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Design of experimental research on influencing factors on the particle emission caused by brake wear

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Abstract *The aim of this paper is to present the design of the experiment to determine the most influential factors on the occurrence of non-exhaust emissions of $PM_{2.5}$ and PM_{10} particles, namely those caused by vehicle's brake wear. The focus in this case is on the operating parameters of the braking process (vehicle speed, brake pressure and vehicle load), ambient conditions (temperature and air humidity), but also output factors (brake pad temperature at the end of braking, braking torque, braking time, deceleration) and analysis of their connection with the formation of particles. The experimental research was carried out on an inertial brake dynamometer. Classical experiment planning is sometimes too complex and time-consuming, so in the case when the number of factors increases, it is necessary to perform a large number of experimental tests. Experiment planning is a method by which the optimal formula of all influential parameters is found, and as such it represents a very important tool that can be used to respond to a well-defined research goal. The basic idea of a planned experiment is to define a minimal set of experiments in which each factor will be varied in a systematic way.*

Keywords *Brakes, particles, emission, design of experiment, Taguchi method*

1. INTRODUCTION

Experimental measurements represent a complex process of determining different occurrences, phenomena and relationships between different variables. The application of experiments in science is often used to confirm or reject various hypotheses. Often, experiments vary various factors to determine the relationship between those factors.

During experimentation, the factors are varied in a planned manner and in this way, analysis is enabled, which could lead to correct conclusions. Today, various methods and algorithms have been developed by means of which it is possible to combine various factors in a way that would lead to the correct conclusions during the analysis of the obtained results, as well as the correct connection of the input factors. Design of an experiment is a set of knowledge and techniques that help the experimenter to conduct the experiment in an economical way, to analyse the data, and makes connections between the conclusions from the analysis and the original research objectives. By applying the design of experiments, and in the case of a large number of parameters, combinations of those parameters are obtained so that it is an optimal combination for later analysis. In this way, the number of

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measurements that should be performed is reduced.

Designing experiments can be done in different areas, including in the area of performing experiments on vehicles, such as the monitoring the formation of particles due to brake wear.

The airborne particle pollution whose source is the vehicles i.e. traffic is a very serious problem, and it is important from the aspect of the impact on environment and humans. The problems are even bigger if we take into account that it can affect the human immunity, organs, the formation of cancer, but it still has a number of negative effects on other aspects. If we look at the pollution of different European countries in the past 20 years, it can be seen that some of the countries have a high concentration of particles caused by tire and brake wear.

By researching brakes as a source of respirable particles, it is concluded that the formation of particles is the result of the wear process of the elements of the friction pair of the brake, which in the case of disc brakes, as the most applied constructive solution, are the disc (rotor) and brake pads. It is a well-known fact that after a certain number of braking, it is necessary to replace the brake pads due to the wear of the friction linings, but to a lesser extent, the disc wear is also present. All worn brake material is released during vehicle movement, primarily into the air, in the form of particles of various sizes. The harmfulness of particles is reflected not only in their size, but also in their composition, bearing in mind that the composition of particles depends on the material of the source from which they originate, so it is also necessary to analyse the composition of friction pairs that is, the materials used to make them. In some countries, legislation has been introduced that limits the percentage of certain materials in the composition of friction pairs in order to reduce harm. Numerous research projects have been launched in Europe and the world, with the aim of reducing the concentration of emitted particles, and thus reducing their harm, by applying modern production technologies.

The activation of the braking system, as well as its functionality, depends on various parameters. During braking, the friction pairs of the brakes wear out, and thus the formation of particles. Input factors related to braking system activation can also affect wear and particle formation. In order to determine the relationship of various parameters on the formation of particles and to reach a conclusion about the influence of various factors on the phenomenon, experimental measurements can also be performed.

An example of designing an experimental measurement using the Taguchi method is presented in this paper. The method of designing the experimental measurement based on some input data that were varied during the measurement of PM_{10} and $PM_{2.5}$ particle emissions is explained. Furthermore, an example of analysis using this method based on data obtained by planning an experiment using this method is presented.

2. TAGUCHI DESING OF EXPERIMENT AND ANALYSIS METHOD

Applying the Taguchi method is a fairly simple process if the user is sufficiently familiar with the functions offered by the analysis. In this case, the Minitab software package was used for data analysis. The use of parameter arrangement in the Taguchi approach is an engineering method that specializes in determining parameter settings giving optimal levels of quality with minimal variance around target value for a product or technique (Figure 1) [1,2].

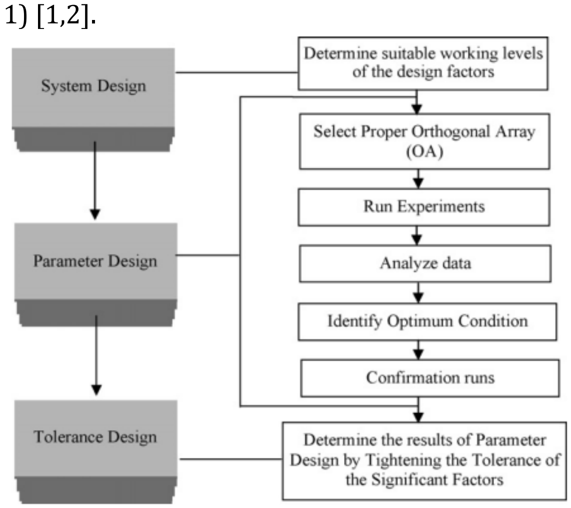


Fig. 1. Taguchi design process [3]

Planning experiments is one of the processes, should to be noted that reducing the combination of factors, and everything is done in several steps [4, 5]. Taguchi configuration is a planned test that allows you to choose an item or cycle that is more reliable in the operating environment. Taguchi's plans note that not all factors that cause inconsistency can be controlled. These wild factors are called disturbance factors. Taguchi plans attempt to identify control variables (control factors) that limit the influence of a factor on other different variables. During trial and error, signal-to-noise ratios (S/N factor) are controlled to encourage variability of the various factors. An interaction planned with this goal in mind will create a more reliable result. An item designed with this goal in mind will have a more predictable factor performance regardless of the environment in which it is used [6]. Taguchi designs of experiments use symmetric exponents, which measure the effects of elements on the mean and diversity of a reaction.

Taguchi designs use orthogonal arrays, which estimate the effects of factors on the mean and variance of responses. An orthogonal array means that the design is balanced, so the factor levels are equally weighted. Therefore, each factor can be evaluated independently of all other factors, so that the effect of one factor does not affect the evaluation of another factor. This can reduce the time and cost associated with an experiment when fractionated designs are used [6].

The L(number) (number^exponent) notation informs you of the following:

- L(number) = number of runs (number^exponent)
- number = number of levels for each factor
- exponent = number of factors [7].

For example, L27(3^13) means that the design has 27 runs and 13 factors with 3 levels [7]. If the notation is L (number^exponent number^exponent), then it is a mixed-level design. For example, L18 (2^1 3^7) means that the design has 18 runs, 1 factor with 2 levels and 7 factors with 3 levels [7].

Because of the complexity of the brake pad-disc wear process, a scientific methodology is required to analyse the tribological properties of this friction pair. Design of the experiment (DOE) is one of the most important statistical techniques for studying diverse influencing factors by lowering the number of multiple trials. The Taguchi design technique leads to the removal of unnecessary experiments in the process [8].

In this paper, two different levels were applied to investigate the influence of the design of the experiment on the obtained research results. Those two levels in this case are mixed levels, namely L16 (4^2 2^1) and L32 (2^1 4^2).

3. PARTICLE MEASUREMENT METHODOLOGY

The examination of the formation of particles that occur during brake wear in this case was carried out in laboratory conditions. The research used an inertial brake dynamometer (Figure 2), which is developed at the Faculty of Engineering at the University of Kragujevac. The application of an inertial brake dynamometer is suitable for simulating and analysing the processes that occur during braking under different test conditions. In the case of measuring particles caused by brake wear on the dynamometer, it is necessary to install additional devices that collect particles or that prevents the collection of particles from the environment.

The device Trotec PC220 was used to measure the emission of particles. This device measures the emission of PM_{10} and $PM_{2.5}$ particles. The device is mounted on the housing inside which there is a disc brake and a brake caliper with brake pads. The display of the installed device on the housing is shown in Figure 3. The reason for using the housing on the inertial brake dynamometer is that there are particles in the atmosphere whose source is not the braking system. The housing enables the extraction of only the particles that are produced during the braking process, which means that the device measures only the particles that are the subject of this research. Before each measurement, the housing is cleaned of particles from the atmosphere and particles from the previous braking process.

Fig. 2. Inertial brake dynamometer Brake Dyno 2020

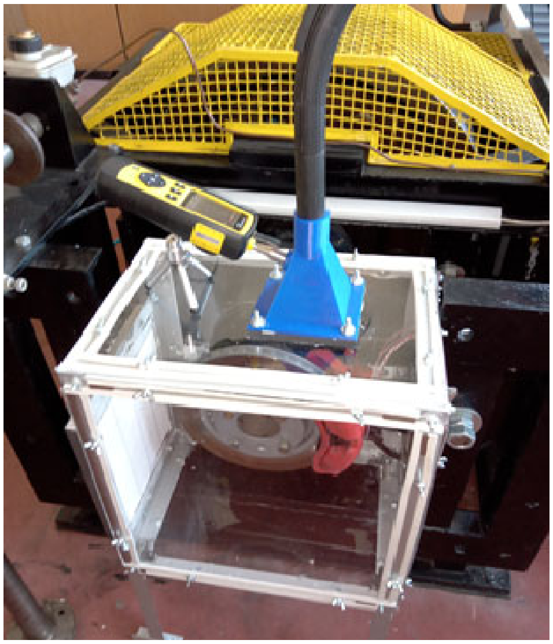


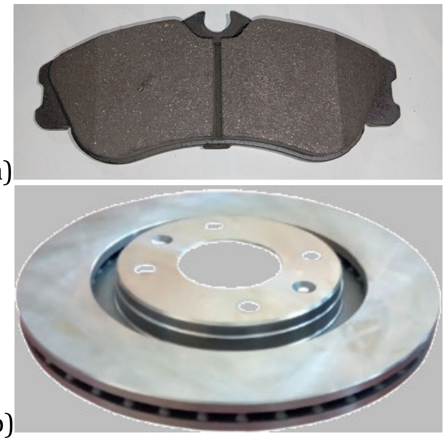
Fig. 3. Housing in which the brake is located on the inertial brake dynamometer

By analysing numerous researches in which different driving tests and cycles were applied [1, 9], the authors obtained data on the most frequently applied parameters that were varied in those tests, as well as their value ranges. Based on those studies, the values of speed, brake pressure and load of one quarter of the vehicle were varied as input braking parameters. The data that were chosen as the parameter values in this case are shown in Table 1. Also, these parameter values were used to design the experiment.

Table 1. Values of parameters that are varied in particle emission measurement

Parameter	Value
Brake pressure in hydraulic system [MPa]	1, 2, 3, 4
Simulated mass of quarter vehicle-load [kg]	150, 250
Simulated initial brake speed [km/h]	20, 40, 60, 80

As a friction pair in this research, a disc and brake pads was used, which are shown in Figure 4. Figure 4a shows the brake pad that was used in this case, it has an eco-friendly formulation, which means that it is applied very a small percentage of metal, i.e. ecologically clean materials were used.

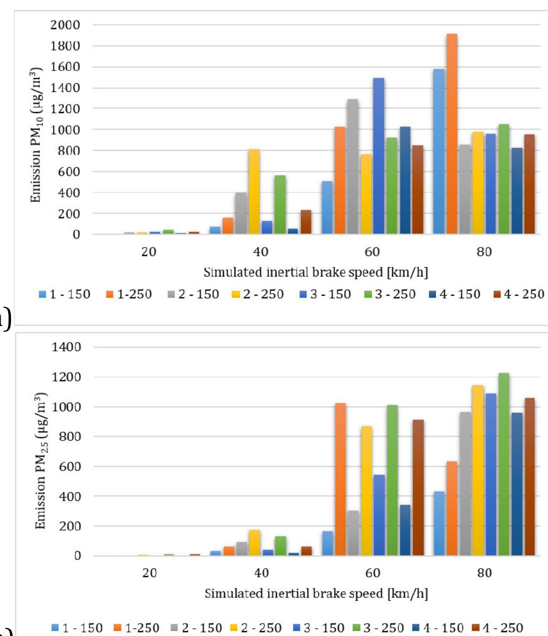


a)
b)

Fig. 4. Applied brake friction pairs, where: a) brake pad, b) brake disc

4. RESULTS ANALYSIS

Using the inertial brake dynamometer in this case, the results related to the formation of PM_{10} and $PM_{2.5}$ particles were obtained. Figure 5 shows the obtained results of particle measurements on an inertial brake dynamometer. These data were used later in the data analysis. In this case, all the data were varied in order to later determine if there is a difference in the obtained data as analysed.



a)
b)

Fig. 5. Obtained results of particles measurements, where: a) PM_{10}, b) $PM_{2.5}$

The obtained measurement data can also be displayed using a 3D diagram, which can be used to display the obtained measurement data in detail. Figure 6 shows the measurement data based on several analysed parameters. All the data presented refer to the various obtained values of particle emissions.

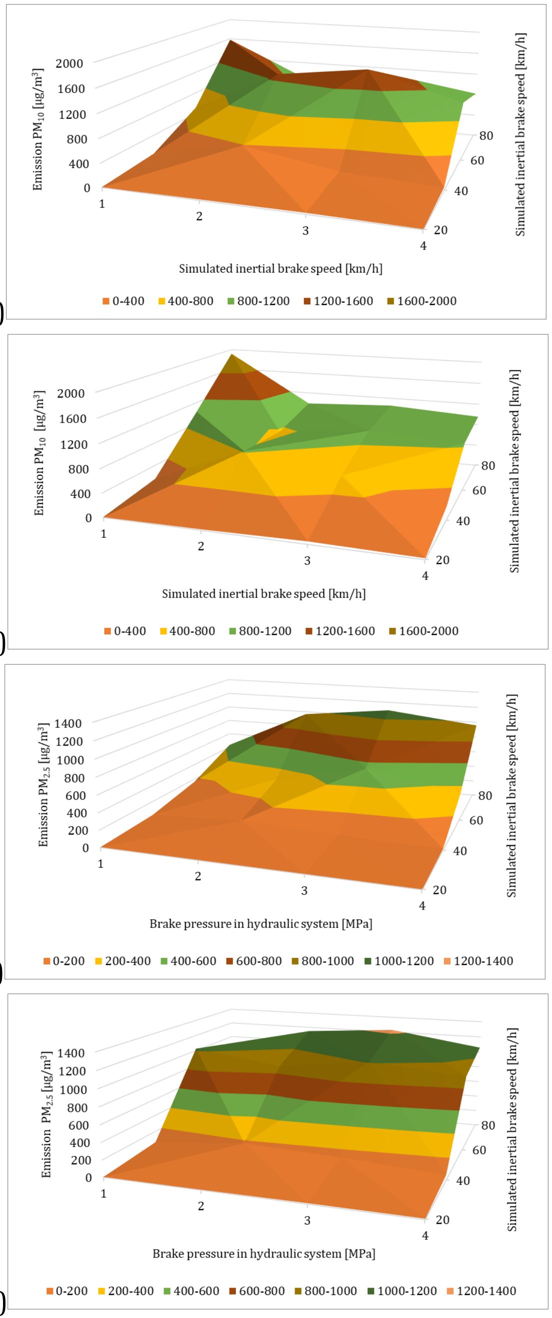


Fig. 6. Obtained results of the particles measurement, where: a) PM_{10} at a simulated load of 150 kg, b) PM_{10} at a simulated load of 250 kg c) $PM_{2.5}$ at a simulated load of 150 kg c) $PM_{2.5}$ at a simulated load of 250 kg

By applying the analysis of the interactions of various factors and combining them, the obtained data can also be displayed. Figure 7a shows the obtained results of varying the parameters for PM_{10} particles, while Figure 7b shows the data for $PM_{2.5}$ particles. In this case, it is noticeable that some factors have a different effect on the formation of particles, i.e. the intensity of action varies depending on the particles being observed.

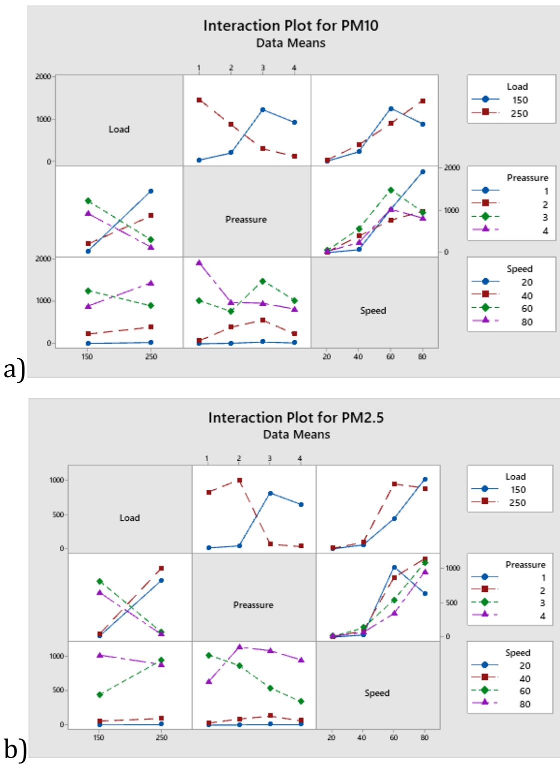
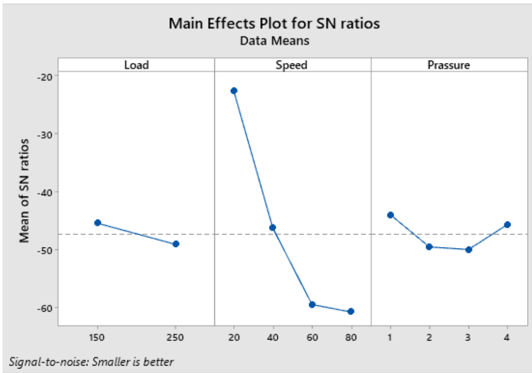


Fig. 7. Obtained results of the analysis of interactions of different parameters: a) PM_{10}, b) $PM_{2.5}$

Figure 8 and Tables 2 and 3 show data from the analysis of influencing factors on the emission of PM_{10} particles. Figure 8a and Table 2 show the results of influential factors and S/N ratio in the case of L32. On the other hand, Figure 8b and Table 3 show the results for the analysis case L16. In both cases, looking at the graphic displays, it is noticeable that speed, the load of one quarter of the vehicle, and the pressure in the braking system have the greatest influence on the resulting particle emission. On the other hand, there is a difference in the analysis of tabulated data, where it is noticeable that speed is the most influential factor in both cases. In the case of L32, the most influential factor is the load of one quarter of the vehicle, following by the pressure in the brake system. For the L16 case, the second most influential factor is the pressure in the brake system, followed by the load.



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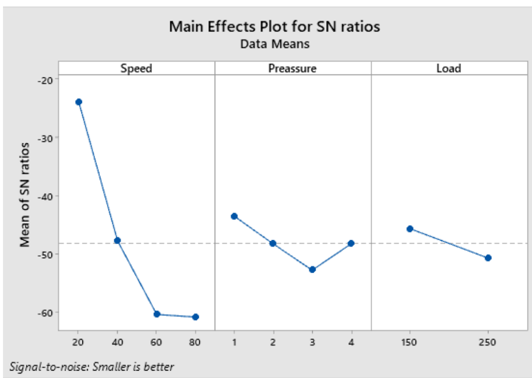


b)

Fig. 8. The obtained results of analysis according to PM_{10} particles, where: a) L_{32}, b) L_{16}

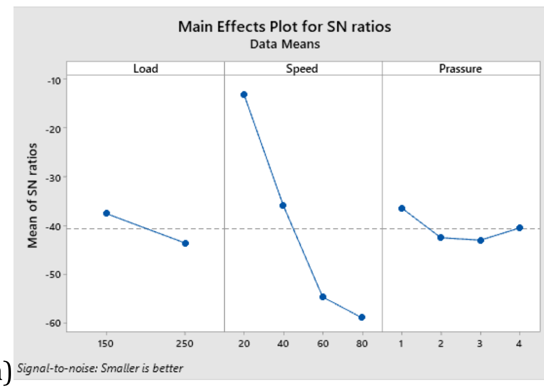
Table 2. S/N ratio for PM_{10} – L_{32}

Level	Load	Speed	Pressure
1	-33.89	-10.84	-39.74
2	-41.21	-32.84	-35.81
3		-48.09	-37.06
4		-58.41	-37.58
Delta	7.32	47.57	3.94
Rank	2	1	3

Table 3. S/N ratio for PM_{10} – L_{16}

Level	Speed	Pressure	Load
1	-23.85	-43.54	-45.71
2	-47.82	-48.30	-50.76
3	-60.41	-52.82	
4	-60.86	-48.28	
Delta	37.02	9.28	5.06
Rank	1	2	3

A graphic presentation of the results of the analysis of the influential factors that affect the emission of $PM_{2.5}$ particles, is given in Figure 9, while the tabular data of the obtained calculation are shown in Tables 4 and 5. As in the previous case for L32, the most influential factors are the simulated speed, the load of one quarter of the vehicle and pressure in the braking system. In the case of L16, the difference is in the results obtained, where the pressure in the braking system is more influential than the load of one quarter of the vehicle. However, the graphic data show identical diagrams, so it can be concluded that there is an equal effect and influence in both cases.



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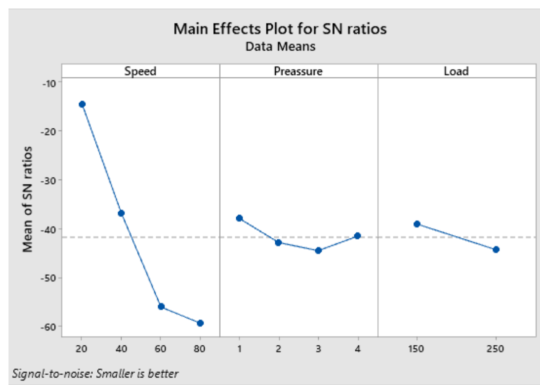

b)

Fig. 9. The obtained results of analysis according to $PM_{2.5}$ particles, where: a) L_{32}, b) L_{16}

Table 4. S/N ratio for $PM_{2.5}$ – L_{32}

Level	Load	Speed	Pressure
1	-37.63	-13.01	-36.45
2	-43.69	-35.88	-42.58
3		-54.72	-43.07
4		-59.03	-40.54
Delta	6.05	46.03	6.62
Rank	3	1	2

Table 5. S/N ratio for $PM_{2.5}$ – L_{16}

Level	Speed	Pressure	Load
1	-14.52	-37.95	-39.12
2	-36.96	-42.89	-44.38
3	-56.11	-44.56	
4	-59.40	-41.59	
Delta	44.88	6.61	5.25
Rank	1	2	3

5. CONCLUSION

The planning of the experiment measuring the emission of particles caused by the wear of friction pairs of brakes is a complex 5, bearing in mind the complex nature of the formation of particles and the effect of various parameters. In this case, the Taguchi method of experiment planning was applied. Two orthogonal arrays, namely L32 and L16, were applied, with the application of three different factors. In both cases, the graphical results led to the same conclusion about the influencing factors. According to the analysis of the calculation data and according to the rank, there was a change in the influencing factors. Thus, in the case of L32, the second most influential factor on particle emission was the load, while in the case of L16, the second most influential factor was the pressure in the braking system. Also, if we consider the third most influential factor in the case of L32 according to the calculation, it was the pressure in the braking system, while in the case of the orthogonal array L16, it turned out that the third most influential factor was the load of one quarter of the vehicle.

Based on the previously concluded, it can be seen that when planning, it is very important to know the specificity of the measurements that are performed. In the case of complex measurements and when there is a smaller number of factors or variations of those factors, it is necessary to determine a proper orthogonal array that would give correct results in the analysis. In this case, the authors concluded that measurements with a larger number of data and variations give, for such cases, better and more accurate results. This conclusion can also be reached by analysing differently presented data, where the correct conclusion and accurate data were reached by applying the orthogonal array L32.

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REFERENCES

[1] Vasiljević, S., Glišović, J., Lukić, J., Stojanović, N., Grujić, I. (2022). Analiza radnih parametara kočenja pri ispitivanju habanja kočnica i nastanka čestica na inercijalnom kočnom dinamometru. *Tehnika-Mašinstvo*, vol. 72, no. 2, p. 195-202. DOI: 10.5937/tehnika2202195V

[2] Hamzaçebi, C. (2021). Taguchi Method as a Robust Design Tool. Quality Control - Intelligent Manufacturing, Robust Design and Charts. Li, P., Pereira, P., Navas H. (editors). Quality Control - Intelligent Manufacturing, Robust Design and Charts. IntechOpen, London, DOI: 10.5772/intechopen.94908

[3] Pang, J. S., Ansari, M. N. M., Zaroog, O. S., Ali, M. H., Sapuan, S. M. (2014). Taguchi design optimization of machining parameters on the CNC end milling process of halloysite nanotube with aluminium reinforced epoxy matrix (HNT/Al/Ep) hybrid composite. *HBRC Journal*, vol. 10, no. 2, p. 138–144. DOI: 10.1016/j.hbrcj.2013.09.007

[4] Zhang, J. Z., Chen, J. C., Kirby, E. D. (2007). Surface roughness optimization in an end-milling operation using the Taguchi design method. *Journal of Materials Processing Technology*, vol. 184, no. 1-3, p. 233–239. DOI: 10.1016/j.jmatprotec.2006.11.029

[5] Popović, B. (2020). Planiranje, analiziranje i optimizacija eksperimenata. *Journal of Engineering Management and Competitiveness (JEMC)*. vol. 10, no. 1, p. 15-30. DOI: 10.5937/jemc2001015P

[6] Minitab, Taguchi desings, *https://support.minitab.com/en-us/minitab/21/help-and-how-to/statistical-modeling/doe/supporting-topics/taguchi-designs/taguchi-designs/,* accessed on: april 02, 2023.

[7] Minitab, Notation for Taguchi designs, *https://support.minitab.com/en-us/minitab/21/help-and-how-to/statistical-modeling/doe/supporting-topics/taguchi-designs/notation-for-taguchi-designs/*, accessed on: april 02, 2023.

[8] Saurabh, A., Joshi, K., Manoj, A., Verma, P.C. (2022). Process Optimization of Automotive Brake Material in Dry Sliding Using Taguchi and ANOVA Techniques for Wear Control.

Lubricants, vol. 10, no. 161, p. 1-16. DOI: 10.3390/lubricants10070161

[9] Vasiljević, S., Glišović, J., Stojanović, N., Grujić, I. An overview of non-exhaust brake emission measuring methods. *Proceedings of 15th International Conference on Accomplishments in Mechanical and Industrial Engineering DEMI 2021*, 28-29 May 2021, Banja Luka, Republic of Srpska, p. 339-348.