DOKUMEN BUKTI KORESPONDENSI JURNAL INTERNASIONAL SCOPUS Q2 SEBAGAI PENULIS PERTAMA DAN KORESPONDENSI

Judul Artikel: Modeling Fuel Consumption of Heavy-duty Trucks Using Telematics Data

Jurnal: Periodica Polytechnica Transportation Engineering (Scopus Q2, ISSN: 1587-3811)

Penulis: Pradhana Wahyu Nariendra (Penulis Pertama & Korespondensi), Wimpy Santosa, Anastasia Caroline Sutandi

DAFTAR ISI KELENGKAPAN BERKAS

1. IDENTITAS ARTIKEL DAN PROFIL JURNAL
1.1. Profil Jurnal

Artikel berjudul “Modeling Fuel Consumption of Heavy-duty Trucks Using Telematics Data” telah diterbitkan pada jurnal Periodica Polytechnica Transportation Engineering, Vol. 54 No. 1 Tahun 2026, hlm. 41–48. Artikel ini ditulis oleh Pradhana Wahyu Nariendra sebagai penulis pertama sekaligus penulis korespondensi, bersama Wimpy Santosa dan Anastasia Caroline Sutandi, dengan afiliasi pada Department of Civil Engineering, Faculty of Engineering, Parahyangan Catholic University.

Artikel ini relevan dengan bidang Teknik/Rekayasa Transportasi karena membahas pemodelan konsumsi bahan bakar truk berat berbasis data telematika pada truk Euro-3 dan Euro-4 di jalan tol Indonesia. Substansi artikel mencakup pengaruh kecepatan operasi rata-rata, berat kendaraan, gradient jalan, dan tipe truk terhadap konsumsi bahan bakar, serta berkaitan dengan kinerja angkutan barang, efisiensi energi, biaya operasi kendaraan, emisi, dan keberlanjutan transportasi.

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Modeling Fuel Consumption of Heavy-duty Trucks Using Telematics Data

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1.2. Relevansi Karya Ilmiah dengan Bidang Ilmu

Bagian Aim and Scope jurnal Periodica Polytechnica Transportation Engineering menunjukkan bahwa cakupan jurnal meliputi bidang transportation, logistics, vehicle engineering, pemodelan dan pengukuran sistem kompleks, isu lingkungan dan perkotaan, serta analisis kendaraan dan mesin. Cakupan tersebut relevan dengan artikel "Modeling Fuel Consumption of Heavy-duty Trucks Using Telematics Data" karena artikel membahas pemodelan konsumsi bahan bakar truk berat berbasis data telematika pada operasi angkutan barang di jalan tol Indonesia. Kesesuaian ini diperkuat oleh objek kajian artikel, yaitu heavy-duty trucks, serta variabel yang dianalisis, meliputi kecepatan operasi rata-rata, berat kendaraan, gradient jalan, dan tipe truk. Dengan demikian, artikel ini berada dalam lingkup Aim and Scope jurnal dan mendukung kesesuaian bidang ilmu Teknik/Rekayasa Transportasi.

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Aims and Scope

The main scope of the journal is to publish original research articles in the wide field of transportation, logistics and vehicle engineering, e.g. in the field of modeling and measuring complex systems, and also relating to environmental and urban problems just as much as the economic and social questions of transport (e.g.: travel or driver behavior). Handling and modeling of large networks, the analysis of vehicles and engines are also considered. Special attention is paid to the future emerging technologies (autonomous vehicles and alternative propulsion mobility) within the transport sector.

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The journal is recommended to researchers, faculty professors, and PhD students active in its field.

1.3. Bukti Indeksasi Scopus Q2

Berdasarkan Scopus Preview, jurnal Periodica Polytechnica Transportation Engineering masih tercakup dalam indeks Scopus hingga tahun 2026, diterbitkan oleh Budapest University of Technology and Economics, serta memiliki subject area yang relevan, yaitu Engineering: Automotive Engineering, Mathematics: Modeling and Simulation, Engineering: Aerospace Engineering, dan Engineering: Mechanical Engineering. Pada CiteScore Rank 2024, jurnal ini berada pada kategori Engineering: Automotive Engineering dengan peringkat #67/133 dan percentile 50th, yang menunjukkan posisi Q2 pada kategori tersebut. Selanjutnya, tampilan SINTA Executive juga menunjukkan bahwa artikel "Modeling Fuel Consumption of Heavy-duty Trucks Using Telematics Data" tercatat sebagai publikasi Scopus dengan label Q2. Dengan demikian, bukti Scopus Preview dan SINTA Executive memperkuat bahwa artikel ini relevan dengan bidang Teknik/Rekayasa Transportasi dan memenuhi kualifikasi sebagai publikasi pada jurnal internasional bereputasi terindeks Scopus.

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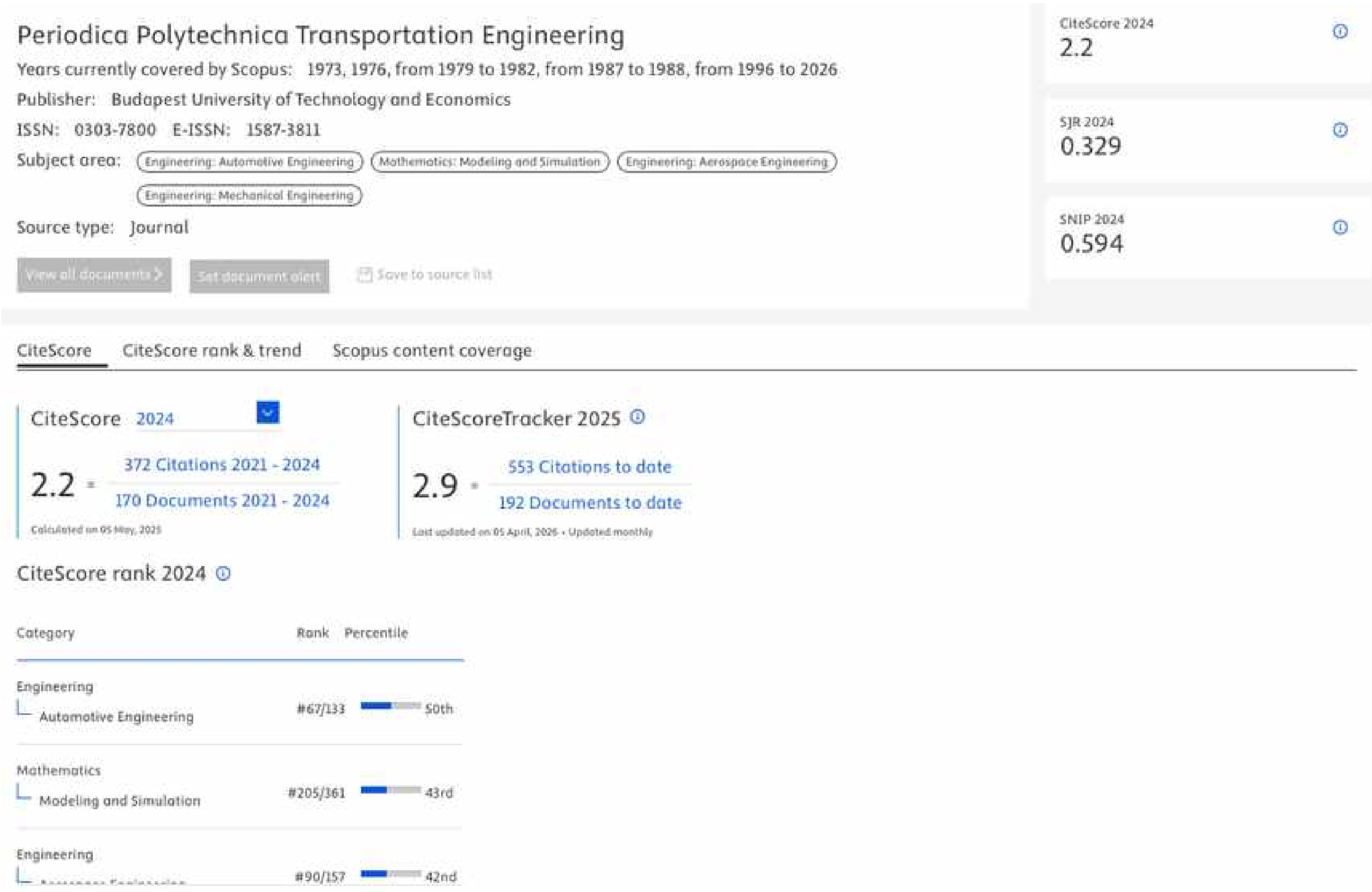


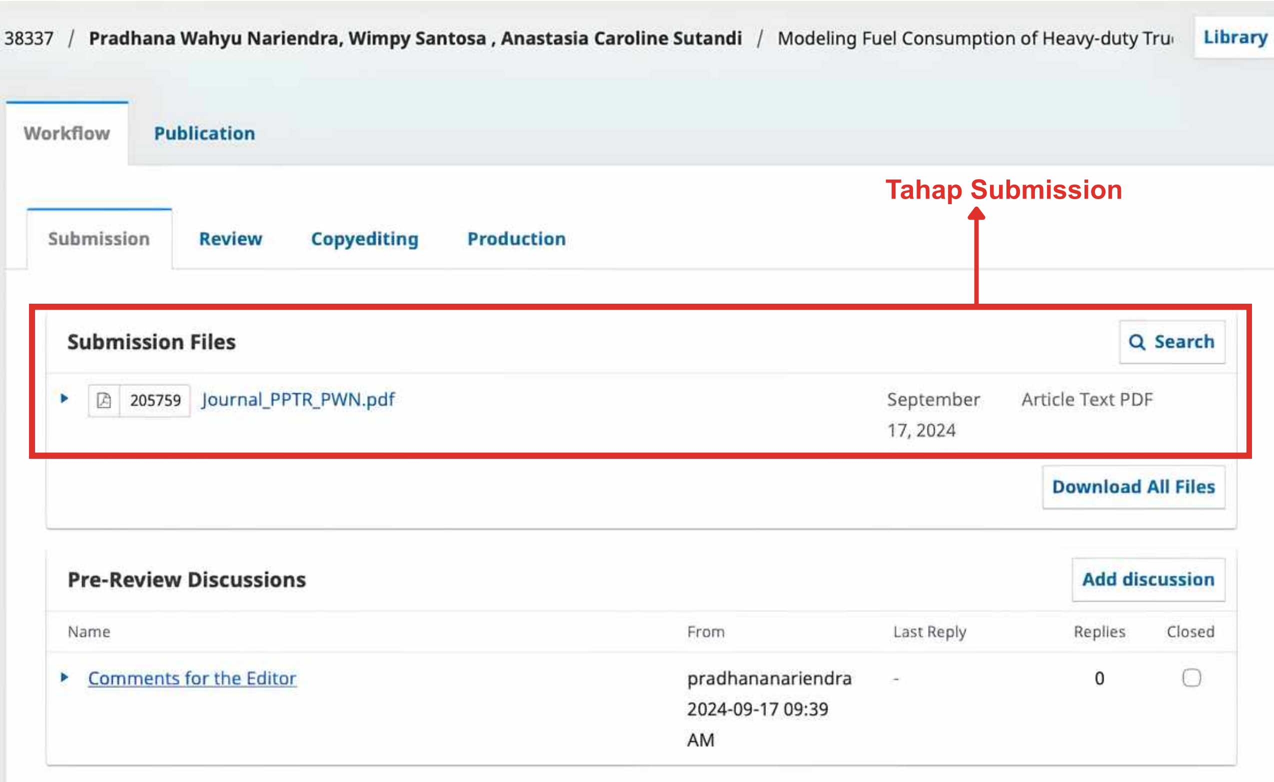
2. KRONOLOGIS KORESPONDENSI (LOG SUMMARY)

No.	Tahapan Korespondensi	Tanggal	Keterangan
1	Submission	17 Sept 2024	Naskah awal diunggah ke sistem OJS jurnal dengan file Journal_PPTR_PWN.pdf.
2	Pre-Review Discussion	17 Sept 2024	Penulis mengisi Comments for the Editor pada tahap awal submission.
3	Tahap Review	8 Mei 2025	Editor menyampaikan hasil review dan meminta penulis mengunggah naskah revisi dalam format DOCX serta file gambar terpisah dalam JPG.
4	Komentar Reviewer	8 Mei 2025	Reviewer memberikan masukan substansial terkait pendahuluan, novelty, tujuan penelitian, nomenclature, bahasa, hasil numerik, kesimpulan, kontribusi ilmiah, dan potensi metode lanjutan.
5	Revised Manuscript Submission	12 Mei 2025	Penulis mengunggah naskah revisi dan memberikan tanggapan formal terhadap komentar reviewer.
6	Tambahan Figure 1 JPG	16 Mei 2025	Penulis mengunggah Figure 1 dalam format JPG karena belum tercakup pada unggahan sebelumnya.
7	Accept Submission	3 Agustus 2025	Editor menyampaikan keputusan Accept Submission dan artikel dilanjutkan ke tahap copyediting.
8	Editing Completed / Sent to Production	4 Nov 2025	Editor menyampaikan bahwa proses editing selesai dan artikel dikirim ke tahap production.
9	Proofreading Request	4 Nov 2025	Editor mengirimkan typeset proof dan meminta penulis memeriksa koreksi minor.
10	Proof Correction Response	5 Nov 2025	Penulis mengunggah koreksi proof dengan penjelasan bahwa koreksi bersifat minor dan tidak mengubah substansi artikel.
11	Proofreading Request 2	6 Nov 2025	Editor mengirimkan proof kedua untuk diperiksa kembali oleh penulis.
12	Proof 2 Corrections Submitted	6 Nov 2025	Penulis mengunggah koreksi proof kedua.
13	Article Published Online	7 Nov 2025	Editor menyampaikan bahwa artikel telah dipublikasikan secara online dengan tautan DOI.

3. TAHAP SUBMISSION

3.1. Bukti Submission Confirmation

Artikel diajukan melalui sistem OJS Periodica Polytechnica Transportation Engineering dengan nomor submission 38337. Pada tahap awal, naskah diunggah sebagai file Journal_PPTR_PWN.pdf pada tanggal 17 September 2024.



3.2. Naskah Awal / Pre-Review Manuscript

Naskah awal merupakan dokumen pertama yang diajukan sebelum melalui proses review, revisi, dan publikasi akhir. Dokumen ini menjadi bukti bahwa artikel telah masuk ke sistem editorial jurnal sejak tahap submission.

Modeling Fuel Consumption of Heavy-Duty Trucks Using Telematics Data

Pradhana Wahyu Nariendra[1*], Wimpy Santosa [1], Anastasia Caroline Sutandi [1]

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Abstract

Road transport, particularly heavy-duty trucks, is a significant contributor to CO_2 and NOx emissions, especially in developing nations such as Indonesia. This research introduces a novel fuel consumption model for trucks compliant with Euro-3 and Euro-4 emission standards, leveraging real-time telematics data to enhance fuel efficiency and mitigate emissions. The two main approaches are multiple linear regression with Box-Cox transformation and Generalized Linear Models (GLM), with independent variables including average operation speed, gross vehicle weight, and road gradient, collected from major logistics corridors in Indonesia. Empirical results indicate that the Box-Cox transformation model outperforms the GLM, exhibiting lower deviance and Root Mean Square Error (RMSE). The analysis reveals that average operation speed and truck type positively influence fuel consumption, while gross weight and road gradient negatively impact it. Euro-4 trucks demonstrate higher fuel efficiency and lower emissions compared to Euro-3 trucks, though further refinement of the predictive model for Euro-4 trucks is warranted. This study underscores the critical role of enhancing fuel efficiency in reducing emissions, with Euro-4 technology not only boosting efficiency but also substantially cutting greenhouse gas emissions. Moreover, the integration of telematics technology facilitates precise data acquisition, fostering energy optimization and emission reduction initiatives within the transportation sector. Future research should explore the integration of machine learning techniques to capture more complex patterns and extend model applicability across diverse operating conditions, particularly within the context of developing countries.

Keywords

fuel consumption model, emission reduction, euro-4 truck, telematics data, heavy-duty truck

1 Introduction

The transportation sector, particularly the trucking industry, is a significant contributor to global CO_2 emissions, accounting for approximately 25% of total emissions within the sector (Al-Hasan, 2007). In Indonesia, freight trucks represent a notable source of air pollution, contributing to both local air quality degradation and climate change. Heavy-duty trucks are responsible for approximately 25% of CO_2 emissions from road transportation and 5% of total GHG emissions within the European Union (Yang et al., 2021; White et al., 2017). These vehicles also emit higher levels of CO_2 and NOx compared to light trucks (Mahalana et al., 2022). In Indonesia, the trucking industry faces high operational costs, where fuel alone represents approximately 28% of total operating expenses (Brasukra and Hergesell, 2008).

The practice of overloading, although often employed to increase short-term profits, negatively impacts fuel efficiency and increases emissions (Jacob and Feypell-de La Beaumelle, 2010; Titi et al., 2018). Countries such as the United States and China have adopted aerodynamic-enhancement technologies, heat recovery systems, and low-rolling resistance tires to reduce fuel consumption in heavy-duty trucks (White et al., 2017). In response to global climate agreements, such as the Paris Agreement and Sustainable Development Goals, the Indonesian government has introduced Euro-4 emission standards with the aim of reducing emissions and improving fuel efficiency (Ministry of Environment and Forestry, 2017). Euro-4 standards are reported to offer 10-15% improvements in fuel efficiency compared to Euro-3 trucks, with CO_2 and NOx emissions reduced by up to 30% (Erkkilä and Nylund, 2007; Maulidya, 2019). This improvement not only enhances environmental sustainability but also significantly reduces operating costs for the trucking industry, which is critically important given the high operational costs.

Despite the potential benefits offered by Euro-4 technology, there remains a lack of studies directly comparing the fuel consumption of Euro-4 and Euro-3 trucks under actual operational conditions within the Indonesian context. Previous studies have frequently relied on the HDM-4 model, which often requires recalibration to align with local conditions (Zaabar and Chatti, 2010). However, the accuracy of such calibrations is limited in the absence of relevant local data, resulting in significant errors in fuel consumption predictions for heavy-duty trucks (Greenwood et al., 2007). This research addresses this gap by integrating manufacturer-authorized telematics technology, enabling real-time data collection without the need for complex and expensive field experiments (Perrotta et al., 2019).

Unlike traditional methodologies that rely on manual calibration and rigid assumptions, the use of telematics data allows for the comprehensive capture of key variables such as average operation speed, vehicle gross weight, and road gradient, all of which are critical determinants of fuel consumption (Wang et al., 2017; Posada-Henao, 2023). Building on the work of Iskandar (2000), who developed a fuel consumption model for Euro-1 trucks, this study employs Euro-4 standards and telematics technology, representing a novel and underexplored approach in Indonesia.

The research focuses on 5-axle trucks, the most common type of heavy-duty vehicle in Indonesia, which enhances the representativeness of the findings in actual operational contexts. It is expected that this approach will produce a more accurate fuel consumption model, which will not only contribute to scientific knowledge but also inform policies related to fuel efficiency and GHG emission reduction in Indonesia. The research outcomes are anticipated to have significant implications, offering a more accurate model of fuel consumption and presenting the potential of Euro-4 technology to improve fuel efficiency by up to 15%, thus contributing to both emissions reductions and operational cost savings (Erkkilä and Nylund, 2007; Brasukra and Hergesell, 2008; Maulidya, 2019).

2 Methodology

This study focuses on containerized semi-trailer trucks with Euro-3 and Euro-4 emission standards operating on the Tanjung Priok Port - Bandung route, one of the major logistics corridors in Indonesia. The selection of Hino FG 260 TH (Euro-4) and UD Quester GKE (Euro-3) trucks was based on the results of an initial survey. Both trucks feature a fully integrated telematics system and exhibit similar weight-to-power ratios of 5.6 kW/ton and 5.7 kW/ton, respectively, ensuring uniformity in truck performance (Mahalana et al., 2022; Environmental Agency of DKI Provincial Government, 2019).

Data were collected over two months (February and March 2024) through a manufacturer-authorized telematics system, which integrates GPS, Hino Connect, My UD Fleet, and a Transport Management System (TMS) to capture real-time information on speed, gross vehicle weight, fuel consumption, and road gradient. Telematics data refers to information collected from vehicle sensor systems, including GPS, On-Board Diagnostic (OBD-II), and Mobile Network IoT systems. This data encompasses critical vehicle performance metrics such as speed, location, fuel consumption, and operational efficiency, which are transferred via the Electronic Control Unit (ECU) or IoT mobile network (Farzaneh et al., 2020; SAE International, 2022; Perrotta et al., 2019).

Road gradient was derived using Google Earth elevation data, providing sufficient accuracy for transportation applications, with a Mean Absolute Error (MAE) of approximately 1.32 meters and a Root Mean Square Error (RMSE) of 2.27 meters (Wang et al., 2017). The data collection was conducted under controlled, distraction-free conditions with consistent average speeds and road conditions (Zhang et al., 2019). Data pre-processing included outlier removal via the Z-score method (using a threshold of ±3 standard deviations) and linear interpolation to address missing data and maintain dataset integrity.

Two models were employed for analysis: Model 1 utilized Ordinary Least Squares (OLS) regression to model the relationship between speed, gross vehicle weight, and road gradient on fuel consumption. Assumptions of linear regression, such as residual normality and homoscedasticity, were tested; where violations occurred, corrections were made using robust standard errors and the Box-Cox transformation (King and Roberts, 2014; Malik et al., 2018). Alternatively, Model 2 applied Generalized Linear Models (GLM) with a Gamma distribution and log links to address skewness in fuel consumption data, providing a robust solution for heteroscedasticity issues (Dobson and Barnett, 2018).

Model validation was conducted using the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) to identify the optimal model, both of which offer advantages over the traditional R^2 statistic for model selection (Dobson and Barnett, 2018). To ensure model reliability, predicted values were compared with observed fuel consumption data, and a null hypothesis test was performed to assess whether the differences were statistically significant. The Wilcoxon Signed-Rank test, a nonparametric method that does not rely on normality assumptions, was utilized to test the similarity between paired observations. The null hypothesis (H_0) posited no significant difference between predicted and observed fuel consumption, implying that the discrepancy between the two would be zero (Deshpande et al., 2017). By rejecting or accepting the null hypothesis, the accuracy of the model in capturing real-world fuel consumption data can be rigorously evaluated (Deshpande et al., 2017).

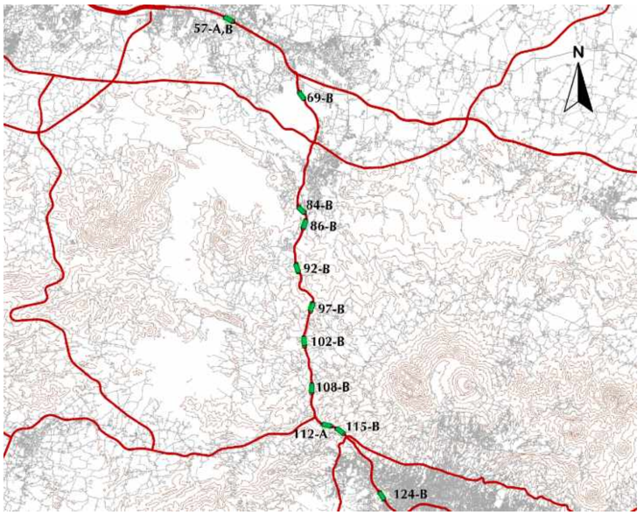
3 Data and Result

Section 3 provides a detailed analysis of the data processing and modeling steps undertaken in this research. Section 3.1 elaborates on the data management procedures, including segmentation, clustering, and outlier detection, within the context of truck fuel consumption modeling. The process ensures that the dataset is clean and suitable for further analysis. Section 3.2 presents a comprehensive examination of the factors influencing fuel consumption, followed by the development of a fuel consumption model specifically designed for Euro-3 and Euro-4 emission standard trucks. Lastly, Section 3.3 evaluates the accuracy and predictive performance of the proposed truck fuel consumption model. Various validation metrics, such as the AIC and BIC, are employed to assess the model's robustness and alignment with observed data.

3.1 Data Processing

Data management in this study begins with the segmentation of road sections based on road gradient and vehicle speed under non-congested or free-flow conditions. This segmentation is intended to yield more homogeneous and representative observation segments, facilitating a more accurate analysis of the impact of road gradient on vehicle performance and fuel consumption. The study classifies road gradients into three categories: flat, hilly, and mountainous terrains, which were identified from 12 road segments on the Jakarta-Cikampek, Cipularang, and Purbaleunyi Toll Roads. The flat terrain segments include segments 57-A and 57-B, with maximum gradients of 0.01% and 0.07%, respectively. The hilly and mountainous segments include segment 108-A, with a gradient of 4.72%, and segment 92-B, with a gradient of 6.13%. The specific details of the gradients in each observation segment are provided in Table 1. A total of 1,094 speed observations were collected during February and March 2024, comprising 474 data points for Euro-4 trucks and 620 data points for Euro-3 trucks. These data were categorized based on vehicle speed, gross vehicle weight, and road gradient. Speed was divided into three categories: low (below 20 km/h), medium (20-40 km/h), and high (above 40 km/h). Gross vehicle weight (load factor) was classified into three categories: low (below 30%), medium (30-75%), and high (more than 75%). Road gradient was categorized as flat (maximum 4%), hilly (maximum 5%), and mountainous (maximum 6%).

Fig. 1 The road sections classified based on road gradient



The results, as shown in Table 1, indicate significant variations in speed between Euro-4 and Euro-3 trucks. The highest recorded speed was observed on segment 57-A for Euro-4 trucks, with an average of 46.88 km/h and a standard deviation of 7.78. In comparison, Euro-3 trucks recorded an average of 42.92 km/h and a standard deviation of 6.36. The lowest speed for Euro-4 trucks was recorded on segment 92-B, averaging 31.01 km/h and a standard deviation of 8.85 km/h), whereas Euro-3 trucks recorded an average of 26.59 km/h and a standard deviation of 8.71. These findings demonstrate that Euro-4 trucks generally operate at higher speeds than Euro-3 trucks, particularly on segments with flat and hilly gradients.

Significant differences were also observed in terms of gross vehicle weight. On segment 92-B, Euro-3 trucks recorded the highest gross vehicle weight, averaging 33.04 tons and a standard deviation of 1.035, while Euro-4 trucks had an average weight of 28.33 tons and a standard deviation of 0.901. Conversely, the lowest gross weight for Euro-4 trucks was recorded on segment 124-B, averaging 23.87 tons and a standard deviation of 0.736. In contrast, Euro-3 trucks recorded their lowest gross weight on segment 57-B, with an average of 30.78 tons and a standard deviation of 1.072. This difference suggests that Euro-4 trucks are more frequently operated with lighter loads compared to Euro-3 trucks, which likely contributes to their superior fuel efficiency.

Regarding fuel consumption, Euro-4 trucks exhibited significantly higher efficiency on segment 57-B, recording an average consumption of 6.98 km/l and a standard deviation of 2.86, while Euro-3 trucks recorded 3.76 km/l and a standard deviation of 1.25. In steeper gradient segments, such as segment 92-B, fuel consumption decreased for both truck types. However, Euro-4 trucks maintained better efficiency, with an average consumption of 0.69 km/l and a standard deviation of 0.27, compared to Euro-3 trucks, which consumed 0.61 km/l and a standard deviation of 0.29. The higher load of Euro-3 trucks likely contributed to their lower efficiency, while Euro-4 trucks exhibited greater resilience in maintaining performance under steeper gradient conditions.

3.2 Fuel consumption modeling

This study models fuel consumption (FC) as the dependent variable, with independent variables including average operating speed (V), gross vehicle weight (W), positive road gradient (G), and truck type as a dummy variable (T). Average operating speed refers to the mean speed of a vehicle over a specified period, influenced by traffic conditions, road gradients, and interactions between vehicles, where gradient resistance reduces speed on uphill roads (Odoki and Kerali, 2006). Gross vehicle weight encompasses the total weight of the vehicle, including the cargo, truck crew, components, and vehicle equipment, which in heavy cargo trucks typically exceeds 11,794 kg (Bennett, 2020). Initial simple linear regression analysis revealed that V exhibited a significant non-linear relationship with fuel consumption, with an R^2 of 0.509 and an F-statistic of 856.769. W showed a non-linear logistic and exponential relationship, with an R^2 of 0.349 and an F-statistic of 442.222. S also had a significant influence, with an R^2 of 0.356 and an F-statistic of 228.128. Given the statistical significance of all variables, the analysis proceeded with multiple linear regression.

Table 1 Summary of speed, gross weight, and fuel consumption data by road gradient

Segment	Road Gradient (%)	Truck Type	Data count	Average operation speed (V)		Gross vehicle Weight (W)		Fuel consumption (FC)	
				Mean V (km/jam)	Standard Deviation	Mean W (ton)	Standard Deviation	Mean FC (km/l)	Standard Deviation
57-A	0.01	Euro-4	44	46.88	7.78	32.09	5.57	5.38	1.41
		Euro-3	54	42.92	6.36	32.67	7.48	3.16	0.77
57-B	0.07	Euro-4	37	47.16	8.73	28.42	8.72	6.98	2.86
		Euro-3	51	46.42	7.81	30.78	10.72	3.76	1.25
69-B	1.00	Euro-4	37	46.44	7.50	26.58	9.01	6.88	2.96
		Euro-3	52	46.05	6.26	30.04	10.67	3.58	1.14
84-B	4.32	Euro-4	44	41.07	9.97	27.62	9.79	3.12	1.32
		Euro-3	54	34.63	9.85	31.18	11.16	1.99	0.88
86-B	5.24	Euro-4	47	39.82	10.03	27.51	9.63	1.97	0.87
		Euro-3	53	31.36	11.22	31.23	11.33	1.36	0.63
92-B	6.13	Euro-4	39	31.01	8.85	28.33	9.01	0.69	0.27
		Euro-3	59	26.59	8.71	33.04	10.35	0.61	0.29
97-B	4.41	Euro-4	44	35.96	10.04	29.79	10.01	2.69	1.23
		Euro-3	51	33.29	9.84	31.12	10.82	1.84	0.85
102-B	2.76	Euro-4	39	38.54	10.68	26.81	8.84	4.32	1.71
		Euro-3	50	35.54	12.35	31.52	10.61	2.19	1.02
108-A	4.72	Euro-4	42	28.63	9.26	30.81	5.96	1.80	0.48
		Euro-3	52	26.43	7.53	33.02	7.12	1.21	0.43
112-B	2.85	Euro-4	38	41.79	9.48	30.02	9.08	3.59	1.47
		Euro-3	55	38.98	10.49	32.14	10.53	2.48	0.99
115-B	3.68	Euro-4	34	43.56	8.69	28.35	9.22	3.09	1.25
		Euro-3	50	39.65	9.65	31.88	10.20	2.01	0.74
124-B	3.37	Euro-4	31	45.53	6.82	23.87	7.36	3.93	1.14
		Euro-3	39	40.13	8.90	30.64	9.98	2.24	0.84

At the next stage, Model 1 was analyzed using multiple linear regression with the application of a Box-Cox transformation (λ = 0.25) to address issues of non-normal residual distributions. Following the transformation, the Kolmogorov-Smirnov test yielded a p-value of 0.095, indicating that the residuals approached a normal distribution. Multicollinearity tests revealed Variance Inflation Factor (VIF) values ranging from 1.0313 to 1.578, confirming the absence of multicollinearity. Additionally, the Durbin-Watson test produced a value of 1.953, close to the ideal value of 2, suggesting no significant autocorrelation. While the Glejser test identified heteroscedasticity in the W and T variables, the Breusch-Pagan test (p = 0.165) indicated that residual variance was constant.

The multiple linear regression results for Model 1 demonstrate that all independent variables have a statistically significant impact on fuel consumption. Average operating speed (V) is positively correlated with fuel consumption, with increased speeds resulting in higher fuel consumption. Conversely, gross vehicle weight (W) and positive road gradient (G) exhibit a negative correlation, where increases in weight or gradient are associated with decreased fuel consumption. Additionally, Euro-4 trucks were found to be more fuel-efficient than Euro-3 trucks, as evidenced by the significant coefficient on the truck type dummy variable, indicating the superior fuel efficiency of Euro-4 trucks. Table 2 presents the coefficients, t-values, and p-values for each variable, confirming that all variables are statistically significant at the 5% significance level, with the critical t-value being 1.647.

Table 2 Model 1 parameter estimation

Parameter	Coefficient	Robust Standard Error	t-value	p-value
Intercept	1.539	0.009	178,989	<0.001
V2	6.64E-02	2.33E-03	28,542	<0.001
W	-0.009	0.000	-66,986	<0.001
G	-0.048	0.001	-54,371	<0.001
T	0.098	0.003	35,953	<0.001

As an alternative approach, Model 2 employs Generalized Linear Models (GLM) with a Gamma distribution and log links to model the relationship between the same set of variables. The Goodness of Fit test indicated a strong fit for the model, with a deviance of 8.827 and a deviance/df ratio of 0.011. In contrast, the Pearson Chi-Square test yielded a value of 8.755 with a Pearson Chi-Square/df ratio of 0.011, further confirming the model's adequacy.

The results of the GLM parameter estimation indicate that both average operating speed (V) and truck type (T) exhibit a statistically significant positive effect on fuel consumption, as demonstrated by their respective coefficients of 0.018 and 0.316. Conversely, gross vehicle weight (W) and positive road gradient (G) are found to have a statistically significant negative influence on fuel consumption, with coefficients of -0.030 and -0.148, respectively. The complete parameter estimation results, including detailed coefficient values, can be found in Table 3.

Table 3 Model 2 parameter estimation

Parameter	Coefficient	Robust Standard Error	Wald Chi-Square Value	*p*-value
Intercept	1.399	0.0360	1,507.653	<.0.001
V	0.018	0.0006	1,025.472	<.0.001
W	-0.030	0.0004	4,435.602	<.0.001
G	-0.148	0.0025	3,433.817	<.0.001
T	0.316	0.0082	1,465.779	<.0.001

A comparative analysis between Model 1 and Model 2 demonstrates that Model 1 outperforms Model 2 in terms of predictive accuracy and model fit. Model 1 exhibits a lower deviance value of 0.947 compared to 8.827 for Model 2, as well as smaller Root Mean Squared Errors (RMSEs) of 0.033 and 0.296, respectively. Furthermore, the adjusted R-squared value of 0.85 suggests that the independent variables in this model explain 85.8% of the variability in fuel consumption. The AIC for Model 1 is -3,246.625, which is substantially lower than that of Model 2, indicating a reduced prediction error and superior model performance.

Based on the comparative analysis of performance metrics shown in Table 3, the multiple linear regression model with Box-Cox transformation is recommended as the best model for predicting fuel consumption in Euro-3 and Euro-4 trucks, as it offers greater accuracy and a better ability to explain the variability in fuel consumption. The final regression equation derived from Model 1 is:

$$FC^{0,25} = 1{,}539 + 0{,}000066\mathrm{V}^2 - 0{,}009\mathrm{W} - 0{,}048\mathrm{G} + 0{,}098\mathrm{T} \quad (1)$$

where:
FC = Fuel consumption (km/l)
V = Average operating speed (km/jam)
W = Gross vehicle weight (ton)
G = Positive road gradient (%)
T = Truck type (Euro-4=1 dan Euro-3=0)

Table 4 Comparison of model performance metrics

Indicator	Model 1	Model 2
Deviance	0.947	8.827
Pearson Chi-Square	0.947	8.755
Log Likelihood	1,629.313	7.241
AIC	-3,246.625	-2.483
AICC	-3,246.523	-2.380
BIC	-3,218.311	25.832
CAIC	-3,212.311	31.832
RMSE	0.033	0.296
MAE	0.027	0.217
RSS	0.947	72.810

3.3 Comparison of modeled predictions and observed outcomes

Based on the Wilcoxon Signed Ranks Test, a comparison was made between observed and predicted fuel consumption for Euro-4 and Euro-3 trucks to evaluate the accuracy of the predictive model. Regarding Euro-4 trucks, the Z value is -1.700, and the Asymptotic Significance (2-tailed) value of 0.089 indicates that the p-value is greater than 0.05, implying no statistically significant difference between the observed and predicted fuel consumption. These findings suggest that while the model's predictions are generally close to the observations, there are slight discrepancies that may become relevant in operational contexts, potentially due to factors such as terrain variation or other external conditions.

In the case of Euro-3 trucks, the Z value was calculated as -0.072, and the Asymptotic Significance (2-tailed) value of 0.943 indicates that the difference between observed and predicted values is minimal, with a p-value much greater than 0.05. These numbers demonstrate that the predictive model for Euro-3 trucks more accurately reflects actual fuel consumption, offering a higher level of confidence in its reliability for predicting field performance.

Overall, for both Euro-4 and Euro-3 trucks, there were no significant differences between the predicted and observed results, with the Euro-3 model showing a higher level of accuracy. These findings support the validity of the predictive model used in this study, particularly for real-world applications. These results align with previous research, which has demonstrated that predictive models based on telematics data can reduce prediction errors for trucks with lower emission standards. However, the small discrepancies observed in Euro-4 trucks could be the focus of future research, particularly by considering additional variables such as road surface conditions to improve model accuracy further.

4 Conclusion

This study has successfully developed a telematics data-based truck fuel consumption model using two primary approaches: multiple linear regression with Box-Cox transformation and Generalized Linear Models (GLM). The results demonstrate that the model incorporating Box-Cox transformation is superior in terms of deviance, RMSE, and AIC compared to the GLM model, with operating speed, vehicle gross weight, road grade, and truck type identified as significant factors influencing fuel consumption. The predictive model for Euro-3 trucks exhibited a high level of accuracy, while the model for Euro-4 trucks requires further refinement. This study also underscores the critical role of energy efficiency in the trucking industry in developing countries, particularly through the utilization of real-time telematics technology to promote fuel savings in Euro-4 standard trucks.

Despite these positive outcomes, this study has several limitations, including its geographical focus, which was restricted to specific routes in Indonesia, and the fact that it only considered Euro-3 and Euro-4 emission standards. Moreover, the reliance on manufacturer-authorized telematics data may limit the model's applicability in sectors where such technologies are not yet widely implemented. Additionally, factors such as weather conditions, traffic, and driver behavior were not incorporated into the model, which may affect its predictive accuracy under more complex operational conditions.

For future research, the application of machine learning could offer a more advanced approach to fuel consumption modeling, especially in capturing complex patterns and providing more accurate predictions across varying operating conditions. Expanding the geographical scope and testing the model under different road and infrastructure conditions are also necessary to enhance the model's validity. Moreover, developing models for trucks with higher emission standards, such as Euro-5 and Euro-6, is crucial to support global emission reduction and energy efficiency improvement targets. Future research should also consider integrating additional variables, such as weather conditions and drivers' behavior while investigating the long-term impact of telematics and machine learning technologies on operational cost savings and energy efficiency. Finally, the adaptation of these technologies for small-scale transportation companies in developing countries represents an important avenue for exploration to ensure broader and more sustainable adoption.

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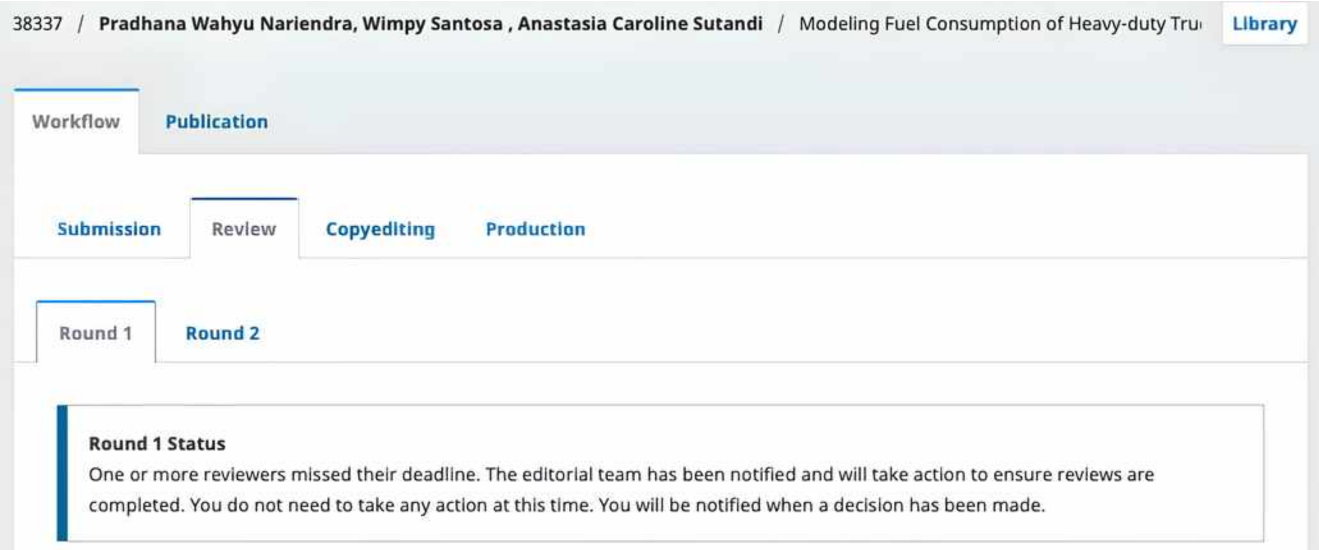
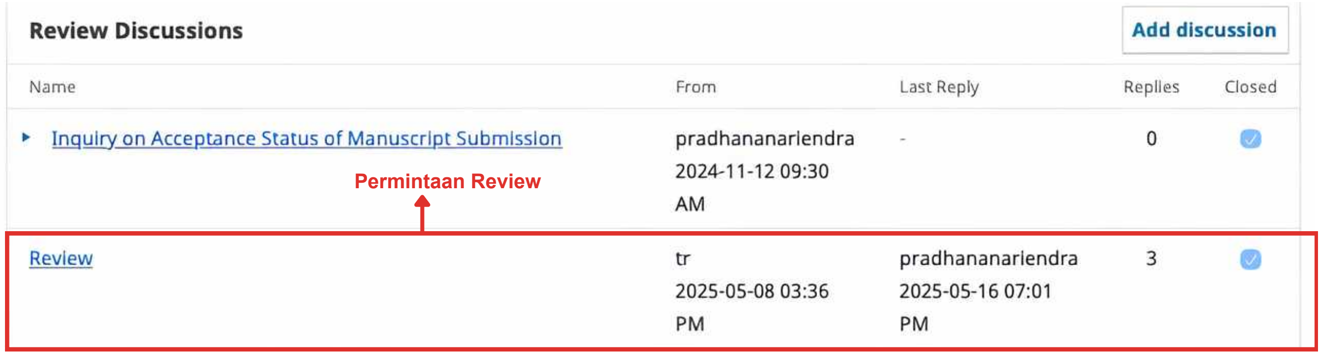
4. TAHAP REVIEW & REVISI

4.1. Tahap Review Round 1

Setelah proses submission, artikel masuk ke tahap Review Round 1. Tahap ini menunjukkan bahwa naskah tidak langsung diterima, tetapi melalui proses telaah editorial dan reviewer dalam sistem jurnal.
Pada tanggal 8 Mei 2025, editor menyampaikan hasil review kepada penulis. Editor meminta agar penulis mengunggah naskah yang telah diperbaiki dalam format DOCX dan file gambar secara terpisah dalam format JPG.





4.2. Komentar Reviewer

Komentar reviewer mencakup masukan substansial terhadap kualitas akademik artikel. Reviewer memberikan catatan pada bagian pendahuluan, novelty, tujuan penelitian, nomenclature, struktur bahasa, hasil numerik pada abstrak dan kesimpulan, kontribusi ilmiah, serta potensi penggunaan metode lanjutan seperti Artificial Neural Networks dan Decision Trees.

Review ×

Participants

Ádám Török (tr)

Ádám Török (atorok)

Pradhana Wahyu Nariendra (pradhananariendra)

Messages

Note	From
Dear Author,	tr 2025-05-08 03:36 PM

Please find below the results of reviews.

Please upload the modified paper in DOCX version, and each separate IMAGE file in JPG.

Many thanks:

Editor in Chief

RW1:

Please add the co-authors' name, e-mail address and affiliation in the List of Contributors of Publication in the Open Journal System.

The Figure 1 and Table 4 are missing from the text. Please add them.

Please refer to each item of the text in the reference list: King and Roberts 2014

Please cite every source correctly in the text: King and Roberts 2015

RW2:

This manuscript is within the scope of the journal. The topic is interesting. However, some problems still need to be clarified and revised. I would recommend for a major revision of the manuscript after addressing the significant improvement requirements.

The points of concern are as follows:

1. The introduction is disordered and aimless. Author/ Authors just simply list the lows of literature reviews. However, the important information, such as innovations, focused issues, methods, and value of this article, are missing or oversimplified. It is necessary to rewrite the introduction. The literature review has been how written which leads to misunderstanding.

1. The novelty of the work must be clearly addressed and discussed, compare your research with existing research findings, and highlight novelty, (compare your work with existing research findings and highlight novelty).

1. The main objective of the work must be written more clearly. Also, you should have a subsection on the strengths and limitations of your study.

1. Nomenclature section is also missing. Add completely in the table.

1. There is a strong need to improve the manuscript's language as it is inappropriate for the Journal of Periodica Polytechnica Transportation Engineering. The text has lots of grammatical errors. Most of the sections cannot be read well.

1. There are some typos in the text, refine them. According to the journal template, edit the text completely.

1. Author/ Authors need to add more results in the abstract and the conclusion section and abstract section (especially numerical results) to thoroughly support the main findings. The results are not clear and complete and must be more. The abstract and the conclusion section should be rewritten with the complete data.

1. It is suggested to include a paragraph at the end of the conclusion section that should describe the applications of the present work, recommendations, and future scope to other researchers.

1. Explain how your research has moved the body of scientific knowledge forward.

1. why were more advanced modeling techniques like Artificial Neural Networks or Decision Trees not considered, given their potential to capture complex patterns? Was there any comparative evaluation between these models and more sophisticated approaches?

1. How can the findings of this study be applied to other countries or different geographical conditions? Have there been any efforts to validate the model in diverse environments to ensure broader applicability?

4.3. Response to Reviewer

Pada tanggal 12 Mei 2025, penulis mengunggah naskah revisi dan menyampaikan tanggapan formal kepada editor. Dalam tanggapan tersebut, penulis menjelaskan bahwa naskah telah diperbaiki sesuai komentar reviewer. Perbaikan mencakup penambahan data kontributor, penyisipan Figure 1 dan Table 4, perbaikan referensi, penguatan pendahuluan, pengembangan novelty, perbaikan tujuan penelitian, penyempurnaan abstrak dan kesimpulan, serta penjelasan kontribusi ilmiah artikel.

Dear Editor in Chief,

pradhananariendra 2025-05-12 11:46 AM

Thank you for your detailed review and valuable feedback.

We have revised the manuscript as per the reviewers' comments and incorporated the requested modifications. The updated manuscript in DOCX format and the separate image files in JPG format (300 DPI) have been uploaded to the system.

We have thoroughly revised the manuscript based on the reviewers' comments. The following modifications have been implemented:

RW1:

1. The authors' names, affiliations, and email addresses have been added to the List of Contributors of Publication in the Open Journal System to ensure complete and accurate author information.
2. Figure 1 and Table 4 have been inserted in the appropriate sections of the manuscript, in line with the article structure. The image file for Figure 1 has been uploaded in JPG format (300 DPI) as specified by the reviewer.
3. All references have been reviewed for consistency, and the missing citation for King and Roberts (2015) has been added in the methodology section to reinforce the theoretical basis for multiple linear regression and GLM.
4. The reference list has been fully revised to ensure accuracy and consistency in citations throughout the manuscript. King and Roberts (2015) is now appropriately cited in the methodology section.

RW2:

1. The introduction section has been revised to clearly present the innovation, focus, methodology, and noveltyof the study. The study introduces a real-time telematics-based predictive model for Euro-3 and Euro-4 trucks, using operational speed, vehicle weight, and road gradient data as a simpler alternative to the parameter-heavy HDM-4 model. The focus is on fuel efficiency for trucks in Indonesia, given that fuel costs account for 28-32% of VOC. The methodology includes multiple linear regression, GLM, and the Wilcoxon Signed-Rank Test to assess model accuracy. The contributions and applications of the model, particularly for 5-axle trucks on toll roads, are now clearly outlined, setting the stage for potential testing in non-toll roads and extreme terrains.
2. The novelty section has been expanded in both the introduction and discussion to emphasize the transition from HDM-4 to a simpler, telematics-based model, which eliminates the need for complex parameter calibration and aligns with Euro-4 emission reduction targets.
3. The research objectives have been clearly stated in the introduction, focusing on developing a telematics-based predictive model for Euro-4 and Euro-3 trucks and evaluating its accuracy. A new subsection on strengths and limitations has been added to highlight the use of real-time telematics data as a key strength, while noting the model's current application is limited to toll roads and 5-axle trucks.
4. The manuscript has been thoroughly edited for grammar, sentence structure, and clarity, aligning the academic tone with the standards of Periodica Polytechnica Transportation Engineering.
5. Typographical errors have been corrected, and the paragraph structure and formatting have been adjusted to align with the journal template.
6. The abstract and conclusion have been revised to include specific findings, such as deviance, RMSE, AIC values, and Wilcoxon Signed-Rank Test results for both Euro-3 and Euro-4 trucks. These data points have been added to reinforce the model's predictive accuracy.
7. A closing paragraph in the conclusion has been added to outline the application of the predictive model for fleet management in Euro-4 trucks, along with recommendations for future research focusing on machine learning integration and testing on non-toll routes. The model contributes a new telematics-based framework for 5-axle truck fuel consumption prediction, aligning with Euro-4 policies and having potential applications in regions with similar road and transport conditions.
8. The research contribution section in the conclusion has been added to explain how the study developed a more practical and accurate telematics-based predictive model for Euro-4 and Euro-3 trucks, replacing the HDM-4 model and supporting Euro-4 emission reduction policies. Additionally, the model opens opportunities for further studies involving machine learning techniques, testing on non-toll routes, and the inclusion of additional variables such as weather, fuel type, and driver behavior.
9. The choice of multiple linear regression and GLM was based on data availability and interpretability. However, for future studies, machine learning techniques (ANN, Decision Trees) will be considered to capture more complex patterns and enhance model accuracy across different operational settings. Testing on non-toll roads, urban routes, and regions with extreme weather will also be prioritized, along with the inclusion of variables like weather, traffic density, and driver behavior to broaden the model's applicability.
10. The model is currently applicable to operational conditions similar to those in the study, particularly on toll roads with comparable terrain and vehicle characteristics. Future research will focus on testing in non-toll routes, urban roads, and incorporating additional variables to expand the model's applicability under more diverse operational scenarios.

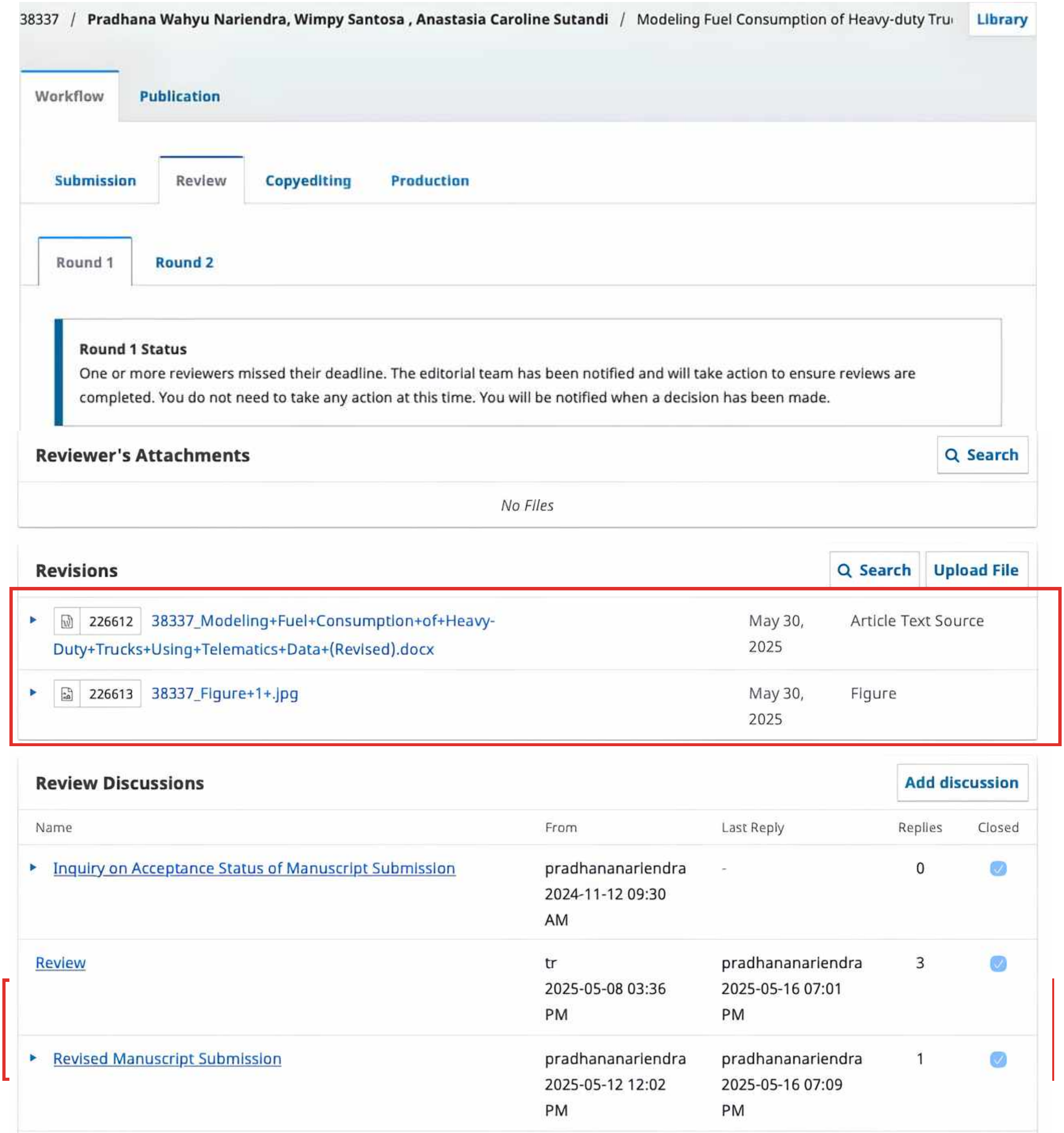
Please let us know if further modifications or clarifications are needed. We appreciate your continued guidance and look forward to your feedback.

Thank you for your time and consideration.

Sincerely,

Pradhana W. Nariendra

4.4. Revised Manuscript Submission



revised paper

Calibration of HDM-4 Model for Fuel Consumption in Heavy-Duty Trucks: Integration of Telematics, Engine Speed, and Aerodynamics

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Abstract

Fuel efficiency in heavy-duty trucks in Indonesia faces significant challenges, while the current HDM-4 fuel consumption model has limitations in reflecting local conditions. This study calibrates the HDM-4 model using telematics data, engine speed modeling, aerodynamic simulations, and calibration factors. The novelty lies in updating parameters such as engine speed, vehicle frontal area, and calibration factors for engine power efficiency (Kpea) and rolling resistance (Kcr2) to account for tire-road interaction in Indonesian conditions. Data were collected from 5-axle trucks on the Tanjung Priok–Bandung toll road, analyzed using regression, Computational Fluid Dynamics (CFD) simulations, and non-parametric paired tests. Results show updated engine speed parameters (RPM_a0 = 680.11, RPM_a1 = -4.9031, RPM_a2 = 0.3858, RPM_a3 = -0.0028), a drag coefficient of 1.0556, and a frontal area of 8.2 m^2. Calibrating Kpea and Kcr2 (both 0.6) improved prediction accuracy, with no significant difference between predicted and observed data ($p = 0.186$). The enhanced HDM-4 model supports operational decisions, infrastructure planning, and sustainable transport policies, improving energy efficiency, reducing emissions, and boosting national logistics competitiveness.

Keywords: fuel consumption; HDM-4; telematics; heavy-duty trucks; aerodynamics.

revised paper

Calibration of HDM-4 Model for Fuel Consumption in Heavy-Duty Trucks: Integration of Telematics, Engine Speed, and Aerodynamics

1. Introduction

Fuel efficiency in heavy-duty trucks, particularly 5-axle vehicles, has become a critical issue due to their high contribution to greenhouse gas (GHG) emissions and increasing freight logistics costs. In Indonesia, these trucks account for a substantial portion of CO_2 and NO_x emissions, impacting environmental and economic sustainability [1]. A global analysis shows that the combustion of 1 liter of diesel per 100 km increase in fuel consumption adds 26.4 g/km of CO_2 emissions [2], [3]. In Indonesia, fuel consumption accounts for up to 49.3% of Vehicle Operational Costs (VOC) in South Sumatra and 32% in Jakarta and West Java [4], [5]. As the freight sector increasingly relies on road transport, improving fuel efficiency is both an environmental and economic necessity.

Various methods have been developed to improve fuel efficiency, and one of the most notable is the Highway Development and Management (HDM-4) model. Created by the World Bank, this model helps predict fuel consumption and assess how road infrastructure affects vehicle efficiency [6], [7]. Countries like the United States, the United Kingdom, and South Korea have successfully used HDM-4 to support eco-routing and eco-driving strategies, which have proven effective in reducing greenhouse gas emissions [8], [9]. Furthermore, research has shown that average operating speed plays a key role in determining the fuel efficiency of heavy trucks. This insight can serve as a foundation for developing more sustainable transportation strategies [8], [10], [11], [12].

Implementing HDM-4 in Indonesia comes with significant challenges due to differences in vehicle specifications, road conditions, and varying truck loads [8], [13]. Research has shown that calibrating key parameters like engine power, rolling resistance, frontal area, and engine speed can greatly improve the accuracy of fuel consumption predictions [14]. Several studies have explored HDM-4 calibration in different countries to enhance model accuracy. For example, in Michigan, when calibrating fuel consumption models for sedans, SUVs, light trucks, and heavy trucks, researchers considered factors like engine power, rolling resistance, frontal area, engine speed, weather, and road conditions. Studies have shown that fine-tuning these key parameters can greatly enhance the accuracy of fuel consumption predictions [14]. In Florida, similar calibrations were conducted for passenger cars and trailer trucks [15], while in South Korea, the focus was on passenger cars [16]. Meanwhile, in the UK, researchers verified the HDM-4 model for various types of trucks, also considering engine power, rolling resistance, and frontal area [17]. Therefore, more tailored calibrations are needed to ensure the model accurately represents the operational conditions of trucks in Indonesia.

A telematics-based approach offers a practical way to tackle these challenges. With telematics technology, we can gather real-time data on essential factors like operational speed, vehicle weight, and fuel consumption [18], [19], [20]. Studies show that calibrating HDM-4 fuel consumption models using telematics data works well for trucks with lighter loads, though improvements are needed for heavy-load trucks [17]. Moreover, accurately simulating aerodynamic drag is crucial for improving model accuracy, especially for trucks that travel through routes with challenging terrain [21], [22]. With this in mind, our study focuses on refining the HDM-4 Level II model by incorporating engine rotation parameters, aerodynamic resistance, calibration factors, and real-world operational conditions, such as speed, load weight, and road gradient. Specifically, we aim to develop a model that reflects the realities faced by 5-axle Euro-4 semi-trailer trucks operating in Indonesia, ensuring the results are relevant and applicable to local conditions.

This study enhances the HDM-4 Level II fuel consumption model to more accurately represent the real-world efficiency of 5-axle Euro-4 semi-trailer trucks in Indonesia [23]. By refining key calibration factors including engine rotation, aerodynamic resistance, frontal area, engine power efficiency, speed, load weight, and road gradient. The model is better aligned with actual trucking operations. These improvements enhance accuracy and practical relevance, making it a valuable tool for optimizing fuel consumption in Indonesia's trucking industry. The research focuses on the Tanjung Priok Port–Bandung route, one of the busiest logistics corridors in Indonesia [24]. This route includes toll roads with gradients of up to 6%, in line with the standards set by the Directorate General of Highways [25]. The trucks in this study use Pertamina's Bio Solar fuel for Euro-4 engines, ensuring a realistic setting for fuel consumption analysis. By combining real-time telematics data with aerodynamic simulations, this study aims to create a more accurate fuel consumption model. The end goal is to improve fuel efficiency, reduce greenhouse gas emissions, cut operational costs, and support more sustainable freight transportation in Indonesia.

A key breakthrough of this study is the empirical calibration of Kcr2 and Kpea parameters using real toll road data, something that has not been done before. Furthermore, the study uncovers a clear relationship between engine speed (RPM) and fuel consumption, offering critical insights for optimizing HDM-4's operational parameters. It also revises aerodynamic parameters, , including the drag coefficient (Cd) and frontal area (AF), to more accurately represent the actual conditions of heavy-duty trucks in Indonesia. With these improvements, HDM-4 now delivers more accurate fuel consumption predictions, particularly by factoring in aerodynamic resistance. These refinements make the model more applicable and valuable for transportation planning, fleet management, and logistics operations in Indonesia.

2. Method

This study employs an integrated approach that leverages telematics data, engine speed parameter modeling, aerodynamic analysis, and the calibration of the Highway Development and Management Model (HDM-4) to analyze the fuel consumption of heavy-duty trucks in Indonesia. This systematic approach aims to produce accurate and replicable fuel consumption predictions. The research process begins with a preparation phase, which involves defining the research focus, identifying data collection routes, and coordinating with trucking companies to ensure smooth data collection [23], [26]. Following this, a literature review and methodology planning are conducted to understand fuel consumption models, the use of telematics data, and HDM-4 calibration techniques.

The data collection for this study incorporates both primary and secondary sources. Primary data include measurements of vehicle dimensions and wheel diameter, which were obtained using manual tools. The vehicle selected for this study is a 2022 Hino 5-axle truck, specifically a 2-axle head truck paired with a 3-axle semi-trailer. According to the Indonesian Trucking Association (APTRINDO), this configuration is the most common for heavy-duty trucks in Indonesia. Previous studies have highlighted that rolling resistance can vary significantly between vehicles, influenced by factors such as tire specifications, load distribution, and road conditions [27]. To enhance the model's accuracy, empirical calibration factors have been incorporated, including commonly used tire specifications, varying load conditions, and diverse road characteristics. While differences between individual trucks are inevitable, the methodology applied in this study ensures that the model accurately represents real-world trucking operations, offering a more precise reflection of actual conditions. Secondary data were collected alongside engine and vehicle speed data from the On-Board Diagnostics (OBD-II) system [28], [29], including actual fuel consumption, vehicle speed, position, and gross vehicle weight (GVW). While previous studies, have noted that CAN-bus vehicle weight data can often be unreliable, we took specific steps to ensure data accuracy. To address potential inaccuracies, GVW readings were validated against weighbridge records at the port, and necessary adjustments were made [30]. Furthermore, in 2022, Hino Motors re-certified their CAN-bus system, eliminating the need for calibration modifications and improving measurement reliability. As the vehicles in this study are 2022 Hino models, the collected data benefits from the latest, more accurate monitoring system. These efforts ensure that the CAN-bus data used in this study is reliable and accurately reflects real-world vehicle operations [31].

The data were gathered over a one-month period along the Tanjung Priok to Bandung route, a critical corridor for container semi-trailer truck operations in Indonesia. Road geometry and gradient data from Google Earth remote sensing provided sufficient accuracy for transportation analysis, with an MAE of 1.32 meters and an RMSE of 2.27 meters [32]. Other secondary data were sourced from government agencies such as the Ministry of Public Works and Housing and the Central Statistics Agency. These datasets provide information on International Roughness Index (IRI), and road surface texture depth [26], [28].

Using telematics data offers significant advantages because passive data collection methods provide high spatial and temporal resolution at a low cost [28]. Devices such as Photochemical Assessment Monitoring Stations (PAMS), Global Positioning Systems (GPS), and cellular networks facilitate real-time vehicle activity monitoring. Modern trucks equipped with sensors record operational parameters like fuel consumption, vehicle speed, and throttle position, which are then transmitted via the Electronic Control Unit (ECU) for analysis. Although manufacturer-provided telematics systems are not explicitly designed for HDM-4 calibration, the data they generate are reliable and reflect real-world driving conditions [17], [29].

The calibration is conducted at the whole-trip level to capture real-world operational variations, including travel distance, average speed, vehicle weight, and road gradient. To ensure balanced data representation, the data is split into 70% for calibration and 30% for validation using stratified random sampling. The model's accuracy is assessed using R^2, RMSE, and MAPE to evaluate its ability to explain the data, measure prediction errors, and assess percentage discrepancies. Outliers that reflect actual operational conditions are kept to ensure the model's relevance. This method ensures that the model is both accurate and applicable to real-world scenarios [33], [34].

The next step involves calibrating vehicle parameters by modeling the relationship between engine speed and vehicle speed. This relationship is critical because higher vehicle speeds require higher engine speeds, which directly impacts fuel efficiency [35]. To make the HDM-4 model more relevant to modern vehicle technology, calibration is essential, as the model's default values are based on older engine designs [14]. This process starts with gathering telematics data on vehicle speed and RPM, followed by filtering to remove any anomalies. Then, a third-degree polynomial regression is applied to capture the non-linear relationship between these two variables, as outlined in Equation (7). The resulting calibrated parameters replace the default HDM-4 values, ensuring the model aligns better with modern engines, which feature common-rail fuel injection systems and advanced emission controls. To confirm the accuracy of the model, the coefficient of determination (R^2) is used, ensuring the model captures the true dynamics of speed and RPM, ultimately improving fuel consumption predictions.

Following this, aerodynamic analysis is conducted using Computational Fluid Dynamics (CFD) in SolidWorks Flow Simulation [36], [37]. This software applies the k-ε turbulence model, which is suitable for steady-state flow simulations but has limitations in capturing complex turbulent dynamics such as wake formation and vortex shedding. Since the focus of this research is on the macroscopic calibration of aerodynamic parameters in the HDM-4 model, this approach is considered sufficient [38], [39]. The process includes three main stages: pre-processing, processing, and post-processing. During pre-processing, a vehicle model based on actual dimensions is created, validated, and meshed. Boundry conditions such as flow type, gravity, fluid type, and test speed are defined. In the processing stage, numerical simulations are run to calculate frontal area (AF) and the drag coefficient (Cd). The calculation follows Equation (1). In the post-processing stage, simulation results are interpreted to evaluate the vehicle's aerodynamic efficiency, where a lower drag coefficient indicates a more streamlined and fuel-efficient design [40], [41], [42].

$$Cd = \frac{2\,FA}{\rho\, V^2\, AF} \quad (1)$$

where Cd represents the drag coefficient (dimensionless), FA is the aerodynamic drag force (N), ρ denotes the air density (kg/m³), V corresponds to the relative velocity between the vehicle and air (m/s), and AF is the frontal area of the vehicle (m²). Once the calculation is completed, the post-processing stage is conducted to interpret the simulation results and evaluate the vehicle's aerodynamic efficiency. Consequently, the lower the Cd value, the more aerodynamic and fuel-efficient the vehicle design becomes [40], [41], [42].

In addition to the aerodynamic analysis, HDM-4 model calibration is performed by considering various factors such as vehicle weight, speed, and road gradient [26]. The fuel consumption estimation process begins by determining the total resistance force acting on the vehicle, which is calculated using Equation (2).

$$FTR = FA + FG + FR + FCV \quad (2)$$

where FA represents the aerodynamic drag force (N), FG is the gradient resistance force (N), FR is the rolling resistance force (N), and FCV refers to the curvature resistance force (N). After calculating the total resistance force, the traction power required to overcome this resistance is determined using Equation (3).

$$PTR = \frac{FTR \times V}{1000} \quad (3)$$

where PTR denotes the traction power (kW) and V is the vehicle speed (m/s). Once the traction power is obtained, the total engine power is calculated using Equation (4).

$$PTOT = \left(\frac{PTR}{EDT} + PENGACCS\right) \quad (4)$$

where PTOT represents the total engine power (kW), EDT corresponds to the drivetrain efficiency, and PENGACCS is the power required for engine accessories (kW). The total engine power is a crucial factor in determining the vehicle's fuel consumption under different operational conditions. Following this, the instantaneous fuel consumption is estimated using Equation (5).

$$IFC = \max\,[ID\_FUEL, ZETA \times PTOT \times (1 + dFUEL)] \quad (5)$$

where IFC represents the instantaneous fuel consumption (ml/s), ID_FUEL is the fuel consumption at idle, ZETA refers to the engine efficiency, and dFUEL is an additional fuel consumption factor due to speed variations. After determining the instantaneous fuel consumption, the specific fuel consumption is calculated using Equation (6).

$$FC = \frac{IFC}{V} \quad (6)$$

where FC refers to the specific fuel consumption (ml/km) and IFC is the instantaneous fuel consumption (ml/s). This calculation ensures that the model accurately reflects real-world fuel consumption behavior. To ensure that the fuel consumption predictions align with actual operational conditions, calibration is applied to several engine parameters. One of these parameters is the engine speed (RPM), which is determined using Equation (7).

$$\text{RPM} = \text{RPM\_a0} + \text{RPM\_a1} \times \text{V} + \text{RPM\_a2} \times \text{V}^2 + \text{RPM\_a3} \times \text{V}^3 \quad (7)$$

where RPM_a0, RPM_a1, RPM_a2, and RPM_a3 are engine speed model parameters obtained through calibration. Engine speed is a key variable affecting fuel consumption, as it influences both power output and mechanical efficiency.

Rolling resistance is a critical factor affecting vehicle fuel consumption, particularly for heavy-duty trucks operating on diverse road surfaces. To account for this, the rolling resistance factor is determined using Equation (8).

$$\text{CR2} = \text{Kcr2} \times (\text{CR\_CR2\_a0} + \text{CR\_CR2\_a1} \times \text{TD} + \text{CR\_CR2\_a2} \times \text{RI}) \quad (8)$$

where Kcr2 represents the rolling resistance factor, TD denotes the road texture depth (mm), and RI refers to the average road roughness value (m/km), while CR_CR2_a0, CR_CR2_a1, CR_CR2_a2 are rolling resistance coefficients calibrated based on field data. Rolling resistance plays a significant role in fuel efficiency, especially for heavy-duty vehicles operating under varying road conditions. Furthermore, the engine power factor is adjusted using Equation (9).

$$\text{PENGACCS} = \text{Kpea} \times \text{PRAT} \times \left[\text{PACCS\_a1} + \frac{(\text{PACS\_a0} - \text{PACCS\_a1})(\text{RPM} - \text{RPM\_IDLE})}{(\text{RPM100} - \text{RPM\_IDLE})}\right] \quad (9)$$

where, Kpea is the calibration factor, PRAT is the maximum engine power (kW), RPM_IDLE is the engine speed at idle (rev/min), RPM100 is the engine speed at 100 km/h (rev/min), RPM is the engine speed at operational speed (rev/min), PACCS_a0 is the ratio of engine and accessory resistance to the engine power at 100 km/h, and PACCS_a1 is a model parameter.

The comparison between the calibrated HDM-4 model predictions and the observed fuel consumption data is analyzed using the Wilcoxon Signed-Ranks Test. This non-parametric method is ideal for paired samples that do not meet normality assumptions [43]. The null hypothesis (H_0) states that the median difference is zero, while the alternative hypothesis (H_1) suggests a significant difference. The Z value is compared to the critical Z value of ±1.96 at a 0.05 significance level. The results are reported by comparing the number of negative ranks, positive ranks, and ties as indicators of the model's stability. In refining the model, we used an empirical trial and error calibration approach, where we adjusted Kcr2 (rolling resistance factor) and Kpea (engine efficiency factor) along with aerodynamic factors (Cd and AF). These adjustments ensured that the model effectively reflects real-world operational scenarios, enhancing its ability to predict fuel consumption with greater accuracy. The calibration was conducted in three scenarios: (1) scenario 1: Using the default HDM-4 parameters without adjustments, which showed a significant difference between predicted and actual fuel consumption, (2) scenario 2: Involving aerodynamic calibration with adjustments to the drag coefficient (Cd) and frontal area (AF), as well as engine RPM adjustments, and (3) scenario 3: Adding the calibration factors Kcr2 and Kpea through a trial and error process. With adjustments in all three scenarios, the model now represents real-world fuel consumption more accurately, with Scenario 3 providing the closest results.

3. Result and Discussion

The calibration was done at the whole-trip level instead of shorter road segments, as each data entry reflects key operational parameters such as travel distance, average speed, vehicle weight, and road gradient, with 94 trips included. To prevent ill-conditioning issues, we ensured that our dataset covered a wide range of operational conditions, including vehicle weights from 15.27 to 38.16 tons, operating speeds from 5.1 to 52.3 km/h, and road gradients between +4.9% and -6.7%. This diversity in input parameters means that the model is not restricted to a single type of trip but can adapt to various real-world scenarios, maintaining a high level of accuracy without being biased by overly similar data. The results showed strong predictive ability, with R^2 values of 0.83 for the training set and 0.79 for the test set. RMSE values of 0.39 km/l for the training set and 0.43 km/l for the test set, alongside a MAPE of 9.5%, confirm that the model remains reliable even with new data. Additionally, an outlier analysis using the Interquartile Range (IQR) method was performed, retaining extreme values as they accurately represent real-world operational conditions.

3.1. Calibration of Engine Speed Model Parameters

These differences can be attributed to advancements in engine technology, particularly in modern engines equipped with common-rail injection systems and advanced emission controls, which enable lower engine RPMs at the same speeds due to improved torque and fuel efficiency. Since the HDM-4 model was developed based on older engine characteristics, it tends to overestimate RPM at lower speeds and underestimate it at higher speeds. Although the Zaabar & Chatti model offers a more recent perspective, it still exhibits a sharp increase in RPM at higher speeds, which does not fully reflect the real-world conditions observed in Indonesia [14].

These differences reflect advancements in engine technology and how they impact truck performance and fuel consumption. The default engine RPM parameters in the HDM-4 model are RPM_a0 = 1900, RPM_a1 = -10.178, RPM_a2 = 0.1521, and RPM_a3 = 0.00004 [6]. These values represent the characteristics of conventional truck engines used during that period. As a result, the HDM-4 model tends to overestimate engine RPM at low to medium speeds, leading to higher predicted fuel consumption than what actually occurs. On the other hand, at higher speeds, the HDM-4 model underestimates engine RPM and does not fully account for the increased aerodynamic resistance and higher power demands. In comparison, the study by Zaabar & Chatti model presents more modern engine RPM parameters with values of RPM_a0 = 833.7, RPM_a1 = -17.717, RPM_a2 = 0.9671, and RPM_a3 = -0.0055. These parameters reflect improvements in combustion efficiency, fuel injection precision, and emission control. Although this model offers a more accurate prediction than HDM-4, it still falls short, especially at high speeds where the predicted engine RPM increases more sharply than observed in real-world conditions. This indicates that although the models used are based on more advanced technology, they still do not fully reflect the operational conditions of trucks in Indonesia. In line with previous research, differences in vehicle characteristics including rolling resistance and engine response are influenced by drivetrain configuration, control strategies, and local topography [27]. In this study, the 5-axle truck with a manual transmission showed that driving patterns, such as the use of engine braking on downhill slopes, significantly affect RPM behavior. Therefore, calibration based on local and up-to-date data is essential to improve the model's accuracy.

The current study provides parameters that are more tailored to the real-world conditions of Indonesian trucks. The parameters derived are RPM_a0 = 680.11, RPM_a1 = -4.9031, RPM_a2 = 0.3858, and RPM_a3 = -0.0028. These values align with Euro-4 engine technology, which incorporates common-rail injection systems and modern emission controls [44], [45]. This technology allows trucks to produce optimal power at lower RPMs, improving fuel efficiency and reducing emissions. These results highlight the efficiency of Euro-4 engines in maintaining stable RPMs across different speeds compared to older engine technologies. To better understand the relationship between speed and engine RPM, this study used a third-degree polynomial model. The equation derived from the data is: $y = -0.0028\,x^3 + 0.3858\,x^2 - 4.9031\,x + 680.11$. With a coefficient of determination $R^2 = 0.9838$. This high R^2 value indicates that the model fits the observed data very well. The model developed in this study captures the gradual increase in RPM as vehicle speed rises, providing a more accurate representation of fuel consumption trends compared to the HDM-4 and Zaabar & Chatti models. By recalibrating key parameters, the model aligns with modern truck engine technology, incorporating common-rail injection and advanced emission controls. These refinements enhance the accuracy of fuel consumption predictions while supporting efforts to optimize vehicle performance and reduce emissions.

The differences between the HDM-4 model, the Zaabar & Chatti model, and actual observations are clearly illustrated in Figure 1 and supported by Table 1. The blue dots represent observed telematics data, which show a gradual and consistent increase in engine RPM as vehicle speed rises. In contrast, the orange dots from the HDM-4 model tend to overestimate RPM at lower speeds and underestimate it at higher speeds. Meanwhile, the green dots from the Zaabar & Chatti model show a much sharper increase in RPM at higher speeds, diverging from actual operating conditions. The red dashed line derived from a third-degree polynomial regression developed in this study closely follows the observed trend, offering a more accurate reflection of modern engine performance. The curve shown in the graph represents the average engine RPM in relation to vehicle speed, calculated from full-trip telematics data. Average RPM values were obtained by aggregating all RPM data points and pairing them with the corresponding average speed for each trip. This approach provides a representative picture of typical vehicle operations. Furthermore, the average RPM values were validated against predictions from the HDM-4 model and prior studies, with the resulting polynomial regression achieving a coefficient of determination (R^2) of 0.9838. This indicates the model captures nearly all variation in the observed data. Despite inherent fluctuations in engine speed due to shifting patterns and terrain, using averaged values proves to be a reliable method for modeling RPM and forms a solid basis for further analysis.

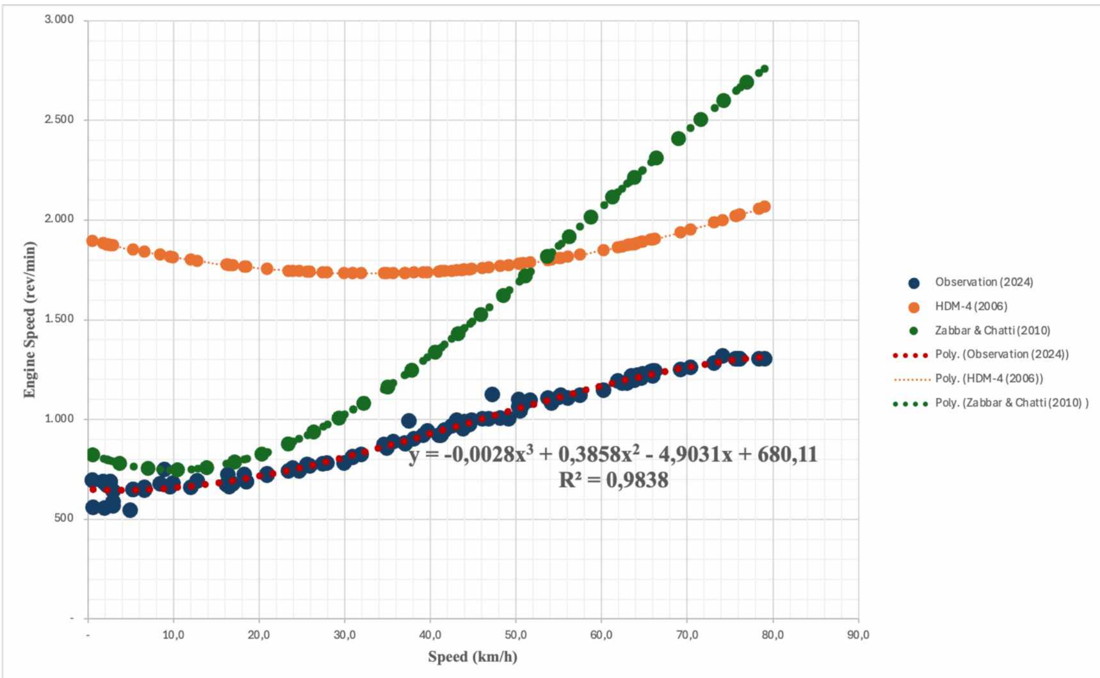

Figure 1. Calibration of Engine Speed Model Parameters

Table 1. Comparison of engine speed model parameters for heavy-duty trucks

Model	RPM_a0	RPM_a1	RPM_a2	RPM_a3
HDM-4	1900.0	-10.178	0.1521	0,00004
Zaabar & Chatti	833.7	-17.717	0.9671	-0.0055
Current Study	680.11	-4.9031	0.3858	-0.0028

3.2. Calibration of Aerodynamic Parameters

The aerodynamic simulation results for heavy-duty vehicles offer a clear picture of how air flows around the vehicle, the drag force, and the drag coefficient. The airflow distribution, shown through streamlines with color gradients, reveals that air moves smoothly over the cabin and body of the vehicle. However, as the vehicle speed increases, significant turbulence forms behind the vehicle, known as the wake region. This turbulence creates a low-pressure zone, which in turn increases drag force [46]. From the simulation, the average drag force recorded is 1,455.792 N, with a minimum of 1,455.556 N and a maximum of 1,455.851 N. These values highlight that air resistance on heavy-duty vehicles is quite substantial, especially at higher speeds [46]. The simulation also indicates a drag coefficient (Cd) of 1.0556, with a range between 1.0551 and 1.0558, and a frontal area (AF) of 8.2 m^2. In contrast, the default values used in the HDM-4 model assume a drag coefficient (Cd) of 0.80 and a frontal area (FA) of 9.0 m^2 [26].

The differences between the simulation results and the HDM-4 defaults can be explained by the turbulence created in the wake region, which leads to increased pressure drag. This means the engine needs to work harder to maintain speed. Additionally, the turbulence behind the vehicle raises drag force and fuel consumption. Although the drag coefficient from the simulation is higher than the default HDM-4 value, aerodynamic drag still plays a major role in fuel efficiency, particularly because air resistance increases exponentially with speed [46].

These findings align with earlier research, which shows that aerodynamic drag significantly affects the performance of heavy-duty vehicles, especially at high speeds [26]. Therefore, this simulation underscores the importance of calibrating the HDM-4 model to match the real aerodynamic conditions of modern heavy-duty vehicles. Such calibration is crucial to improve the accuracy of fuel consumption predictions, ensuring they reflect current vehicle technology and real-world operations [14], [17]. Given these significant differences between the simulation results and the default HDM-4 values, it is clear that modern vehicle designs have evolved aerodynamically. Therefore, adjusting parameters such as the drag coefficient (Cd) and frontal area (AF) is essential to improve the accuracy of fuel consumption predictions. As presented in Table 2, the differences between the default HDM-4 values and the calibrated model emphasize the significant role of aerodynamic resistance in influencing vehicle efficiency. The aerodynamic simulation shown in Figure 2 illustrates the formation of intense wake turbulence behind the container, with airflow speeds reaching 31.324 m/s and a pressure drop to 67,568.17 Pa indicating flow separation behind the vehicle body. This turbulence generates a low-pressure zone at the rear, increasing aerodynamic drag, reducing energy efficiency, and ultimately raising fuel consumption [46], [47]. Although this wake effect is not visually prominent in Figure 2, the airflow behavior is consistent with previous studies on heavy-duty vehicles. Since this research primarily focuses on estimating Cd and AF for HDM-4 calibration purposes, detailed turbulence visualization falls outside the study's scope.

However, future research is encouraged to apply advanced CFD tools for a more comprehensive analysis of wake dynamics.

Table 2. Comparison of aerodynamic parameters for heavy-duty trucks

Model	Drag Coefficient (Cd)	Frontal Area (AF) [m²]
HDM-4	0.8	9.0
Current Study	1.05	8.2

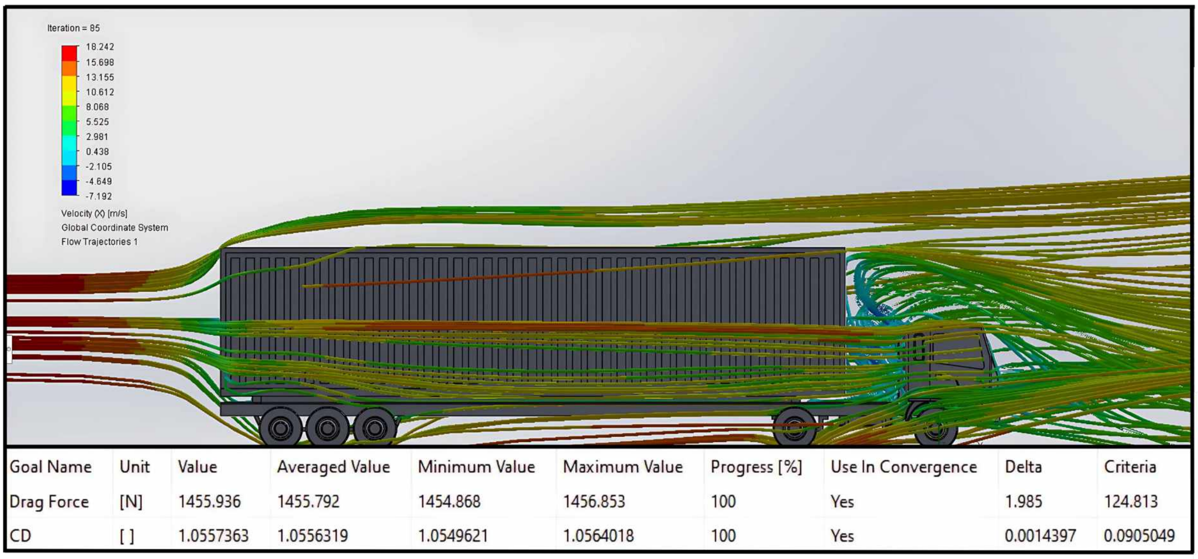

Figure 2. Aerodynamic Simulation Results

3.3. Calibration of the HDM-4 Model

This analysis explores fuel consumption predictions using the HDM-4 model, comparing three different approaches. In Scenario 1, the model relies on default HDM-4 values without any adjustments. Moving to Scenario 2, the approach incorporates aerodynamic calibration by setting the drag coefficient (Cd) to 1.05 and the frontal area (AF) to 8.2 m^2, along with adjustments to the engine rotation model. In Scenario 3, the addition of correction factors Kpea and Kcr2 using a trial-and-error approach significantly improved the accuracy of fuel consumption predictions, resulting in differences that were no longer statistically significant compared to actual observations.

In Scenario 1, the results show that 85 out of 91 cases fall into the negative ranks category, with an average rank of 48.51 and a total rank of 4,123.00. In contrast, only 6 cases fall into the positive ranks category, with an average rank of 10.50. The Wilcoxon test produces a Z-value of -8.035 and a significance level of $p < 0.001$, clearly indicating a significant gap between the model predictions and real-world observations [26]. This suggests that the default HDM-4 values underestimate fuel consumption, likely because they do not consider the vehicle's aerodynamic properties or the unique operational conditions on the ground. In Scenario 2, after calibrating the aerodynamic parameters and adjusting the engine rotation model, prediction accuracy improves. The number of negative ranks drops to 79 cases, with an average rank of 50.53, while the positive ranks increase to 12 cases, with an average rank of 16.21. Despite this improvement, the Wilcoxon test still yields a Z-value of -7.514 and $p < 0.001$, indicating that the differences between predicted and observed data remain significant. In Scenario 3, introducing the correction factors Kpea and Kcr2, both set at 0.6, further enhances prediction accuracy. The negative ranks drop significantly to 50 cases, with an average rank of 48.55, while the positive ranks rise to 41 cases, averaging 42.89. The Wilcoxon test returns a Z-value of -1.324 and a significance level of $p = 0.186$, indicating that the difference between the predictions and the observed data is no longer statistically significant. A summary of the calibration parameters and statistical results is presented in Table 3.

These results align with earlier research comparing HDM-4 fuel consumption predictions with telematics data from the UK. Significant discrepancies in fuel consumption estimates for heavy-duty trucks under the Base Case were found, although updates to vehicle weight and frontal area in the Update Case improved predictions. However, notable differences still persisted [17]. Overall, this study reinforces that default HDM-4 values often fall short in predicting fuel consumption for heavy-duty trucks because they do not reflect real-world operational weight and aerodynamic factors [23], [48]. While calibrating these parameters in Scenario 2 enhances prediction accuracy, it does not fully resolve the discrepancies. However, the adjustments introduced in Scenario 3 substantially minimized the discrepancies, as indicated by the statistically insignificant outcome.

Despite these improvements, some discrepancies remain even after updating vehicle weight and frontal area. These differences are likely due to recent technological advancements in heavy-duty truck design and performance [21], [49]. Therefore, further calibrations of the HDM-4 model at Level III are essential to accurately reflect the operational conditions of today's heavy-duty trucks [23].

Table 3. Calibration of HDM-4 fuel consumption model parameters for heavy-duty trucks

Scenario	Drag Coefficient (Cd)	Frontal Area (AF) [m²]	Kcr2	Kpea	p-value
1	0.8	9.0	Default = 1	Default = 1	< 0.001
2	1.05	8.2	Default = 1	Default = 1	< 0.001
3	1.05	8.2	0.6	0.6	0.186

4. Conclusion

This study aimed to enhance the accuracy of fuel consumption predictions for heavy-duty trucks by calibrating the HDM-4 model to better reflect modern engine technology and real-world operating conditions in Indonesia. The results clearly show that the default HDM-4 parameters no longer match the characteristics of today's trucks. Therefore, it is crucial to update these parameters by considering current engine technology and local operational factors. Firstly, calibrating the engine speed model revealed that the default HDM-4 parameters tend to overestimate fuel consumption at low to medium speeds, while underestimating it at higher speeds. The new parameters derived for Euro-4 engines capture the efficiency of modern engines, which deliver optimal power at lower RPMs, leading to more accurate fuel consumption predictions. Secondly, the calibration of aerodynamic parameters found that the default drag coefficient (Cd) and frontal area (AF) values in HDM-4 do not reflect real-world truck configurations. The simulation results thus provide a better representation of actual aerodynamic performance. In addition, calibrating the rolling resistance and engine efficiency factors further improved the model's accuracy across various road conditions and vehicle loads.

Moreover, calibrating the HDM-4 model through three different scenarios showed a steady improvement in prediction accuracy. In Scenario 1, the default HDM-4 parameters significantly underestimated fuel consumption. In Scenario 2, incorporating aerodynamic calibration and engine RPM adjustments improved accuracy, though some differences remained. Finally, in Scenario 3, adding technical correction factors (Kpea and Kcr2) resulted in predictions that closely matched real-world data, with no significant statistical difference. The most significant finding of this study is that Scenario 3 incorporating aerodynamic calibration and technical correction factors yielded fuel consumption predictions that were statistically consistent with observed values ($p = 0.186$), confirming the robustness and reliability of the calibrated HDM-4 model. By delivering updated HDM-4 parameters tailored to Euro-4 trucks and incorporating modern aerodynamic profiles, this study provides practical contributions to support data-driven decisions in logistics efficiency, cost management, and emission control. As a result, heavy-duty truck operations in Indonesia can become more efficient, economical, and environmentally sustainable.

Looking forward, future research should incorporate additional influencing factors such as detailed road surface conditions, short-gradient variability, ambient temperature, and driver behavior, which were beyond the scope of this study. Furthermore, as vehicle technology advances, continuous calibration using HDM-4 Level III will be necessary to preserve model accuracy over time. To enhance the quality of aerodynamic analysis, advanced Computational Fluid Dynamics (CFD) simulations using high-performance computing can deliver high-resolution insights into airflow separation, wake turbulence, and drag dynamics. Additionally, wind tunnel testing is recommended to validate CFD outputs and further refine aerodynamic coefficients. By adopting these approaches, future studies can develop a more robust, flexible, and adaptive HDM-4-based fuel consumption model, aligned with the latest truck technologies and diverse real-world operating environments.

5. Author's declaration

Authors' contributions and responsibilities

Write the contribution of each author here, or mark the following column.

- [√] The authors made substantial contributions to the conception and design of the study.
- [√] The authors took responsibility for data analysis, interpretation and discussion of results.
- [√] The authors read and approved the final manuscript.

Availability of data and materials

- [√] All data are available from the authors.

Competing interests

- [√] The authors declare no competing interest.

Additional information

Write additional information related to this research, if any.

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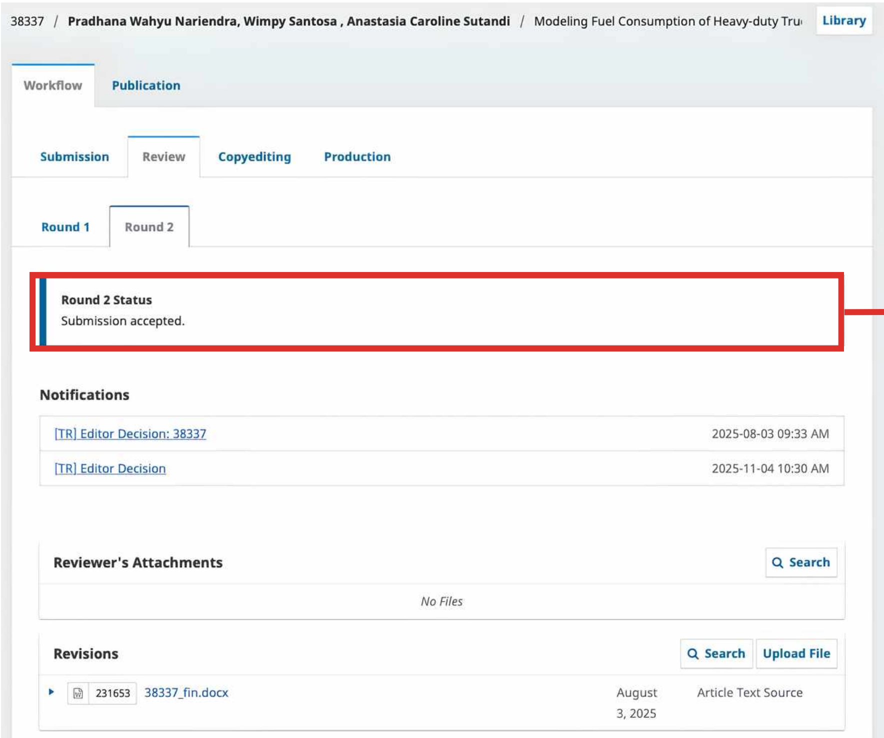
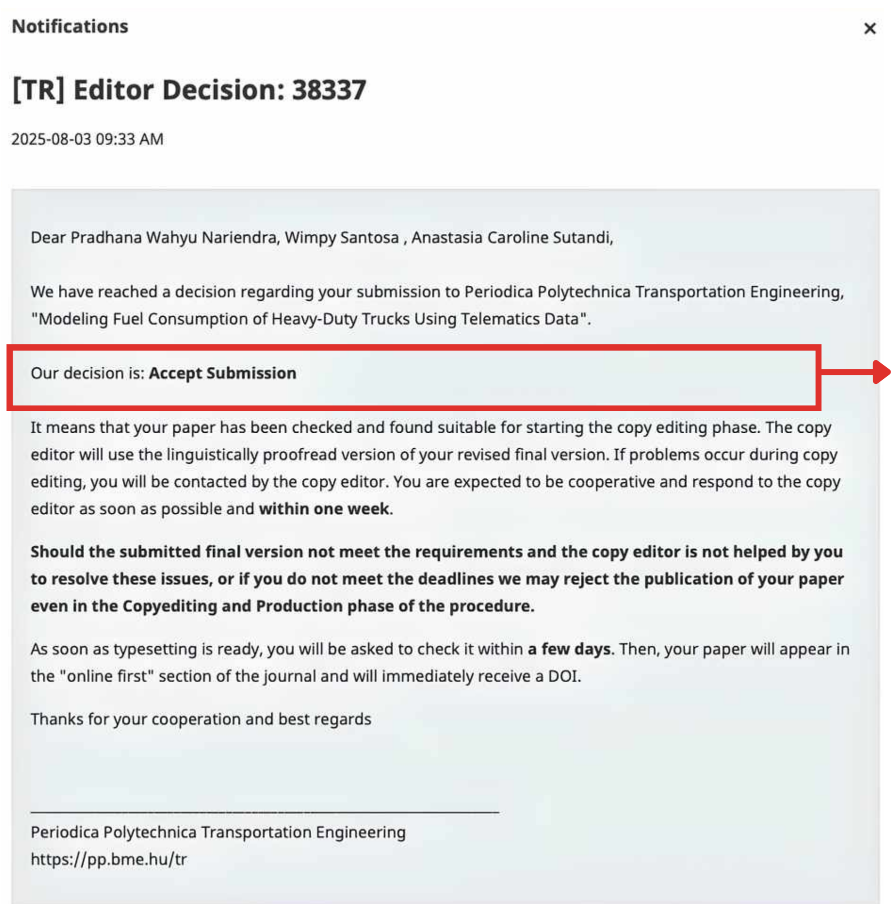
5. TAHAP ACCEPTANCE
5.1. Bukti Status Round 2: Submission Accepted

Pada tanggal 3 Agustus 2025, editor menyampaikan keputusan Accept Submission untuk artikel berjudul "Modeling Fuel Consumption of Heavy-duty Trucks Using Telematics Data". Keputusan ini menunjukkan bahwa artikel telah melalui proses review dan revisi, dinilai layak oleh editor, serta dilanjutkan ke tahap copyediting. Status pada sistem OJS juga menunjukkan Round 2 Status: Submission accepted, yang memperkuat bukti bahwa artikel telah resmi diterima oleh jurnal.



Keputusan Editor


Notifications

[TR] Editor Decision: 38337

2025-08-03 09:33 AM

Dear Pradhana Wahyu Nariendra, Wimpy Santosa , Anastasia Caroline Sutandi,

We have reached a decision regarding your submission to Periodica Polytechnica Transportation Engineering, "Modeling Fuel Consumption of Heavy-Duty Trucks Using Telematics Data".

Our decision is: **Accept Submission**

It means that your paper has been checked and found suitable for starting the copy editing phase. The copy editor will use the linguistically proofread version of your revised final version. If problems occur during copy editing, you will be contacted by the copy editor. You are expected to be cooperative and respond to the copy editor as soon as possible and **within one week**.

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As soon as typesetting is ready, you will be asked to check it within **a few days**. Then, your paper will appear in the "online first" section of the journal and will immediately receive a DOI.

Thanks for your cooperation and best regards

____

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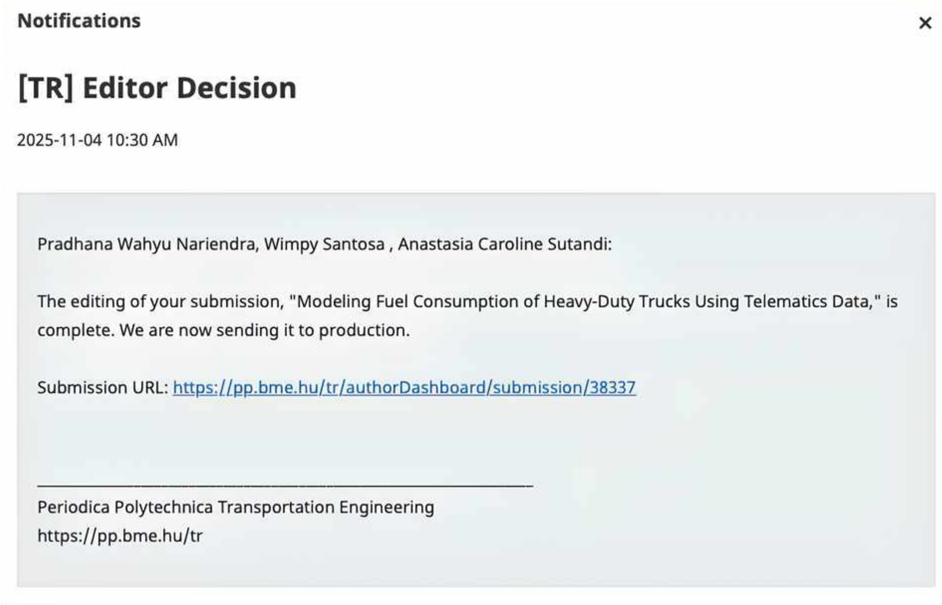
Keputusan Editor

6. BUKTI TAHAP COPYEDITING & PRODUCTION

6.1. Editor Decision: Editing Completed / Sent to Production

Pada tanggal 4 November 2025, editor menyampaikan bahwa proses editing telah selesai dan artikel dikirim ke tahap production. Hal ini menunjukkan bahwa naskah telah melewati proses pasca-acceptance dan siap diproses untuk publikasi akhir.



Notifications ×

[TR] Editor Decision

2025-11-04 10:30 AM

Pradhana Wahyu Nariendra, Wimpy Santosa , Anastasia Caroline Sutandi:

The editing of your submission, "Modeling Fuel Consumption of Heavy-Duty Trucks Using Telematics Data," is complete. We are now sending it to production.

Submission URL: https://pp.bme.hu/tr/authorDashboard/submission/38337

____

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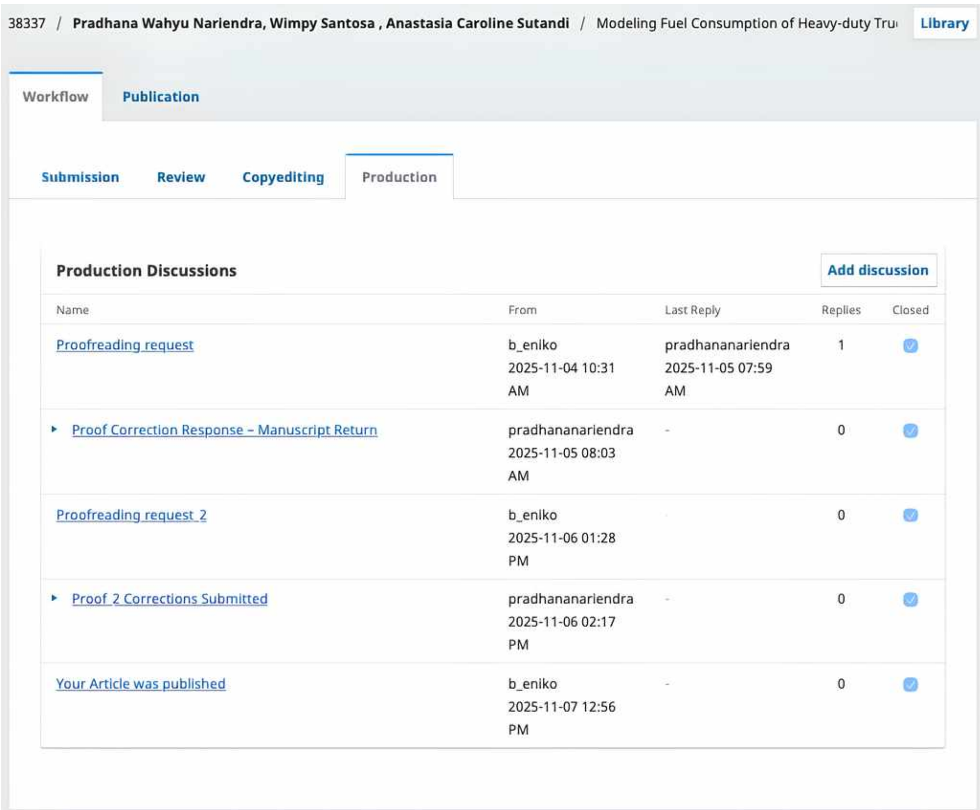
6.2. Bukti Tahap Production

Pada tahap production, artikel diproses dalam bentuk typeset proof untuk diperiksa kembali oleh penulis. Tahap ini mencakup pemeriksaan layout, format, referensi, dan kesalahan tipografi sebelum artikel diterbitkan.



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Proofreading request 2	b_eniko 2025-11-06 01:28 PM	-	0	✓
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6.3. Proofreading Request

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Anna Schubertné Dobóczi (adoboczi)

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Enikő Boczkó-Balla (b_eniko)

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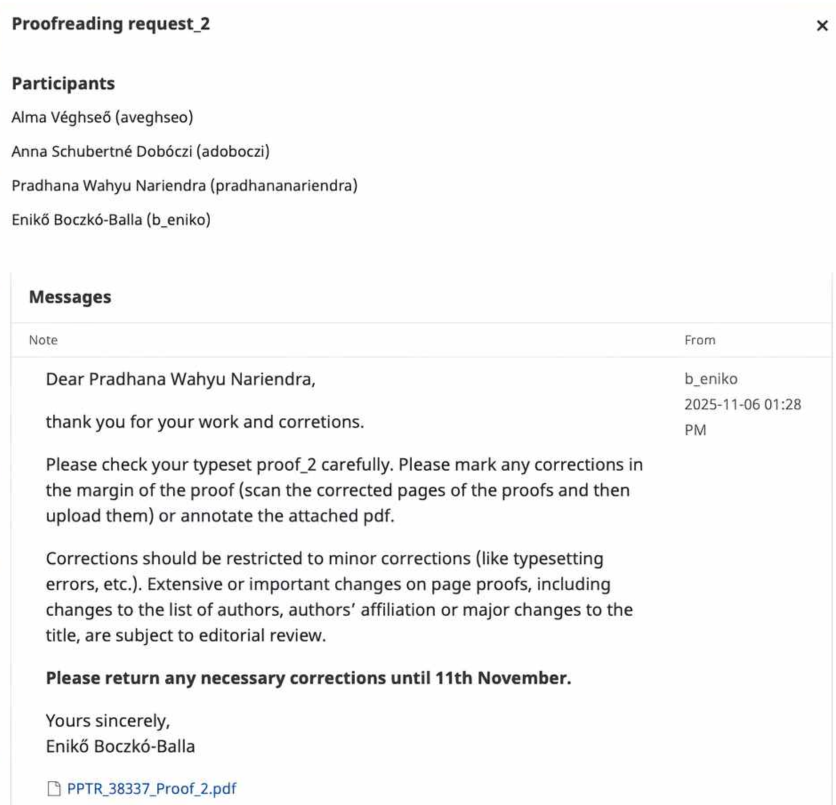
6.5. Proofreading Request 2

Pada tanggal 6 November 2025, editor mengirimkan proofreading request kedua. Penulis diminta kembali memeriksa proof_2 dan mengunggah koreksi apabila masih diperlukan.



Proofreading request_2 ×

Participants

Alma Véghseő (aveghseo)

Anna Schubertné Dobóczi (adoboczi)

Pradhana Wahyu Nariendra (pradhananariendra)

Enikő Boczkó-Balla (b_eniko)

Messages

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6.6. Proof 2 Corrections Submitted

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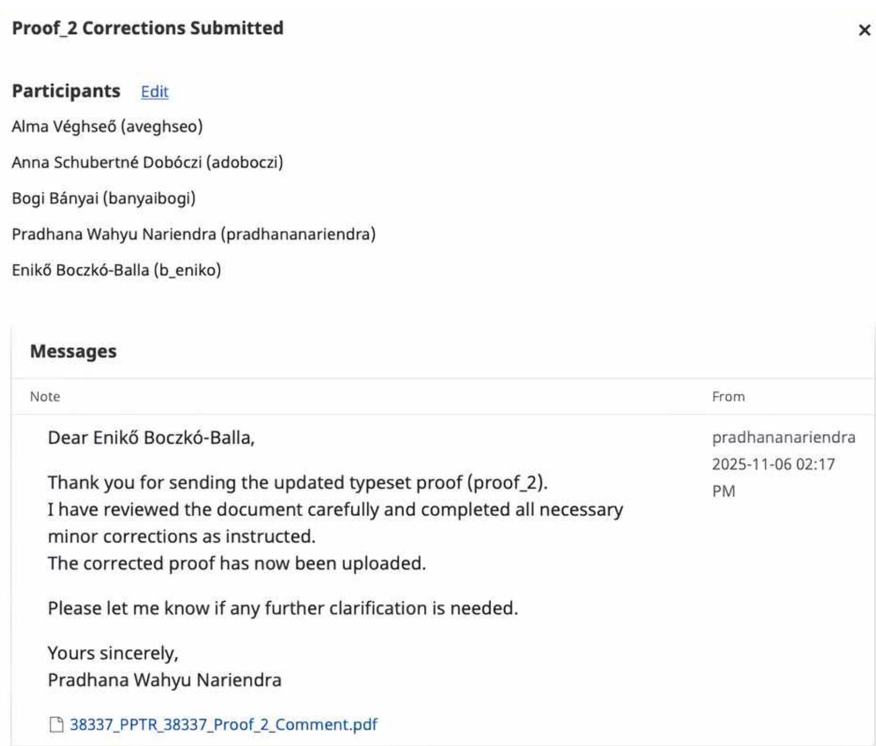

Proof_2 Corrections Submitted ×

Participants Edit

Alma Véghseő (aveghseo)

Anna Schubertné Dobóczi (adoboczi)

Bogi Bányai (banyaibogi)

Pradhana Wahyu Nariendra (pradhananariendra)

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7. TAHAP PUBLISHED

7.1. Bukti Artikel Published Online

Pada tanggal 7 November 2025, editor menyampaikan bahwa artikel telah dipublikasikan secara online. Pesan tersebut menyertakan tautan DOI artikel sebagai bukti bahwa artikel telah terbit secara resmi.

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Enikő Boczkó-Balla (b_eniko)

Messages

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7.2. Bukti Artikel Terbit dengan DOI

BArtikel telah diterbitkan pada Periodica Polytechnica Transportation Engineering, Vol. 54 No. 1, halaman 41–48, tahun 2026, dengan DOI 10.3311/PPtr.38337. Status published online pada tanggal 7 November 2025 menunjukkan bahwa artikel telah menyelesaikan seluruh proses editorial, review, revisi, acceptance, copyediting, production, proofreading, dan publikasi.

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SECTION

Articles

ABSTRACT

Fuel is the largest cost component in Vehicle Operating Costs (VOC) and a significant contributor to greenhouse gas (GHG) emissions in the trucking sector. This study developed a real-time telematics-based fuel consumption model for Euro-3 and Euro-4 trucks operating on toll roads in Indonesia, focusing on 5-axle heavy-duty trucks. The model utilizes telematics data, including average speed, gross vehicle weight, and road gradient under free-flow conditions, a novel aspect of this research. Two modeling approaches were applied: Model 1 employed multiple linear regression with Box-Cox transformation, while Model 2 utilized Generalized Linear Models (GLM) with a Gamma distribution and log link. Model 1 performed better, explaining 85.8% of the variability in fuel consumption (adjusted R^2 = 0.858) with a deviance of 0.947, RMSE of 0.033, and AIC of −3.246.625. Conversely, Model 2 recorded a deviance of 8.827, RMSE of 0.296, and AIC of −2.483. The Wilcoxon Signed Ranks Test indicated no significant differences between predicted and observed fuel consumption for both truck types, with a Z value of −1.700 (p = 0.089) for Euro-4 and −0.038 (p = 0.970) for Euro-3, supporting the model's reliability. Beyond optimizing fuel consumption, the model offers practical recommendations for truck operators considering conversion to Euro-4 and provides valuable insights for policymakers developing energy efficiency strategies in the transportation sector. Further research is recommended to expand the model's application to non-toll routes and integrate machine learning for more complex patterns.

https://doi.org/10.3311/PPtr.38337

Periodica Polytechnica Transportation Engineering, 54(1), pp. 41–48, 2026

Modeling Fuel Consumption of Heavy-duty Trucks Using Telematics Data

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Abstract

Fuel is the largest cost component in Vehicle Operating Costs (VOC) and a significant contributor to greenhouse gas (GHG) emissions in the trucking sector. This study developed a real-time telematics-based fuel consumption model for Euro-3 and Euro-4 trucks operating on toll roads in Indonesia, focusing on 5-axle heavy-duty trucks. The model utilizes telematics data, including average speed, gross vehicle weight, and road gradient under free-flow conditions, a novel aspect of this research. Two modeling approaches were applied: Model 1 employed multiple linear regression with Box-Cox transformation, while Model 2 utilized Generalized Linear Models (GLM) with a Gamma distribution and log link. Model 1 performed better, explaining 85.8% of the variability in fuel consumption (adjusted $R^2 = 0.858$) with a deviance of 0.947, RMSE of 0.033, and AIC of −3.246.625. Conversely, Model 2 recorded a deviance of 8.827, RMSE of 0.296, and AIC of −2.483. The Wilcoxon Signed Ranks Test indicated no significant differences between predicted and observed fuel consumption for both truck types, with a Z value of −1.700 ($p = 0.089$) for Euro-4 and −0.038 ($p = 0.970$) for Euro-3, supporting the model's reliability. Beyond optimizing fuel consumption, the model offers practical recommendations for truck operators considering conversion to Euro-4 and provides valuable insights for policymakers developing energy efficiency strategies in the transportation sector. Further research is recommended to expand the model's application to non-toll routes and integrate machine learning for more complex patterns.

Keywords

fuel consumption, emission, euro-4, telematics data, heavy-duty truck

1 Introduction

Logistics plays a significant role in economic growth. However, the high logistics costs remain a major challenge to Indonesia's economic competitiveness (Kanungo, 2014; Wirabrata and Silalahi, 2012). Transportation expenses contribute 46.4% of the total national logistics costs, with road transport dominating at 67.13% (Santoso et al., 2021). In Indonesia, trucking constitutes 80–90% of road transportation, making it a crucial sector within the national logistics system (Ministry of Transportation, 2021; Yang et al., 2021). Economically, fuel represents the largest component of truck Vehicle Operating Costs (VOC). In the United States, fuel accounts for approximately 21% of truck VOC (Leslie and Murray, 2022), while in Indonesia, this figure is higher, reaching 28% (Brasukra and Hergesell, 2008). In the regions of DKI Jakarta and West Java, fuel's share in truck VOC further increases to 32% (Burhanudzaky and Nariendra, 2022). An even more severe scenario occurs on non-toll roads in South Sumatra, where fuel costs constitute between 44.3% and 49.3% of total VOC (Kadarsa et al., 2019). On the Kanci-Pemalang route, fuel costs for 5-axle trucks range from 40.76% to 46.87% of the total trip cost, emphasizing the significant role of fuel in logistics costs (Nariendra, 2024). High fuel consumption affects not only transport expenses but also has broader implications for local and national economies (Posada-Henao et al., 2023).

Several studies indicate that vehicle fuel consumption is influenced by both vehicle and road conditions (Ahn et al., 2002; Zhou et al., 2016). Gross weight and road gradient have a more pronounced impact than speed, particularly under overloaded conditions (Wang et al., 2017a; Posada-Henao et al, 2023). In Indonesia, inclines significantly increase operational costs, while reducing gradients can decrease these costs by up to 13% (Sudjana, 2011). Flat routes can save between 5% and 20% in fuel consumption compared to hilly routes (Zaabar and Chatti, 2014; Zhou et al., 2016). Implementing eco-driving systems on hilly terrain can

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enhance efficiency by approximately 7% (Kamal et al., 2011), whereas low gradients can save up to 9% for fully loaded trucks (Carrese et al., 2013; Zaabar and Chatti, 2014). Mathematical models have demonstrated that road gradients significantly affect engine power, fuel consumption, and exhaust emissions (Gao et al., 2019; Posada-Henao et al., 2023). Within the VOC context, vehicle speed and gross weight are critical factors differentiating operational costs between normal and overloaded conditions (Setiawan and Tjahjono, 2020).

In addition to affecting operational costs, trucking significantly contributes to greenhouse gas (GHG) emissions. Each increase of 1 liter/100 km in fuel consumption corresponds to an increase of 26.4 g/km of CO_2 emissions (Yang et al., 2021; Department for Energy Security & Net Zero, 2023). Heavy-duty trucks are major emitters of CO_2 and NOx, emitting higher levels compared to other vehicles (Mahalana et al., 2022). To address rising emissions, the Indonesian government has implemented Euro-4 emission standards aligned with the Paris Agreement and Sustainable Development Goals (Ministry of Environment and Forestry, 2017). Euro-4 standards provide fuel efficiency improvements of 10–15% over Euro-3 trucks, reducing CO_2 and NOx emissions by up to 30% (Erkkilä and Nylund, 2007; Maulidya, 2019).

The HDM-4 model has been widely applied to predict fuel consumption through local calibration in various countries. However, its complexity due to the need for calibrating engine parameters, frontal area, and rolling resistance renders it less effective for rapid applications in the transport industry and less accurate for heavy-duty trucks (Jiao and Bienvenu, 2015; Perrotta et al., 2019; Nariendra and Lestiani, 2025).

The novelty of this research lies in the development of a new, practical, and simplified real-time telematics-based fuel consumption model for 5-axle Euro-4 and Euro-3 trucks, utilizing data on average operational speed, gross vehicle weight, and road gradient. This approach eliminates the need for complex parameter calibration as required in the HDM-4 model, thereby enhancing implementation efficiency and relevance to operational conditions on Indonesian toll roads. Additionally, the model aligns with Euro-4 GHG reduction policies (Ministry of Environment and Forestry, 2017) by developing a model more suited to modern heavy vehicles and road conditions in Indonesia.

The objective of this research is to develop a real-time telematics-based fuel consumption model for Euro-4 and Euro-3 trucks operating on toll roads in Indonesia and to compare predictive and observed fuel consumption to assess the model's effectiveness. Linear regression analysis was employed to construct the model, while the Wilcoxon Signed-Rank Test was applied to evaluate its accuracy in reflecting operational conditions.

The main advantage of this research lies in the use of real-time telematics data, which offers higher accuracy because it can collect large datasets. However, its current application is limited to toll roads and 5-axle trucks, indicating the need for further studies to expand its applicability. Additionally, the model's effectiveness heavily relies on the quality of the collected data, particularly under extreme operational conditions.

Overall, this research makes a significant contribution by replacing the Euro-1 parameter-based truck model in the Bina Marga method (Iskandar et al., 2000) with a telematics-based approach for Euro-3 and Euro-4 trucks. By integrating real-time data on speed, gross weight, and road gradient, the proposed model not only enhances accuracy but also increases its relevance to current operational conditions. This approach also provides a methodological framework for future studies related to the implementation of emission standards.

2 Methodology

This research focuses on 5-axle semi-trailer trucks transporting containers with Euro-3 and Euro-4 emission standards, operating along the primary logistics route between Tanjung Priok Port and Bandung. This route features varying road gradients and pavement conditions representative of toll roads in Indonesia. The research objects are the Hino FG 260 TH (Euro-4) and UD Quester GKE (Euro-3) trucks, selected due to their prevalent use by companies, similar comprehensive telematics systems, and nearly equivalent weight-power ratios of 5.6 kW/ton and 5.7 kW/ton, respectively, ensuring consistent truck performance

Data collection occurred over two months (February-March 2024) through manufacturer-integrated telematics systems linked with GPS, including Hino Connect, My UD Fleet, and Transport Management System (TMS), capturing average operational speed, gross vehicle weight, fuel consumption, and road gradient. Telematics data were obtained from vehicle sensors such as GPS, On-Board Diagnostics (OBD-II), and IoT networks, subsequently transmitted through the Electronic Control Unit (ECU) for analysis to evaluate heavy-duty vehicle operational efficiency under real-world conditions (Farzaneh et al., 2020; SAE International Technical Standard, 2022; Perrotta et al., 2019).

Road gradients were calculated using elevation data from Google Earth with an accuracy of MAE 1.32 meters and RMSE 2.27 meters, deemed adequate for transportation applications (Wang et al., 2017b). Road gradient categorization followed the Indonesian Geometric Road Design Guidelines, classifying gradients into flat, hilly, and mountainous categories (Directorate General of Highways, 2020). Data were specifically focused on uninterrupted operations with stable speeds and curve radii greater than 550 meters, as fuel consumption on such curves closely matches straight roads, minimizing impacts on fuel usage and CO_2 emissions (Zhang et al., 2019). The data pre-processing involved identifying and removing outliers using the Z-score method (threshold ±3 standard deviations) and linear interpolation to handle missing data, maintaining dataset consistency.

Two analytical models were employed. Model 1 used Ordinary Least Squares (OLS) to analyze the influence of speed, gross vehicle weight, and road gradient on fuel consumption. Before estimation, linear regression assumptions were validated through residual normality and homoscedasticity tests. Violations of these assumptions were addressed using robust standard errors and Box-Cox transformations to correct data distribution issues (King and Roberts, 2015; Malik et al., 2018). Alternatively, Model 2 utilized Generalized Linear Models (GLM) with Gamma distribution and log link function to effectively handle skewed fuel consumption data and manage heteroscedasticity. Model validation involved comparing Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC), considered more effective than R^2 for optimal model selection (Dobson and Barnett, 2018).

To ensure model reliability, predicted results were compared with observed data. Hypothesis testing evaluated whether significant differences existed between predicted and observed fuel consumption. The Wilcoxon Signed-Rank Test, a non-parametric method not reliant on normal distribution assumptions, was employed to assess paired averages, especially when observed data failed normality assumptions. The null hypothesis (H0) proposed no significant differences between predictive and observed fuel consumption, implying zero difference between them (Deshpande et al., 2017). This test determined whether differences between predictions and observations were sufficiently significant to reject the null hypothesis or if predictive data could accurately reflect observed data.

3 Data and results

The results of data processing and analysis included segmentation, grouping, and outlier identification in truck fuel consumption modeling. This analysis continued with examining factors influencing fuel consumption and developing predictive models. Subsequently, the model's accuracy was evaluated by comparing the predictive data with observed data.

3.1 Data processing

Data management in this research began with segmenting road sections based on gradient and vehicle speed under free-flow conditions. This segmentation aimed to create more homogeneous and representative observation segments, enabling a more accurate analysis of gradient impacts on vehicle performance and fuel consumption. Three gradient categories were utilized: flat, hilly, and mountainous, covering 12 road segments on the Jakarta-Cikampek, Cipularang, and Purbaleunyi Toll Roads. Segment identification codes corresponded to kilometer markers on the toll roads, using Code A for truck movements from Tanjung Priok to Bandung and Code B for the opposite direction. The flat segments included segments 57-A and 57-B, with maximum gradients of 0.01% and 0.07%, respectively. Meanwhile, the hilly and mountainous segments included segment 108-B with a gradient of 4.72% and segment 92-A with a gradient of 6.13%. A total of 1,094 speed data points were collected, comprising 474 data points for Euro-4 trucks and 620 for Euro-3 trucks. These data were categorized based on vehicle speed, gross vehicle weight, and road gradient. Speed was classified into three levels: low (below 20 km/h), medium (20–40 km/h), and high (above 40 km/h). Gross vehicle weight (load factor) was grouped into three categories: low (below 30%), medium (30–75%), and high (above 75%). Road gradients were divided into flat (maximum 4%), hilly (maximum 5%), and mountainous (maximum 6%). The map of observation segments based on road gradient is presented in Fig. 1,

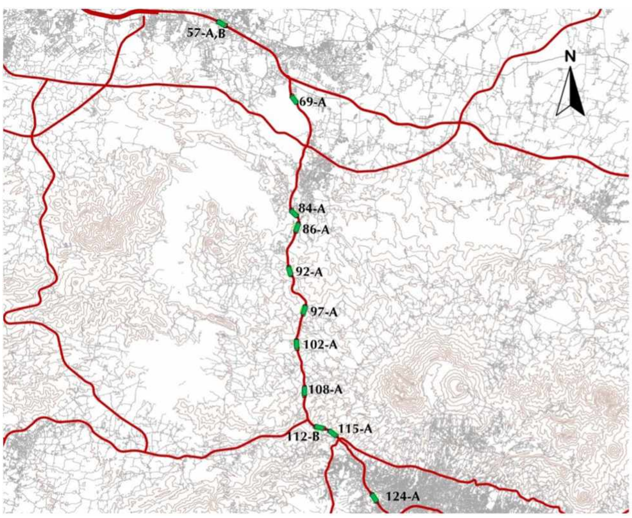

Fig. 1 The road sections classified based on road gradient

while detailed data on operational speed, gross vehicle weight, and fuel consumption according to road gradients are provided in Table 1.

Results in Table 1 indicate significant variations in speed, gross vehicle weight, and fuel consumption between Euro-4 and Euro-3 trucks across the observed segments. The highest speed for Euro-4 trucks was recorded on segment 57-A with an average of 47.16 km/h (standard deviation 8.73 km/h), while Euro-3 trucks recorded an average speed of 46.42 km/h (standard deviation 7.81 km/h). Conversely, the lowest speeds were observed on segment 108-B, with Euro-4 trucks averaging 28.63 km/h (standard deviation 9.26 km/h) and Euro-3 trucks averaging 26.43 km/h (standard deviation 7.53 km/h). Notable differences were also observed in gross vehicle weight. On segment 92-A, Euro-3 trucks had the highest average gross weight of 33.04 tons (standard deviation 10.35 tons), whereas Euro-4 trucks averaged 28.33 tons (standard deviation 9.01 tons). The lowest weight for Euro-4 trucks was on segment 124-A, averaging 23.87 tons (standard deviation 7.36 tons), while Euro-3 trucks averaged 30.78 tons (standard deviation 10.72 tons) on segment 57-A. Fuel consumption demonstrated a consistent pattern, with Euro-4 trucks generally showing greater efficiency than Euro-3. On segment 57-A, Euro-4 trucks had a fuel consumption of 6.98 km/l (standard deviation 2.86), significantly higher than Euro-3 trucks with 3.76 km/l (standard deviation 1.25). However, on segment 92-A, which features steep gradients, fuel consumption dropped for both truck types, although Euro-4 trucks remained more efficient with 0.69 km/l (standard deviation 0.27), compared to Euro-3 trucks at 0.61 km/l (standard deviation 0.29). Overall, these findings illustrate that Euro-4 trucks not only operated with lighter loads but were also more fuel-efficient, particularly on flat and hilly segments, compared to Euro-3 trucks.

3.2 Fuel consumption modeling

This research models fuel consumption (FC) as the dependent variable, with average vehicle operating speed (V),

Table 1 Summary of speed, gross weight, and fuel consumption data by road gradient

Segment	Road Gradient (%)	Truck Type	Data count	Average operation speed (V)		Gross vehicle Weight (W)		Fuel consumption (FC)	
				Mean V (km/h)	Standard Deviation	Mean W (ton)	Standard Deviation	Mean FC (km/l)	Standard Deviation
57-B	0.01	Euro-4	44	46.88	7.78	32.09	5.57	5.38	1.41
		Euro-3	54	42.92	6.36	32.67	7.48	3.16	0.77
57-A	0.07	Euro-4	37	47.16	8.73	28.42	8.72	6.98	2.86
		Euro-3	51	46.42	7.81	30.78	10.72	3.76	1.25
69-A	1.00	Euro-4	37	46.44	7.50	26.58	9.01	6.88	2.96
		Euro-3	52	46.05	6.26	30.04	10.67	3.58	1.14
84-A	4.32	Euro-4	44	41.07	9.97	27.62	9.79	3.12	1.32
		Euro-3	54	34.63	9.85	31.18	11.16	1.99	0.88
86-A	5.24	Euro-4	47	39.82	10.03	27.51	9.63	1.97	0.87
		Euro-3	53	31.36	11.22	31.23	11.33	1.36	0.63
92-A	6.13	Euro-4	39	31.01	8.85	28.33	9.01	0.69	0.27
		Euro-3	59	26.59	8.71	33.04	10.35	0.61	0.29
97-A	4.41	Euro-4	44	35.96	10.04	29.79	10.01	2.69	1.23
		Euro-3	51	33.29	9.84	31.12	10.82	1.84	0.85
102-A	2.76	Euro-4	39	38.54	10.68	26.81	8.84	4.32	1.71
		Euro-3	50	35.54	12.35	31.52	10.61	2.19	1.02
108-B	4.72	Euro-4	42	28.63	9.26	30.81	5.96	1.80	0.48
		Euro-3	52	26.43	7.53	33.02	7.12	1.21	0.43
112-A	2.85	Euro-4	38	41.79	9.48	30.02	9.08	3.59	1.47
		Euro-3	55	38.98	10.49	32.14	10.53	2.48	0.99
115-A	3.68	Euro-4	34	43.56	8.69	28.35	9.22	3.09	1.25
		Euro-3	50	39.65	9.65	31.88	10.20	2.01	0.74
124-A	3.37	Euro-4	31	45.53	6.82	23.87	7.36	3.93	1.14
		Euro-3	39	40.13	8.90	30.64	9.98	2.24	0.84

gross vehicle weight (*W*), road gradient (*S*), and truck type as a dummy variable (*T*) as independent variables. Meanwhile, gross vehicle weight (*W*) includes the total weight of the vehicle, cargo, truck crew, components, and vehicle equipment. For trucks carrying heavy loads, this total weight can reach 11.794 kg or more (Bennett, 2020).

Simple linear regression tests indicated that variable *V* has a significant non-linear relationship with fuel consumption, yielding an R^2 of 0.509 and an F-value of 856.769. Variable W displayed logistic and exponential non-linear relationship patterns with an R^2 of 0.349 and an F-value of 442.222. Additionally, variable *S* significantly influenced fuel consumption, with an R^2 of 0.356 and an F-value of 228.128. Given the significant effects of all variables, the analysis proceeded with multiple linear regression.

In the subsequent stage, multiple linear regression analysis (Model 1) applied the Box-Cox transformation ($\lambda = 0.25$) to address non-normal residual distributions. The Kolmogorov-Smirnov test after transformation yielded a p-value of 0.095, indicating that the residuals approximated a normal distribution. Multicollinearity tests produced Variance Inflation Factor (VIF) values ranging from 1.031 to 1.578, signifying no multicollinearity issues. The Durbin-Watson test provided a value of 1.953, close to the ideal value of 2, indicating the absence of significant autocorrelation. Although the Glejser test suggested heteroscedasticity in variables *W* and *T*, the Breusch-Pagan test, with a p-value of 0.165, indicated constant residual variance.

The multiple linear regression results from Model 1 indicated significant impacts of all independent variables on fuel consumption. Average operational speed (*V*) exhibited a positive influence, meaning an increase in speed tended to elevate fuel consumption. Conversely, gross vehicle weight (*W*) and road gradient (*S*) showed negative impacts, indicating that increased weight or gradient reduced fuel consumption. Additionally, Euro-4 trucks demonstrated higher fuel efficiency than Euro-3 trucks, with the dummy variable coefficient for truck type showing significant fuel savings for Euro-4 vehicles. Detailed coefficient values, t-values, and p-values for each variable are presented in Table 2, demonstrating significance at a 5% significance level with a critical t-value of 1.647.

As an alternative, Model 2 utilized Generalized Linear Models (GLM) with Gamma distribution and a log link function to model the relationships between the same variables. Goodness-of-fit tests indicated excellent model fit, demonstrated by a deviance of 8.827 with a deviance/df of 0.011, and a Pearson Chi-Square value of 8.755 with a Pearson Chi-Square/df of 0.011. Parameter estimation results from the GLM indicated that operational speed (*V*) and truck type (*T*) positively influenced fuel consumption, with coefficients of 0.018 and 0.316, respectively. Conversely, gross vehicle weight (*W*) and road gradient (*S*) showed negative impacts, with coefficients of −0.030 and −0.148. Detailed results of the GLM parameter estimation are provided in Table 3.

Table 2 Model 1 parameter estimation

Parameter	Coefficient	Robust Standard Error	t-value	p-value
Intercept	1.539	0.009	178.989	<0.001
V^2	6.64 E-02	2.33 E-03	28.542	<0.001
W	−0.009	0.000	−66.986	<0.001
G	−0.048	0.001	−54.371	<0.001
T	0.098	0.003	35.953	<0.001

A comparison between Model 1 and Model 2 showed that Model 1 performed better. Model 1 recorded a lower deviance value of 0.947 compared to 8.827 in Model 2 and a smaller RMSE value of 0.033 compared to 0.296. Additionally, the adjusted R-squared value of 0.858 indicated that 85.8% of the variability in fuel consumption could be explained by the independent variables in this model. The AIC value for Model 1 was −3.246.625, superior to Model 2, suggesting lower prediction error levels. Based on performance indicators, multiple linear regression with the Box-Cox transformation (Model 1) is recommended as the optimal model for predicting fuel consumption in Euro-4 and Euro-3 trucks due to its higher accuracy and greater explanatory power, as shown in Table 4. The final regression equation derived from Model 1 is presented in Eq. (1):

$$FC^{0.25} = 1.539 + 0.000066V^2 - 0.009W - 0.048S + 0.098T \quad (1)$$

where:

FC = fuel consumption (km/l),
V = average operating speed (km/h),
W = gross vehicle weight (ton),
G = positive road gradient (%),
T = truck type (Euro-4 = 1 and Euro-3 = 0).

Table 3 Model 2 parameter estimation

Parameter	Coefficient	Robust Standard Error	Wald Chi-Square Value	p-value
Intercept	1.399	0.0360	1.507.653	<.0.001
V	0.018	0.0006	1.025.472	<.0.001
W	−0.030	0.0004	4.435.602	<.0.001
G	−0.148	0.0025	3.433.817	<.0.001
T	0.316	0.0082	1.465.779	<.0.001

Table 4 Comparison of model performance metrics

Indicator	Model 1	Model 2
Deviance	0.947	8.827
Pearson Chi-Square	0.947	8.755
Log Likelihood	1.629.313	7.241
AIC	−3.246.625	−2.483
AICC	−3.246.523	−2.380
BIC	−3.218.311	25.832
CAIC	−3.212.311	31.832
RMSE	0.033	0.296
MAE	0.027	0.217
RSS	0.947	72.810

3.3 Comparison of modeled predictions and observed outcomes

Based on the results of the Wilcoxon Signed Ranks Test, a comparison between observed and predicted fuel consumption was conducted for Euro-4 and Euro-3 trucks to evaluate the accuracy of the predictive model. For Euro-4 trucks, a Z value of −1.700 and an Asymp. Sig. (2-tailed) of 0.089 indicated a p-value greater than 0.05, suggesting no statistically significant difference between observed and predicted fuel consumption. However, slight differences may still hold operational relevance, such as variations in terrain or other external conditions. For Euro-3 trucks, a Z value of −0.038 and an Asymp. Sig. (2-tailed) of 0.970 revealed a minimal difference between observed and predicted results, with a p-value significantly greater than 0.05. These results suggest that the predictive model for Euro-3 trucks accurately reflects actual fuel consumption, providing greater confidence in its reliability for predicting real-world performance.

Overall, no significant differences between predicted and observed outcomes were identified for either Euro-4 or Euro-3 trucks, with the Euro-3 predictive model demonstrating higher accuracy. These findings support the validity of the telematics-based predictive model used in this research, particularly for real-world applications. The results align with previous studies indicating that predictive models based on telematics data can effectively reduce prediction errors for trucks with lower emission standards. Nevertheless, the minor discrepancies observed for Euro-4 trucks suggest potential areas for further refinement, including additional analysis of variables such as road surface conditions or variations in vehicle load.

4 Conclusion

This research successfully developed a novel, practical, and accurate real-time telematics-based predictive model for fuel consumption in Euro-4 and Euro-3 trucks operating on Indonesian highways. The contribution of this study lies in the development of a simplified predictive model that eliminates the need for complex parameter calibration as required in conventional models such as HDM-4. Model 1, utilizing multiple linear regression with Box-Cox transformation, demonstrated superior performance compared to the GLM-based Model 2, indicated by lower AIC, BIC, RMSE, and MAE values. The analysis revealed that operational speed, gross vehicle weight, road gradient, and truck type significantly influenced fuel consumption, with an adjusted R^2 of 0.858, meaning that 85.8% of the variability in fuel consumption could be explained by the model. The accuracy evaluation using the Wilcoxon Signed Ranks Test showed no significant differences between predicted and observed values for both Euro-4 and Euro-3 trucks, indicating that the predictive model is sufficiently accurate.

The findings suggest that telematics-based predictive models for fuel consumption can be optimized for truck operations on highways with similar travel characteristics, weather conditions, vehicles, road types, traffic patterns, and driver behavior. Furthermore, this model provides a useful basis for fleet conversion considerations towards Euro-4 trucks. Implementing this model enables truck operators to identify more efficient operational combinations for Euro-4 trucks, optimizing fuel consumption and effectively reducing greenhouse gas emissions. However, to broaden the model's application, testing on non-toll roads, mountainous terrain, and areas with extreme weather conditions is necessary to ensure the model's effectiveness under various operational scenarios.

Future research should focus on challenging terrains, higher load factors, and Euro-5/Euro-6 trucks to support global emission reduction targets. Although multiple linear regression and GLM were chosen for interpretability and data constraints, machine learning methods such as Artificial Neural Networks (ANN), or Decision Trees could be explored to capture more complex data patterns and strengthen the external validity of the model across different geographic settings. Testing on non-toll routes, urban roads, and regions with varying climatic conditions and infrastructure will also be essential to validate the model globally. Additionally, incorporating supplementary variables such as weather, traffic density, and driver behavior could enhance the predictive power of the model in more complex operational situations.

This research contributes to the development of a practical and accurate telematics-based predictive model for fuel consumption, outperforming manually calibrated models such as HDM-4. Thus, the model is not only relevant for truck operations in Indonesia but also has the potential to be applied in other regions with similar characteristics. It also opens opportunities for further research on the impact of additional variables such as weather, fuel type, and driver behavior on fuel consumption and greenhouse gas emissions. Additionally, the model offers a new methodological framework for fuel consumption prediction in 5-axle heavy trucks, integrating real-time telematics data, which is a significant advancement over traditional parameter-based models and aligns with Euro-4 emission reduction policies.

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