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# ASSESSMENT OF THE EFFECT OF PASSENGER CAR WHEEL UNBALANCE ON DRIVING COMFORT

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## Abstract

This paper presents the results of experimental investigations of the effects of car wheel unbalance on driving safety and comfort. Basic information about types of wheel unbalance, their causes, and effects are included. The test subject was a BMW 3 Series car with rear-wheel drive. A specific unbalance was introduced on the front steered wheels. The vehicle was driven in a straight line on an asphalt road in good condition at speeds between 70 km/h and 140 km/h. During the test runs, acceleration waveforms were recorded from sensors placed on the lower control arm, driver's seat, and steering wheel. The vibration level of the unbalanced wheel increases with the driving speed and with the increase in unbalance. The highest increase in vibration amplitude occurred on the steering wheel at speeds between 100 km/h and 120 km/h. These vibrations have a direct effect on the driver. This is evidenced by negative driver perceptions such as fatigue and driving discomfort. This was also confirmed by the calculated vibration exposure levels. Driving with unbalanced wheels accelerates wear on the tyres, steering, drive, and suspension components of the vehicle.

**Keywords:** comfort; wheel balancing; vibration exposure; correction mass; steering wheel vibration

## 1. Introduction

To ensure comfort and safety while driving a passenger car, it is important to maintain the proper technical condition specified by the manufacturer and normative documents. One of the basic vehicle systems that ensures comfort and safety is the chassis system, including tyred wheels working directly with the road surface. If they are in poor technical condition, they can generate vibrations, deteriorate comfort, and adversely affect driving safety. An important aspect of the proper operation of this system is wheel balancing, which aims to minimise unbalanced centrifugal forces and centrifugal force moments. The value of the resulting forces associated with unbalance depends

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on the square of the angular speed of the wheel. Excessive wheel unbalance generates vibrations that are transmitted to the adjacent components. As a result, they cause accelerated wear to the tyres, bearings, suspension, and steering components, while also reducing driving comfort [21, 23]. From the driver's point of view, wheel unbalance is usually revealed by steering wheel vibration, which is more pronounced at higher driving speeds.

The primary means of determining the degree of wheel unbalance is by measurement using stationary or portable wheel balancing machines. Wheel unbalance is minimised by placing correction masses on the wheel rim. A great deal of information on wheel balancing can be found in the technical literature [9, 17, 18] and garage literature [26]. They describe the practical aspects of wheel balancing, the causes of imbalance in service, the processes for diagnosing vehicle suspension systems, and the methods and equipment used for successful wheel balancing.

Scientific studies address more complex issues and methods to determine the effects of unbalance on various aspects of car operation, including the harmful effects on car occupants. The impact of unbalance on driving comfort is usually assessed by measuring vibrations on the steering wheel and seats. This approach is presented, for example, in [28]. It presents the results of tests conducted for two different cars, in which additional correction masses were installed on the wheels, changing their unbalance. The effective value of the accelerations was used to assess comfort. Similar methods were used in the work [4], where the results of the influence of wheel unbalance on vibrations and comfort of child seats placed on the rear seat of cars were presented. The results confirm that discomfort associated with vibration of the seat increases with wheel unbalance.

Other methods are also used in research work. For example, in [15], a method is presented for identifying the static unbalance of a car wheel based on a simple road test using an acceleration sensor mounted on the windscreen. In [2], the acceleration measurement was performed using sensors placed directly on the road wheels, while in [12], signals from ABS speed sensors were used to determine the degree of wheel unbalance in combination with other information about the state of the vehicle. Modern smartphones provide new diagnostic possibilities. They usually have built-in accelerometers and/or gyroscopes. For example, the work [22] presented the possibility of using a smartphone mounted on the dashboard of a car and machine learning techniques to assess the condition of the road wheels.

The influence of wheel unbalance on other areas of vehicle operation is also considered in the literature. In [3, 11], the results of its influence on the condition of the electric motors fitted in the wheels were presented. Results of similar studies were presented in [24, 27]. In [25] influence of wheel unbalance on the vehicle stability was investigated. On the other hand, in [1] the influence of wheel vibration on the process of integration of chassis control systems and stability of an electrically powered car was considered. Simulation studies [1] have shown that vertical wheel vibrations play a detrimental role in vehicle stability In [10], the impact of unbalanced masses for the basic and adjusted configuration on the frequency response was presented. In [16] the possibility of detecting wheel unbalance during road tests on various quality roads was presented.

https://doi.org/10.14669/AM.VOL94.ART5

In [14], the new approach to the detection of wheel unbalance based on MEMS accelerometers and gyroscopes was presented. A commercial balancing machine was tested in various sensors placement configurations to improve detection levels. Based on the amplitude and phase extracted from acquired data, the proposed algorithm was capable to detect unbalanced mass including an angular position with reasonable accuracy.

This study attempts to assess the level of front wheel unbalance of a passenger car on driving comfort. A BMW 3 Series car was used for the study, and the assessment was made by determining the vibration exposure level.

## 2. Methods

The purpose of the study was to determine the level of comfort of driving a car on a road with unbalanced wheels on the front axle. A technically roadworthy BMW 3 Series car was used. Tyres of size 195/65R15 were mounted on the wheels. Before starting the measurements, the wheels were cleaned and balanced and the tyres were pressure checked.

An Endevco 44A16-1032 acceleration sensor with a measurement range of up to 500 $m/s^2$ was used to measure vibrations on the steering wheel (Figure 1a). The second sensor (triaxial seat pad accelerometer B&K 4515) placed in the measurement disk was located on the driver's seat (Figure 1b, also shows the measurement coordinate system). Additionally, vertical wheel accelerations were measured. The acceleration sensor was mounted on the lower control arm of the left front wheel near the ball joint. Vehicle speed was measured using a DS-IMU1 GPS module mounted on the dashboard by the right front pillar (Figure 1c). Sensors were connected by signal cables to a SIRIUS measurement card.

The research was carried out on the A2 motorway on straight sections of the road between Warsaw and Skierniewice. The motorway makes it possible to perform measurements at higher traffic speeds. Experimental investigations were carried out for the following configurations of wheel unbalance configurations:
a) conf. 1 – balanced wheels,
b) conf. 2 – an additional correction mass of 30 g placed on the left wheel,
c) conf. 3 – an additional correction mass of 60 g placed on the left wheel,
d) conf. 4 – an additional correction mass of 60 g placed on the left wheel and 30 g on the right wheel,
e) conf. 5 – an additional correction mass of 60 g placed on the left wheel and 60 g on the right wheel.

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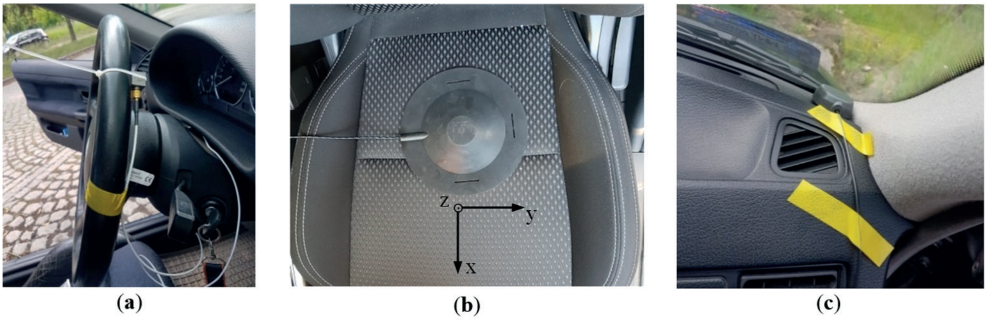

Fig. 1. Measuring equipment: (a) Endevco accelerometer on steering wheel, (b) B&K triaxial seat pad accelerometer and coordinate system - x, y, and z direction, (c) GPS module mounted on the dashboard

For each configuration, three runs were made at speeds ranging from 80 km/h to 140 km/h (in increments of 10 km/h). The driving speed was determined based on the GPS signal (indications of the car speedometer were overestimated by about 10 km/h). Each measurement had a duration of about 30 sec. In the beginning, to determine the reference level, vibration measurements were performed with the wheels balanced. Subsequently, additional masses of 30 g and 60 g were attached to the rim, performing subsequent measurements at different speeds (Figure 2).

Fig. 2. Correction masses mounted on the wheel; (a) 30 g, (b) 60 g

Perception and annoyance of vibrations generated by means of transport are subjective in nature [5]. Comfort was assessed based on steering wheel vibrations (hand-arm vibrations) and vibrations recorded at the driver's seat (whole-body vibrations). The basic quantity used to evaluate the exposure to hand-arm and whole-body vibrations is the frequency-weighted root-mean-square (r.m.s) acceleration, measured in the x, y and z directions at the workstation for each identifiable operation. The measured acceleration values are corrected (weighted) using correction curves, depending on

https://doi.org/10.14669/AM.VOL94.ART5

the type of vibration under consideration. This is due to the different human perception of vibrations depending on the frequency.

To assess local vibration exposure (on the steering wheel), the vector sum of frequency-weighted root-mean-square (r.m.s) acceleration (vibration total value) $a_{hvi}$ and 8-hour vibration exposure is calculated according to [7, 8, 13]. For each measurement, the value of $a_{hvi}$ is calculated according to the relation (1):

$$a_{hvi} = \sqrt{a_{hwxi}^2 + a_{hwyi}^2 + a_{hwzi}^2} \tag{1}$$

$a_{hwxi}$, $a_{hwyi}$, $a_{hwzi}$ are r.m.s values of the acceleration measured in the directions x, y, and z in the performance of the i-th operation, m/s$^2$.

Next, the value used is called 8-hour [7] (or otherwise daily) vibration exposure A(8) calculated by the relationship (2):

$$A(8) = \sqrt{\frac{1}{T_0} \sum_{i=1}^{n} a_{hvi}^2 \cdot t_i} \tag{2}$$

$n$ – number of operations,
$i$ – the number of the next operation performed in the vibration exposure,
$t_i$ – the total duration (per day) of vibration exposure for the i-th operation, min.
$T_o$ – the reference duration of 8 hours or an equivalent of 480 min.

During the assessment, it was assumed that $t_i = T_o$, i.e., it was determined what exposure would occur if a person drove a car continuously at a given forcing for eight hours.

The assessment of the exposure to the whole body vibration exposure is based on the highest value of 8-hour (daily) vibration exposure [6] among the exposures measured in three directions: $\max\{Ax(8), Ay(8), Az(8)\}$. $A_l(8)$ values for individual directions are calculated from the relation (3):

$$A_l(8) = k_l \cdot \sqrt{\frac{1}{T_o} \cdot \sum_{i=1}^{n} a_{wli}^2 \cdot t_i} \tag{3}$$

$n$ – number of operations,
$i$ – the number of the next operation performed in the vibration exposure,
$l$ – direction of vibration (x, y, andz),
$k_x = k_y = 1.4$, in x and y direction; $k_z = 1$ in z direction,
$a_{wli}$ – the root-mean-square frequency-weighted value of the acceleration, measured in the x, y and z direction, determined over the time period $ti$, m/s$^2$
$t_i$ – the total duration (per day) of vibration exposure for the i-th operation, min.

For hand-arm vibrations, the calculations assume that $t_i = T_o$.

The A(8) values shall be compared with the threshold values: the exposure action value (EAV) and the daily exposure limit value (ELV). When the value of vibration exceeds the EAV, the employer is obliged to take the actions specified in the law to reduce the occupational risk associated with vibrations. The ELV is the highest vibration intensity

https://doi.org/10.14669/AM.VOL94.ART5

in the working environment. The action value and the limit value are given in [19] and presented in Table 1.

**Tab. 1. Threshold values of mechanical vibrations [19, 20]**

| Types of human vibrations | The quantities characterizing mechanical vibrations | Action value | Limit value |
|---|---|---|---|
| Hand-arm vibration | Daily vibration exposure, A(8) | 2.5 m/s$^2$ | 2.8 m/s$^2$ |
| Whole-body vibration | Daily vibration exposure, A(8) | 0.5 m/s$^2$ | 0.8 m/s$^2$ |

## 3. Results discussion

The results obtained from the measurements were analysed according to the presented methodology. Figure 3 shows an example of the vertical vibrations of the lower control arm for a balanced wheel (conf. 1) and a wheel with additional mass (60 g on the left wheel, conf. 3) at a speed of 120 km/h. There are no significant differences in the nature of the waveform. It is the result of vibrations caused by the operation of the driveline and movement on a rough road surface. The lack of unambiguous differences in the waveforms indicates that the unbalance generates vibrations in a different plane. During the measurements, a uniaxial sensor was used, measuring only accelerations in the vertical direction.

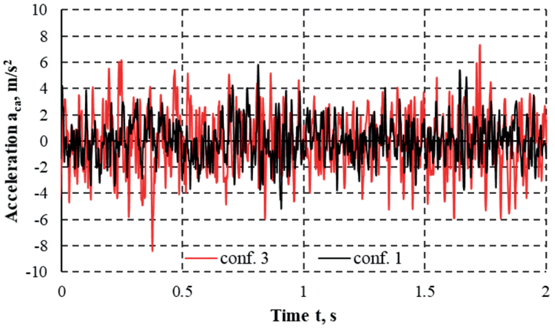

**Fig. 3. Vertical acceleration of the lower control arm $a_{ca}$ – speed 120 km/h**

Figure 4a shows an example of an acceleration waveform of the steering wheel $a_{sw}$. The highest vibration occurs in the direction tangential to the steering wheel. When driving with the wheels balanced, small vibrations are perceptible on the steering wheel, mainly related to the operation of the car engine. These are random in nature. The introduction of unbalance changed the course of the vibrations. In addition to a significant increase in amplitude, a dominant vibration frequency is noticeable, which is directly related to the rotational speed of the road wheels. The recorded acceleration amplitudes reached values of up to approximately 15 m/s$^2$. At a speed of 120 km/h, the fundamental vibration frequency was 17.5 Hz. The effect of unbalance is also noticeable on the driver's seat

(Figure 4b). The amplitude of the acceleration ads does not change as significantly as in the case of the steering wheel, but vibrations with a frequency resulting from the speed of the rotating wheels also begin to dominate.

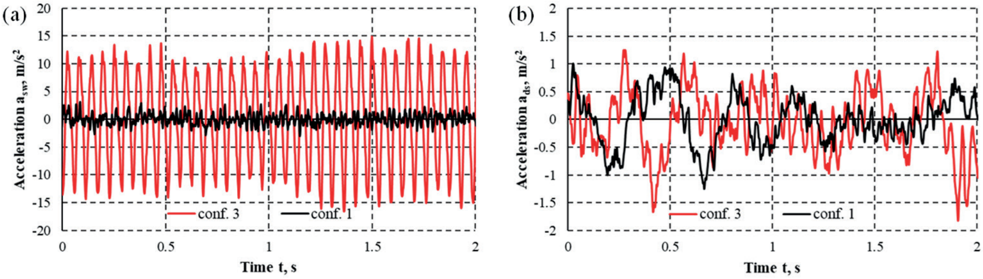

Fig. 4. Acceleration runs at a speed of 120 km/h; (a) steering wheel $a_{sw}$, (b) driver's seat $a_{ds}$

To assess the influence of the wheel unbalance value and the driving speed on the vertical vibration of the control arm, the root-mean-square value of the accelerations $a_{rms}$ was calculated. The result is shown in Figure 5. The occurrence of vertical wheel vibrations is directly related to traffic safety. They influence the value of the contact force and thus the value of the adhesion force and the braking force that can be developed. As stated previously, unbalance does not influence vibrations in the vertical direction unambiguously. The differences between the effective acceleration values for the different variants are not very large, although, for most speeds, the smallest values were recorded for the balanced wheels. The speed of movement has a greater influence. For practically all unbalance variants, an increase in the speed of movement of the car caused an increase in acceleration values. For higher speeds, the changes in the effective acceleration values are greater. Only for a wheel balanced with an additional mass of 30 g (smallest unbalance, conf. 2) at speeds higher than 120 km/h a stabilisation of the vibration level is observed.

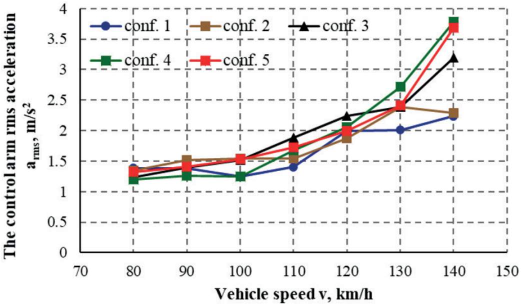

Fig. 5. RMS acceleration values of the lower control arm

https://doi.org/10.14669/AM.VOL94.ART5

To determine travel comfort, daily vibration exposure was calculated. Exposure to general vibration was determined from the accelerations recorded on the driver's seat. Figure 6 summarises the changes in the A(8) index as a function of the type of unbalance and the driving speed. Based on the obtained results, it can be concluded that the introduction of different unbalances does not unambiguously affect the level of observed accelerations. However, it must be stated that they depend on driving speed. As the speed increases, the exposure to overall vibration increases. When increasing the speed from 80 km/h to 140 km/h, the value of A(8) increased by approximately 30%. The lack of a clear effect of unbalance on the recorded accelerations can be explained by vibration damping by subsequent elements of the suspension, body structure, and first of all, vibration-insulating properties of the seat. At the same time, it should be emphasised that the tested car is not characterised by appropriate driving comfort. For all considered variants of unbalance and speed of movement, not only the permissible values of acceleration action threshold (0.5 m/s$^2$) were exceeded, but also the values of the highest permissible vibration intensity (0.8 m/s$^2$). In a work situation with this vehicle, it would not be possible to work continuously for eight hours a day.

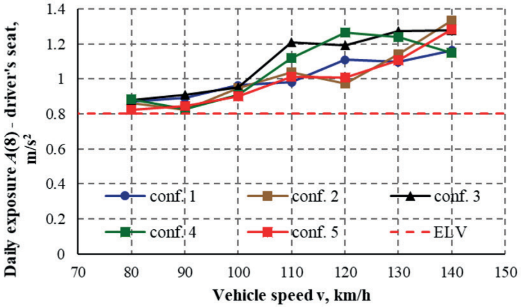

Fig. 6. Daily exposure A(8) on driver's seat

A different character of changes is observed for vibrations recorded at the steering wheel (Figure 7).

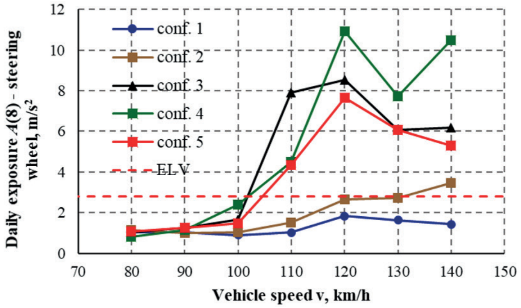

Fig. 7. Daily exposure A(8) on steering wheel

At speeds below 90 km/h, the A(8) values for all variants have similar values. For a balanced wheel, the changes in vibration level are not very rapid, although at 120 km/h a clear increase in A(8) can be observed. The introduction of an unbalance of 30 g (conf. 2) increases this phenomenon. For an unbalance of 60 g (conf. 3), a rapid increase in vibration is observed from a speed of 110 km/h. Extreme values of A(8) occur at 120 km/h. This corresponds to the resonance frequency of the wheel. Beyond this speed, the vibration amplitude decreases. The vibrations of the wheel are transmitted directly to the steering wheel through the rigid steering components and are mainly observed in the circumferential direction. Vibration in the direction perpendicular to the wheel plane changes only slightly. Above a speed of 100 km/h, for the variants in which a mass of 60 g (conf. 3, conf. 4, and conf. 5)was placed on the left wheel, the permissible vibration level was exceeded, while for a mass of 30 g (conf. 2) for speeds greater than 120 km/h.

At 120 km/h, the vibration level was so high that the driver felt fatigued after only a few minutes of driving. Prolonged driving with such a high level of vibrations not only leads to accelerated wear of the suspension elements and steering system, but it is also dangerous to the driver. It directly affects driving safety (perceptible deterioration of perception and exhaustion).

## 4. Conclusions

Observing the principles of wheel balancing contributes to prolonging the service life of the vehicle and its components, not only those most exposed to vibrations but also those which are indirectly affected. Moreover, it allows for the comfortable and safe movement of the vehicle. The correct balancing of the wheel components is important for the durability and reliability of the entire chassis system.

The decisive factor for the level of vibration of the control arm vibration in the vertical direction is the speed of the drive. Changing the unbalance did not significantly affect its level. Most probably, unbalance generates vibrations in the lateral direction, but a uniaxial accelerometer was used in the study. Only at a maximum speed of 140 km/h, the control arm vibration level of the driver for a vehicle with unbalanced wheels increases significantly.

The driver's seat prevents to some extent the propagation of high-frequency vibrations to the driver's body. An increase in speed from 80 km/h to 140 km/h resulted in an approximately 30% increase in vibration levels. It should be noted that the car used for the tests was not characterised by good comfort. Even at the lowest speed, the daily vibration exposure limit was exceeded.

The greatest influence of unbalance is observed on steering wheel vibrations in the circumferential direction. At a speed of 120 km/h, the introduction of 30 g (conf. 2) of unbalance increased the vibration level by approximately 50% and for 60 g by as much as 360% (conf. 5), significantly exceeding the permissible level. The driver experienced

https://doi.org/10.14669/AM.VOL94.ART5

exhaustion and discomfort after a short period of driving. The study confirmed that wheel unbalance negatively impacts driving safety and comfort.

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