

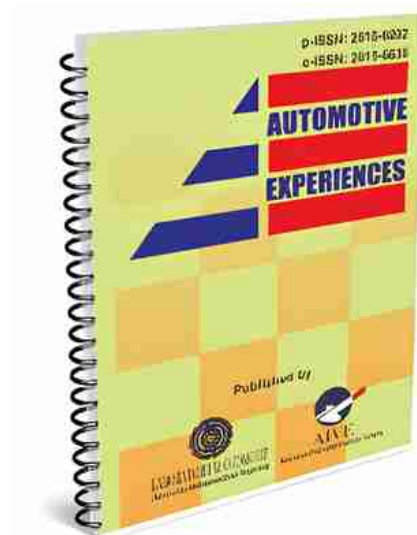
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1 **Calibration of HDM-4 Model for Fuel Consumption in Heavy-**
2 **Duty Trucks: Integration of Telematics, Engine Speed, and**
3 **Aerodynamics**

4
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Abstract

13 Fuel efficiency in heavy-duty trucks in Indonesia faces significant challenges, while the current
14 ⁹ HDM-4 fuel consumption model has limitations in reflecting local conditions. This study
15 ⁹ calibrates the HDM-4 model using telematics data, engine speed modeling, aerodynamic
16 simulations, and calibration factors. The novelty lies in updating parameters such as engine
17 speed, vehicle frontal area, and calibration factors for engine power efficiency (K_{pea}) and
18 rolling resistance (K_{cr2}) to account for tire-road interaction in Indonesian conditions. Data
19 were collected from 5-axle trucks on the Tanjung Priok–Bandung toll road, analyzed using
20 regression, Computational Fluid Dynamics (CFD) simulations, and non-parametric paired
21 tests. Results show updated ⁶ engine speed parameters (RPM_{a0} = 680.11, RPM_{a1} = -4.9031,
22 RPM_{a2} = 0.3858, RPM_{a3} = -0.0028), a drag coefficient of 1.0556, and a frontal area of 8.2 m².
23 Calibrating K_{pea} and K_{cr2} (both 0.6) improved prediction accuracy, with no significant
24 difference between predicted and observed data (p = 0.186). The enhanced HDM-4 model
25 supports operational decisions, infrastructure planning, and sustainable transport policies,
26 improving energy efficiency, reducing emissions, and boosting national logistics
27 competitiveness.

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

37 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 CO₂ and NO_x emissions, impacting environmental and economic sustainability [1], [2]. A global analysis shows that a 1 liter/100 km increase in fuel consumption adds 24.17 g/km of CO₂ emissions [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 [9], [10], [11], [12].

Implementing HDM-4 in Indonesia comes with significant challenges due to differences in vehicle specifications, road conditions, and varying truck loads [9], [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,

1 frontal area, engine speed, weather, and road conditions. Studies have shown that fine-tuning
2 these key parameters can greatly enhance the accuracy of fuel consumption predictions [14].
3 In Florida, similar calibrations were conducted for passenger cars and trailer trucks [15], while
4 in South Korea, the focus was on passenger cars [16]. Meanwhile, in the UK, researchers
5 verified the HDM-4 model for various types of trucks, also considering engine power, rolling
6 resistance, and frontal area [17]. Therefore, more tailored calibrations are needed to ensure the
7 model accurately represents the operational conditions of trucks in Indonesia.

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

20 This study aims to develop an HDM-4 Level II fuel consumption model tailored for 5-
21 axle trucks in Indonesia. The calibration process focuses on factors such as engine rotation,
22 aerodynamic drag, frontal area, engine power efficiency, and operational conditions like
23 average speed, load weight, and road gradient to better capture the realities of daily truck
24 operations. The research is centered on the Tanjung Priok Port–Bandung route, one of the
25 busiest logistics corridors in Indonesia [23]. This route includes toll roads with gradients of up
26 to 6%, in line with the standards set by the Directorate General of Highways [24]. The trucks
27 in this study use Pertamina’s Bio Solar fuel for Euro-4 engines [1], ensuring a realistic setting
28 for fuel consumption analysis. By combining real-time telematics data with aerodynamic
29 simulations, this study aims to create a more accurate fuel consumption model. The end goal
30 is to improve fuel efficiency, reduce greenhouse gas emissions, cut operational costs, and
31 support more sustainable freight transportation 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 [25], [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.

Data collection integrates both primary and secondary sources. The primary data include measurements of vehicle dimensions and wheel diameter using manual tools, along with engine speed and vehicle speed data collected through the On-Board Diagnostics (OBD-II) system [27], [28]. These primary data were collected using a Hino 5-axle truck, model year 2021, which is widely employed for heavy-duty transportation in Indonesia. 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. Secondary data were obtained from trucking companies utilizing Truck Telematics Systems and from government agencies such as the Ministry of Public Works and Housing and the Central Statistics Agency. These datasets include information on actual fuel consumption, vehicle speed, vehicle position, gross vehicle weight, road geometry, elevation, International Roughness Index (IRI), and road surface texture depth [25], [27].

Using telematics data offers significant advantages because passive data collection methods provide high spatial and temporal resolution at a low cost [27]. 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], [28].

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1 The next step involves calibrating vehicle parameters by modeling ⁵ the relationship
 2 between engine speed and vehicle speed. This relationship is critical because higher vehicle
 3 speeds require higher engine speeds, which directly impacts fuel efficiency [29]. The telematics
 4 data for vehicle speed and engine speed are processed using regression analysis, and the
 5 results are evaluated using ¹⁹ the coefficient of determination (R^2) to assess the strength of the
 6 relationship.

7 Following this, aerodynamic analysis is conducted using Computational Fluid
 8 Dynamics (CFD) in SolidWorks Flow Simulation [30], [31]. The process includes three main
 9 ⁸ stages: pre-processing, processing, and post-processing. During pre-processing, a vehicle
 10 model based on actual dimensions is created, validated, and meshed. Boundary conditions
 11 such as flow type, gravity, fluid type, and test speed are defined. In the processing stage,
 12 numerical simulations are run to calculate frontal area (FA) and the drag coefficient (C_d). The
 13 calculation follows Eq.1. ⁸ In the post-processing stage, simulation results are interpreted to
 14 evaluate the vehicle's aerodynamic efficiency, where a lower drag coefficient indicates a more
 15 streamlined and fuel-efficient design [32], [33], [34].

$$16 \quad C_d = \frac{2FA}{\rho V^2 AF} \quad (1)$$

17 where, C_d is the drag coefficient, FA is the aerodynamic drag force (N), ρ is the fluid density
 18 (kg/m^3), V is the relative velocity between the vehicle and air (m/s), and AF is the frontal area
 19 (m^2).

20 During the ⁹ HDM-4 model calibration, fuel consumption is estimated by taking into
 21 account factors like vehicle weight, speed, and road gradient [25]. This process relies on several
 22 key equations: (1) Total Resistance to Motion (FTR), which is calculated using Eq. 2; (2) Tractive
 23 Power (PTR), defined in Eq. 3; (3) Total Engine Power (PTOT), outlined in Eq. 4; (4)
 24 Instantaneous Fuel Consumption (IFC), described in Eq. 5; and (5) Specific Fuel Consumption
 25 (FC), determined in Eq. 6.

$$26 \quad FTR = FA + FG + FR + FCV \quad (2)$$

27 where, FTR is the total resistance force (N), ⁴ FA is the aerodynamic drag force (N), FG is the
 28 gradient resistance force (N), FR is the rolling resistance force (N), and FCV is the curvature or
 29 cornering resistance force (N).

$$30 \quad PTR = \frac{FTR \times V}{1000} \quad (3)$$

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1 where, FTR is the total resistance force (N), and V is the vehicle speed (m/s).

$$2 \quad P_{TOT} = \left(\frac{P_{TR}}{EDT} + P_{ENGACCS} \right) \quad (4)$$

3 where, P_{TOT} is the total engine power (kW), P_{TR} is the traction power (kW), EDT is the
4 driving efficiency, and $P_{ENGACCS}$ is the engine and accessory power (kW).

$$5 \quad IFC = \max [ID_{FUEL}, ZETA \times P_{TOT} \times (1 + dFUEL)] \quad (5)$$

6 where, IFC is the instantaneous fuel consumption (ml/s), and $dFUEL$ is the additional fuel
7 consumption factor due to changes in vehicle speed.

$$8 \quad FC = \frac{IFC}{V} \quad (6)$$

9 where, FC is the fuel consumption (ml/km), and IFC is the instantaneous fuel consumption
10 (ml/s).

11 In simpler terms, engine calibration parameters are fine-tuned to match local driving
12 conditions [25]. These parameters include: (1) Engine Speed (RPM), explained in Eq. 7; (2)
13 Rolling Resistance Factor (K_{cr2}), illustrated in Eq. 8; and (3) Engine Power Factor (K_{pea}),
14 detailed in Eq. 9.

$$15 \quad RPM = RPM_{a0} + RPM_{a1} \times V + RPM_{a2} \times V^2 + RPM_{a3} \times V^3 \quad (6)$$

16 where, RPM_{a0} , RPM_{a1} , and RPM_{a3} are engine speed model parameters.

$$17 \quad CR_2 = K_{cr2} \times (CR_{CR2_a0} + CR_{CR2_a1} \times TD + CR_{CR2_a2} \times RI) \quad (6)$$

18 where, K_{cr2} is the rolling resistance factor, TD is the texture depth (mm), RI is the average
19 road roughness value (m/km), and CR_{CR2_a0} to CR_{CR2_a2} are rolling resistance
20 coefficients.

$$21 \quad P_{ENGACCS} = K_{pea} \times PRAT \times \left[PACCS_{a1} + \frac{(PACCS_{a0} - PACCS_{a1})(RPM - RPM_{IDLE})}{(RPM_{100} - RPM_{IDLE})} \right]$$

22 where, K_{pea} is the calibration factor, $PRAT$ is the maximum engine power (kW), RPM_{IDLE}
23 is the engine speed at idle (rev/min), RPM_{100} is the engine speed at 100 km/h (rev/min), RPM
24 is the engine speed at operational speed (rev/min), $PACCS_{a0}$ is the ratio of engine and
25 accessory resistance to the engine power at 100 km/h, and $PACCS_{a1}$ is a model parameter.

26 The comparison between the calibrated HDM-4 model predictions and the observed fuel
27 consumption data is analyzed using the Wilcoxon Signed-Ranks Test. This non-parametric
28 method is ideal for paired samples that do not meet normality assumptions [35]. The null
29 hypothesis (H_0) states that the median difference is zero, while the alternative hypothesis (H_1)
30 suggests a significant difference. The Z value is compared to the critical Z value of ± 1.96 at a

1 0.05 significance level. The results are reported by comparing the number of negative ranks,
2 positive ranks, and ties as indicators of the model's stability.

3

4 3. Result and Discussion

5 3.1. Calibration of Engine Speed Model Parameters

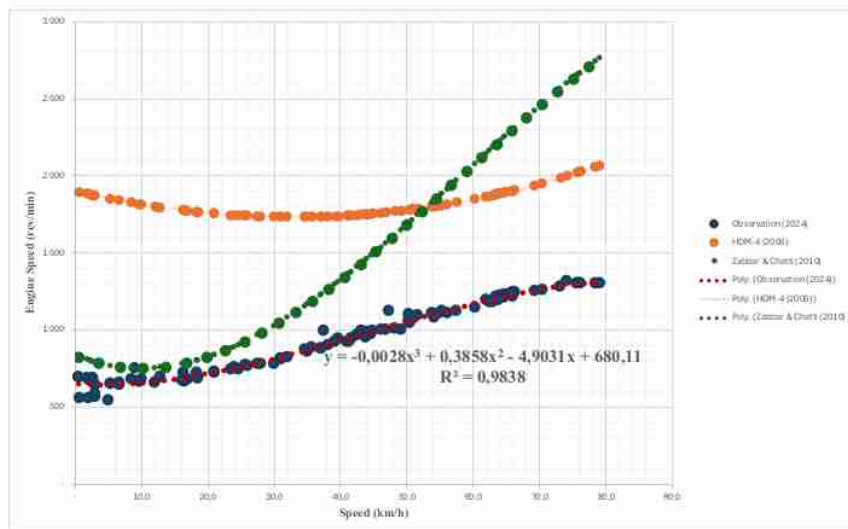
6 The findings of this study reveal significant differences in engine RPM parameters when
7 comparing the HDM-4 model, the study by Zaabar & Chatti model [14], and the actual
8 observations collected. These differences reflect advancements in engine technology and how
9 they impact truck performance and fuel consumption. The default engine RPM parameters in
10 the HDM-4 model are $RPM_{a0} = 1900$, $RPM_{a1} = -10.178$, $RPM_{a2} = 0.1521$, and $RPM_{a3} =$
11 0.00004 [6]. These values represent the characteristics of conventional truck engines used
12 during that period. As a result, the HDM-4 model tends to overestimate engine RPM at low to
13 medium speeds, leading to higher predicted fuel consumption than what actually occurs. On
14 the other hand, at higher speeds, the HDM-4 model underestimates engine RPM and does not
15 fully account for the increased aerodynamic resistance and higher power demands. In
16 comparison, the study by Zaabar & Chatti model presents more modern engine RPM
17 parameters with values of $RPM_{a0} = 833.7$, $RPM_{a1} = -17.717$, $RPM_{a2} = 0.9671$, and RPM_{a3}
18 $= -0.0055$. These parameters reflect improvements in combustion efficiency, fuel injection
19 precision, and emission control. Although this model offers a more accurate prediction than
20 HDM-4, it still falls short, especially at high speeds where the predicted engine RPM increases
21 more sharply than observed in real-world conditions. This suggests that while the technology
22 used in this model is more advanced, it still does not perfectly match the operating conditions
23 of trucks in Indonesia.

24 The current study provides parameters that are more tailored to the real-world
25 conditions of Indonesian trucks. The parameters derived are $RPM_{a0} = 680.11$, $RPM_{a1} = -$
26 4.9031 , $RPM_{a2} = 0.3858$, and $RPM_{a3} = -0.0028$. These values align with Euro-4 engine
27 technology, which incorporates common-rail injection systems and modern emission controls
28 [36], [37]. This technology allows trucks to produce optimal power at lower RPMs, improving
29 fuel efficiency and reducing emissions. These results highlight the efficiency of Euro-4 engines
30 in maintaining stable RPMs across different speeds compared to older engine technologies. To
31 better understand the relationship between speed and engine RPM, this study used a third-

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1 degree polynomial model. The equation derived from the data is: $y = -0.0028 x^3 + 0.3858 x^2 -$
 2 $4.9031 x + 680.11$. With a coefficient of determination $R^2 = 0.9838$. This high R^2 value indicates
 3 that the model fits the observed data very well. The polynomial model captures the gradual
 4 increase in engine RPM as speed rises, reflecting a more realistic trend in fuel consumption
 5 compared to the HDM-4 and Zaabar & Chatti models.

6 These differences are clearly illustrated in Figure 4. The blue dots represent actual
 7 observations, showing a steady increase in engine RPM with speed. In contrast, the orange
 8 dots from the HDM-4 model overestimate RPM at lower speeds and underestimate it at higher
 9 speeds. Meanwhile, the green dots from the Zaabar & Chatti model show a sharp increase in
 10 RPM at higher speeds, deviating from real-world observations. The red dashed line,
 11 representing the third-degree polynomial model, aligns closely with the observed data,
 12 offering a more accurate depiction of modern engine performance. In conclusion, this study
 13 emphasizes the need to calibrate fuel consumption models to reflect current engine technology
 14 and local operating conditions. By doing so, we can achieve more accurate fuel consumption
 15 predictions and develop efficient, sustainable operational strategies for heavy-duty trucks in
 16 Indonesia.



17

18

Figure 1. Calibration of Engine Speed Model Parameters

1 3.2. Calibration of Aerodynamic Parameters

2 The aerodynamic simulation results for heavy-duty vehicles offer a clear picture of how
3 air flows around the vehicle, the drag force, and the drag coefficient. The airflow distribution,
4 shown through streamlines with color gradients, reveals that air moves smoothly over the
5 cabin and body of the vehicle. However, as the vehicle speed increases, significant turbulence
6 forms behind the vehicle, known as the wake region. This turbulence creates a ²¹ low-pressure
7 zone, which in turn increases drag force [38]. From the simulation, the average drag force
8 recorded is 1,455.792 N, with a minimum of 1,455.556 N and a maximum of 1,455.851 N. These
9 values highlight that air resistance on heavy-duty vehicles is quite substantial, especially at
10 higher speeds [38]. The simulation also indicates a drag coefficient (Cd) of 1.0556, with a range
11 between 1.0551 and 1.0558, and a frontal area (FA) of 8.2 m². In contrast, the default values
12 used in the HDM-4 model assume a drag coefficient (Cd) of 0.80 and a frontal area (FA) of 9.0
13 m² [25].

14 The differences between the simulation results and the HDM-4 defaults can be explained
15 by the turbulence created in the wake region, which leads to increased pressure drag. This
16 means the engine needs to work harder to maintain speed. Additionally, the turbulence behind
17 the vehicle raises ² drag force and fuel consumption. Although the drag coefficient from the
18 simulation is higher than the default HDM-4 value, aerodynamic drag still plays a major role
19 in fuel efficiency, particularly because air resistance increases exponentially with speed [38].

20 These findings align with earlier research, which shows that aerodynamic drag
21 significantly affects the performance of heavy-duty vehicles, especially at high speeds [25].
22 Therefore, this simulation underscores the importance of calibrating the HDM-4 model to
23 match the real aerodynamic conditions of modern heavy-duty vehicles. Such calibration is
24 crucial ³⁴ to improve the accuracy of fuel consumption predictions, ensuring they reflect current
25 vehicle technology and real-world operations [14], [17]. Given these significant differences
26 between the simulation results and the default HDM-4 values, it is clear that modern vehicle
27 designs have evolved aerodynamically. Therefore, adjusting parameters like the drag
28 coefficient and frontal area is essential for making accurate fuel consumption predictions. The
29 aerodynamic simulation results are ²⁴ shown in Figure 2.

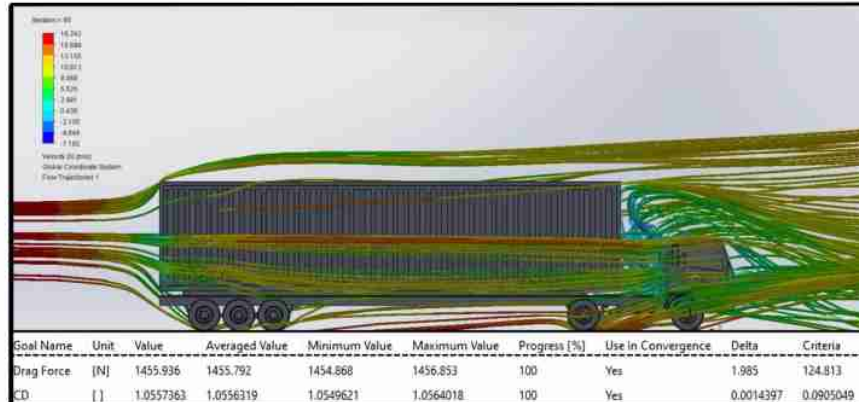


Figure 2. Aerodynamic Simulation Results

3.3. Calibration of the HDM-4 Model

This analysis explores ³⁵ fuel consumption predictions using the HDM-4 model, comparing three different approaches. In Scenario 1, ³⁸ 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 (FA) to 8.2 m², along with adjustments to the engine rotation model. Finally, in Scenario 3, additional calibration factors, K_{pea} and K_{cr2}, are introduced through a trial-and-error process until the differences between predictions and actual data become statistically insignificant. 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 [25]. 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 K_{pea} and K_{cr2}, both set at 0.6, further enhances prediction accuracy. The

1 negative ranks drop significantly to 50 cases, with an average rank of 48.55, while the positive
2 ranks rise to 41 cases, averaging 42.89. The Wilcoxon test returns a Z-value of -1.324 and a
3 significance level of $p = 0.186$, indicating ¹³ that the difference between the predictions and the
4 observed data is no longer statistically significant.

5 These results align with earlier research comparing HDM-4 fuel consumption
6 predictions with telematics data from the UK. Significant discrepancies in ³³ fuel consumption
7 estimates for heavy-duty trucks under the Base Case were found, although updates to vehicle
8 weight and frontal area in the Update Case improved predictions. However, notable
9 differences still persisted [17]. Overall, this study reinforces that default HDM-4 values often
10 fall short in predicting fuel consumption for heavy-duty trucks because they do not reflect
11 real-world operational weight and aerodynamic factors [26], [39]. While calibrating these
12 parameters in Scenario 2 enhances prediction accuracy, it does not fully resolve the
13 discrepancies. However, the adjustments made in Scenario 3 reduce these differences
14 significantly, as evidenced by the statistically insignificant result of $p = 0.186$ [26].

15 Despite these improvements, some discrepancies remain even after updating vehicle
16 weight and frontal area. These differences are likely due to recent technological advancements
17 in heavy-duty truck design and performance [21], [40]. Therefore, further calibrations of the
18 HDM-4 model at Level III are essential to accurately reflect the operational conditions of
19 today's heavy-duty trucks [26].

20

21 4. Conclusion

22 This study aimed to enhance the accuracy ²⁹ of fuel consumption predictions for heavy-
23 duty trucks by calibrating the HDM-4 model to better reflect modern engine technology and
24 ³² real-world operating conditions in Indonesia. The results clearly show that the default HDM-
25 4 parameters no longer match the characteristics of today's trucks. Therefore, it is crucial to
26 update these parameters by considering current engine technology and local operational
27 factors. Firstly, calibrating the engine speed model revealed that the default HDM-4
28 parameters tend to overestimate fuel consumption ²³ at low to medium speeds. In contrast, at
29 higher speeds, the model underestimates fuel consumption. As a solution, the new parameters
30 derived for Euro-4 engines capture the efficiency of modern engines, which deliver optimal
31 power at lower RPMs. This leads to more accurate fuel consumption predictions. Secondly,

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1 the calibration of aerodynamic parameters found that the default drag coefficient (Cd) and
2 frontal area (FA) values in HDM-4 do not align with real-world truck conditions.
3 Consequently, the simulation results provide a better representation of the actual aerodynamic
4 performance of modern trucks.

5 Moreover, calibrating the HDM-4 model through three different scenarios showed a
6 steady improvement in prediction accuracy. In Scenario 1, the default HDM-4 parameters
7 significantly underestimated fuel consumption. In Scenario 2, incorporating aerodynamic
8 calibration and engine RPM adjustments improved accuracy, though some differences
9 remained. Finally, in Scenario 3, adding technical correction factors (K_{pea} and K_{cr2}) resulted
10 in predictions that closely matched real-world data, with no significant statistical difference.
11 These findings highlight the importance of updating the HDM-4 model to reflect the realities
12 of modern truck technology and local operating conditions. By providing more accurate
13 parameters for Euro-4 engines and current aerodynamic profiles, this study helps planners
14 and policymakers make better fuel consumption predictions. As a result, heavy-duty truck
15 operations in Indonesia can become more efficient and sustainable. Looking ahead, future
16 research should consider additional factors such as detailed road surface conditions, variations
17 in shorter gradient lengths, ambient temperature, and driver behavior. Furthermore, ongoing
18 calibration of the HDM-4 model at Level III will be necessary to keep up with the continuous
19 advancements in truck design and performance.

20

21 **5. Author's declaration**

22 **Authors' contributions and responsibilities**

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

24

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.

25

26

27 **Availability of data and materials**

All data are available from the authors.

28

29 **Competing interests**

√ The authors declare no competing interest.

1 2 **Additional information**

3 Write **additional information** related to **this** research, if any.

4 5 **6. Acknowledgement**

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11 12 **7. References**

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