MOBILITY & VEHICLE MECHANICS

DOI: 10.24874/mvm.2018.44.04.05
UDC: 656.13:534.836

EXPERIMENTAL AND NUMERICAL MODAL ANALYSIS OF BRAKE SQUEAL NOISE

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Received in August 2018 Accepted in November 2018

RESEARCH ARTICLE

ABSTRACT: In addition to different kinds of pollutants emitted by the vehicles, noise can also negatively effect on human health. It does not only threaten drivers, but also people living near major intersections and roads, as well as roads where traffic-flow is high. One of the biggest problems of the vehicle is the noise that occurs in the braking process. Despite the large scope of research into the development of brake systems, there are still no reliable procedures during the development phase to evaluate the robustness of these systems with respect to friction-induced vibrations. Therefore, the identification of the modal properties by using experimental methods has become even more important. Experimental and numerical modal analysis of the venting disc with radial ribs was performed in this paper. This approach enables the determination of the natural frequencies of the brake disc, as well as the verification of results obtained by the numerical methods. Changes in modal properties-resonance frequencies and modal damping values due to variation in operating conditions were also analysed.

KEY WORDS: vehicle, braking, noise, disc with radial ribs, natural frequency

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EKSPERIMENTALNA I NUMERIČKA MODALNA ANALIZA BUKE KOČNICA

REZIME: Osim emisije zagađujućih materija koje emituju vozila, buka takođe može negativno uticati na zdravlje ljudi. Nisu samo ugroženi vozače, već i ljude koji žive u blizini velikih raskrsnica, kao i puteva na kojima je protok saobraćaja visok. Jedan od najvećih problema vozila jeste buka koja se javlja u procesu kočenja. Uprkos velikom obimu istraživanja pri razvoju kočnih sistema, još uvek nema pouzdanih procedura u fazi razvoja za procenu otpornosti ovog sistema na vibracije izazvane trenjem. Međutim, indentifikacija modalnih osobina upotrebom eksperimentalnih metoda postala je jako važna. U radu je izvršena eksperimentalna i numerička analiza ventilirajućeg diska sa radijalnim rebrima. Ovakav pristup omogućava određivanje prirodnih frekvencija kočnog diska, kao i verifikaciju rezultata dobijenih numeričkim metodama. Analizirane su i promene modalnih karakteristika-rezonantnih frekvencija i vrednosti modalnog prigušenja usled varijacija radnih uslova.

KLJUČNE REČI: vozilo, kočenje, buka, disk sa radijalnim rebrima, prirodna frekvencija

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1. INTRODUCTION

Noise affects the heart and cardiovascular system and has a significant effect on various psychosomatic diseases. Different opinions of the authors have been noted in relation to the noise effect on the cardiovascular system, while one considers that there is an increased blood pressure, and the others, in contrast to its decrease. Research conducted for study the prevention of ischemic heart disease in people living in cities or parts of the city, where the level of public noise exceeds 65 dB, has shown a relative risk of disease from ischemic disease. Today, cardiovascular diseases are one of the most common causes of death, and these data has a high public health and social significance. It has been found, by investigating ECG waves and a cardiac rhythm that sounds of higher intensity have a greater impact on the occurrence of cardiac disorders [1].

It can be said that traffic noise is one of the most prevalent urban polluters in the city environment. Moreover, WHO (World Health Organization) categorizes the noise as the second worst ecological cause of poor health (PM2.5 is the first) [2]. This means that road traffic is the most dominant source of environmental noise, it is estimated that 125 million people are exposed to a noise level higher than 55 dB. While noise causes at least 10.000 cases of premature death in Europe each year, 8 million people have a sleep disorder, hypertension occurs in 900,000 inhabitants, and only 43.000 are examined by a doctor. A research performed by the Environmental Protection Agency of Ministry of Environmental Protection for 2016 was carried out in 14 cities in the Republic of Serbia at 195 measuring points. Statistics included residents exposed to a noise level of 55 dB and more for all sections of the state road network for which SNM (strategic noise map) was made, where the average annual flow is over 3.000.000 vehicles. During 24 hours, the largest number of inhabitants is exposed to a noise level of 55-59 dB, Figure 1. If it's a residential area, the noise level exceeds the allowed values, and in the case of the city centre, the zone along highways, main and urban roads, then it is below the allowed values [3]. The largest number of people exposed to night noise is 43.132, and the noise level ranges from 45-49 dB, Figure 2. Results of measurement of night-time noise, which represents the noise in the period from 22 to 06 hours, vary depending on the area in question. If it is a residential area, then it exceeds the permissible values, and in the case of a city centre or zone along highways, the main and city roads then it is below the permitted limits [3].

People primarily use passenger cars for their own personal needs, such as going to work, vacation, shopping, etc., simply saying, to travel from one point to another. The biggest problem with today's vehicles is the comfort and noise produced by the vehicle during its exploitation. The level of noise inside the vehicle has been steadily falling over the past few years. So the appearance of any sound can lead to disturbance of the driver, as well as to his distrust in his own vehicle. One of the vehicle components occasionally produces unwanted vibrations, and unpleasant sounds are their braking systems. Manufacturers of brake and friction materials face very challenging requirements [5]. They need to know what are the characteristic noise, as well as the cause of the noise generation [6].

Dynamic oscillations in friction brakes that cause noise, vibration and rigidity can be classified into two groups [7]:

- Dynamic instability which results in a constant resonant frequency independent of rotor and
- Mechanical vibration with a frequency related directly to rotor speed.

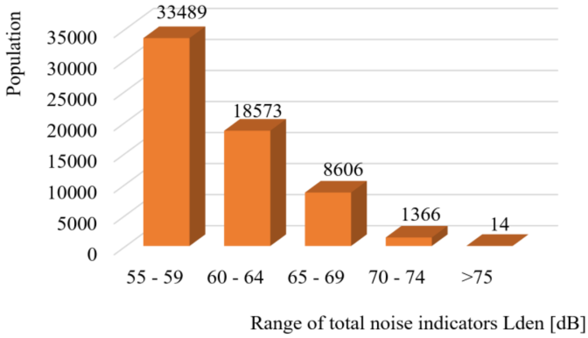


Figure 1. Population exposed to road traffic noise expressed over the range of total noise indicator Lden [4]

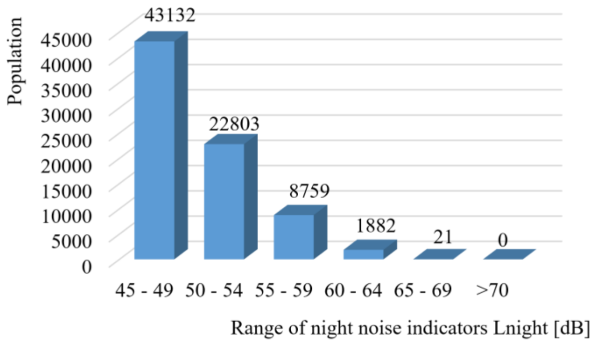


Figure 2. Population exposed to night road traffic noise expressed over the range of average night noise level Lnight [4]

The brake noise usually occurs in the range from 100 Hz to 20 kHz (which is the upper limit of human hearing) and in the case of classic brakes, the braking squeal occurs in the range of 1-6 kHz, where the human ear is the most sensitive. Within the definition of noise and brake judder, there are many subcategories of noise and judder of the brake [7, 8], Figure 3. A typical estimate of the proportion of warranty claims based on the different categories of brake NVH (Noise, Vibration and Harshness) is shown in Figure 4.

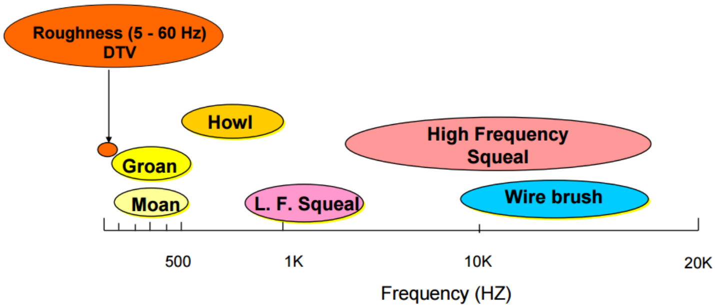


Figure 3. Frequency range of different vibro-acoustic phenomena generated by vehicle brakes [9]

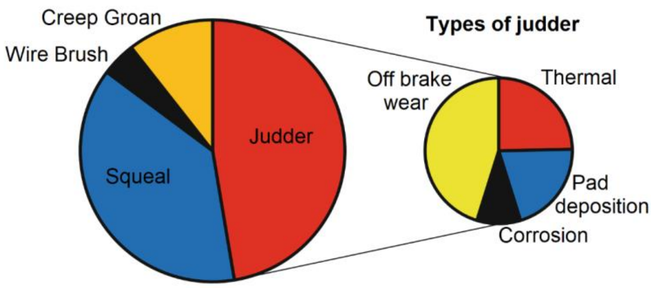


Figure 4. Typical distributions of warranty issues reported by high performance vehicle manufacturer [7]

There are several basic methods for determining the resonance vibrations of a brake disc such as [10]:

- Using a pulsator with any of the commonly used excitation functions, e.g., sine, random, transient
- Using a dynamometer and braking system, and
- Impact Hammer.

The most commonly used method is the impact hammer method. The reason for this is the cost of the equipment, as well as the simplicity of the experiment. As is the case in this study, in a large number of analysed researches, the response to the excitation is measured by acceleration sensors, while in some studies, the measurement was performed by a microphone [11]. If the measurement is done by acceleration sensors, the number of sensors used in the experiment can range from one to four sensors [12-14]. In addition, depending on the sensor, it also depends on the connection to the brake disc itself. For example, the sensor can be coupled with brake disc by using the beeswax [15]. Competition on the market is only possible if the experiments are fast, and this is achieved only by the use of numeric analysis. Of course, the accuracy of the results obtained this way should not be omitted, and this is achieved if the numeric analysis is calibrated with the experiment [16]. If the obtained numerical results are satisfactory, they can be used for further analysis [12].

However, an experimental study of structural dynamics has always contributed greatly in understanding and controlling the vibrational phenomenon that is encountered in practice.

Regardless of the fact that today, there are computers with high performance and capabilities, but the need for an experiment is the same as before, for several reasons [17]:

- Determining the nature and level of vibration that occurs during operation
- Verification of the theoretical models and the prediction of various dynamic phenomena which are collectively referred to as "vibrations", and
- Measurement of the basic properties of materials due to the effects of dynamic loads, such as damping, friction and fatigue endurance.

The problem of structural vibrations continues to be a huge danger and design constraints for a wide range of engineering products. These disorders in the system may be unacceptable for the system's planned operation. In this case, the engineer must determine how to minimize or eliminate unwanted vibrations occurring within the system. However, it can sometimes be very difficult when the cause is unknown [18]. At the end, it is most important that the vibration level is reduced to permissible level.

One of the aims of the paper is to determine the natural frequency of the passenger car's brake disc experimentally, then to modify numeric analysis based on the results obtained by the experiment. So for the future research it is not necessary to conduct experiment first.

2. MODAL ANALYSIS

In the past two decades, modal analysis has become one of the main technologies for determining, improving and optimizing the dynamic characteristics of the different types of structures. Application of modal analysis is very wide, engineering disciplines where she found the application in engineering, aerospace and civil engineering [19]. The reason for the application is [20]:

- Revealing the causes of unpredictable material behaviour
- Construction modification
- Sensitivity analysis
- Simplification of mathematical models
- Predicting the response on disturbance force and
- Detection of structural damage.

Modern constructions are expected to have a small mass and to be a simple as possible, and at the same time sufficiently strong [20]. The requirement to reduce the mass of the construction is highest in the automotive and aviation industry. Unless sufficient attention is paid to reduce the mass, unwanted vibrations may occur in certain exploitation regimes. Modal analysis represents the process of determining the basic dynamic characteristics of the structure, such as natural frequency, damping and oscillation modes, in order to formulate the dynamic behaviour of the model [21].

There are two approaches to the modal analysis, the so-called experimental modal analysis, where the modes are determined by using the acceleration and displacement sensors. The second approach is the theoretical modal analysis, where the prediction of modes is performed by using the appropriate mathematical methods (FE-based eigenvalue extraction or MBD analysis of the vibration behaviour of the brake assembly) [9]. Today's software for modes determination is working according to the principle of mentioned mathematical models. The lack of experimental research is reflected in the fact that they cannot be examined during exploitation, or more accurate in road conditions. The vehicle must be examined in the laboratory, on dynamometer rollers, or the brake assembly must be mounted on the appropriate dynamometer for testing. If a person conducting a test, rather than a robot, the repeatability of the results is almost impossible. Verification of results obtained by the numeric analysis requires that they must be approximate to the experimental results or to be a very close to them. So after the experiment, numerical analysis can be performed. The research in this paper is performed by using the experiment and numeric analysis. The braking disc that was research subject in this paper is the vented disc with radial ribs, Figure 5.

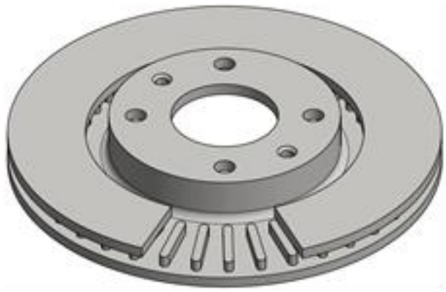


Figure 5. 3D model of vented brake disc

2.1 Experimental analysis

The applied experimental method is based on using impact hammer and with this method, it is necessary to provide the following:

- Impact hammer with head which can measure input force
- Acceleration sensor
- FFT analyser for determining the frequency response function, and
- Software for data processing and results showing.

Before starting the experiment, it is necessary to provide the appropriate conditions. This refers to base on which the measurement object will be placed, in this case the brake disc. It can be noticed, In reviewed literature that the disc can be located on a sponge, or to hang on elastic ropes that are used for securing cargo during the transportation, or to be fixed [12, 13, 22-24]. In this research, the chosen way of mounting the brake disc is to place a disc on the sponge. Measurement installation used for the experiment is shown in Figure 6. Experiment is performed using the NetdB 12 acquisition device. Excitation of the brake disc is performed by impact hammer (PCB Piezotronics 086C03). The impact hammer consists of a top, a force sensor, a balancing mass and handles. The top, which is placed on the impact hammer, is a soft impact cap. The force sensor is a piezoelectric and is embedded in the hammer's head to capture the impact force. The response is measured by acceleration sensor AC102, marked with a black circle in Figure 6. The acceleration sensor is connected to brake disc by the magnet. Figure 7 shows the disc with the sensors used for measurement, as well and disc placement. The experiment results have been stored on a computer, which was later processed.

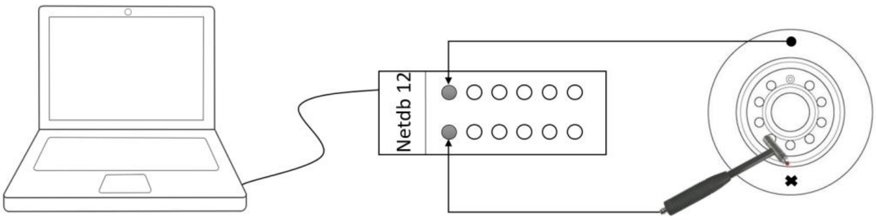


Figure 6. Measurement installation scheme

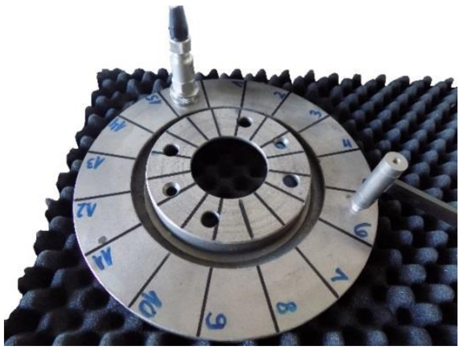


Figure 7. Brake disc with sensors

When performing such an experiment, two conditions must be provided are:

- The location of the acceleration sensor is very important to get the best record of the response. If the acceleration sensor is placed where impact impulse is very small, it will be very difficult to record FRF. Acceleration sensor should be placed where high structure responses are expected. By analysis that is earlier performed on different variants of the disc, it can be concluded that highest modes occur on friction ring of a brake disc [25].
- The applied top for the impact hammer - the top to be used is the one that activates as many natural frequencies as possible [15].

The Frequency Response Function (FRF) describes how the system will react to the impulse. If a particular amplitude and frequency impulse is introduced into the system, the system will start vibrating at the same frequency as the impulse, but with the phase shift. The response amplitude depends on the amplitude and frequency of the impulse. The relationship between the amplitude of the response and the excitation impulse is the FRF and is phase-shifted to any frequency [26].

2.2 Numerical analysis

First, the brake disc shown in Figure 5 is created in CATIA software package, and as such is imported into the analysis software – ANSYS. 3D model of brake disc is created in real size.

The conditions in which the experiment was conducted are also defined in the analysis software. This means that it is first necessary to define the temperature at which the experiment was performed. The used type of final elements is tetrahedral; the number of elements is 21.137, while the number of nodes is 38.978. As the disc is tested under static conditions, the degree of freedom is zero, which is also defined in the analysis software. In order to bring the results of the numerical analysis closer to the values obtained by the experiment, it is necessary to get the accurate data on the used material characteristics. The results of the modal analysis carried out by using numerical analysis are most influenced by the Young's module, which has proven both in this research and in the research of other authors [15, 27]. The characteristics of the disc brakes' material are shown in Table 1.

Table 1. Material characteristics of the brake disc

Density, kg/m^3	Young's module, MPa	Poison ratio
7600	197,000	0.26

The results obtained by numerical analysis are presented in the form of nodal diameters since they are the most dominant in the occurrence brake squeal. The reason for this is that the disc tends to vibrate around one or more node diameters at the same time, Figure 8. The operation of nodes in this case causes the disc to get a waveform. The number of node diameters is based on the number of nodes and anti-nodes that appeared on the surface of the disc that is in contact with the brake pads [7]. The number of nodal diameters gives the so-called number of vibration modes. The result of this phenomenon in the form of a brake disc noise is usually due to one or more nodal diameters.

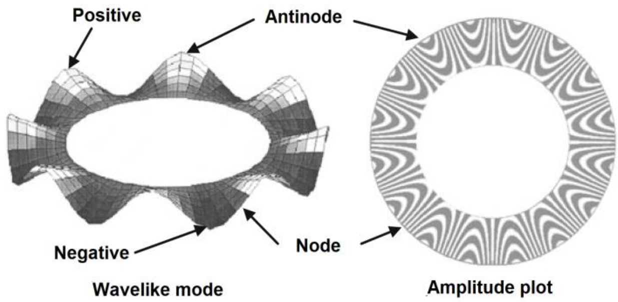


Figure 8. Typical 8 diametrical mode of vibration—16 antinodes [7]

2.3 Results and discussion

The result frequencies of the experiment and numerical analysis are in range up to 11 kHz. This value corresponds to the upper limit of high-frequency brake noise. The numerical analysis has been modified so that the deviations between the values of the experiment and the numerical model are as small as can be seen in Figure 9, while the error values are given in Table 2.

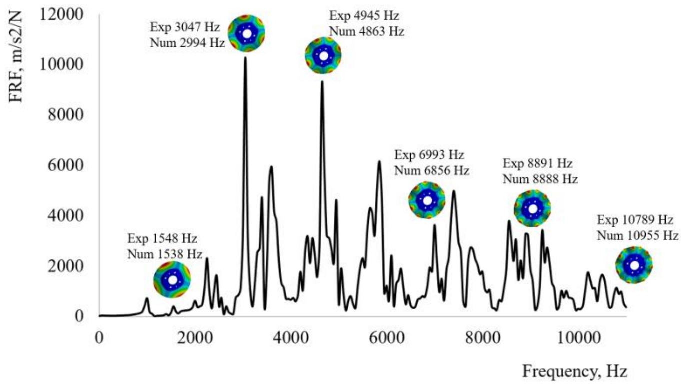
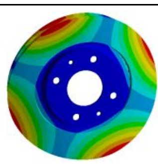
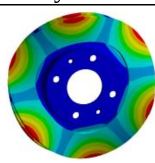
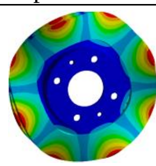
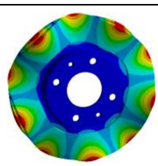
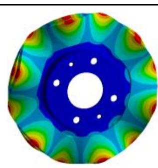
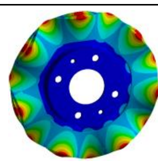


Figure 9. Experimental and numeral response of the free-free disc

The optimum choice of material's characteristic has resulted in a maximum obtained error value of 1.96%, Table 2. The error between the results of the experiment and the numerical analysis is small, so for the future research the characteristics of the materials shown in Table 1 can be used. The number of nodes can be displayed related to the frequency, which should be approximated by the smooth curve [7], shown in Figure 10. If this condition is satisfied, the results obtained by the numerical analysis can be accepted completely. For better illustration of the frequency, the geometry of the disc is observed. This means that the frequency means can be represented related to the angle between the nodal diameters. Analysing Figure 11, it can be noticed that as the frequency increases, the angle decreases. The higher the frequency, the higher the number of nodes is, which directly affects the reduction of the angle between them.

Table 2. Error between numerical analysis and the experiment

			
Experimental, Hz	1548	3047	4945
Numerical, Hz	1538	2994	4863
Error, %	0.65	1.74	1.66
			
Experimental, Hz	6993	8891	10789
Numerical, Hz	6856	8888	10955
Error, %	1.96	0.03	-1.54

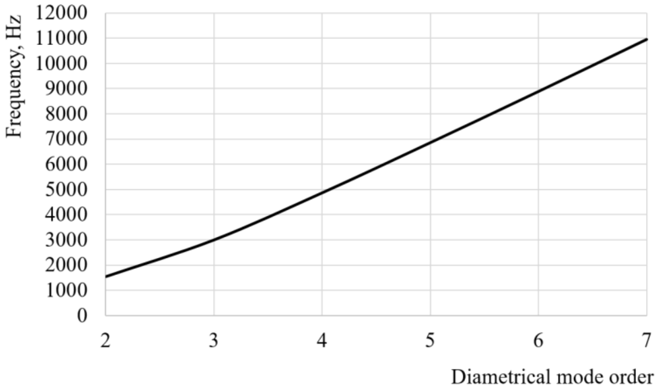


Figure 10. Natural frequency of free-free in function of number of nodes

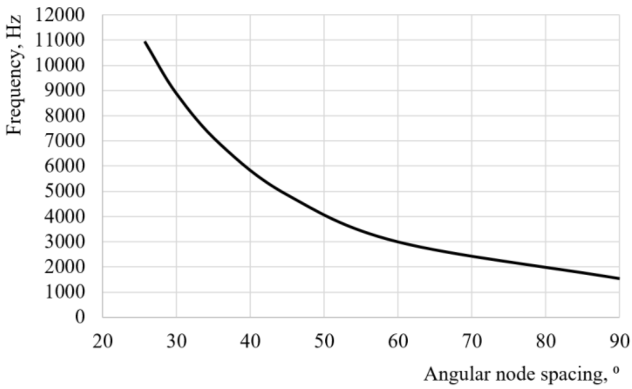


Figure 11. Frequency in function of antinode angular spacing

3. CONCLUSIONS

Traffic noise is one of the dominant sources of noise in urban areas. Today there is a tendency to reduce noise to a greater extent. One of the main reasons is that noise has a very negative impact on the health of humans living in her immediate vicinity. Car manufacturers have, in recent years, been able to reduce the noise generated by the vehicle during the exploitation. So any sound that occurs during the exploitation can cause distrust from the driver and that the vehicle spent most of the time on the service instead of what is its primary purpose. One of the most undesirable and irritating sounds that can occur during the exploitation is the brake noise. The experimental methods for determining the brake noise are the application of pulsator, dynamometer or impact hammer method. The method used during research represented in this paper was using the impact hammer. It is very important to determine the natural frequency of any system and tries to reduce it as much as possible. In this process, it must be ensured that there are no disturbances of other characteristics that are very important for the safety of vehicles in traffic.

The modal analysis was performed by the experiment, and then, based on the results of the experiment, the verification and modification of the numerical analysis results were performed. The numerical results do not deviate to a large extent, so that for future research, the initial parameters for the performed analysis, or the characteristics of the material, can be used. Further research can be carried out on determining the natural frequency for the other components and verification of the numerical data based on the results obtained by the experiment. The next step would be to determine the natural frequency for the assembly as well to determine the frequency during braking process.

ACKNOWLEDGMENT

This paper was realized within the researching project “The research of vehicle safety as part of a cybernetic system: Driver-Vehicle-Environment” ref. no. 35041, funded by Ministry of Education, Science and Technological Development of the Republic of Serbia.

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