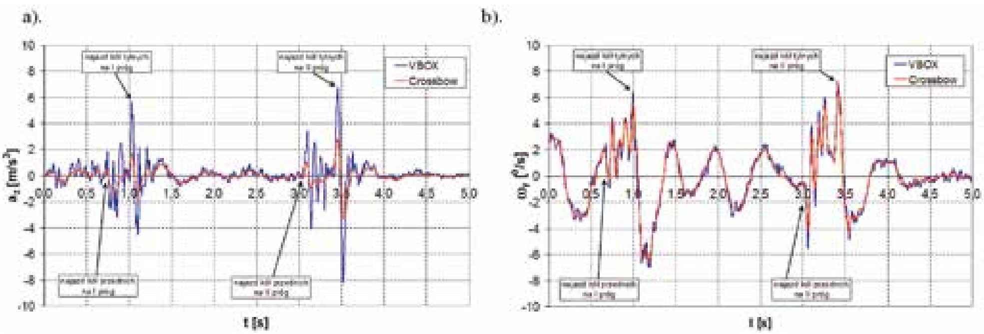

Fig. 9. Time histories of the vertical acceleration a_z and pitch rate ω_y measured with the use of the Crossbow and VBOX instruments for the vehicle crossing the speed bumps with a speed of 40 km/h

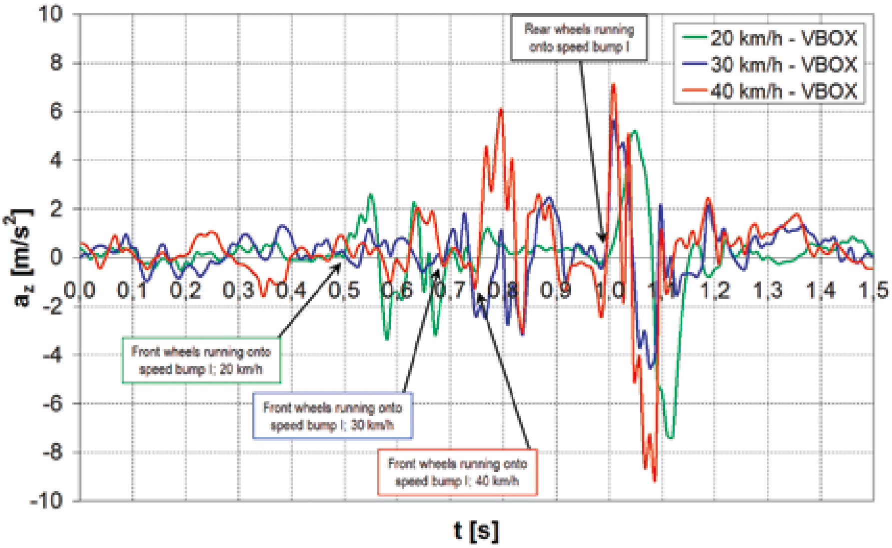

Fig. 10. Comparison of time histories of vertical vehicle acceleration a_z recorded when the car with the "sport" shock absorbers crossed a speed bump with speeds of 20 km/h, 30 km/h, and 40 km/h

The vertical acceleration vs. time curves, recorded by the VBOX and Crossbow measuring equipment with a sampling frequency of 100 Hz at almost the same place in the car, clearly differ from each other. The relatively smooth signal received from the Crossbow measuring block indicates that the signal has been filtered by instrument's electronic circuitry. In result of the filtering, even considerable changes in the measured quantity are smoothed if their duration time is short. Alas, the actual filtering parameters are not revealed by the equipment manufacturer and they cannot be modified by the user. In consequence, the maximum acceleration values obtained from one of the two measuring systems are 2.5 to 3 times as high as those read out from the other one (see Fig. 7a). A time history of the a_z acceleration similar to that recorded by the Crossbow apparatus can be obtained by averaging the VBOX IMU measurement results over 9–10 measuring points. A comparison between time histories of the vertical acceleration of a point over the rear wheel axle, determined for the "sport" shock absorbers by calculations from the parameters measured by the Crossbow and VBOX methods and directly measured by an HBM B12/200 acceleration sensor situated over the rear wheel axle (on the level of the floor panel of the car body), has been shown in Fig. 11.

The research results presented show that the VBOX system is more suitable for the measurements of vehicle body vibrations in comparison with the Crossbow measuring block and the data obtained from the VBOX system are closer to the results of measurements carried out with the use of a high-class acceleration transducer. The signal filtering system used in the Crossbow measuring block is related to the roll angle estimation procedure using the Kalman filtration method, where signals from acceleration sensors (in quasi-static conditions) or micro-electro-mechanical (MEMS) sensors of angular velocity (in

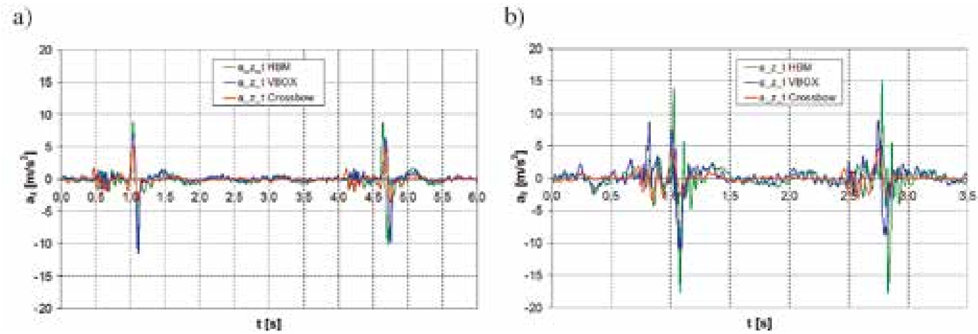

Fig. 11. Time histories of the vertical acceleration of a car body point over the rear wheel axle, calculated (red and blue curves) and measured (green curve), for the car with the "sport" shock absorbers crossing the speed bump with speeds of 20 km/h (graph "a") and 40 km/h (graph "b"),

dynamic conditions) are taken into account with a higher weight, depending on the rate of changes in the state of motion.

Conversely, such differences do not occur in the time histories of the vehicle pitch rate. Based on the research results presented, the consistency of the Crossbow and VBOX systems with each other may be considered good, both in qualitative and quantitative terms, within the scope of measurements of angular velocities.

3. Computer simulation of the crossing of a speed bump by a motor car

The computer simulations of the motion of a motor vehicle when crossing speed bumps were aimed at ascertaining whether it is possible to obtain simulation results sufficiently consistent with road test results if the vehicle model adopted in the V SIM 3.0 program is properly parametrized as regards the suspension system stiffness and damping characteristics and mass distribution among vehicle wheels. Therefore, the following data were introduced as inputs at the simulations presented.

- Data of the VW Passat car regarding the mass distribution as determined at preliminary rig tests, taken from the V-SIM program database.
- Appropriate data adopted for the model: suspension system stiffness – 32 kN/m (front) and 28 kN/m (rear); average vibration damping coefficients for standard shock absorbers (bump/rebound) – 1.37/2.06 kNs/m (front) and 1.16/1.73 kNs/m (rear); average vibration damping coefficients for sport shock absorbers (bump/rebound) – 0.95/2.6 kNs/m (front) and 1.30/2.80 kNs/m (rear). These data were obtained from suspension characteristics determined in the conditions of quasi-static and rig testing of the shock absorbers (which was mentioned in item 2.1 of this article); they differed from the "default" data of the program.
- Tyre model: TM-Easy, for tyres 195/55 R16.

- Speed bump: 0.05 m high, composed of flats consistent with the profile shown in Figs. 4 and 12.

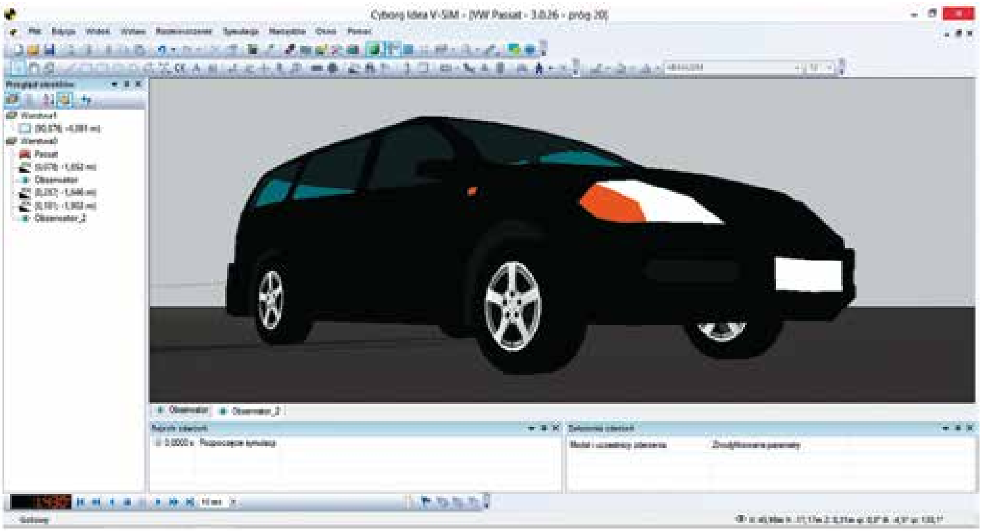

Fig. 12. 3D view of the crossing of a speed bump by a motor car, as modelled in the V SIM program

Figs. 13 and 14 show a comparison between the vertical accelerations of a car body point over the rear wheel axle as obtained from the road testing of the car with "sport" shock absorbers (measured with an HBM B12/200 acceleration sensor and calculated from the data produced by the VBOX system) and calculated for the said car body point from the data computed by the V SIM program for the centre of vehicle mass, for speed bump crossing speeds of about 20 km/h and 40 km/h. The vertical accelerations of the car body point over the rear wheel axle were calculated with the use of such data obtained from the V SIM program as distance between the centre of vehicle mass and the rear wheel axle and the vertical and angular (pitch) accelerations of the centre of vehicle mass.

Based on the road test and simulation results, the following findings may be formulated.

- The sensors and other measuring equipment used for the measurements of vertical accelerations of a vehicle body should not be provided with any filtering systems. Before a measuring instrument is selected for this purpose, its characteristics should be known; in special cases when this is justified, preliminary tests should also be carried out to verify the suitability of the instrument for specific tests.

- For low speeds of a motor vehicle crossing a speed bump, close to the value of 20 km/h imposed as a speed limit by the traffic signs placed before traffic calming devices of this kind, good consistency between the results of road tests and simulations was observed (Fig. 13).

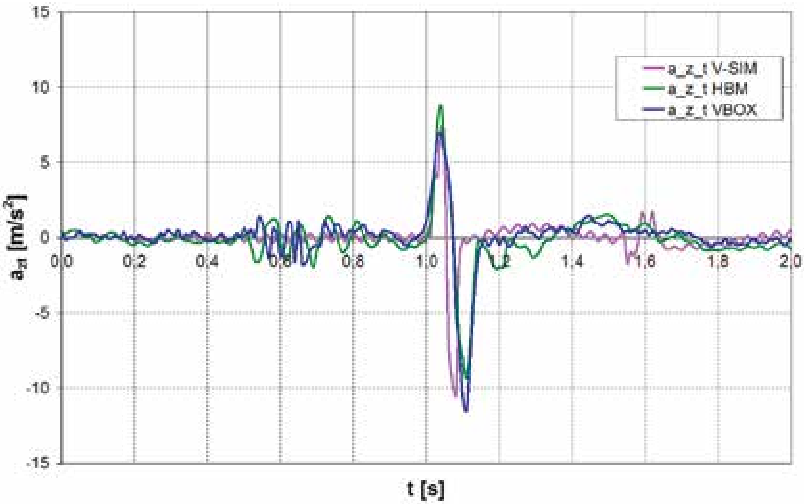

Fig. 13. Time histories of the vertical acceleration of a car body point over the rear wheel axle, obtained by calculation from the V SIM program (pink curve) and from the VBOX data (blue curve) and measured with an HBM B12/200 acceleration sensor (green curve), for the car with the "sport" shock absorbers crossing the speed bump with a speed of 20 km/h

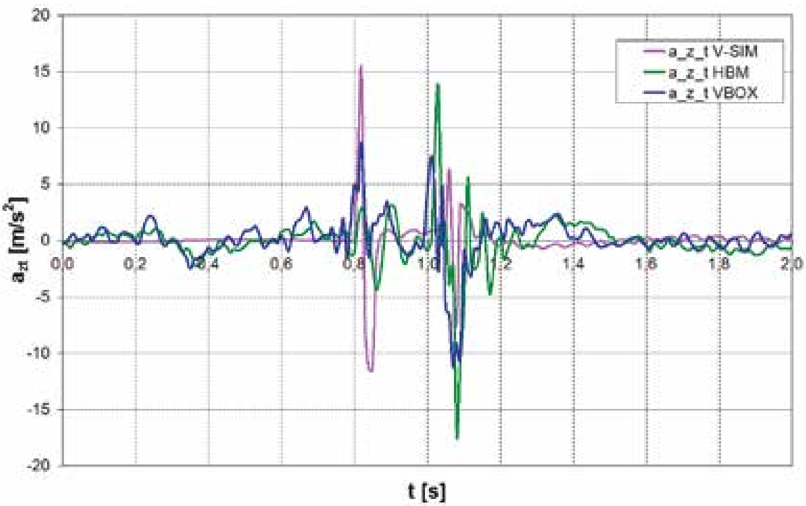

Fig. 14. Time histories of the vertical acceleration of a car body point over the rear wheel axle, obtained by calculation from the V SIM program (pink curve) and from the VBOX data (blue curve) and measured with an HBM B12/200 acceleration sensor (green curve), for the car with the "sport" shock absorbers crossing the speed bump with a speed of 40 km/h

- For the speed bump crossing speed of 40 km/h, the results of simulation tests carried out with the use of the V-SIM program revealed a problem of mathematical "simplification" of, inter alia, the models of vehicle suspension systems in relation to the real systems they represent. Obviously, it is impossible to introduce individual characteristics of the suspension system of a specific vehicle model, including its actual flexibility and capability of insulating the vibrations generated in the tyre-road contact zone, to a program of this kind.
- When the speed of crossing a speed bump by a car provided with shock absorbers of over-standard damping forces was doubled, the vertical accelerations of a car body point over the rear wheel axle were almost doubled as well. In such a case, the highest measured vertical acceleration related to the lifting of the car body when vehicle wheels were running onto the speed bump reached a value of about 14 m/s^2.
- If the vertical accelerations of a specific vehicle crossing a traffic calming device have to be evaluated then it would be reasonable to carry out road tests with the use of appropriate measuring equipment, such as e.g. an acceleration sensor or a VBOX system with an IMU inertial block. The road tests of this kind may be subsequently supplemented with appropriate calculations, providing that the point for which the accelerations are determined is rigidly connected with the vehicle body, unless the test objective is to carry out the measurements for a specific location in the vehicle.
- For the research on ride comfort or accelerations on vehicle seats, a special approach is required, where the method and area of loading the seat under test should be taken into account.

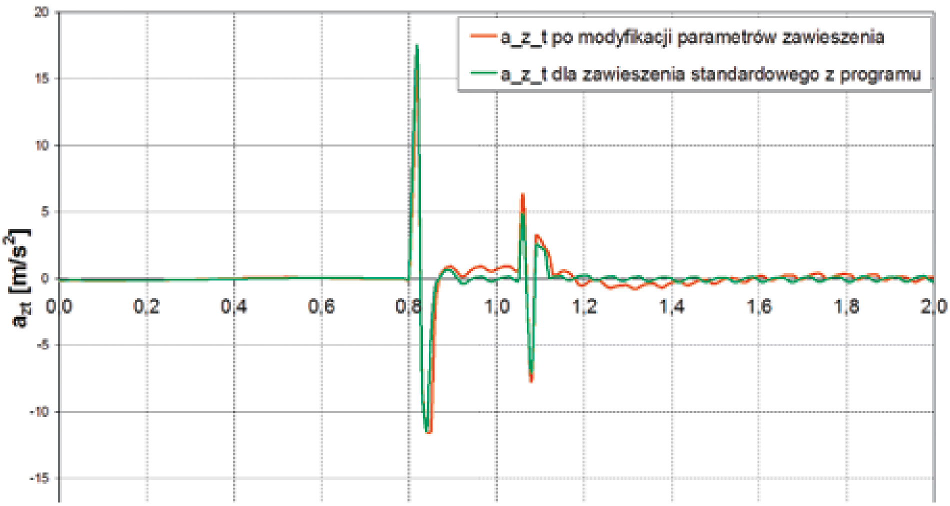

Fig. 15. Time histories of the vertical acceleration of a car body point over the rear wheel axle, calculated from a simulation in the V SIM program for the crossing of a single speed bump with a speed of about 40 km/h and for the standard suspension system parameters available from the program database (green curve) and for the parameters having been modified as described above (orange curve)

– The satisfactory consistency between the time histories of the quantities measured by the VBOX system and obtained from simulations carried out with the use of the V SIM program makes it possible to determine, at least approximately, the vertical vehicle body accelerations that may occur when the vehicle is crossing a traffic calming device. A separate issue is the possibility of appropriate parametrization of the vehicle model adopted in the computer program. An example of the differences in the effect of simulation of the crossing of a speed bump at modified and standard values of the stiffness and damping of the motor vehicle suspension system has been shown in Fig. 15.

4. Recapitulation

Devices intended to reduce the vehicle traffic speed are increasingly often installed on estate roads and on other roads where it is necessary to "discipline" vehicle drivers by forcing them to reduce the driving speed because of the presence of particularly dangerous spots (e.g. pedestrian crossings). Even if such spots are properly marked with appropriate road signs, an excessive speed of crossing the speed bumps, speed humps, or speed tables installed there may result in discomfort or even injuries to vehicle occupants and damage to the objects being transported.

The evaluation of the accelerations that occur at a specific speed of crossing such road infrastructure devices is a difficult research task. Detailed conclusions drawn from the road tests and simulations carried out and concerning both the measuring equipment used and the evaluation of parameters of the vibrations caused by the crossing of a speed bump have been presented in section 3 of this article.

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