

Analysis of Torque Rod Bushing Damage in Hino 500 Dump Truck Units at PT XYZ

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ABSTRACT

Bushing torque rod is a critical component of the suspension system in heavy-duty vehicles, functioning to absorb vibrations and maintain axle stability. In practice, repeated failures of this component have been observed in dump truck units operating with high hour meters, leading to reduced vehicle stability, driver discomfort, and increased downtime for maintenance. This study aims to analyze the relationship between operational hours and the severity of torque rod bushing damage, as well as to identify the most vulnerable positions in Hino 500 dump trucks at PT XYZ. The research applied a quantitative approach using descriptive statistics, Pearson correlation, and simple linear regression. Data were collected from 50 dump truck units, covering six bushing positions: Front Upper, Rear Upper, Front Left, Front Right, Rear Left, and Rear Right. The results showed that Rear Left and Rear Right bushings had the highest frequency of severe damage, each at 70%, followed by Front Left (50%) and Front Right (44%), while Front Upper and Rear Upper recorded the lowest rates. Regression analysis revealed a strong positive correlation between operational hours and damage severity. The developed model predicts that for every 1,000 additional hours of operation, the potential for bushing failure increases by a quantifiable measure. Consequently, a preventive replacement strategy is recommended at 6,000–7,000 operational hours, particularly for the rear axle positions, to mitigate downtime.

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INTRODUCTION

Several previous studies have discussed the role of torque rod and bushing components in heavy-duty vehicles. Keeler et al. (2016) explained that torque rods play a crucial role in reducing longitudinal and torsional forces on suspension systems. Unfortunately, this study did not explicitly analyze the correlation between operational hours and the severity of bushing damage. Similarly, Ikeda et al. (1993) emphasized the importance of selecting appropriate rubber materials for bushings to

enhance vibration damping and durability. However, their work remained focused on material characteristics rather than field failure patterns under actual operational conditions. Dwiky (2024) investigated hydraulic cylinder dust seal failures using laboratory-based testing such as hardness, oil resistance, and tensile tests. The present study provides a methodological reference, although it was limited to seals rather than torque rod bushings. Ginder et al. (2001) and Dorfmann and Ogden (2003) explored magnetorheological elastomers (MREs) as adaptive vibration dampers, demonstrating innovative potential in suspension applications. As such, it helps to highlight the opportunity for future material advancements, but not the current degradation behavior in dump truck operations. Setiawan and Winursito (2023) applied simple linear regression to evaluate machine performance against production backlog, showing the effectiveness of statistical modeling in technical analyses. Odeyar et al. (2022) reviewed reliability and fault analysis methods for heavy equipment, stressing the importance of data-driven maintenance strategies. Likewise, Gunawan (2020) and Wahyuni & Santoso (2022) confirmed that regression and correlation analysis are highly suitable for predictive damage assessments. From the above studies, it can be concluded that most research focuses either on material design, experimental testing, or general statistical modeling. Very few researchers reported empirical correlations between hour meter data and bushing torque rod failure patterns in dump trucks. Therefore, this research intends to bridge that gap by analyzing statistical relationships between operational hours and bushing failures using real operational data from PT XYZ.

Various studies have shown that the performance and durability of torque rod bushings are strongly influenced by material properties and suspension design. Unfortunately, they do not specifically examine the correlation between operational hours and the actual damage patterns of bushings in dump trucks. The present study provides an empirical analysis using real field data from Hino 500 units operating in mining and construction projects. As such, it helps companies to establish predictive maintenance strategies that are more precise and data-driven.

The main objective of this paper is to find the correlation between dump truck operational hours (hour meter) and the severity of torque rod bushing damage. Even though many researchers were worked on suspension design, vibration damping materials, and elastomer performance, very few researchers were reported about empirical failure patterns of torque rod bushings under heavy-duty operational conditions. This data are very useful in developing maintenance intervals based on hour meter readings to minimize downtime and improve reliability.

A few researchers focused on laboratory testing of elastomer degradation or design modifications of bushings. There have been limited studies concerned on statistical correlations between operational hours and field damage distribution. Therefore, this research intends to analyze the frequency and position of bushing damage, quantify the effect of operational hours using regression and correlation methods, and propose data-based preventive maintenance intervals. The objectives of this research are to describe the relationship between operational hours and damage severity and to determine the most vulnerable bushing positions in Hino 500 dump trucks.

Existing literature has examined bushing design and material properties, but there is a notable gap in empirical studies linking operational hour meter data to specific failure patterns in the field. To address this gap, this study aims to: (1) statistically validate the relationship between operational hours and torque rod bushing damage, (2) identify the most failure-prone bushing positions on Hino 500 dump trucks, and (3) develop a simple regression model to support predictive maintenance scheduling.

METHOD

This study employs a quantitative research approach to examine the relationship between operational hours and torque rod bushing damage in Hino 500 dump trucks. The research was conducted at PT XYZ, which operates these vehicles for material transportation in mining and construction projects. Primary data were obtained from bushing inspection records and hour meter readings collected at the time of maintenance. Damage data covered six bushing positions: Front Upper (FU), Rear Upper (RU), Front Lower (FL), Front Right (FR), Rear Left (RL), and Rear Right (RR).

The severity of bushing damage was determined through visual inspection and measurement based on maintenance department standards. Each bushing was classified into three categories—minor, moderate, and severe—according to the observed wear level. These categories were assigned numerical scores, which were used to calculate the total damage value for each dump truck unit.

Damage severity for each unit was classified based on the number of failed bushing points out of six total positions. Damage was categorized as minor (1–2 failed points), moderate (3–4 failed points), and severe (5–6 failed points). Data analysis was performed using descriptive statistics, Pearson correlation to measure the strength of the relationship, and simple linear regression to model the failure prediction.

Data analysis was performed using descriptive statistics to identify damage patterns and trends, followed by Pearson correlation to evaluate the strength and direction of the relationship between operational hours and damage severity. Simple linear regression analysis was then applied to estimate the rate of increase in damage severity per additional operational hours. All statistical computations were carried out using SPSS software, with a significance level set at 0.05.

RESULTS AND DISCUSSION

The analysis results show a significant variation in the severity of torque rod bushing damage across different positions. Based on the descriptive statistics, the Rear Left (RL) and Rear Right (RR) bushings recorded the highest frequency of severe damage, each at 70%, followed by the Front Lower (FL) at 50% and Front Right (FR) at 44%. The lowest frequencies were observed in the Front Upper

(FU) at 26% and Rear Upper (RU) at 28%. This distribution suggests that rear bushings are subjected to greater operational loads and environmental stress, making them more vulnerable to wear and failure.

The simple linear regression model further quantified this relationship, showing that for every additional 1,000 operational hours, the damage severity score increases by 0.565 points. This quantitative insight enables more precise preventive maintenance scheduling. For example, with the observed rate of wear, it is recommended to conduct bushing replacement every 6,000–7,000 operational hours to prevent severe failures and reduce unexpected downtime.

The descriptive statistics showed a clear pattern of higher failure rates in the rear positions (Table 1). To test the hypothesis that operational hours correlate with damage, a Pearson correlation analysis was conducted. The analysis yielded a strong positive correlation between the hour meter reading and the level of bushing damage, with a Pearson coefficient (r) of 0.84 ($p < 0.05$), indicating a statistically significant relationship. Furthermore, the coefficient of determination (R^2) was 0.705, which means that 70.5% of the variation in bushing damage can be explained by the vehicle's operational hours.

Comparing these findings to other literature, such as Taş et al. (2020) and Palomino-Valles et al. (2020), the results align with the notion that operational conditions and loading patterns are primary drivers of bushing degradation. The high wear rates in RL and RR positions can be attributed to their role in bearing heavier loads during vehicle operation, particularly under uneven road conditions in mining sites. Implementing condition-based or predictive maintenance strategies, as suggested by recent studies (Benhanifia, 2025; Zhong, 2023; Molęda et al., 2023), could further optimize replacement intervals and enhance fleet reliability.

Bushing Damage Frequency by Position

The objective of this study was to analyze the relationship between operational hours and the severity of torque rod bushing damage in Hino 500 dump trucks, and to determine the most vulnerable bushing positions. The findings from the descriptive statistical analysis revealed that the Rear Left (RL) and Rear Right (RR) positions experienced the highest frequencies of severe damage, each accounting for 70% of the observed cases. The Front Lower (FL) and Front Right (FR) followed with 50% and 44%, respectively, while the Front Upper (FU) and Rear Upper (RU) recorded the lowest frequencies at 26% and 28%

Table 1. Total Damage Distribution per Point

Bushing Point	Frequency of Damaged Units	Percentage
FU	13	26%
RU	14	28%
FL	25	50%
FR	22	44%
RL	35	70%
RR	35	70%

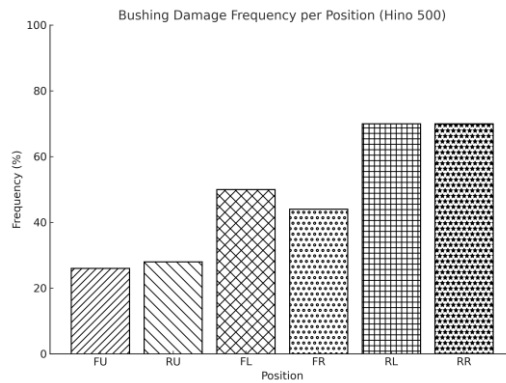


Figure 1. Damage Graph by Bushing Point

These results are scientifically consistent with the mechanical load distribution characteristics of dump truck suspension systems, where rear bushings bear a greater portion of vertical and horizontal loads during operation, especially under heavy-duty and uneven road conditions. The high wear rates in RL and RR positions can be attributed to increased load transfer when the dump body is raised during unloading, causing additional stress on these components.

Damage Categories

The first step in the analysis was to classify the torque rod bushings according to the severity of the observed damage. Based on the maintenance department’s inspection criteria, the damage was categorized into three levels: minor, moderate, and severe. Minor damage was characterized by visible wear without significant deformation, moderate damage showed partial cracks or deformation affecting functionality, while severe damage involved major cracks, deformation, or complete failure of the bushing.

Table 2. Damage Category

Damage Category	Number of Trucks	Percentage	Average Hour Meter
Minor (1–2 points)	25	50%	7,234 hours
Moderate (3–4 points)	12	24%	11,726 hours
Severe (5–6 points)	13	26%	13,875 hours

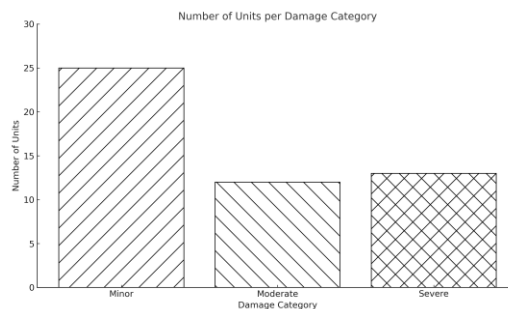


Figure 2. Graph of Number of Trucks by Damage Category

The results indicated that 50% of the bushings fell into the severe category, 24% into moderate, and 26% into minor. This distribution suggests that a substantial proportion of the bushings had reached an advanced stage of deterioration, requiring immediate replacement to maintain vehicle stability and safety.

Damage Classification by Position

The next stage of the analysis focused on classifying bushing damage by position. Table 3 presents the average number of damaged points for each position, namely upper, front, and rear. The descriptive results indicate that the rear position experienced the highest average damage, with 1.40 points per unit, followed by the front position with 0.94, while the upper position recorded the lowest value at 0.54.

Table 3. Average Damage by Position

Position	Number of Trucks	Average Damage per Unit
Upper	14	0.54
Front	25	0.94
Rear	35	1.40

These results highlight that the rear position is the most vulnerable area, which is consistent with the findings from the point-based frequency analysis. The higher average damage in the rear bushings, particularly RL and RR, reflects the greater operational load and stress transferred to this section of the suspension system. During loading and dumping operations, the rear axle bears additional vertical and torsional forces, which accelerate wear compared to the front and upper positions.

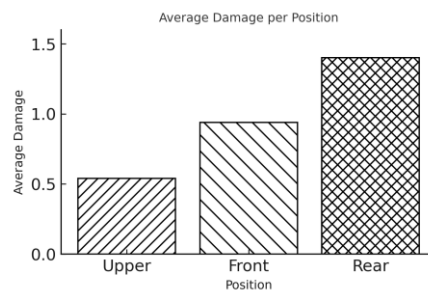


Figure 3. Number of Trucks by Damage Position

This figure shows the average number of damaged points per truck unit based on position. The rear position recorded the highest average damage (1.40), followed by the front position (0.94), while the upper position experienced the lowest average damage (0.54). These results indicate that rear bushings are the most vulnerable components due to higher operational loads.

Descriptive Statistical Analysis

In the descriptive statistical analysis stage, measures of central tendency and measures of dispersion were calculated. The statistical measures employed include the mean, median, mode, variance, and standard deviation to provide a general overview of the data characteristics. The statistical measures used are as follows:

Average Hour Meter at the Time of Failure The mean represents the average value of all data, which is calculated using the following formula:

$$\bar{X}_{HM} = \frac{\sum_{i=1}^n HM_i}{n} \quad (1)$$

Total Damage, the total damage is calculated as the sum of damage points across all six bushing positions, expressed as:

$$Total\ Damage = FU_i + RU_i + FL_i + FR_i + RL_i + RR_i \quad (2)$$

FU_i = damage score at the Front Upper position

RU_i = damage score at the Rear Upper position

FL_i = damage score at the Front Lower position

FR_i = damage score at the Front Right position

RL_i = damage score at the Rear Left position

RR_i = damage score at the Rear Right position

Standar Deviasi, standard deviation was employed to measure the extent of data dispersion from the mean. A smaller standard deviation indicates that the data points are closer to the mean, while a larger standard deviation reflects greater variability in the dataset. The formula for calculating the standard deviation is expressed as:

$$s = \sqrt{\frac{\sum_{i=1}^n (X_i - \bar{X})^2}{n-1}} \quad (3)$$

s = standard deviation

X_i = individual data values

X = mean of the data

n = number of observations

Simple Linear Regression Analysis

To determine the functional relationship between the independent variable and the dependent variable, a simple linear regression analysis was employed. The simple linear regression equation can be formulated as follows:

$$Y = \alpha + bX \tag{4}$$

$$r = \frac{n \sum xy - (\sum X)(\sum Y)}{\sqrt{[n \sum X^2 - (\sum X)^2][n \sum Y^2 - (\sum Y)^2]}} \tag{5}$$

$$a = \bar{Y} - b\bar{X} \tag{6}$$

Y = dependent variable (damage level)

X = independent variable (operating hours)

a = constant

b = regression coefficient

Pearson Correlation Analysis

To determine the relationship between vehicle operating hours (X) and the level of torque rod bushing damage (Y), Pearson correlation analysis was employed. The Pearson correlation coefficient (r) is calculated using the following formula:

$$r = \frac{n \sum xy - (\sum X)(\sum Y)}{\sqrt{[n \sum X^2 - (\sum X)^2][n \sum Y^2 - (\sum Y)^2]}} \tag{7}$$

Table 4. Interpretation of r Values

r	Correlation Strength
0.00 – 0.20	Very Weak
0.21 – 0.40	Weak
0.41 – 0.60	Moderate
0.61 – 0.80	Strong
0.81 – 1.00	Very Strong

Coefficient of Determination (R^2)

The coefficient of determination is used to assess the extent to which the independent variable contributes to explaining the variance of the dependent variable. The coefficient of determination is calculated as follows:

$$R^2 = r^2 \tag{7}$$

The value of R^2 indicates the proportion of the variability in Y that can be explained by X .

Data Presentation Technique

The results of data processing will be presented in the form of tables and charts to facilitate interpretation. The charts used include line charts, bar charts, and pie charts, in accordance with the standard practices of statistical data presentation

Results of Calculation.

Classification of Total Damage by Unit

Descriptive Statistical Analysis

Mean of Total Damage

$$\bar{Y} = \frac{\sum Y}{n} = \frac{144}{50} = 2.88$$

Mean of Working Hours

$$\bar{X} = \frac{\sum X}{n} = \frac{501966}{50} = 10039.32$$

Standard Deviation of Damage

$$s = \sqrt{\frac{\sum_{i=1}^n (Y_i - \bar{Y})^2}{n-1}} = \sqrt{5.544} = 2.35$$

Simple Linear Regression Analysis

$$Y = \alpha + bX = -2.794 + 0.000565 * X$$

Pearson Correlation Analysis

$$r = \frac{n \sum xy - (\sum X)(\sum Y)}{\sqrt{[n \sum X^2 - (\sum X)^2][n \sum Y^2 - (\sum Y)^2]}}$$

$$r = \frac{\sum (x_i * y_i)}{\sqrt{\sum x_i^2 * \sum y_i^2}}$$

$$r = \frac{477812.16}{\sqrt{845199422.8 * 795.84}} = \frac{119976.84}{151230.45} = 0.875$$

Coefficient of Determination

$$R^2 = r^2$$

$$R^2 = r^2 = (0.875)^2 = 0.766$$

The results obtained from the calculation of bushing damage frequency by position. Table 5. Bushing damage frequency by position, presents the results of the calculation of bushing damage frequency by position. The data illustrate the distribution of failures across different positions, highlighting the areas with the highest frequency of damage and thus requiring more focused maintenance efforts.

Table 5. Bushing damage frequency by position

Bushing Point	Mean	Linear Regression	r	R ²
FU	0.26	Y = -0.509 + 0.000077 X	0.630	0.397
RU	0.28	Y = -0.579 + 0.000086 X	0.687	0.473
FL	0.50	Y = -0.581 + 0.000108 X	0.777	0.604
FR	0.44	Y = -0.549 + 0.000099 X	0.716	0.513
RL	0.70	Y = -0.288 + 0.000098 X	0.775	0.600
RR	0.70	Y = -0.288 + 0.000098 X	0.775	0.600

A simple linear regression model was developed to predict the level of damage based on operational hours. The resulting prediction equation is:

$$Y = -0.455 + 0.000098X$$

Where Y is the predicted damage level, and X is the number of operational hours. This model indicates that for every 1,000-hour increase in operation, the damage index is expected to increase by approximately 0.098 points.

The analysis revealed that the damage categories can be classified into three levels: minor, moderate, and severe. This classification provides a clearer understanding of the severity of damage observed in the torque rod bushings and serves as a basis for further evaluation.

Table 6. Results of the calculation of damage categories

Damage Category	Number of Trucks	Average Hour Meter	Average Damage
Minor (1–2 points)	25	7,234 hours	0.8 points
Moderate (3–4 points)	12	11,726 hours	3.83 points
Severe (5–6 points)	13	13,875 hours	6.0 points

Simple Linear Regression Analysis

$$Y = \alpha + bX = -0.091 + 0.000184 * X$$

Pearson Correlation Analysis

$$r = \frac{n \sum xy - (\sum X)(\sum Y)}{\sqrt{[n \sum X^2 - (\sum X)^2][n \sum Y^2 - (\sum Y)^2]}}$$

$$r = \frac{\sum(x_i * y_i)}{\sqrt{\sum x_i^2 * \sum y_i^2}}$$

$$r = \frac{119976.84}{\sqrt{65086151688 * 35.12}} = \frac{119976.84}{151230.45} = 0.794$$

Coefficient of Determination

$$R^2 = r^2$$

$$R^2 = r^2 = (0.794)^2 = 0.630$$

The results obtained from the calculation of damage classification by position. Table 7 Damage classification by position. Damage classification by position presents the distribution of damage levels across the front, top, and rear positions.

Table 7 Damage classification by position

Posisi	Mean	Regresi Linear $Y = a + bX$	r
Atas	0.54	$Y = -1.088 + 0.000162 X$	0.667
Depan	0.94	$Y = -1.131 + 0.000206 X$	0.769
Belakang	1.40	$Y = -0.575 + 0.000197 X$	0.775

The results confirm the initial hypothesis, demonstrating a strong, statistically significant relationship between operational hours and torque rod bushing failure. The finding that over 70% of the damage variation is attributable to operational hours provides a solid empirical basis for maintenance planning. The significantly higher failure rates observed in the Rear Left (RL) and Rear Right (RR) positions can be attributed to the specific operational dynamics of dump trucks. These positions bear the brunt of the load during both loading and dumping cycles, subjecting them to greater vertical stress, vibration, and torsional forces compared to the upper or front positions. The practical implication of the regression model is its utility as a predictive maintenance tool. For instance, maintenance managers at PT XYZ can use the equation to forecast when a unit is likely to reach a critical damage threshold, allowing them to schedule inspections and replacements proactively rather than reactively. The recommendation to perform preventive replacement at 6,000-7,000 hours is a direct application of this data-driven approach, aimed at optimizing fleet availability and reducing catastrophic failures.

CONCLUSION

This study successfully demonstrates a strong, statistically significant positive correlation between operational hours and the severity of torque rod bushing damage in Hino 500 dump truck units. The findings identified the Rear Left (RL) and Rear Right (RR) positions as the most vulnerable to failure, exhibiting the highest damage frequency at 70% each. The developed linear regression model serves as a practical tool for predictive maintenance, quantifying the impact of operational hours on component degradation. Based on these results, a preventive replacement strategy is recommended at an interval of 6,000–7,000 operational hours, particularly for the rear axle bushings, to mitigate failure risk. The implementation of this data-driven approach is expected to significantly reduce unplanned downtime, lower repair costs, and enhance overall fleet reliability.

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REFERENCES

- Adam, C., Lackner, R., & Schmied, M. (2025). Fatigue life assessment of vehicle suspension components based on strain signals under various road conditions. *International Journal of Fatigue*, 192, 108502.
- Benhanifia, A., Ben Cheikh, Z., Oliveira, P. M., Valente, A., & Lima, J. (2025). Systematic review of predictive maintenance practices in the manufacturing sector. *Intelligent Systems with Applications*, 26, 200501. <https://doi.org/10.1016/j.iswa.2025.200501>
- Dorfmann, A., & Ogden, R. W. (2003). Magnetoelastic modelling of elastomers. *European Journal of Mechanics - A/Solids*, 22(4), 497–507. [https://doi.org/10.1016/S0997-7538\(03\)00023-1](https://doi.org/10.1016/S0997-7538(03)00023-1)
- Dwiky, R. (2024). Analisis kerusakan dust seal hydraulic cylinder boom pada unit wheel loader XCMG LW300KN di PT Surya Karya Setiabudi [Undergraduate thesis, Universitas Gadjah Mada].
- Ginder, J. M., Schlotter, W. F., & Nichols, M. E. (2001). Magnetorheological elastomers in tunable vibration absorbers. In *Smart Structures and Materials 2001: Damping and Isolation* (Vol. 4331, pp. 103–110). SPIE. <https://doi.org/10.1117/12.432672>
- Gunawan, R. (2020). Aplikasi regresi dan korelasi dalam analisis data hasil penelitian. Universitas Airlangga.
- Hasanah, I. (2018). Ringkasan materi kuliah statistika dasar. Fakultas Dakwah, UIN Sultan Maulana Hasanuddin Banten.
- Hunsaker, O. K. (1966). Torque rod suspension for truck axles (U.S. Patent No. 3,256,007). United States Patent and Trademark Office.
- Ikeda, K., & Sakuragi, A. (1993). Rubber bushing (U.S. Patent No. US5190269A). United States Patent and Trademark Office.
- International Organization for Standardization. (2013). ISO 1629:2013 - Rubber and latices nomenclature. ISO.
- Keeler, M. J., Zawacki, J. R., Massa, S. A., Fugitt, J. C., & Kowalski, M. D. (2016). Torque rod for vehicle suspension (Patent No. US20160347145A1). United States Patent and Trademark Office.
- Mallioris, E., Papandroulakis, G., & Drosatos, G. (2024). A survey on predictive maintenance using Industry 4.0 and machine learning. *Evolving Systems*, 15(1), 1-28.
- Nataraj, S., Khanduja, T., & Khanduja, C. (2014). Torque rod (U.S. Patent No. 8,714,571 B2). United States Patent and Trademark Office.
- Odeyar, P., Apel, D. B., Hall, R., Zon, B., & Skrzypkowski, K. (2022). A review of reliability and fault analysis methods for heavy equipment and their components used in mining. *Energies*, 15(17), 6158. <https://doi.org/10.3390/en15176158>
- Rachman, A., Yochanan, E., Samanlangi, A. I., & Purnomo, H. (2024). Metode penelitian kuantitatif, kualitatif dan R&D. CV Saba Jaya Publisher.
- Reynolds, R. C., & Jones, L. (1966). Torque rod bushing (U.S. Patent No. US3256007A). United States Patent and Trademark Office.
- Setiawan, R., & Winursito, Y. C. (2023). Analisis pengaruh kemampuan mesin capping terhadap penumpukan work in progress menggunakan regresi linear sederhana. *INDEXIA: Informatic and Computational Intelligent Journal*, 6(2), 72–80.
- Sulaiman, F., & Rahmat, A. (2017). Pengaruh tingkat keandalan alat berat terhadap produktivitas perusahaan. *Jurnal Teknik Sipil*, 13(2), 123-134.
- Tas, M., Okur, M. Z., & Biçer, S. G. (2020). New designed bushings for reaching intended stiffness values and their analysis in torque rod of heavy commercial vehicles. *GU Journal of Science, Part A: Engineering and Innovation*, 7(2), 33–41.

- Thillikkani, P., & Nataraj, M. (2020). Failure analysis of leaf spring in a light commercial vehicle. *Engineering Failure Analysis*, 110, 104423.
- Wahyuni, D., & Santoso, A. (2022). Analisis algoritma regresi linear sederhana dalam memprediksi nilai. *Jurnal Literasi Sains*, 5(1), 13–19.
- Winastra, Y. (2025). Analisis kegagalan komponen suspensi pada kendaraan niaga di Indonesia. Institut Teknologi Bandung.
- Zhong, D., Xia, Z., Zhu, Y., & Duan, J. (2023). Overview of predictive maintenance based on digital twin technology. *Heliyon*, 9(3), e14534. <https://doi.org/10.1016/j.heliyon.2023.e14534>
- Zhu, T., Ran, Y., Zhou, X., & Wen, Y. (2024). A survey of predictive maintenance: Systems, purposes and approaches. *IEEE Transactions on Industrial Informatics*. Advance online publication. <https://doi.org/10.48550/arXiv.1912.07383>