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Vehicle Model Development for Energy Consumption Study: For Diesel Mining Truck

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ABSTRACT

The study develops a model of a mining truck with a 709-kW diesel engine, focusing on fuel consumption from simulation results. The model was validated by comparing reference data with simulation results of vehicle speed using a longitudinal dynamic model. Speed variations simulated the vehicle's operating dynamics. This model is a basis for developing vehicle models with other propulsion types. It follows the driving cycle under various conditions but shows decreased accuracy with increased load, indicating reliability for baseline scenarios but needing refinement for extreme conditions. The study also investigates the impact of road inclination and external factors on fuel consumption. Higher inclines increase fuel consumption, particularly during acceleration due to elevated torque demand. Scenarios without added load from road inclines or wind resistance exhibit lower and more stable fuel consumption. Analysis confirms that increased road incline and wind speed significantly heighten engine load and fuel consumption. The no-load scenario demonstrates less variability, indicating more consistent engine operation without external disturbances. A research gap exists in understanding the effects of high-incline conditions on energy consumption, particularly for mining trucks. Existing models provide a good foundation but must be more accurate in steep inclines, high payloads, and adverse weather. This gap suggests further refinement of the models to enhance their accuracy and reliability in predicting fuel consumption under challenging scenarios. Future research should focus on developing more sophisticated models for these conditions, potentially integrating simulation techniques and data records to understand better and mitigate the incline impact on energy consumption in heavy-duty vehicles.

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INTRODUCTION

Various countries worldwide, including Indonesia, are currently being carried out reducing fuel emissions. According to a report from the Ministry of Energy and Mineral Resources, in 2022, Indonesia will see an actual reduction in carbon emissions of 91.5 million tons. The sectors contributing to greenhouse gas emissions are energy, waste, industrial process and product uses (IPPU), agriculture, and forestry (Pribadi, 2023). Mining has been an essential part of human activity for thousands of years, supplying raw materials to generate products that provide better safety and quality of life and build the current industrial society. Our society's most important mining commodities are iron, gold, silver, copper, tin, lead, diamond, and coal (Fernandes et al., 2018). Excavators and mining trucks are two of the main production tools used in open-pit coal mining. Apart from that, currently, the use of mining equipment throughout the world in general and in Indonesia, in particular, uses equipment driven by diesel engines, which is the source of costs for 46% of mining operations, with fuel costs being the highest in this percentage (Bozorgebrahimi et al., 2003; Curry et al., 2014; Rodovalho et al., 2016; Shafiee & Topal, 2012). The open-pit mining industry generally depends on the transportation of overburdened soil, which is excavated and transported, so the more significant the capacity excavated and transported, the higher the fuel consumption produced (Shafiee & Topal, 2012).

Fossil fuels are the majority requirement for energy use in Indonesia, where, in particular, fuel oil products are required by the majority in the industrial and transportation categories. The mining industry is one of the industries that contribute to carbon emissions, where open-pit mining uses equipment and vehicles, the majority of which use diesel fuel or diesel engine drives because the mining areas are generally not fixed and remote, so cannot be connected directly to the Indonesian Electricity network (Perusahaan Listrik Negara, PLN/ Indonesia's state-owned electricity company), as well as the terrain. The mining area is quite extreme, resulting in the need for vehicles in mining operations to be vehicles with diesel engine drives, which are suitable for off-road terrain.

Diesel-powered construction vehicles emit about 400 million tons of CO_2 annually, accounting for about 1.1% of global carbon emissions (Nordstrand, 2022). This research was created to develop a dynamic vehicle model for applying truck production equipment in open-pit coal mining. Currently, battery-powered trucks can only be diesel trucks without changes in the freight sector. Despite the challenges, electric trucks can be developed by first developing diesel truck models, especially regarding energy consumption (Çabukoglu et al., 2018). This model is the basis for developing electric vehicles based on mining production equipment models. This model was created to see the energy consumption produced by a mining truck driven by a diesel engine. The model's output created is fuel consumption, which will be compared with actual fuel consumption on mining trucks.

METHODS AND MATERIAL

Modeling the system dynamics of construction machines presents unique challenges. Their typically low speeds and unconventional operating conditions often make standard equations for highway vehicles inadequate. As a result, these standard models may not accurately capture the behavior of construction equipment. This discrepancy highlights the need for specialized approaches to simulate these machines' performance better. Developing tailored models can improve accuracy and reliability in representing their dynamic behavior (Alexander & Vacca, 2017).

The dynamics of the vehicle's drive system are based on the balance of forces by Newton's second law. The resultant force produced is the force needed to move the vehicle, as depicted in the equation (Eriksson & Nielsen, 2014).

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$$F_w = (m\, a + F_{aero} + F_{roll} + F_{grade}) \quad (1)$$

$$F_w = (m\, a + \frac{1}{2}\, \rho\, C_d\, A_f\, v^2 + C_r\, m\, g + m\, g \sin\alpha) \quad (2)$$

$$P_o = F_w * v \quad (3)$$

$$P_o = (m\, a + \frac{1}{2}\, \rho\, C_d\, A_f\, v^2 + C_r\, m\, g + m\, g \sin\alpha) * v \quad (4)$$

F_w is the force the vehicle requires to move, m is the vehicle weight, a is the vehicle acceleration, F_{aero} is the aerodynamic force, F_{roll} is the rolling resistance force, and F_{grade} is the gravitational force. Then, C_d (drag coefficient) measures a vehicle's aerodynamic efficiency, and A_f (frontal area) is the surface area facing the airflow, influencing air resistance. v (velocity) is the vehicle's speed, with drag force increasing proportionally to the square of the speed. C_r measures a vehicle rolling resistance efficiency. P_o (power output) is the engine or motor's energy required to overcome resistances like an aerodynamic drag, rolling resistance, and gravity, affecting performance and efficiency. The resistance that results in losses from the potential energy of the vehicle itself is produced by gravitational forces, rolling resistance, air resistance, and the driveline, where the most significant losses are from gravitational forces caused by vehicle terrains such as road slopes, turns, and braking (Kruse & Huls, 1973).

This model is an initial development of transport trucks in the coal mining industry, especially in Indonesia. Model development uses the Simulink-Matlab software tool, with standard model blocks built into the software used in modeling vehicle systems. The development of this model uses a longitudinal dynamic vehicle; the vehicle model is assumed to move straight and ignores lateral and vertical movements. The force resulting from the bends and slopes of the road in this model is still there but in the form of a resultant force on the terrain conditions. The input in this model is a speed reference, which is determined based on decreases and increases in speed caused by road slopes and curves. Where the reference speed is in the form of a vehicle operating cycle, namely speed data in a cycle or speed cycle, the input speed reference determined for the model will then validate the success of model development, with the speed response produced by the model being similar to the input speed reference.

The schematic or diagram of vehicle dynamics (Fig 1) shows components or forces acting on a vehicle system. It likely highlights the interaction of external factors like wind (aerodynamic drag) with internal components such as the motor, which provides propulsion. The driver controls the vehicle's speed and direction, emphasizing the role of human input in overall performance. The first is to determine the type of vehicle to be modeled and then obtain vehicle specification data as the basis for the vehicle model. Limitations are determined in model development to obtain the objectives of the modeling results; in this case, the objective is to obtain vehicle performance results, especially regarding energy consumption. In the modeling process, validation is carried out to see whether the model is working well or needs improvement from the input data or the creation of the model. The modeling process has been validated well; the next step is to analyze the modeling results.

The generalities of weight distribution, power, torque, torque-to-weight ratio, and speed are outlined in the dynamics overviews (Fig 2). The features of aerodynamic drag force are exemplified as the act in opposition to the vehicle motion, including the effects of wind resistance. The motor plays a central role in the system, which extracts the power needed to overcome these resistive forces and continue the motion. The driver has a similar important function, for that one controls the speed and the motor vehicle direction through the management of the wheel. This complication of the interaction between the external environment, including the forces of wind, and internal equipment, including the motor and the driver, is crucial for the model's performance capability. Moreover, these interactions directly influence energy efficiency and point to the need for fine-tuning mechanical and aerodynamic concepts.

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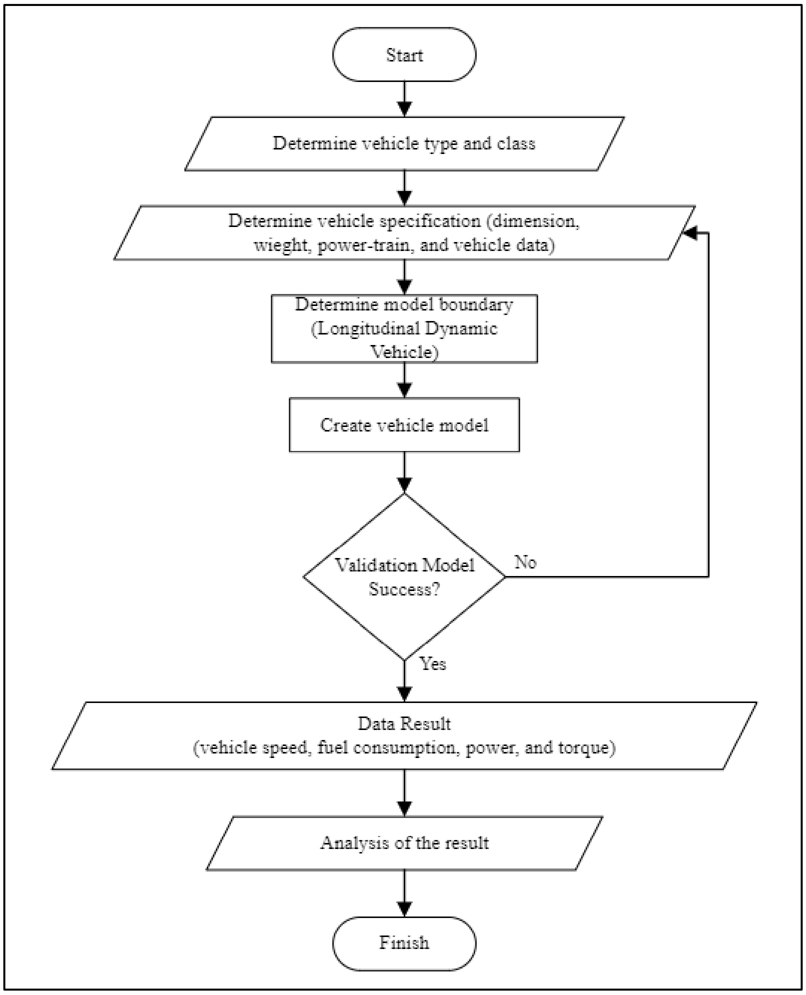

Fig. 1. Flow chart of the development process.

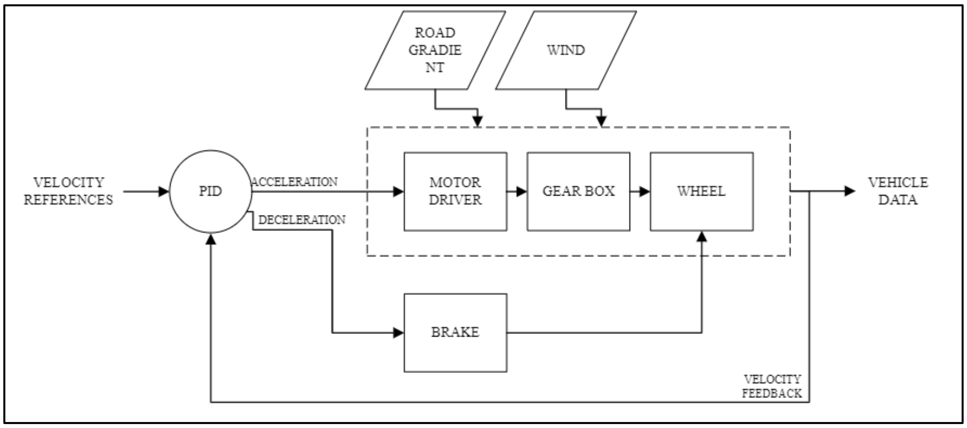

Fig. 2. Longitudinal vehicle model system.

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The Simulink model for a diesel truck provides a comprehensive platform to simulate and analyze vehicle dynamics under various operating conditions. Each block in the model represents a crucial aspect of the vehicle's performance, from engine behavior to environmental interactions. Basic equations governing each block and provide literature references for further study. The drive cycle source block provides the reference speed (V_{ref}) over time, which is essential for simulating real-world driving conditions. This block often uses standard drive cycles such as federal test procedure (FTP), worldwide harmonized light vehicles test procedure (WLTP), etc (Delphi Technologies, 2018; (Slibar & Springer, 1977).

$$Vref(t) \tag{5}$$

$$a_{cmd} = K_p(V_{ref} - V_{fbk}) + K_d(\frac{d(V_{ref} - V_{fbk)}}{dt}) \tag{6}$$

$$b_{cmd} = f(grade, V_{ref,} V_{fbk}) \tag{7}$$

The longitudinal driver block mimics the behavior of a human driver by comparing the reference speed with the actual vehicle speed (V_{fbk}) and generating acceleration (a_{cmd}) and brake commands (b_{cmd}) (Kiencke & Nielsen, 2000; Heywood, 2018). These commands control the vehicle's throttle and braking systems, ensuring the vehicle follows the desired speed profile accurately. K_p controls the system's response to error, increasing speed but risking overshoot. Then, K_d moderates the response by factoring in the error change rate, enhancing stability. This block is essential for developing and testing vehicle control systems like cruise control, adaptive cruise control, and automated driving systems, providing a realistic and flexible simulation environment that enhances safety and performance.

The engine subsystem is crucial in converting throttle input into engine power and fuel rate. This conversion is typically achieved using engine maps or mathematical models that accurately represent the engine's behavior under various conditions. When the throttle input is adjusted, the subsystem interprets this signal to determine the required engine power output. Simultaneously, it calculates the fuel rate needed to achieve this power, ensuring optimal engine performance and efficiency. By utilizing detailed engine maps or sophisticated mathematical models, the subsystem can precisely control the engine's response to throttle changes, providing a realistic and efficient simulation of engine dynamics for vehicle control and performance analysis. The engine subsystem converts throttle input to engine power and fuel rate, using engine maps or mathematical models (Isermann, 2014; Crolla & Mashadi, 2011).

$$P_{eng} = f_{map}(thr) \tag{8}$$

$$m_{fuel} = g_{map}(P_{eng}) \tag{9}$$

When the engine generates power (P_{eng}), it is determined by a function $f_{map}(thr)$ of the throttle position, showing how the throttle inputs affect the power output. Then fuel mass flow rate (m_{fuel}) is the function of (g_{map}) of the engine power (P_{eng}), illustrating how the power output influences the rate of fuel consumption. This block translates that power into torque applied to the vehicle's wheels (T_{wheel}), ensuring that the vehicle moves effectively, η_{trans} represents the transmission efficiency, ω_{wheel} is the angular velocity of the wheel, then ω_{eng} is the angular velocity of the engine. The gear ratios are crucial in determining how much torque is delivered to the wheels based on the selected gear. The transmission and driveline block optimize the vehicle's performance by adjusting the torque through various gear ratios, enabling smooth acceleration, efficient power distribution, and effective handling under different driving conditions. This precise conversion and adjustment mechanism is vital for achieving vehicle dynamics and

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performance. The transmission and driveline block converts engine power to wheel torque and adjusts it based on gear ratios (Gillespie, 1992).

$$T_{wheel} = \frac{P_{eng} \ x \ \eta_{trans}}{\omega_{wheel}} \tag{10}$$

$$\omega_{wheel} = \frac{\omega_{eng}}{gear \ ratio} \tag{11}$$

The vehicle dynamics block is responsible for computing the actual vehicle speed by considering the various forces acting on the vehicle. These forces include engine power, braking forces, aerodynamic drag, rolling resistance, and road grade. By accurately modeling these forces, the vehicle dynamics block can determine how interact to influence the vehicle's motion. This computation is crucial for understanding and predicting the vehicle's behavior under different driving conditions, ensuring that the vehicle operates safely and efficiently. This block enables better design, testing, and optimization of vehicle control systems by providing a realistic simulation of the vehicle's dynamics. Vehicle dynamics block computes the actual vehicle speed based on various forces acting on the simulation (Rajamani, 2011; Rill, 2012).

$$m\frac{dV}{dt} = \frac{T_{wheel}}{r} - F_{aero} - F_{roll} - F_{grade} \tag{12}$$

$$F_{aero} = \frac{1}{2}\rho C_d A_f v^2 \tag{13}$$

$$F_{roll} = C_r m \ g \tag{14}$$

$$F_{grade} = m \ g \sin\alpha \tag{15}$$

The tire model block is crucial to vehicle dynamics simulation software or systems. Its primary function is to convert the torque the driveline generates into the tractive force exerted by the tires on the road surface. This conversion is essential for understanding how the vehicle interacts with its environment, particularly propulsion and traction. Additionally, the tire model block calculates the slip ratio, which is the relative difference between the tire's rotational speed and the vehicle's linear speed. This slip ratio information is fundamental for analyzing tire behavior under various driving conditions, such as acceleration, braking, and cornering. Overall, the tire model block plays a pivotal role in simulating and understanding vehicle motion and handling dynamics. The tire model block translates driveline torque to tractive force and computes the slip ratio, also considering the condition of the friction coefficient (μ) (Pacejka, 2006; Slibar & Springer, 1977)).

$$F_{traction} = \mu \ T_{wheel} \tag{16}$$

$$slip = \frac{r\omega_{wheel} - v}{r\omega_{wheel}} \tag{17}$$

In addition to translating driveline torque to tractive force and computing slip ratio, the tire model block incorporates environmental factors crucial for understanding vehicle dynamics. These factors are wind velocity and road incline, significantly influencing vehicle behavior. By integrating the effects of wind velocity, the block can simulate how gusts or steady winds impact the vehicle's stability and fuel efficiency,

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particularly at higher speeds. Similarly, considering road incline allows the model to predict how the vehicle's weight distribution and tire traction change when driving on slopes, affecting acceleration, braking, and overall handling. Thus, accounting for these environmental conditions, the tire model block provides a more comprehensive simulation of real-world driving scenarios, enhancing our understanding of vehicle performance and behavior in diverse conditions. This block models the effects of wind velocity and road incline on the vehicle's dynamics for environmental conditions (Byrne, 1999; Rajamani, 2011).

$$F_{wind} = \frac{1}{2}\rho C_d A_f (v + v_{wind})^2 \tag{18}$$

$$F_{grade} = m\ g\ sin(\theta) \tag{19}$$

The main components of the drive system in this model are the diesel engine, torque converter, gearbox, and final drive. The power-train system, empty weight, filled weight, wheels, and vehicle dimensions use the drive specifications used for 100-ton class transport trucks, which are generally used in the mining industry in Indonesia. The overall vehicle specification data used in this model can be seen in Table 1.

Table 1. Vehicle parameters of 100-ton mining truck

Vehicle Parameters	Value	Unit
Rider mass	80	kg
Vehicle mass	68092	kg
Payload mass	96562	kg
CG height	2425	mm
Drag coefficient	1.2	-
Front axle to CG	1980	mm
Rear axle to CG	2970	mm
Front area	27.674	m^2
Tire diameter	2733	mm
Tire inertia	$1x10^{-3}$	$kg * m^2$
Rolling resistance	0.2	-

The engine parameters used are based on the engine map with data from the following chart, where the data from the engine is used for the fuel consumption model data in the engine model block. By Fig 3 the engine specification is a 709 kW diesel engine with a rated speed of 1800 rpm and maximum torque obtained at 1400 rpm.

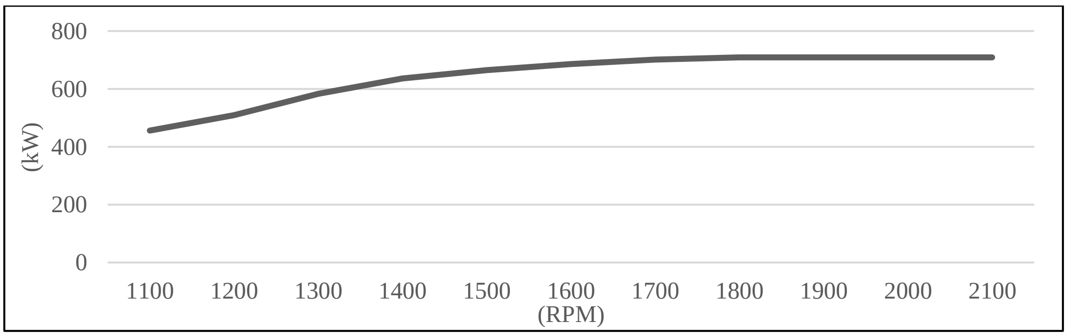

Fig. 3. Engine power data of 100-ton mining truck.

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The maximum engine torque, illustrated in Fig 4, surpasses 4000 Nm and is attained at 1400 RPM. After this point, torque starts to decline as RPM increases. This suggests that the engine achieves optimal performance at 1400 RPM; however, its torque efficiency diminishes as the engine speed continues to rise.

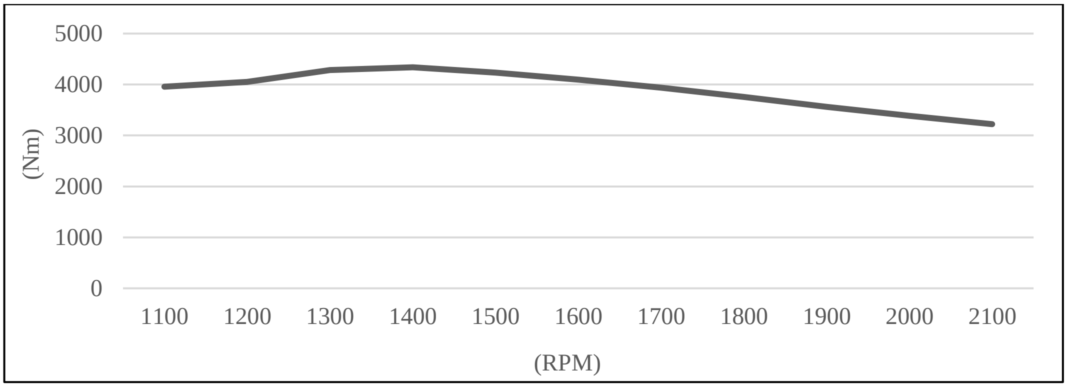

Fig. 4. Engine torque data of 100-ton mining truck.

Fig 5, Brake-specific fuel consumption (BSFC) is fuel rate data from the engine map, which has been determined based on the vehicle engine specifications determined in Fig 4. The highest BSFC is 215 g/kWh, and the lowest is 198 gr/kWh at 1300 RPM.

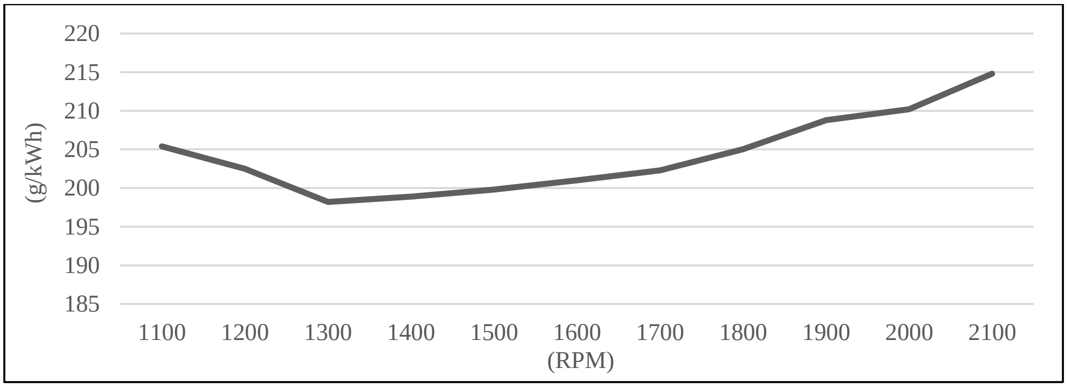

Fig. 5. Engine Brake Specific Fuel Consumption of 100-ton mining truck.

The BSFC simulated in the model will produce Fuel Consumption (FC) fuel consumption in the vehicle operating cycle (T_i) (Gillespie, 1992).

$$\overline{FC} = \frac{\sum_{t=1}^{T_i} FC_i}{T_i} \tag{20}$$

$$\overline{BSFC} = \frac{\sum_{t=1}^{T_i} BSFC_i}{T_i} \tag{21}$$

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The transmission modeled in this model is automatic and simplified using a torque converter component as a clutch from the engine to the gearbox. The gearbox gear ratio data determines the transmission's gear ratio. The PID (Proportional-Integral-Derivative) control system uses a longitudinal driver model block, which produces acceleration and deceleration commands based on speed reference and feedback. A longitudinal speed tracking controller is installed in the driver block. Based on the reference and feedback velocity, the block generates standard acceleration and braking commands ranging from 0 to 1. Block to model a driver's dynamic response or generate commands that are needed for the longitudinal drive cycle tracking. The resulting acceleration command is used as an input source for the drive system, while the resulting deceleration command is used as an input source for the braking system (The MathWorks Inc., 2019).

In the braking system, the specified data is shown in Table 2 where the practical value of the torque radius is determined from the wheel radius specifications, while the static coefficient is determined at 0.6 and the kinetic coefficient is 0.55. The number of wheels on the vehicle is 4, but only two are used in the wheel block model, with the number of braking model blocks being one. This condition does not eliminate the fact that the number of wheels on the vehicle is 4, and in the vehicle body model, the number of wheels per axle has been determined to be two, so the number of wheels being simulated is 4. Then, one braking model block is used to brake the two rear wheels due to the determination of the system model data. Braking is the same, each tire has its brake components.

Table 2. Brake parameters of 100-ton mining truck

Brake parameters	Value	Unit
Torque radius	1.3	m
Static friction coefficient	0.6	
Kinetic friction coefficient	0.55	
Velocity tolerance	0.001	rad/s
Threshold tolerance	1	N

MODEL VALIDATION

Model validation is performed with collected data and pre-processing to ensure clean and relevant data. The measurement data obtained can be speed, road inclination, and wind speed as input data, followed by speed and fuel consumption data as output data. The more similar or the same output data between actual measurements and simulation results, the better the model developed. This validation technique is carried out to ensure the reliability of the model.

Fig 6 compares model results with field measurement data, enhancing the reliability and performance of the model. This validation is critical to ensure the model is ready for use in real applications, such as operational optimization and decision-making at mining sites. The data collected includes vehicle speed, road slope, and wind speed from mining location X in Indonesia. Masurements are carried out on specific routes in the mining area to get a comprehensive picture of field conditions. The image in Fig 7 shows the measurement locations and routes used during the data collection. This data is used as a reference for model validation to ensure that the developed model can accurately reflect actual conditions.

Additionally, a wind speed of 5.1 m/s is factored into the model to simulate environmental conditions that can impact vehicle performance at mining sites. The model can assess natural conditions and generate reliable outputs using these parameters, even though specific physical wear and tear are not accounted for. This thorough validation is crucial for ensuring the model's robustness and readiness for practical applications, such as operational planning, process optimization, and informed decision-making at mining sites.

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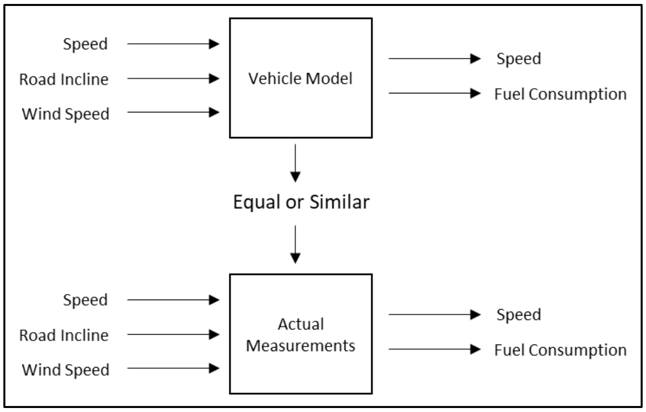

Fig. 6. Validation method.

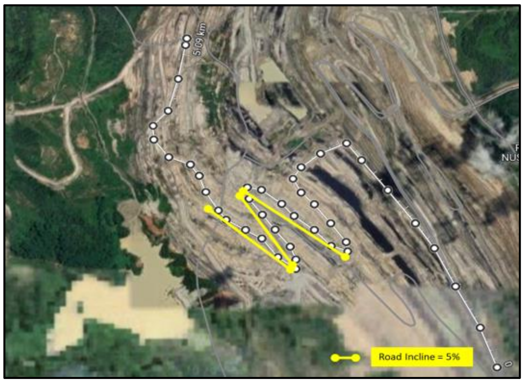

Fig. 7. Measurement locations in the mining area.

Fig 8 illustrates the velocity references employed during the model validation process. These references are critical benchmarks for comparing the model's performance against expected outcomes. By providing a target speed profile over time, the velocity references allow for a comprehensive assessment of how accurately the model can simulate real-world driving conditions. The validation process involves running the model with these predefined velocity references and analyzing the output to ensure the model's behavior aligns with the desired performance. Any discrepancies between the actual vehicle response and the velocity references highlight areas for further refinement in the model, ensuring its accuracy and reliability in predicting vehicle dynamics under various operating conditions.

To further refine the validation process (Fig 9), it is essential to acknowledge that the vehicle used in the field may have some wear and tear on components such as bushings, suspension systems, wheels, and other parts. While critical in real-world operations, this model validation does not consider these factors. Instead, the focus is on ensuring the model can handle speed variations over a relatively long and realistic period, as represented by a speed reference in cycles of 2000 seconds. The road slope used in this validation is 5%, referring to the challenging terrain conditions typically encountered in mining operations.

Results from Fig 10 illustrate the comparison between velocity references (depicted in magenta) and velocity feedback (depicted in blue) over 2000 seconds. The x-axis represents time in seconds, while the y-axis represents speed in kilometers per hour (km/h). The graph shows that the velocity feedback follows the velocity references throughout the test, indicating that the model can accurately replicate the set

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reference speeds. The speed patterns, which include multiple accelerations, decelerations, and steady states, are mirrored almost perfectly by the feedback, showing only minimal deviations. The minimal discrepancies suggest that the model's control system effectively tracks the reference speeds under varying conditions. These conditions likely include different road inclines and wind speeds, as specified in the initial parameters for validation. The tight correlation between the reference and feedback velocities indicates the model's reliability and precision. Overall, this performance evaluation demonstrates that the model's feedback mechanism is robust and capable of maintaining desired speeds under realistic and dynamic conditions. This validation provides confidence in the model's application for operational planning and predictive simulations in the context of the mining site operations. The high fidelity in speed tracking ensures that the model can be trusted to simulate real-world scenarios with high accuracy, which is crucial for optimizing processes and decision-making in practical applications.

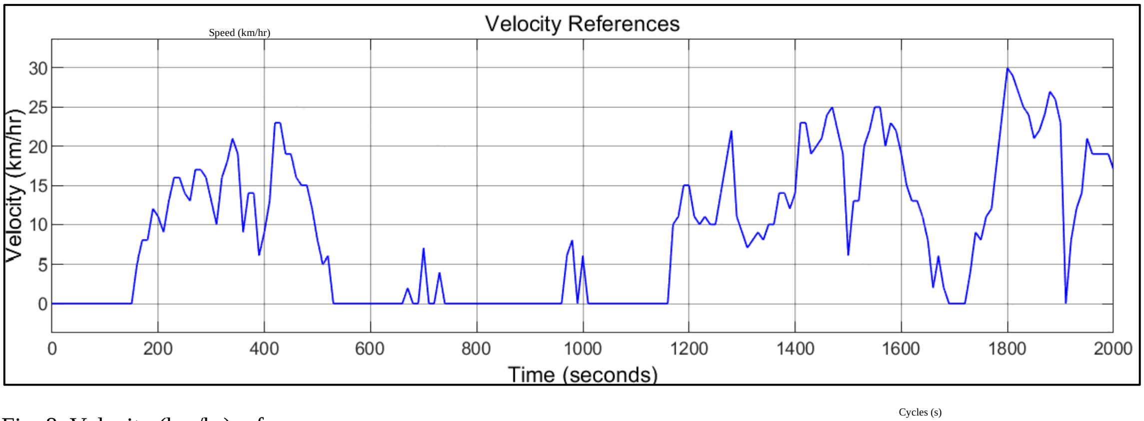

Fig. 8. Velocity (km/hr) references.

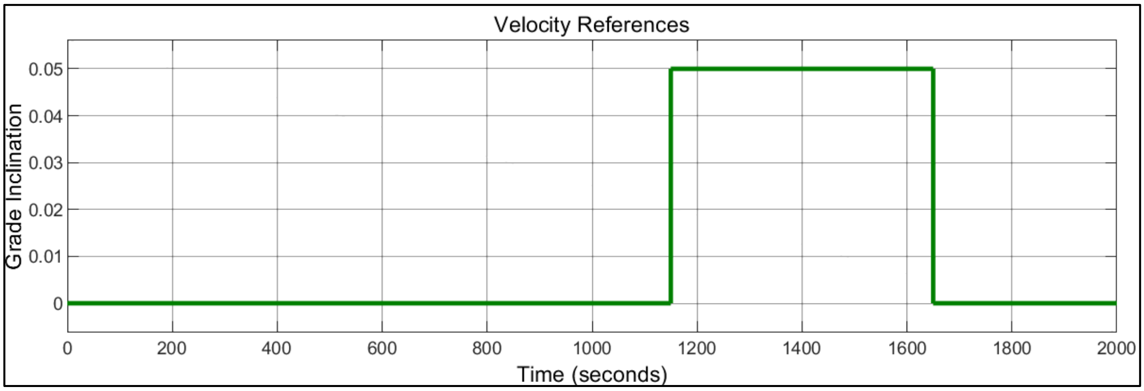

Fig. 9. Road incline reference.

Fuel consumption data comes from the Dump Truck's operational logs, which track fuel use during regular operations. This data provides practical insights into fuel consumption across different conditions. Results from Fig 11 the simulated fuel consumption (red) and the actual fuel consumption measuremen ts (blue) over 2000 seconds were compared. The *x*-axis represents time in seconds, while the *y*-axis indicates fuel consumption. The simulated results closely match the measurements, demonstrating the model's effectiveness in reflecting fuel usage patterns. Both datasets show multiple fluctuations, with the simulation

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capturing these changes well. During steady periods and varying consumption phases, the alignment is generally strong. However, there are minor differences in the magnitude and timing of peaks, especially during the high consumption phase, around 1200 seconds - 1600 seconds.

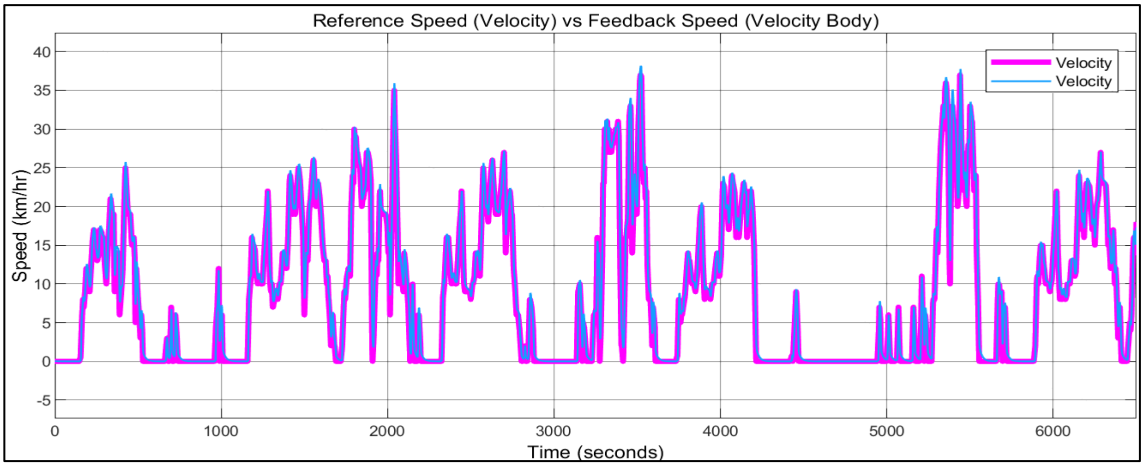

Fig. 10. Velocity validation.

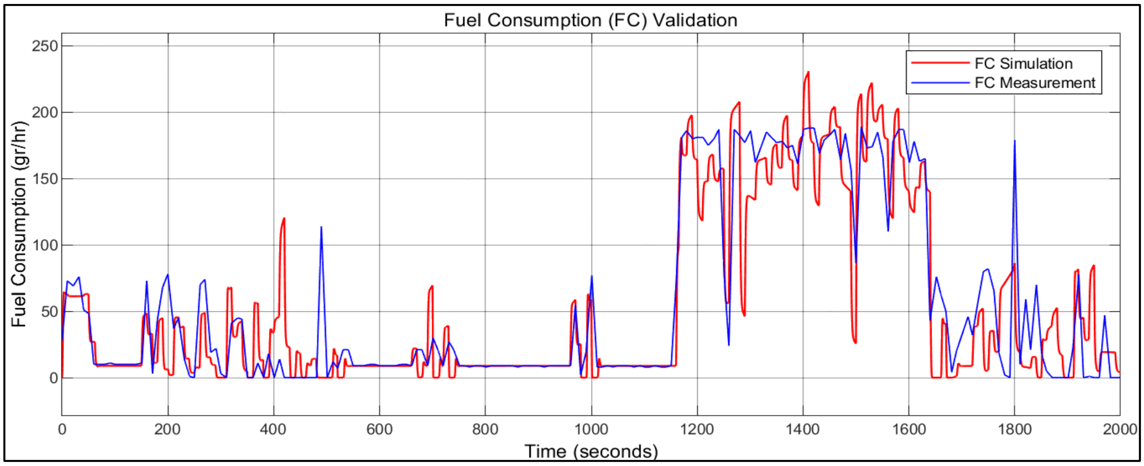

Fig. 11. Fuel consumption validation.

RESULTS AND DISCUSSION

The block diagram (Fig 12) is created based on data from a 100-ton class mining truck that uses a diesel engine as the main drive. The model is created based on block diagrams provided by Matlab-Simulink. This software is commonly used in various kinds of system simulations, where the development of vehicle models uses this software. This block provides a reference velocity over time (RefSpd), which typically comes from standard drive cycles such as FTP, WLTP, etc; however, in this model, the speed reference is used using actual speed data of trucks operating in the mine site in Indonesia. The speed reference mentioned contains velocity vs. time data. This subsystem mimics the behavior of a driver. It takes the

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reference speed (VelRef) and the actual vehicle speed (VelFdbk) as inputs and outputs acceleration (AccelCmd) and deceleration (BrakeCmd) commands. The driver also accounts for the road grade (grade). The engine subsystem converts the throttle input (Thr) into engine power (engine power) and fuel consumption (fuel rate). This uses lookup tables or mathematical models that map throttle input to power output and fuel consumption. The engine power is transmitted through a gearbox and driveline, adjusting the torque and speed as per gear ratios to drive the wheels. The blocks involved here might simulate the gear-shifting logic and torque conversion. This subsystem considers the forces acting on the vehicle, such as aerodynamic drag (wind velocity) and rolling resistance (road incline). It computes the actual vehicle velocity (VelFdbk) based on the engine output and resistance forces. The tire model converts the driveline torque into tractive force and slip ratio, which helps determine the actual vehicle acceleration and speed. Wind velocity and road incline are inputs that simulate real-world driving conditions that affect vehicle dynamics. The simulation begins with the drive cycle source providing a target velocity over time. The longitudinal driver compares the target and actual velocity and generates acceleration and braking commands. These commands are sent to the engine subsystem, which generates corresponding engine power and fuel consumption rates. The power is transmitted through the gearbox and driveline to the tires. The tire model and vehicle dynamics calculate the actual vehicle velocity considering environmental conditions. The feedback loop continuously adjusts the engine's power output and the vehicle's acceleration to match the target velocity.

The feedback loop is essential for maintaining the desired speed by adjusting the throttle and braking. Environmental inputs are crucial for the realistic simulation of vehicle dynamics. Subsystems represent a significant part of the truck's dynamics, from engine power generation to tire-ground interaction. This model comprehensively analyzes a diesel truck's performance under various driving conditions, providing insights into fuel efficiency, drivability, and emissions.

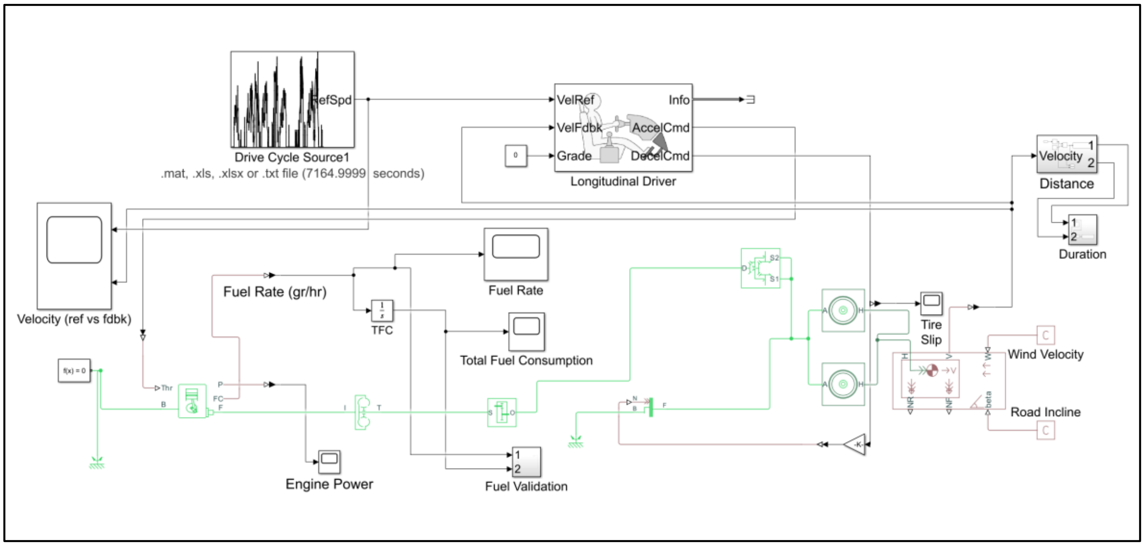

Fig. 12. Block diagram of a 100-ton mining-truck-based vehicle model with a diesel engine drive.

By referring to the previously determined engine data, calculations are then carried out using software to produce an engine map as a 3D depiction of the engine's character for torque, engine power, and rpm (engine speed). BSFC is measured in grams per kilowatt-hour (g/kWh). It represents the fuel efficiency of the engine: the amount of fuel consumed to produce one kilowatt-hour of energy. Lower values indicate

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the higher efficiency. The BSFC map shows how the engine's fuel efficiency varies with different engine speed and torque combinations. The lowest points on the BSFC surface represent the most efficient operating regions of the engine, where it consumes the least fuel to produce a given amount of power. These are often in the range of moderate rpm and high torque. Higher BSFC values indicate less efficient regions where the engine consumes more fuel to produce the same power output. The blue and dark green areas represent the most efficient zones (low BSFC values). In the provided map, this appears around 1000 rpm - 2200 rpm and moderate to high torque (1000 Nm - 4500 Nm). The yellow and orange areas at higher speeds and lower torques indicate less efficient operating conditions. Diesel engines are generally more efficient under higher load conditions (higher torque), as seen by the lower BSFC values at higher torque levels. Optimal operating range: the BSFC map helps determine the optimal operating range for the engine to achieve the best fuel efficiency. This information is crucial for optimizing engine tuning, gear-shifting strategies, and overall vehicle performance. This BSFC map shown in Fig 13 would calculate fuel consumption based on the engine's operating conditions during different drive cycles for the drive cycle analysis of the previously discussed Simulink model. The BSFC map is a critical tool for engineers to understand and optimize the fuel efficiency of a diesel engine. Analyzing the map can identify the best engine speed and torque combinations to minimize fuel consumption and enhance performance.

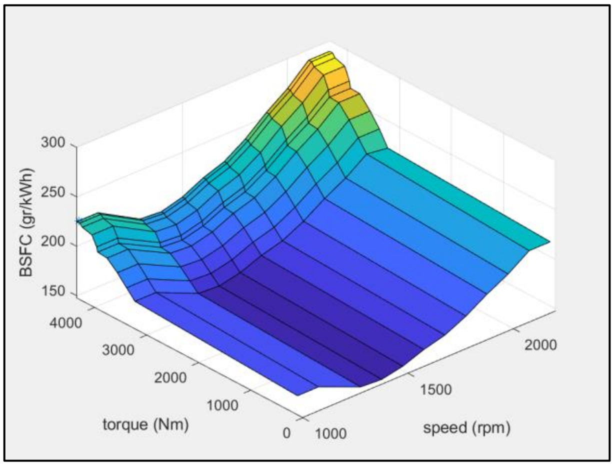

Fig. 13. Engine map of the 100-ton mining truck.

Model validation is carried out by ensuring that the speed diagram produced by the model can follow the speed input reference used. Where the speed input reference uses actual data from trucks operating in the mine site, in the speed results from Fig 14., it can be seen that the resulting speed can follow the specified speed reference. This illustrates that the model can work according to speed commands using a speed reference as input. In the initial validation conditions, the model was not given wind or grade loads, and there were no additional ratios from the gearbox. Later, the grade load and wind load are given to determine the additional gear ratio required for a vehicle model to run according to the instructions from the speed reference given as model input. Then, in this simulation, the maximum load that can be carried by a mining truck is used. The simulation cycle is carried out based on actual speed data at a coal mining site in Indonesia, where the 100-ton mining truck, the vehicle model in this simulation, is usually used to transport overburden material. The sample speed data from the data sample starts at 08.36 AM to 10.35 AM.

Incline load is given to the model with two variations, namely 5% and 8%. This is done to compare two road conditions, especially the difference in load inclination. Where at a maximum load incline of 8%, the vehicle model can work with an additional gear ratio of 2 or cannot work without an additional gear ratio

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of 2. Fig 15 is the speed result of the modeling simulation with a grade inclination of 5%; in this result, it can be seen that the speed result can follow the command from the speed in the velocity references. The validation process confirms that the model performed as intended, aligning with the parameters defined in the model block configuration. This outcome provides substantial evidence that all specified settings and variables were accurately integrated, thereby affirming the model's precision and reliability in its intended application.

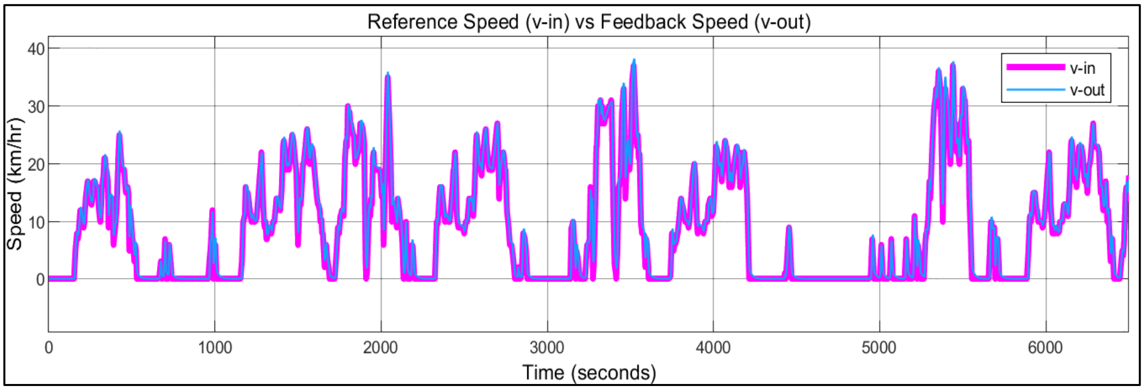

Fig. 14. Speed results diagram for validation.

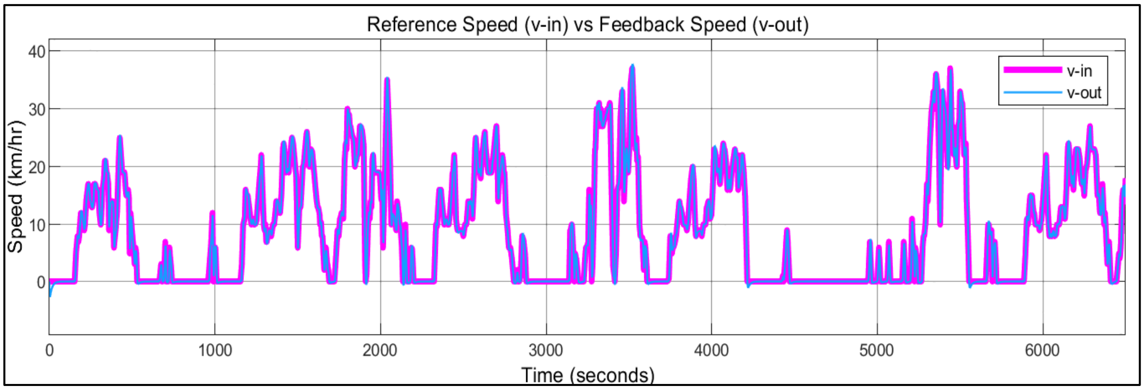

Fig. 15. Speed results diagram with inclination load 5% and wind speed 5.1 m/s.

The 8% (Fig 16) inclined load is the maximum inclination, this is a common practice in road regulations for 100-ton mining trucks in Indonesia. So, based on the simulation results with a maximum load, an inclined load of 8%, and a wind speed of 5.1 m/s, the mining truck model can run following the speed reference command given. Load variations are carried out on the model to compare fuel consumption results. The variations carried out are a model without load, an inclined load of 5%, a wind speed of 5.1 m/s, and a model with an incline of 8% and a wind speed of 5.1 m/s. The y-axis of fuel rate represents the fuel consumption in grams/hour during cycles, and the y-axis of total fuel consumption represents the cumulative fuel consumption in grams. The x-axis shows the time in seconds. The data spans reaching at 6500 seconds.

The speed simulation results presented in Fig 15 for a 5% incline and Fig 16 for an 8% incline demonstrate that the model performs effectively under varying conditions. The model accurately simulates

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the vehicle's speed response to these different inclines, indicating its robustness in handling changes in road gradient. The consistency in performance across these two scenarios suggests that the model is well-calibrated and reliable for predicting vehicle dynamics. These results validate the model's capability to simulate real-world driving conditions, ensuring that it can be used confidently in further analyses and optimizations.

The first experiment was a simulation with a no-load scenario illustrated by Fig 17 for fuel rates, and Fig 18 for total fuel consumption. Without the added load of a road incline or wind resistance, the fuel consumption is considerably lower and more stable. Without load significantly impacts external factors like incline and wind on fuel consumption. The no-load scenario clearly shows much lower fuel consumption rates, confirming that the road incline and wind speed in the loaded scenario significantly increased the engine load and fuel consumption. There is less variability in the no-load scenario, indicating more consistent engine operation without external disturbances.

Many regions show low and steady fuel consumption rates, close to zero or minimal values, indicating low engine load or idling. There are occasional spikes in the fuel consumption rate, but do not reach the high values in the loaded scenario. These spikes may correspond to minor accelerations or slight changes in driving conditions. The fuel consumption rate peaks around 186 gr/hr. Meanwhile, the total fuel consumption in grams produced was 50,531 gr (or 50.5 kg)

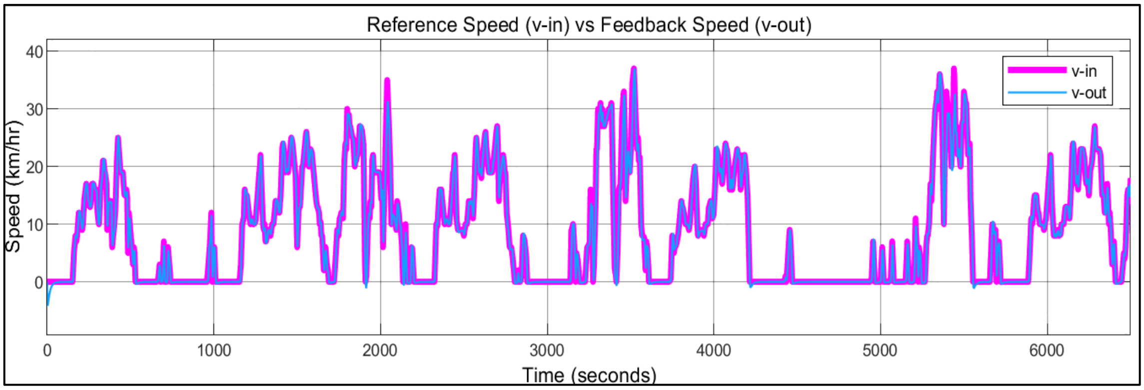

Fig. 16. Speed results diagram with inclination load 8% and wind speed 5.1 m/s.

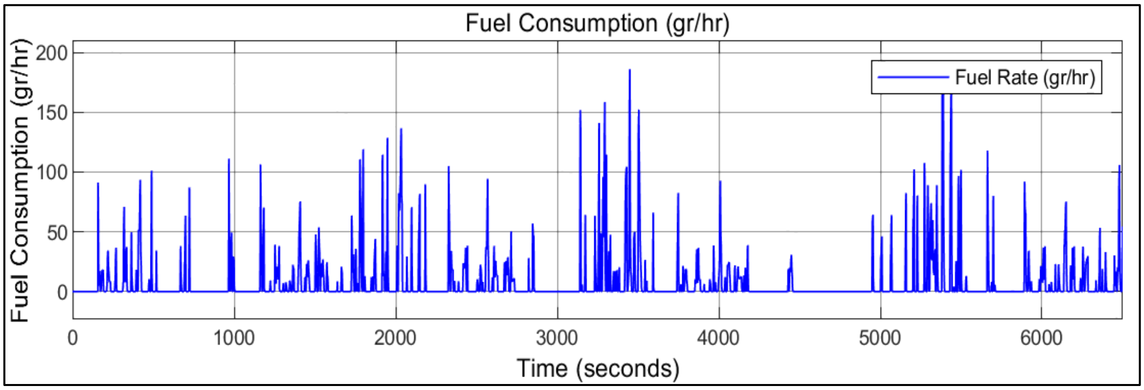

Fig. 17. Fuel rates (gr/hr) during cycles with no-load.

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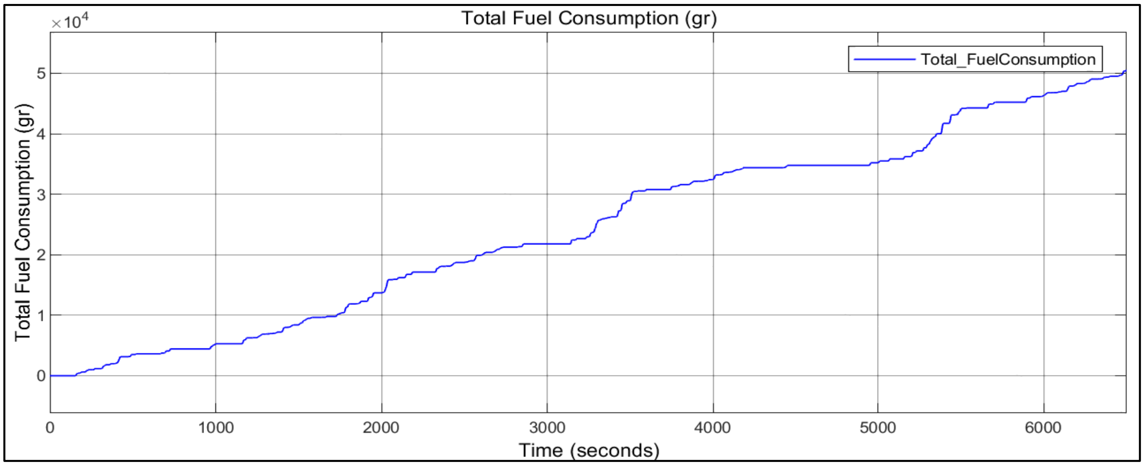

Fig. 18. Total fuel consumption (gr) during cycles with no-load.

Next, a load variation of 5% of the road inclination was carried out. The fuel rate results (Fig 19) indicate that spikes represent moments of increased engine load., possibly due to acceleration, increased grade, or overcoming wind resistance. The highest spikes around 300 gr/hr - 379.9 gr/hr suggest periods of significant load or harsh driving conditions. Drops to near zero suggest idle periods or low engine load. These drops could occur during deceleration, downhill segments, or when the vehicle is stationary. Constant fluctuations show the dynamic nature of driving conditions over a given period. Variations are typical in real-world driving due to changes in speed, road grade, and environmental factors. The graph exhibits relative stability periods in fuel consumption, possibly during cruising at a constant speed or under consistent load conditions.

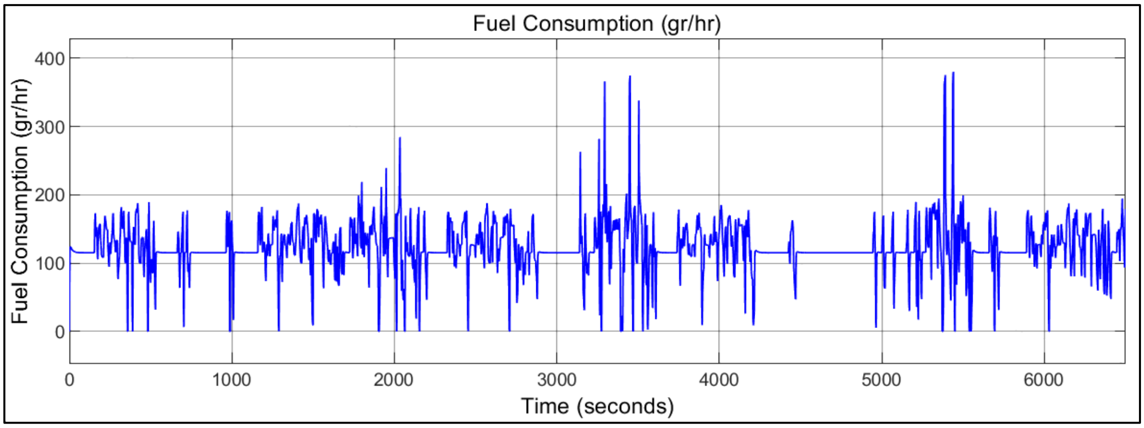

Fig. 19. Fuel consumption(gr/hr) during cycles with 5% load inclination and 5.1 wind speed.

The graph (Fig 20) indicates a steady increase in total fuel consumption over time, reaching 801,180.00 grams (or 801.1 kg) by the end of the recorded period. The graph shows a nearly linear trend of increasing total fuel consumption. The increase suggests a relatively consistent fuel consumption rate over time despite the variability in instantaneous fuel consumption shown in the first graph. The slope of the graph represents the rate of fuel consumption. A constant slope indicates a uniform fuel consumption rate. The instantaneous

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fuel consumption graph showed high variability, with many spikes and drops. Despite this variability, the total fuel consumption graph smooths out these fluctuations, indicating that the overall trend is consistent.

The fuel consumption rate exhibits significant fluctuations throughout the simulation. There are periods of relatively stable fuel consumption interspersed with spikes, which suggests variable driving conditions or changes in the engine load. Between these spikes, there are periods where the fuel consumption rate remains relatively constant, indicating steady-state driving or consistent engine load. The spikes in fuel consumption rate (Fig 21) are frequent and vary in magnitude. These spikes could be due to acceleration events, increased load, or other transient conditions like sudden increases in incline or changes in wind resistance. The fuel consumption rate ranges from around 150 gr/hr to above 350 gr/hr. The highest was 380.5 gr/hr. This range suggests that the engine is experiencing a wide range of operating conditions, from low to high load. The 8% road incline increases the load on the engine, leading to higher fuel consumption. The wind speed of 5.1 m/s contributes to aerodynamic drag, further increasing fuel consumption, especially at higher speeds. There appear to be semi-periodic patterns in the fuel consumption spikes, indicating cyclical driving patterns such as repeated acceleration and deceleration.

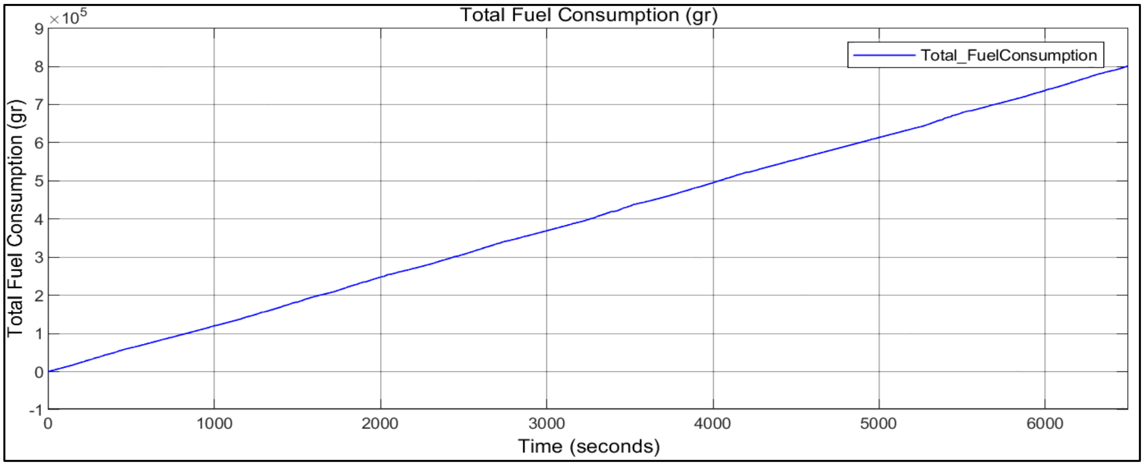

Fig. 20. Total fuel consumption (gr) during cycles with 5% load inclination and 5.1 wind speed.

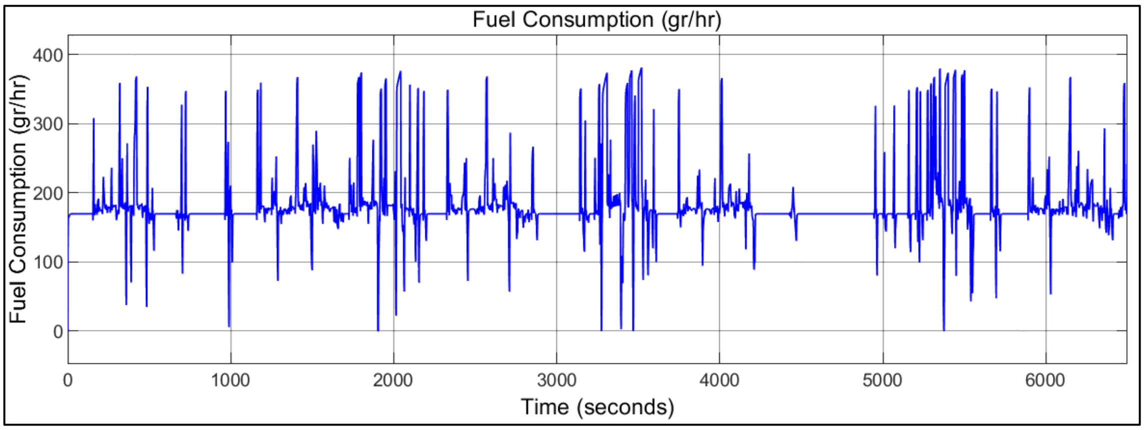

Fig. 21. Fuel consumption (gr/hr) during cycles with 8% load inclination and 5.1 wind speed.

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The total fuel consumption (Fig 22) increases steadily over time, forming an almost linear trend. The results suggest a consistent rate of fuel consumption throughout the simulation. The slope of the curve represents the rate of fuel consumption. Given the steady increase, the vehicle consumes fuel nearly constantly when considering the cumulative effect over time. By the end of the simulation (at 6500 seconds), the total fuel consumption is approximately 1,193,000.00 gr (or 1,193 kg). This significant amount reflects the impact of the 8% road incline and 5.1 m/s wind speed on fuel consumption. Minor deviations or small inflections in the otherwise linear trend indicate slight instantaneous fuel consumption rate variations. These could correspond to the fluctuations seen in the instantaneous fuel consumption graph, but their effect on the total fuel consumption is minimal. If a baseline (flat road, no wind) total fuel consumption were available, it would provide a comparative measure of the impact of the incline and wind speed. Typically, an 8% incline and a wind speed of 5.1 m/s would significantly increase fuel consumption compared to a baseline scenario.

It can be seen from the difference in road inclination that the higher the inclined load traversed by the vehicle, the greater the resulting fuel consumption, where the highest fuel consumption is produced by the acceleration carried out by the vehicle while operating due to the increased torque demand when the vehicle accelerates at a certain speed. Without the added load of a road incline or wind resistance, the fuel consumption is considerably lower and more stable. This highlights the significant impact of external factors like incline and wind on fuel consumption. The no-load scenario and 5% road incline clearly show much lower fuel consumption rates, confirming that the road incline and wind speed in the loaded scenario significantly increased the engine load and fuel consumption. There is less variability in the no-load scenario, indicating more consistent engine operation without external disturbances.

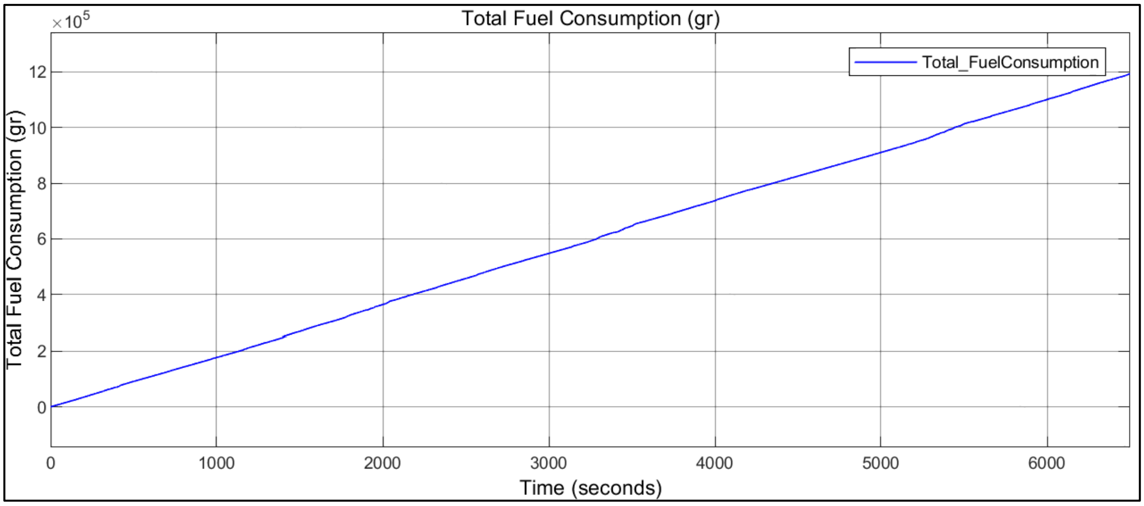

Fig. 22. Total fuel consumption (gr) during cycles with 8% load inclination and 5.1 wind speed.

CONCLUSIONS

The simulation results demonstrate that different road incline conditions significantly influence fuel consumption. Additionally, the speed dynamics used as an input reference in the model reveal the vehicle's energy consumption variations. The analysis shows that road incline and wind speed are critical factors affecting fuel efficiency. Under high load conditions, the vehicle's fuel consumption increases markedly in terms of instantaneous spikes and total cumulative consumption. Conversely, the vehicle maintains much

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lower and more stable fuel consumption rates in a no-load scenario. This emphasizes the importance of minimizing road incline to optimize driving conditions and vehicle performance, thereby improving fuel efficiency and reducing overall consumption.

Regulatory standards in the open-pit mining industry typically set the maximum road inclination at a mining site to 8%. By reducing the slope in a mining area, the fuel consumption of mining equipment can be significantly decreased. Designing roads with minimal incline will reduce the fuel costs of mobile equipment in mining areas. Minimizing road incline conserves fuel and reduces fuel consumption's operational costs and environmental impact.

Globally, mining equipment predominantly uses diesel engines, which produce emissions, contributing to environmental concerns such as air pollution and climate change. The reliance on diesel engines in mining operations has prompted a push towards cleaner alternatives. Electric motor and battery-based vehicles are being developed and deployed as a response. One such innovation is the Battery Electric Dump Truck, already used in several countries. These vehicles offer a promising solution to reduce emissions and reliance on fossil fuels.

This research is a foundation for further development of dump truck models based on battery electric vehicles (BEVs), employing the same longitudinal dynamic vehicle method used in this study. The findings highlight the potential for BEVs to improve fuel efficiency and reduce emissions in mining operations. Future work will compare the energy consumption of internal combustion engine vehicles (ICEVs) and BEV-type dump trucks. Such comparative studies will provide valuable insights into the efficiency and environmental benefits of transitioning to electric vehicles in mining operations. This transition addresses environmental concerns and aligns with global efforts to adopt sustainable and eco-friendly technologies in various industries.

By establishing a robust model for simulating vehicle dynamics and fuel consumption, this research contributes to the ongoing efforts to optimize mining equipment performance. The insights gained from this study can guide the design and implementation of more efficient, cost-effective, and environmentally friendly mining operations. The development and adoption of BEVs in mining have the potential to revolutionize the industry, leading to significant advancements in sustainability and operational efficiency.

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CONFLICT OF INTERESTS

All authors declare that they have no conflicts of interest.

CONTRIBUTIONS OF AUTHORS

The authors confirm the equal contribution in each part of this work. All authors reviewed and approved the final version of this work. Ilmi, Imanul: methodology, data curation, software, writing - original draft, resources; Adhitya, Mohammad: conceptualization, formal analysis, visualization, supervision; Rawikara Sahisnu, Seno: software, formal analysis, visualization.

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