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Name of first author, Name of University; Name of second author, Name of Company or Institution *(9-point, Times New Roman, centered)*

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Abstract *(14-point, Times New Roman, left justified)*

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The effort to reduce CO2 emissions has been a challenge for automakers to meet the technical regulations for the Worldwide Harmonized Light Duty Test Procedure (WLTP).

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 ***(do not use personal pronouns: “we” “our” etc.)***

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In this present study, the authors focused on the friction factor in differential bearings, which are responsible for a great amount of energy loss due to friction. Bearing manufacturer Schaeffler proposed replacing the tapered roller bearing (TRB) with the tapered ball bearing (TBB), thereby allowing a 50% reduction in friction and reducing CO2 emissions by 1.5%. To understand the increase in differential efficiency by replacing the TRB bearing with the TBB bearing, and using the friction calculation of rolling bearings, a computer simulation of the sliding frictional moment (Msfm) was performed; the authors found the TBB-type bearings had a linear behavior with a progressive increase in friction as a function of rotation, with a significant reduction in friction, when compared with the TRB-type bearing. The authors concluded that TBB-type bearings were more energy efficient than TBR bearings under the same operating conditions, contributing to increased mechanical efficiency and reduced CO2 emissions.

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Introduction *(all headers are 14-point, TNR)*

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Since the time when designers improved the use of the wheel by adding bearings, there was concern over wheel-axle friction. Before the advent of the steam engine, this loss of energy reduced the capacity of human- or animal-powered vehicles and caused a reduction in performance. This resistance to movement was the objective of studies carried out by ancient civilizations. Research has shown that rudimentary bearings were manufactured as early as 900 BC to 400 AD by Romans, Celts, Greeks, and the Chinese. Archaeological research from the end of the 19th century found an ancient ball bearing in Lake Nemi, located 18 miles from Rome (Dowson & Hamrock, 1981; Jacobson, 2011). Apparently, nothing was improved during the Middle Ages; however, the Renaissance genius Leonardo Da Vinci (1894) carried out studies in the field of tribology, establishing the first laws on the interaction of surfaces in relative motion in 1493 (Hutchings, 2016) including the results of his studies in the Codex Atlanticus (Da Vinci, 1894). In his work, he concluded that the sliding friction coefficient was constant and equal to 1/4 for all materials (Dowson & Hamrock, 1981). His research served as a reference for Amonton’s studies (Persson, Sivebæk, Samoilov, Zhao, Volokitin, & Zhang, 2008) on tribology. With the advent of the Industrial Revolution, ball bearings came to take their place in the manufacture of machinery and equipment; and from the beginning of the 20th century, ball bearings were applied to automobiles and other vehicles (Dowson & Hamrock, 1981), playing an important role, because, in addition to reducing the friction of the rotating motion of the wheels, they are an integral part of the suspension and support the weight of the vehicle (Park, Choi, & Kim, 2013). The model designed by Da Vinci was widely used until 1907, when Sven Wingquist patented the self-aligning bearing, whose main benefit was to support greater loads without reducing its useful life, even with limited shaft misalignment (Jacobson, 2011).

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Friction and Losses

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Concerns related to loss of energy by friction are centuries old. Despite the introduction of electric and hybrid cars, most of the fleets made up of such vehicles continue to use fossil-fuel energy sources. These vehicles operate both in the diesel cycle (Institute, 2017; Scoltock, 2010) and in the Otto cycle (Poulton, 1994) and have a common feature: low energy efficiency. Only 12% of the energy available in the fuel is made available to the traction wheels, of which 15% is lost due to friction (Comfort, 2003; Nakasa, 1995; Priest & Taylor, 2000). Only two factors must be considered responsible for fuel consumption.

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* Vehicle load: the work or energy required to move the vehicle and the functioning of its accessories
* Energy efficiency of the engine plus transmission

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In view of the ever-increasing number of vehicles in use, reducing fuel consumption becomes a priority (Ross, 1997). On this topic, the search for improving energy efficiency is not only of economic importance, but also environmental in the face of global warming (Mickūnaitis, Pikūnas, & Mackoit, 2007). The effort to reduce CO2 emissions in internal combustion vehicles, whether they are trucks, buses or automobiles, has been a challenge for automakers (Allmaier, Sander, & Reich, 2013; Kitamura, 2003). The environmental issue is being treated as a global issue and, in 2014, the United Nations Economic Commission for Europe (UNECE) established technical regulations for the Light Services Test Procedure (WLTP) with a global scope (Tsokolis, Tsiakmakis, Dimaratos, Fontaras, Pistikopoulos, Ciuffo, & Samaras, 2016; Mickūnaitis et al., 2007). With the use of new technologies, Holmberg and his colleagues (Holmberg, Andersson, Nylund, Mäkelä, & Erdemir, 2014) pointed to an expectation of savings in diesel consumption in trucks on the order of 75 billion liters and a reduction in emissions of 200 million tons of CO2 by 2022, totaling world-wide annual savings of $127 billion US dollars. The same authors also estimate that frictional energy losses in light vehicles are between 25% and 30%, an unnecessary emission of 25-30g of CO2 / km for a passenger car with a 2-liter engine (Ligier & Noel, 2015).

In the event that you need to quote someone, please note the following parameters. For short quotes, less than roughly 40 words, you should put quotation marks around the words or phrase, but otherwise it remains formatted the same as the rest of the paragraph in which it is placed. After the quote, be sure to put the authors’ names and the date of the article in parentheses. For longer quotes—40 words or more—please use the following formatting structure. Assume that you are writing about work by, say, Ligier and Noel (2015) and want to quote them.

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With a focus on environmental and financial issues, the search for the reduction of internal friction in internal combustion engine vehicles has become a worldwide trend. The study of friction in moving parts of engines, transmission systems, gearboxes, differentials, and systems lubrication and lubricants are the subject of research in several works (Knauder, Allmaier, Sander, & Sams, 2020; Wong & Tung, 2016; Yonggang, Xu, Jin, Braham, & Yuanzhong, 2020). Although there are several points in a vehicle where energy is dissipated in the form of friction (Comfort, 2003; Nakasa, 1995; Priest & Taylor, 2000; Tung & Mcmillan, 2004), the focus of this current study was on the bearings of a transmission differential.

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The Differential Gearbox

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The differential is a highly complex gearbox that compensates for the differences in rotation of the drive wheels, allowing them to turn at different speeds in a curve, where the distance traveled by the inner wheel is shorter than the distance traveled by the outer wheel. For full-drive vehicles, it acts similarly between the front and rear drive axles (Toke, Kurkure, Waghumbare, & Jejurkar, 2018). Excluding special cases, the concept of bevel gears is preferred for axle and wheel differentials, as these gears act as scale dashes establishing the torque balance between the right and left wheels. (Antoni, 2014; Ribbens, Heisler, Blundell, Harty, Brown, Serpento, & Davies, 2009). In association with the transmission, the differential is responsible for the greatest amount of energy loss due to friction (Sharma & Goyal, 2019; Tsokolis et al., 2016). Even though the greatest friction loss within a differential box occurs in its gears (Patil, Shevade, Gund, Utage, Patane, & Patel, 2017), this fact is largely minimized using lubricants (Tung & Mcmillan, 2004; Wong & Tung, 2016); the input and output torque of the entire differential system is supported by bearings, which also contribute to friction loss (Holmberg et al., 2014).

 Although the gears are mainly responsible for the loss of energy due to friction, in a research study carried out by the German-based bearing manufacturer Schaeffler (2014) and published by SAE International (Plank & Schwarzenthal, 2010), the replacement of the tapered roller bearing (TRB) by the tapered ball bearing (TBB) type could lead to a 50% reduction in the differential’s internal friction. The replacement could also provide a 1.5% reduction in the vehicle’s total CO2 emissions; however, the manufacturer does not specify the vehicle model used in the software simulation (Niederbacher, 2016). This statement was evaluated by Pilot Systems International, which identifies in its AWD component analysis (Niederbacher, 2016) report, a considerable reduction in friction in the differential, due to the replacement of TRB-type bearings with the TBB type. Although the result of this substitution is positive, other manufacturers claim that there are alternatives available at lower costs (Niederbacher, 2016). To understand the increase in differential efficiency by replacing the TRB bearing with the TBB bearing, a brief review of the physical phenomena related to bearings is necessary. These concepts are used for the elaboration of several software packages for systems performance evaluation, based on bearings and gears (Geonea, Dumitru, & Dumitru, 2017; Gynning Olofsson, 2017; Otter, Dempsey, & Schlegel, 2000). Taking as a reference the model designed by SKF (2014) to calculate the frictional moment, it is possible to observe that it has numerous variables for its determination. Bearing friction is not constant and depends on certain tribological phenomena that occur in the lubricating film between the rolling elements, the raceways, and the cages (Khonsari & Booser, 2017; Yonggang et al., 2020).

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The Total Frictional Moment

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To calculate the total frictional moment of a bearing, the following variables were adopted.

* The frictional moment and the possible effects of high-speed exhaustion
* The moment of sliding friction and its effect on the integrity of lubrication
* The frictional moment of the sealing system
* The moment of friction of drag losses

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Based on this, the equation that best approximates the real behavior of a bearing is represented by Equation 1.

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*(equations are numbered and right-justified)*

$M=M\_{rfm}+M\_{sfm}+M\_{fms}+M\_{fmd}$ (1)

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where,

*M = moment of total friction –* [Nm]

*Mrfm = rolling frictional moment –* [Nm]

*Msfm = sliding frictional moment –* [Nm]

*Mfms = friction moment of the seals –* [Nm]

*Mfmd = frictional moment of drag losses, agitation –* [Nm]

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Although this equation is relatively simple, its variables result from complex calculations, according to the type of bearing analyzed, lubrication, load, temperature of the lubricating fluid, rotation of the bearing, viscosity of the lubricant, and its drag factor. The model for calculating the frictional moment (SKF, 2014) provides a tutorial on how to calculate the total frictional moment. SKF subsidiary Schaeffler International (2014) makes available and online, free of charge, calculation module for the detailed friction calculation of rolling bearings that go by the name of Bearinx (Schaeffler, 2014). This software allows for the calculation of all the friction forces of the bearing’s surfaces, considering rolling friction as well as sliding friction in the solid body friction, mixed friction and fluid friction ranges, losses in the load-free zone, splashing losses from the lubricant, and seal friction components.

To assess the variation in friction in the differential resulting from the replacement of TRB-type bearings by TBB-type bearings (Niederbacher, 2016; Plank & Schwarzenthal, 2010), the Bearinx computational tool was used, allowing analysis while considering the behavior conditions of non-linear elastic bending of the bearings, elasticity of the shafts, preload or operating clearance of the bearing, profile of rollers and raceways, as well as oscillation, in ball bearings, loading correlated with the change in the contact angle, actual pressure of contact, and taking into account the inclined position and profile of the rolling element, influence of notches (reliefs) in contact regions, influence of lubrication conditions, contamination, and real contact pressure on the fatigue resistance. In the computational analysis of the TRB and TBB bearings, only the sliding frictional moment (Msfm) defined by Equation 2 was considered.

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$M\_{sfm}=G\_{sl+}μ\_{sfc}$ (2)

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where,

*Msfm = sliding frictional moment* [Nm]

*Gsl = variable that, depending on the type of bearing,*

*the radial load Fr* [N] *and the axial load Fa* [N]

*Msfc = sliding friction coefficient*

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For computer simulations of both the TBB-type and TRB-type bearings, the defined contour variables were:

* Temperature: 50⁰C
* Axial load (frictional torque): 1000N, 2000N and 3000N
* Radial load: 0N
* TRB bearing rotation: 50 rpm, 100 rpm, 250 rpm, and 500 rpm

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Table 1 shows the results obtained with the aid of the computational tool.

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*Table 1*. Friction torque (Newton meter) applied to the TRB-type bearing.

*(captions are 9-point, left-justified; use italics and periods as shown)*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| rpm | 50 | 100 | 250 | 500 |
| TRB: 1000N | 0.166 | 0.157 | 0.226 | 0.352 |
| TRB: 2000N | 0.269 | 0.218 | 0.266 | 0.415 |
| TRB: 3000N | 0.381 | 0.271 | 0.293 | 0.453 |

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These results show a significant increase in the torque at low speeds (50 rpm) and at high speeds (500 rpm). Figure 1 shows, however, that a) the system was more efficient at 100 rpm and b) that the TBB-type bearing has a linear behavior with a progressive increase in friction as a function of rotation.

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(a) Simulation of the TRB bearing.

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(b) Simulation of the TBB bearing.

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*Figure 1.* Friction torque simulations.

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Table 2 shows the values obtained for the TBB bearing under the same conditions adopted for the TRB bearing.

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*Table 2.* Friction torque (in Newton meters) applied to the TBB-type bearing.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| rpm | 50 | 100 | 250 | 500 |
| TBB: 1000N | 0.026 | 0.030 | 0.045 | 0.068 |
| TBB: 2000N | 0.042 | 0.048 | 0.063 | 0.084 |
| TBB: 3000N | 0.064 | 0.066 | 0.084 | 0.114 |

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Table 3 shows a relative comparison between the two simulations.

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*Table 3*. Friction reduction (%) between TRB and TBB bearings.

|  |  |  |  |
| --- | --- | --- | --- |
| rpm | 1000N | 2000N | 3000N |
| 50 | 15.66 | 15.61 | 16.84 |
| 100 | 19.11 | 22.02 | 24.54 |
| 250 | 19.91 | 23.68 | 28.67 |
| 500 | 19.32 | 22.17 | 25.17 |

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Figure 2 indicates that, for all computer simulations, the TBB bearing showed a significant reduction in friction when compared to the TRB bearing.

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*Figure 2.* Comparison of friction reduction between TRB and TBB bearings.

Figure 3 shows the performance differences between TRB and TBB bearings under the same operating conditions.

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*Figure 3.* Graphical comparison of friction reduction (%) between TRB and TBB bearings.

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Software Validation

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Before the existence of computers and software for analysis, bearing manufacturers used empirical calculation models that enabled estimations based on the type of bearing, the supported load, speed, and the viscosity of the lubricant. Using equations based on the results of laboratory bench tests (Dudziak & Krome, 2015), the Palmgren equations (Lundberg & Palmgren, 1947) were used most often (which served as the basis for ISO 15312). A bench test was made up of a physical model, where the bearing was experimentally subjected to a test in order to determine the friction torque. This testing device was equipped with sensors that could capture certain variables from the behavior of a specific bearing, obtaining its friction torque curve once it was subjected to a progressive series of radial loads. In contrast to bench tests, there is an analytical method that uses a mechanical and tribological model of the bearing; the mechanical model is used to map the application of forces, load distribution and other variables. The tribological model associated with the mechanical model describes the behavior of different tribological phenomena (Geonea et al., 2017). The analytical method, when transformed into an algorithm, allows the *in-silico* study of the behavior of the bearings, and the validation of the software is performed with the help of other similar computer packages, bench tests, and models, including frictional torque, kinematics, and cage loads (Schaeffler, 2014). Unfortunately, further details about this validation process performed by manufacturers are difficult to access, as they are deemed industrial secrets.

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Conclusions

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From this current study, the authors demonstrated that TBB-type bearings are more energy efficient than TBR bearings under the same operating conditions. Considering that the generation of CO2 is directly related to fuel consumption, which is subject to the mechanical efficiency of the vehicle’s subsystems, the replacement of TRB bearings by TBB bearings in the differential could result in a reduction of emissions. Within this context, it is possible that the extension of this reasoning to all other subsystems of a motor vehicle will result in emission rates and energy efficiency in line with current environmental standards. The results encourage the creation of “in silico” tools from physical models that can contribute to the solution of economic and environmental challenges.

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*(Use APA formatting for references. Begin each reference with the first author’s last name, followed by the author’s initials. Separate all authors’ names with a comma. Indent subsequent lines 1/4". Refer to the Formatting Guide for References on our websites for additional help.)*

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Biographies

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