Відмова гальм є однією з причин нещасних випадків зі смертельними наслідками, оскільки транспортний засіб не може управлятися належним чином. Тому актуальні дослідження з підвищення безпеки гальм. Температура при гальмуванні використовується в якості показника ефективності гальмування. Якщо показання температурного сигналу відрізняються від нормального сигналу гальмування, це стає ознакою несправності гальм. Як виміряти температуру обертових гальмівних роторів і які датчики дозволяють використовувати її в реальних транспортних засобах є головним питанням в даному дослідженні. У цій статті представлені два типи датчиків, що дозволяють визначати температуру при гальмуванні, а саме – тертьова термопара і термопара, вставлена в колодку з отворами. Очікується, що датчик тертьової термопари буде виробляти більш високу температуру, оскільки між тертьовою сталлю і диском ротора існує ефект тертя, тоді як датчик в отворі колодки покаже реальне значення. Однак при використанні реального транспортного засобу вимірювання температури шляхом пробивання отворів не рекомендується, оскільки це може привести до потенційного пошкодження самої колодки. При використанні інфрачервоного датчика установка простіше, проте даний метод є неприйнятним, оскільки брудні умови, такі як пил або липкий бруд на поверхні датчика, будуть перешкоджати зчитуванню показань датчика. Тому використання тертьової термопари буде ефективніше в реальних транспортних засобах. Отже, вимірювання температури тертьовою термопарою необхідно проводити з поправочним коефіцієнтом, який відноситься до фактичної температури. На підставі проведених випробувань результати вимірювань за допомогою тертьової термопари (T_4) можна перетворити в рівняння $T=-0,0058T_4^2+2,7668T_4-81,257$. Це рівняння може бути використане в системі попередження про небезпеку, яка включає в себе пристрої визначення ефективності гальмування

Ключові слова: тертьова термопара, дискове гальмо, визначення температури при гальмуванні

EXPERIMENTAL ANALYSIS IN THE TEST RIG TO DETECT TEMPERATURE AT THE SURFACE DISC BRAKE ROTOR USING RUBBING THERMOCOUPLE

Mohammad Adhitya
Doctor Ingenieur Degree, Lecturer
Department of Mechanical Engineering
Head of Research Center*

Rolan Siregar
Doctoral Student*
Department of Mechanical Engineering
Universitas Darma Persada
Jl. Taman Malaka Selatan, RT.8/RW.6, Pd. Klp., Kec.
Duren Sawit, Kota Jakarta Timur,
Daerah Khusus Ibukota Jakarta, 13450
E-mail: rolansiregar@ft.unsada.ac.id

Danardono A Sumarsono
Professor
Mechanical Engineering Department
Advisor*

Nazaruddin
Doctoral Student*

Ghany Heryana
Doctoral Student*

Sonki Prasetya
Doctoral Student*

Fuad Zainuri
Doctoral Student*
*Research Center for Advanced Vehicle (RCAVe)
Universitas Indonesia
Jl. Margonda Raya, Pondok Cina, Kecamatan Beji,
Kota Depok, Jawa Barat, 16424

1. Introduction

Traffic accidents are one of the highest causes of death in Indonesian society. In 2018 the number of traffic accidents in Indonesia was 103,672 incidents, and 27,910 people died [1]. Many things have been pursued by the government to reduce the number of accidents such as slogans, advertising, and traffic signs that has the aim to drive safely, but the

crash still can not be avoided. Therefore, every cause of an accident must be studied in depth to minimize accidents. The braking system on a vehicle is one of the most important things so that drivers and passengers can drive safely [2]. The braking system is also referred to as active safety, which is controlled by the driver [3]. If braking does not function properly, the possibility of an accident will be large. The cause of the failure of the braking system is low fluid level (27.2 %), Overheating (22.5 %), Air in the system (13.4 %), and other influences [4]. Overheat is one of the cases which significantly affects other elements, such as brake fluid will evaporate so that the volume of fluid in the brake master is reduced and likewise premature wear on the brake pad will occur [5].

This research develops an algorithm in determining brake performance so that an indication of brake failure will be known earlier. Brake temperature is used as an indicator of brake work. If the temperature that occurs is too small or too large than usual for one of the brakes, then this can indicate an indication of abnormal brake work. The pin is stuck, the cylinder is rusted, the rubber cylinder is torn, the brake hose is leaking, from mounting the hose out of oil, these are some of the factors that make the brake not gripping normally. The pressure of the brake cylinder to the pad is proportional to the size of the grip of the pad to the rotor disc, and the grip of the rotor disc is directly proportional to the temperature that occurs.

Specifically, this study discusses the temperature phenomenon that occurs in the rotor disc, and the brake temperature will become an input in the algorithm model to assess the risk of brake failure. The problem is how to measure the temperature of the rotating brake rotors and what sensors allow it to be used in real vehicles. In the research that has been done, two types of sensors are displayed, which allow detecting brake temperature, namely rubbing thermocouple [2] and a thermocouple sensor inserted in a pad with holes [6]. The rubbing thermocouple sensor is expected to produce a greater temperature because there is a friction effect between the rubbing steel and the rotor disc, whereas the sensor in the pad hole will show the true value. But in use in a real vehicle, measuring the temperature by punching holes is not recommended because it can cause potential damage to the pad itself. So the use of a rubbing thermocouple will be better in real vehicles. Therefore, the measurement of temperature by rubbing thermocouple must be made a correction factor that refers to the actual temperature.

This research will continue until a model was obtained to detect brake faults before the brakes fail fully, ie, the brakes cannot stop the vehicle.

2. Literature review and problem statement

Research on brake faults or brake failure detection devices has been developed by previous researchers. Various brake problems have been displayed, such as overheat, pad and rotor wear, the piston-cylinder motion is jammed, and etc. A brake failure diagnosis approach with statistics has been developed by several researchers [7], but most have not yet applied it in a brake failure detection device. The paper [8] show the vibration-based fault diagnosis of the automobile hydraulic brake system using an artificial intelligence technique called CSC algorithm. This test was successfully carried out in a test rig but it might not function optimally

when applied under actual conditions because the vibration noise from outside such as tire and road vibration is great. Furthermore, research conducted by [9] provide such a device to vehicles operator so that any harmful damage and accidents caused by failure of brake switch can be easily prevented by the proper indication of the working condition of brake switch. They make pressure as an indicator of brake performance, but do not display clearly how to measure the brake pressure. As well as [10] present about automobile brake failure indicator in the test rig by using pressure as a signal. This work only displays measurements on one drum brake unit. The development of brake failure detection devices has also been performed by several researchers using microcontroller devices and infrared sensors [11, 12]. This study only shows the form of a series of tools without proving work in actual conditions. The paper [13] make a comparison between the temperature of the disc measured with thermocouple and by thermography and establishes the relations between these measures. This paper is more focused on testing the temperature that occurs in the rotor brake with variations in speed and torque.

Some researchers have led to the detection of brake failure by utilizing brake vibrations and pressure as a signal to show brake performance. However, this still has many problems like too much vibration signal noise from outside. This noise can disturb the correctness of the signal entering the microcontroller module. If the brake pressure is used as an input signal, this has the disadvantage of complicated pressure sensor implementation. It is known that the use of infrared sensors has a disadvantage, where when there is mud attached to the sensor surface it cannot detect the temperature properly. If using an infrared sensor, it will have weaknesses, when there is mud attached to the sensor surface, the sensor cannot detect the temperature properly. Therefore, the problem is how to detect the correct temperature on the rotor disc brake when using a thermocouple sensor.

3. The aim and objectives of the study

The aim of the study is making an algorithm model to find out the vehicle brake performance. This algorithm model is expected to be used for actual conditions so that the brake status can be known earlier before brake dysfunction occurs.

To achieve this aim, the following objectives are accomplished:

– getting the optimal thermocouple location for measuring brake temperature;

– determine the correction factor of the thermocouple rubbing measurement against the actual temperature.

4. Materials and research methods

This research begins with a literature study on brake temperature measurements [11], dynamics of vehicle motion in braking conditions, understanding the conversion of motion energy into heat energy during braking [12], analytical maximum brake force, simulated rotor brake temperature [14], and brake temperature sensor. Then the vehicle data collection is done to calculate the brake load data. The temperature characteristics on the disc surface can be obtained by experiment [15] (Fig. 1).
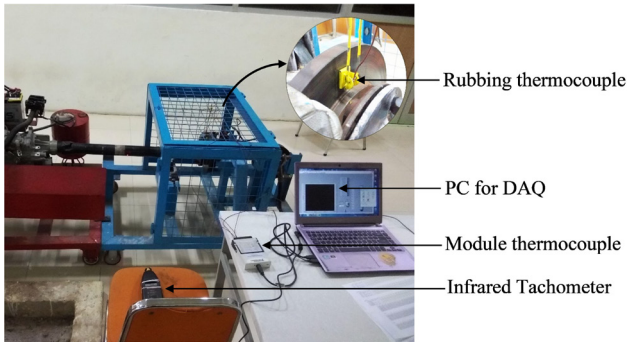
Fig. 1. Set-up experiment test rig

Experiments are made in the test rig model and must be able to represent the actual conditions [16–18] and in the future, the temperature can be used to input data to the brake temperature detection device as an indicator of brake performance. Optimized brake performance can be monitored based on the temperature read by the sensor [13]. If the temperature that occurs is too small or too large than usual on one of the brakes, then this can show an indication of abnormal brake work. The sensor used is a thermocouple sensor embedded in the pad brake and a rubbing thermocouple sensor. The position of the thermocouple is varied, that is, position 1, position 2, and position 3 is on the perforated brake pad, and position 4 is mounted on rubbing thermocouple (Fig. 2).
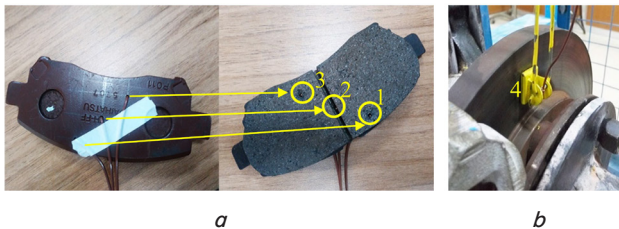

a   *b*

Fig. 2. Thermocouple sensor position: *a* — sensor thermocouple in Pad (position 1, 2, 3); *b* — rubbing thermocouple (position 4)

This is done to see the distribution of brake temperature that occurs on the surface of the rotor disc and to validate the temperature contour on the rotor disc from the results of a thermal transient simulation. The temperature at position two is estimated to be closer to the actual temperature on the rotor disc. If this is correct, then the temperature detection results from the two thermocouples will be made into a reference. However, the measurement model by punching holes is not recommended in the actual implementation of the vehicle. Because the hole made in the pad can cause the initial crack of the pad brake. So the use of rubbing thermocouple is the best choice when used in real conditions, but it is necessary to adjust the measurement results of the rubbing thermocouple to the actual temperature. This adjustment is because the temperature reading results with the rubbing thermocouple will usually be greater than the actual temperature because there is heat arising from rubbing steel friction with the rotor brake itself. Therefore, the temperature of the rubbing thermocouple reading becomes a function of the actual temperature. Experiments carried out to obtain the brake temperature, which is then analyzed data on the increase in brake temperature. The temperature data

collection procedure was developed from various literature [2, 3, 12] for more details can be displayed as follows:

1) see the relationship between shaft rotation with engine power;

2) perform repeated braking with braking time following analytical calculations. In this step, it is adjusted between the machine used on the test rig and the engine that is testing the engine power;

3) large braking force is given to the final speed in accordance with estimates;

4) repeat braking up to 20 times if possible, up to 200 times braking;

5) pay attention to the condition of the braking system, whether it is in a damaged condition or not.

The amount of braking force can be displayed in eq. (1). This braking force is made based on a study of each brake element.

$$F_{brake} = \frac{r}{R} 2 \cdot \mu \cdot \frac{A_{cs}}{A_{mc}} \cdot \frac{F_d \cdot a_1}{a_2 \cdot \sin\theta}. \tag{1}$$

From eq. (1). it can be explained that F_{brake} is the brake force on a wheel (N), r is the distance of the axle to the midpoint of the cylinder pad (m), R is the distance of the midpoint of the cylinder pad to the tire print surface (m), 2 is the friction force on two side, A_{cs} is the surface area of the caliper cylinder (m^2), A_{mc} is the surface area of the master cylinder (m^2), F_d is the compressive force given by the operator's foot (N), a_1 is the distance of the force of the pedal to the support (m), A_2 is the distance of the output shaft to the support (m), and θ is the angle between the output shaft and the pedal arm (º).

This equation applies if there is no skid or adhesion force between the tire and the road is greater than the braking force. Furthermore, to display the temperature contours on the surface of the rotor disc, finite element-based software can be used. The simulation is done by defining the heat flux first (eq. (2)).

$$q = \frac{2\left(\frac{1}{2}mv^2 + I\frac{\omega^2}{2} + \frac{m \times g \times S}{\sqrt{1+S^2}}\right)}{A \times t}. \tag{2}$$

From eq. (2) it can be explained that q is heat flux (W/m^2), m is a mass held by one wheel (kg), v is the speed of the vehicle when braking (m/s), I is mass inertia (*kgm*), ω is angular speed (1/s), g is gravity acceleration (m/s^2), S is slope road (%), A is the surface area of the touch pad with the surface of the rotor (m^2), and t is the braking time (s).

Furthermore, the heat flux can be used as an input for transient thermal simulation.

5. Research result

5. 1. Position the maximum temperature on the rotor disc

Experiments carried out to see the increase in brake temperature, where measurements are made on the rotor brake. The position of the sensor placement can be seen in Fig. 2. Furthermore, the simulation on the rotor brake shows the temperature contour in the friction area (Fig. 3).
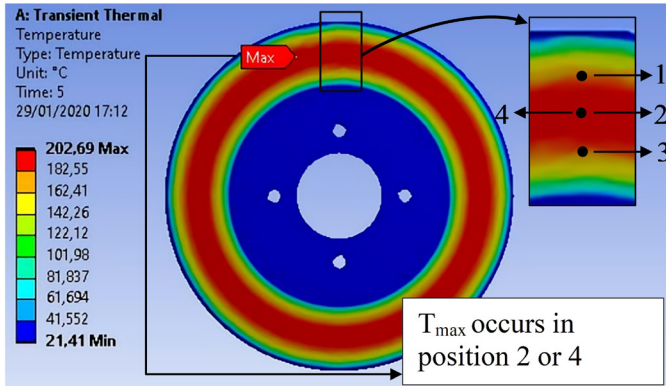
Fig. 3. Temperature rotor brake contours

The temperature contour can be used to validate the temperature measurement position on the rotor brake. From the simulation results it is shown that the maximum temperature is in the radius where thermocouples 2 and 4 are placed (Fig. 3). Temperature contours at positions 1 and 3 show the same colour, meaning that the temperature at this position is not much different. And when compared to position 2 shows similar results. This means that the temperature contours at positions 1, 2, 3 and 4 are not much different. Furthermore, the results of this simulation are validated by experiment. The results of temperature detection from the tests that have been carried out can be displayed on the graph in Fig. 4.

Based on the results of temperature measurements (Fig. 4), it can be seen that the temperature rise in radius 1, 2 and 3 shows results that are not much different. Position radius 2 and 4 are the same, position 2 with the thermocouple inside the pad and position 4 with rubbing thermocouple. Position 2 is chosen as a reference that shows the actual temperature, because this position is validated with the simulation results that show the maximum temperature contour. Therefore, the optimum placement of the rubbing thermocouple sensor is the position of radius 2 or 4.
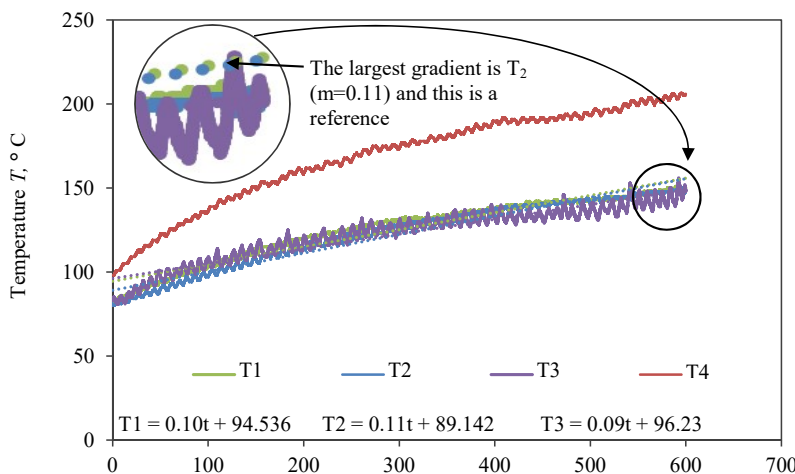

Fig. 4. Brake temperature detection results

5. 2. Temperature of rubbing thermocouple

From the reading of the disc temperature using rubbing thermocouple, the temperature rise obtained is much higher compared to thermocouples installed in positions 1, 2 and 3. The difference is due to the additional heat arising from rubbing steel friction with the rotor brake. Therefore measurements with rubbing thermocouple do not show actual results. However, in the fact that sizes can only be done on rubbing thermocouple because the measurement by punching holes in the pad is not recommended because the holes made in the pad can cause the initial crack of the pad brake. So the use of rubbing thermocouple is the best choice when used in real conditions, but it is necessary to adjust the measurement results of the rubbing thermocouple to the actual temperature. Therefore the temperature of the rubbing thermocouple reading becomes a function of the actual temperature. As for the actual temperature reference, the measurement at position 2. The chart in Fig. 5 shows the correction factor for measuring the rubbing thermocouple.
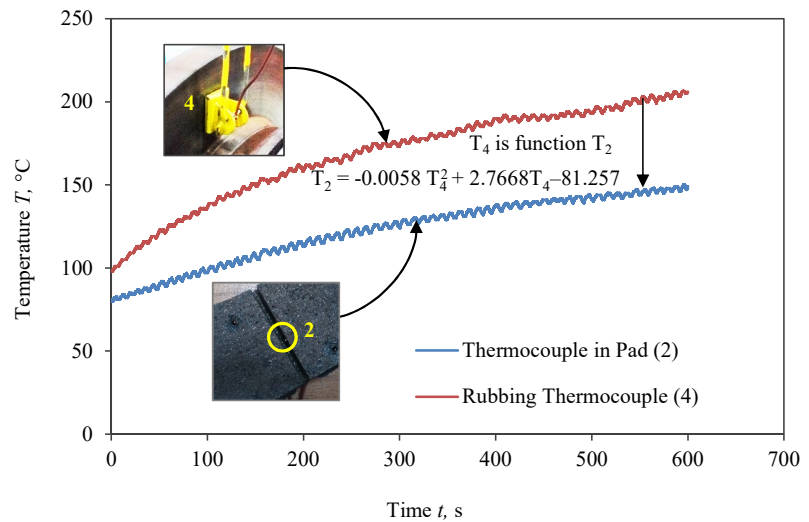

Fig. 5. Relation temperature between position 2 and 4

So that the results of temperature reduction by rubbing thermocouple are correct, then a correction factor is made with eq. (3).

$$T = -0.0058T_4^2 + 2.7668\,T_4 - 81.257, \quad (3)$$

where T_4 is the temperature read directly by the rubbing thermocouple sensor, and T is the actual temperature that occurs in the rotor brake. T refers to the results of the thermocouple 2 (T_2) measurement, or rather T is the same as T_2.

6. Discussion of the research results

Based on the measurement results it can be seen that the temperature of the rubbing thermocouple is different from the thermocouple that is inserted in the brake pad. Where the temperature of the thermocouple rubbing measurement is much greater than the temperature of the ther-

mocouple that is inserted in the pad brake. So to get the actual measurement results needed correction factors. The correction factor is obtained from the least square equation that references the thermocouple measurements entered in the pad. In this study the compressive force of the thermocouple rubbing on the surface of the disc brake rotor is considered to be small according to the stiffness of the handle holding the steel skid is elastic. So that the correction factor equation (eq. (3)) can be used in actual vehicles, the operator must make a very elastic rubbing steel shaft and the placement of the sensor must be right in the middle radius of the pad friction area with the surface of the rotor disc.

The measurement process using thermocouple rubbing in this study requires good skills so that the touch of thermocouple rubbing on the surface of the rotor disc is not too large. The use of sensor data loggers must be more sensitive and real time, this article uses NI-based C-Series sensors. So, in a vehicle brake temperature detection application must have a large data storage capacity, real time, and relatively cheap prices.

In this article the upward trend in brake temperature read by thermocouple rubbing sensors is more stable from 300 seconds to 600 seconds. This value is also verified by the thermocouple sensor which is inserted in the pad; therefore, the result is more likely in a rising temperature brake trend. However, slightly different from the results of tests conducted by [19] where the temperature at the end of the test drops dramatically, and this graph does not show how the temperature rise or fall time.

The results of measurements with this thermocouple rubbing are limited to the large compressive force of thermocouple rubbing with a relatively small rotor brake surface, where the pressure is only estimated by the operator when installing the sensor.

In-depth studies must be carried out to obtain the compressive forces that occur between rubbing thermocouple and rotor disc brakes that are very small and mea-surable. This is so that the heat signal read by the sensor only comes from the braking temperature (friction pad with the surface of the rotor disc) and there is no friction heat between the thermocouple rubbing with the rotor disc. Braking temperature signal that is read correctly becomes the input data in the development of a vehicle brake damage detection device. In the future the development of a brake damage detection tool is expected to be part of the vehicle safety warning system to avoid total brake failure.

7. Conclusions

1. The position of the temperature measurement on the disc brake rotor is in position two. This is evidenced by the maximum temperature contour of the simulation results at that point. In addition, the test data trendline shows that the maximum gradient is at number two position.

2. In the actual condition the use of thermocouples is more optimal by using thermocouple rubbing than it is planted in the pad, but a correction equation is needed so that the results of the thermocouple rubbing measurement are correct. The equation is $T=-0.0058T_4^2+2.7668\ T_4-81.257$ where T_4 is the temperature read by the thermocouple rubbing sensor and T is the actual temperature that will appear on the monitor display. T refers to the results of the thermocouple 2 ($T2$) measurement, or rather T is the same as $T2$.

The results of this study can be used to develop a safety warning system about vehicle brakes.

Acknowledgment

References

1. Lismartini, E., Nugraha, B. (2020). More than 27 Thousands of Lives Hovered on the Street. Available at: https://www.viva.co.id/berita/nasional/

2. Day, A. (2014). Braking of Road Vehicles. Elsevier, 488. doi: https://doi.org/10.1016/c2011-0-07386-6

3. Sumarsono, D. A., Siregar, R., Adhitya, M. (2018). Algorithm For Determining The Feasibility of Braking Systems Operation Of Passengers Car In Matlab Simulink. Prosiding Seminar Nasional Tahunan Teknik Mesin (SNTTM), 17, 1–5.

4. Owusu-Ansah, P., Alhassan, T., Frimpong, A., Agyei Agyemang, A. (2014). Survey of the Causes of Brake Failure in Commercial Mini-buses in Kumasi. Research Journal of Applied Sciences, Engineering and Technology, 7 (23), 4877–4882. doi: https://doi.org/10.19026/rjaset.7.878

5. Chandra Verma, P., Menapace, L., Bonfanti, A., Ciudin, R., Gialanella, S., Straffelini, G. (2015). Braking pad-disc system: Wear mechanisms and formation of wear fragments. Wear, 322-323, 251–258. doi: https://doi.org/10.1016/j.wear.2014.11.019

6. Road vehicles Braking systems - Temperature measuring methods (2010). SASO.

7. Husaini, M., Krishnan, P., Yaacob, S. (2018). Data Analysis for Braking System in Time Domain for Fault Diagnosis. International Research Journal of Engineering and Technology, 05 (08), 348–354.

8. Jegadeeshwaran, R., Sugumaran, V. (2015). Brake fault diagnosis using Clonal Selection Classification Algorithm (CSCA) – A statistical learning approach. Engineering Science and Technology, an International Journal, 18 (1), 14–23. doi: https://doi.org/10.1016/j.jestch.2014.08.001

9. Chaudhary, A., Jariya, K., Sharma, M. K., Kumar, M. V. (2016). Automatic brake failure indicator. International Journal of Engineering Sciences & Research Technology, 5 (4), 928–933.

10. Siva, G. V., Reddy, B. C. M. (2018). Automobile Brake Failure Indicator, 4 (7), 322–326.

11. Agudelo, C. E., Ferro, E. (2005). Technical overview of brake performance testing for Original Equipment and Aftermarket industries in the US and European markets. Link Eng.

12. Sarip, S. (2013). Design Development of Lightweight Disc Brake for Regenerative Braking – Finite Element Analysis. International Journal of Applied Physics and Mathematics, 52–58. doi: https://doi.org/10.7763/ijapm.2013.v3.173

13. Neis, P. D., Kruze, G. A. S., Ferreira, N. F. (2009). Relation between the temperature of the disc measured with thermocouple and by thermography using a reduced scale dynamometer. 20th International Congress of Mechanical Engineering.

14. Pevec, M., Lerher, T., Potrc, I., Vranesevic, D. (2010). Numerical temperature analysis of brake disc considering cooling. Advanced Engineering, 4 (1), 55–64.

15. Km, K. R., Bashir, Q., Dar, R. A., Rather, Y. M. (2014). Experimental Test Rig for Surface Temperature Measurements in Disc Brakes. J. Appl. Eng., 2 (11).

16. Siregar, R., Zainuri, F., Adhitya, M., Sumarsono, R. D. A. (2017). Design a New Generation of Synchromesh Mechanism to Optimization Manual Transmission's Electric Vehicle. Paper presented at The 15th International Conference on Quality in Research (QiR 2017). Bali.

17. Nazaruddin, N., Zainuri, F., Siregar, R., Heryana, G., Adhitya, M., Sumarsono, D. (2019). Electric power steering: an overview of dynamics equation and how it's developed for large vehicle. IOP Conference Series: Materials Science and Engineering, 673, 012112. doi: https://doi.org/10.1088/1757-899x/673/1/012112

18. Adhitya, M., Soemarsono, D. A., Zainuri, F., Prasetyo, S., Fachruddin, Apriana, A. et. al. (2018). Devepolment model of synchromesh mechanism to optimization transmission's electric vehicle. Paper presented at 31st International Electric Vehicle Symposium and Exhibition, EVS 2018 and International Electric Vehicle Technology Conference 2018, EVTeC 2018. Kobe City.

19. Brake testing, Braking of Road Vehicles 2012 (2012). University of Bradford U.K., 662.