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Model for Analysis of CO_2 Emissions in Off-Highway Trucks

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Abstract

In this article, a comprehensive model for the analysis of carbon dioxide (CO_2) emissions from off-highway trucks is presented, expanding the understanding of the contributions of these vehicles to global greenhouse gas (GHG) emissions. Off-highway trucks are key contributors in various sectors, such as mining, construction and agriculture, but their CO_2 emissions have often been underestimated due to their operational complexity. The proposed model combines operational data, vehicle characteristics, load profiles and specific emission factors to create an accurate and adaptable analysis tool that considers the parameters of transported load, track slope, average speed and mechanical efficiency. By integrating these elements, the model calculates CO_2 emissions, allowing for a holistic assessment of the environmental impacts of off-highway trucks. In addition, we highlight the importance of accurate modeling of CO_2 emissions in this context, as these analyses are crucial for formulating mitigation strategies and for adopting highly sustainable practices in the operation of these vehicles. The application of the model to specific case studies demonstrates its effectiveness in different operational scenarios, and it provides valuable insights for informed decision-making. In summary, the proposed model fills a significant gap in the analysis of GHG emissions from off-highway trucks, leading to an increasingly accurate understanding of their environmental impacts.

Keywords

GHG Emissions, Emissions Modeling, Haul Trucks, Rolling Resistance, Road Geometry

1. Literature Review

Transport operations account for approximately 50% of a mine's total costs, with truck productivity closely linked to the average travel speed (Hustrulid & Kuchta, 2013). Fuel consumption represents the main operational cost in truck-based transport and is widely recognized as the most reliable indicator for evaluating CO_2 emissions (Thompson, Peroni, & Visser, 2019). Diesel-powered equipment, still dominant in mining logistics, is a major source of greenhouse gas (GHG) emissions (Norgate & Haque, 2010).

A wide range of operational and mechanical factors influence fuel consumption, including vehicle mass, payload, road conditions, slope, rolling resistance, and operator behavior (Kecojevic & Komljenovic, 2010). Many of these variables can be managed to optimize fuel efficiency without compromising fleet performance, which in turn reduces CO_2 emissions through lower engine loads.

Several studies have examined these influences in mining contexts. Kecojevic and Komljenovic (2010) quantified CO_2 emissions from various Caterpillar trucks, including the 793D (240 t), while Soofastaei et al. (2015) used neural networks to simulate the impact of payload variance on fuel consumption and emissions. Wang et al. (2016) conducted real-time emission monitoring of 797B trucks to calculate fuel emission factors. These studies demonstrate that emissions are highly sensitive to both vehicle characteristics and operating conditions.

Road geometry has also emerged as a critical factor in haulage efficiency. Richardson and McIver (2015) showed that poor road quality leads to higher fuel consumption and emissions, findings echoed by Giakoumis and Triantafillou (2018), who identified vehicle mass, road slope and handling as the most influential parameters for CO_2 output. Steep grades (8% - 10%) result in frequent gear changes, speed reductions, and braking events, all of which contribute to increased fuel use, tire wear, and maintenance costs (Masetti, Oliveira Filho, & Lima, 2012).

From a modeling perspective, Rodovalho (2016) developed regression-based approaches to estimate productivity in mining, considering variables such as cycle time, transport distance and payload. However, that work did not explore geometric or operational optimization. In contrast, studies by Navarro Torres et al. (2019, 2020), Navarro Torres & Paniz (2022) and Da Silva Menezes & Navarro Torres (2021) introduced mathematical models that integrate fixed and variable times, road gradients, and rolling resistance to optimize productivity and emissions outcomes. Their findings indicate that even modest variations in road slope (1%) can yield productivity gains of up to 7%.

These models demonstrate the potential of integrating geometric and mechanical variables into operational decision-making. Nevertheless, many studies remain focused on isolated factors or single variables, lacking a holistic approach to emissions modeling.

Given this context, the present study proposes an integrated and adaptable model to estimate CO_2 emissions from off-highway trucks, combining operational data, road conditions, vehicle parameters and emission factors. This approach aims to fill an important gap in the current literature by providing a tool that can support more sustainable and efficient mining logistics.

2. Methodology

Mathematical productivity models are useful for determining the maximum productivity under the influences of geometric parameters (lane width, radii of curvature, and grid) and fixed and variable times. The fixed times are represented by the maneuvering time and the queue time for loading and tipping. The variable times are determined by the trip time of the full truck to the crusher and the return time of the empty truck. It is observed that the variable times are influenced by the average transport distance, road conditions, road slope (grid) and truck speed. The increase in transport distance causes a considerable increase in costs, especially for diesel consumption.

The model initially developed by Navarro Torres et al. (2019) is adopted for the productivity and cost estimates in this study. Equation (1) expresses the productivity function:

$$P_t = \frac{60 * F_{cc}}{T_f + 2\left(T_a + T_{da}\right) + \frac{1}{16.67}\left(\sum \frac{d_c}{v_R} + \sum \frac{d_l}{v_l}\right) + T_v} \tag{1}$$

where:

P_t: total productivity (t);

F_{cc}: truck payload (t);

T_f: fixed time (min);

T_a: acceleration time (min);

T_{da}: deceleration time (min);

d_c: curvature distance (m);

V_R: speed in the curve (km/h);

v_l: speed referring to the narrowest route (km/h);

T_v: sum of the variable transport times of all round trip segments (min).

The acceleration time T_a and the deceleration time T_{da} can be estimated using manufacturer information or measured data. Another alternative is to consider these times within fixed periods.

The transported payload can be calculated using Equation (2) based on the truck nominal volume capacity C_e, the loose density of the ore/tailings ρ_e, the combined efficiency of the truck and operator E_t, and the tractive force F_t.

$$F_{cc} = C_e * \rho_e * E_t * F_t \tag{2}$$

The tractive force F_t can be calculated as the sum of the inertia, aerodynamic, mechanical, gradient and rolling resistance levels. The rolling resistance (RR) can be defined by the mathematical model for rolling resistance in tires proposed by Rhyne and Cron (2012), which was later adapted by Gali (2015) for freight vehicles and then modified by Navarro Torres et al. (2019) to address the variables of off-highway trucks in mining. By considering the trinomial that governs the phenomenon of rolling resistance—track, tire and vehicle—Equation (3) expresses the adaptation of the model to the RR factor as follows:

$$f_r = 1000\left(\frac{P^2}{E} + \frac{E\left[\frac{F_p}{Pl} + 1.62z\right]^2}{12r^2}\right)\frac{\pi lhRsen(\delta)}{\mu F_c} \tag{3}$$

where:

f_r: coefficient of rolling resistance (kg/t);

P: inflation pressure of the tire (kg/m^2);

E: Young's modulus of the tire (kg/m^2);

F_c: resultant force on a tire (kg);

l: width of the tire tread (m);

z: height of the compact grooves on the track (m);

r: radius of the metallic belt of the tire (m);

h: thickness of the tire tread (m);

R: contact surface ratio;

δ: tire phase angle (˚);

μ: coefficient of road surface roughness;

F_c: load imposed by the tire.

The general cost-per-ton model presented by Navarro Torres (2019) is the product of the inverse of the productivity function and the predicted hourly costs (Ctopex); the specific consumption of liters of fuel per watt (L/W), the rated power in watts (W) and the costs per liter of fuel (US$/L) present the operational expenditure (Opex) function of Equation (4).

$$Ct = \frac{\left[T_f + 2\left(T_a + T_{da}\right) + \frac{1}{16.67}\left(\sum\frac{d_c}{v_R} + \sum\frac{d_l}{v_l}\right) + T_v\right][\text{Ctopex}]}{60 * F_{cc}} \tag{4}$$

The proposed mathematical model correlates the CO$_2$ emissions from the 775G and 777G trucks used at the Capão Xavier mine with the main road parameters expressed by Equations (1)-(4) (Navarro Torres et al., 2019). According to the International Council on Clean Transportation (ICCT) article by Riemersma and Mock (2012), a change in rolling resistance cannot be directly translated to a corresponding effect on CO$_2$ because engine efficiency is affected by a change in road load. However, according to Barrand & Bokar (2009), an almost linear relationship can be found when considering only the mass of the vehicle. The effect of rolling resistance on CO$_2$ is linear.

For the construction of the model, it is important to know that CO$_2$ emissions are proportional to the fuel consumption of the truck (Soofastaei, Aminossadati, & Kizil, 2008). The fuel consumption of this shipment to the destination is calculated considering the load factor in relation to power. The load factor (LF) is the proportion above or below the maximum capacity that the truck can transport. The load factor of an empty truck is 20%, while that of a loaded truck is 50% (Soofastaei et al., 2008).

The engine load factor values are given by manufacturer as follows:

- Low: 20% to 30% (Continuous operation with average gross weight lower than the recommended value. Roads in excellent condition. No overload, low load factor).
- Average: 30% to 40% (Continuous operation at an average gross weight close to the recommended value. Minimum overload. Roads in good condition, moderate load factor).
- High: 40% to 50% (Continuous operation at or above maximum recommended gross weight. Overloaded. Bad haul roads, high load factor).

The energy consumption estimate is formulated according to truck speeds, energy requirements, mine characteristics and truck weight. The gross mass (F_{tu}) is the sum of the empty truck weight (F_{cv}) and the transported payload (F_{cc}). This formula is expressed by Equation (4):

$$F_{tu} = F_{cv} + F_{cc} \tag{4}$$

Truck speeds are calculated using the rimpull curves, rimpull speeds, and delay curves. According to Caterpillar, 2015, the rimpull is the driving force developed by a wheel as it acts on a surface. The rimpull velocity curves are used to determine the maximum attainable speed and tractive force. The calculated speeds are then used to calculate the power required to maintain that specific speed. According to López Jimeno, López Jimeno, Bermudez and Degea (2014), the power required for the truck to go up or down a ramp can be calculated according to Equation (5).

$$P = \frac{V_m F_{tu} \left(f_r \pm f_\theta \right)}{270.4 E_f} \tag{5}$$

where:

P: power (kW) (HP);

V_m: maximum truck speed (km/h);

F_{tu}: gross weight of the loaded truck (t);

f_r: rolling coefficient;

f_θ : coefficient of the influence of the slope, where the sine of the slope is in degrees (˚);

E_f: transmission efficiency, which ranges from 0.7 to 0.8.

Rolling resistance is the force that must be overcome for the truck to move. The inclination resistance is the force that the truck must overcome in traveling up a slope. Likewise, delay curves are used to determine the speed that can be maintained when a truck is descending a ramp.

The energy demand for the truck leaving an excavator/loader for the destination and returning to the mine is calculated by Equation (6); therefore, the fuel consumption can be calculated by Equation (15), according to (Runge, 1998):

$$\text{FC} = \text{P}.0.3.\text{LF} \tag{6}$$

where:

FC: fuel consumption (L/h);

P: required power (kW);

LF: motor load factor (%).

The GHG emissions of the diesel engine of a mining truck are expressed in terms of carbon dioxide equivalent (CO_2-eq):

$$\text{CO}_2\text{-eq} = \text{FC.EF} \tag{7}$$

where EF stands for the emission factor, which according to 2008 studies by the United States Environmental Protection Agency (EPA) and 2012 by the Australian Government, is 2.7 tons of CO_2-eq per kiloliter (KL) of diesel fuel burned; this value may vary according to the type of fuel used. Thus, through algebraic properties and Equations (5), (6) and (7), we obtain Equation (8), in which the coefficient f_θ is positive for uphill stretches and negative for downhill stretches:

$$\text{CO}_2\text{-eq} = \left(\frac{V_m F_{tu}\left(f_r \pm f_\theta\right)}{270.4E_f}\right).0.3\text{LF.EF} \tag{8}$$

To model the CO_2 emissions emitted by the proposed trucks, a database obtained from the manufacturer's catalog was used. The variations in the road slope and total rolling resistance are related to poor road conditions, which cause further gear changes, constant speed reductions, great tire wear and further emission of CO_2 to the environment. For this purpose, the values in **Table 1** are considered. The adopted parameters are adaptable to any off-road or highway truck, as long as the technical parameters are available.

Table 1. Considered values for the study case based in the manufacturer.

	775G	777G
Fuel consumption (L)	24 - 28.5 L/h (low); 28.5 - 36 L/h (medium); 36.0 - 47.0 L/h (high)	33 - 46.0 L/h (low); 46 - 57 L/h (medium); 56.5 - 72.5 L/h (high)
Power (HP)	615	765
Payload (t)	64	90

3. Results and Discussion

CO_2 emissions are directly correlated with engine power. According to the graph in **Figure 1**, the greater the power is, the greater the CO_2 emissions emitted by the truck. According to Giakoumis and Triantafillou (2018), the greater the mass of the truck is, the greater the CO_2 emissions. An increase in vehicle mass from 7350 to 8850 kg (+20%) increases levels of soot by 44%, NO by 5.4% and CO_2 by 15%.

Figure 2 shows this situation with an increase in the payload carried by each truck model studied. The results show that for any value of R_r, $V_{\max}$ decreases as F_{tu} increases (that is, due to the increase in the payload that causes R to increase and V to decrease). The results show that for a fixed F_{tu}, V decreases as R_r increases.

The results show that for any value of R_r, Vmax decreases as F_{tu} increases (that is, due to the increase in the payload that causes R to increase and V to decrease). The results show that for a fixed F_{tu}, V decreases as R_r increases. **Figure 3** and **Figure 4** show the CO_2 emissions for the 775G and 777G trucks.

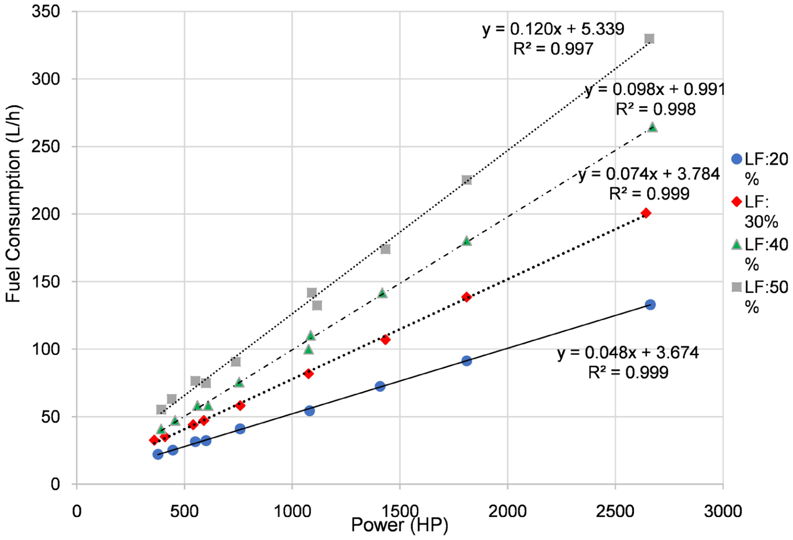

Figure 1. Fuel consumption by power developed. Source: Adapted from Kecojevic & Komljenovic (2010).

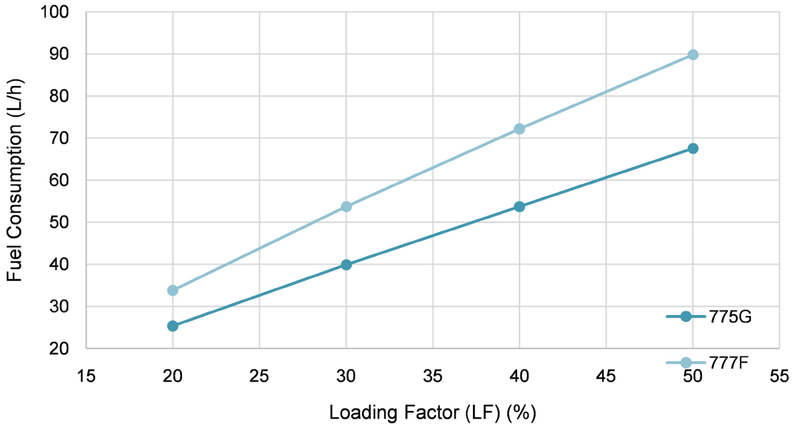

Figure 2. Fuel consumption and loading factor for each truck model. Source: Authors.

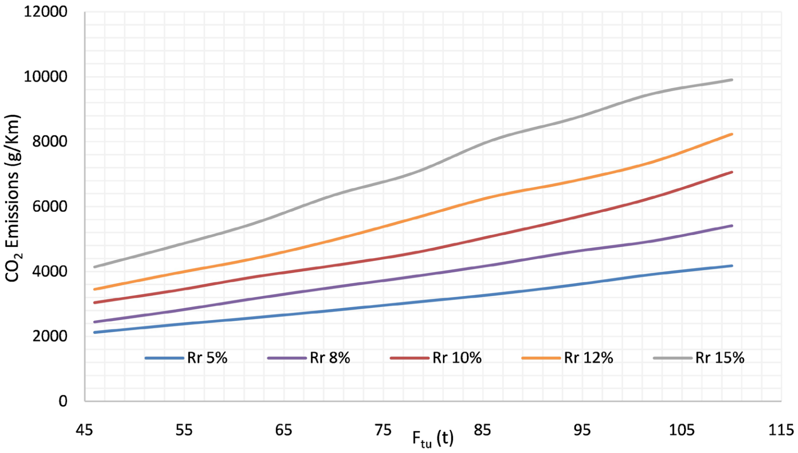

Figure 3. Relationships between CO₂ emissions, F_{tu} and R_r for the Cat 775G model under different LFs. Source: Authors.

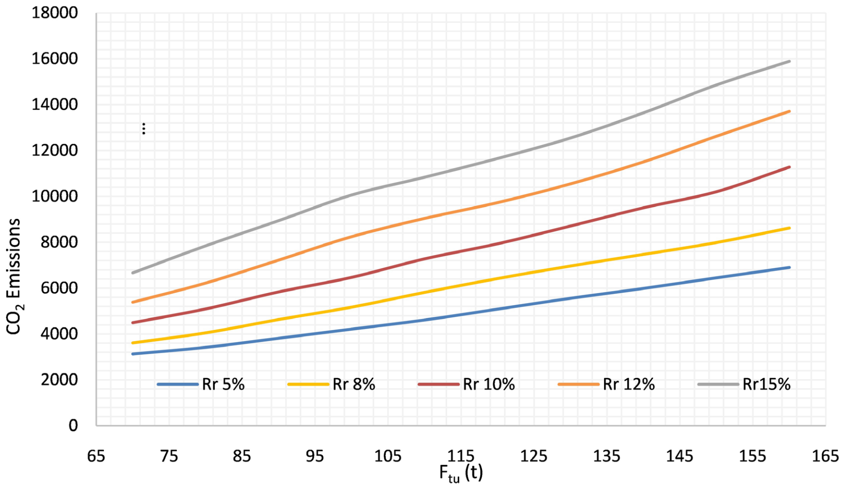

Figure 4. Relationships between CO_2 emissions, F_{tu} and R_r for the CAT 777G model under different LFs. Source: Authors.

The graphs in Figure 5 and Figure 6 show that CO_2 emissions increase as the total resistance increases.

Figure 7 shows the relationship between CO_2 emissions and the grid for the 775G and 777G models in a conceptual manner.

The greater slope of the track is, the greater the engine power that is required to overcome the rolling force and its weight. Figure 7 shows that CO_2 emissions increase considerably to a 10% road slope and to perform stabilization above this slope.

Through the analysis of the data, it is found that the slope of the roads can significantly impact the productivity of trucks. The geometries and structural and functional characteristics of the roads affect the speed developed by the truck, influencing productivity and costs. The slope of the track should be as regular and constant as possible, preventing it from changing at short intervals. Irregular harrows greatly hinder the transmission gear and decrease the speed of the transport equipment. Pronounced grades require trucks to slow on descents to ensure safe stopping distances and frequent downshifts on climbs, causing speed loss. These speed changes result in lost productivity, additional fuel consumption, increased mechanical wear and increased maintenance costs.

Productivity is affected by the slope of the track and the rolling coefficient since these parameters directly affect the speed, altering the cycle time of the trucks. The average transport distance decreases as the road slope increases, but the cycle time is impaired due to the decrease in the average truck speed. It is observed that the rolling coefficient directly influences the productivity of trucks because at high coefficient values, the truck has difficulty moving due to the road conditions. The cost increases due to the long cycle time of the equipment as it reaches its destination. Through the proposed model, it is possible to perceive that the CO_2 emissions are calculated as a function of the fuel consumption level. Several pathway-correlated parameters influence CO_2 emissions. Roads with poor conditions require constant gear changes and a reduction in speed, which increases the CO_2 emissions.

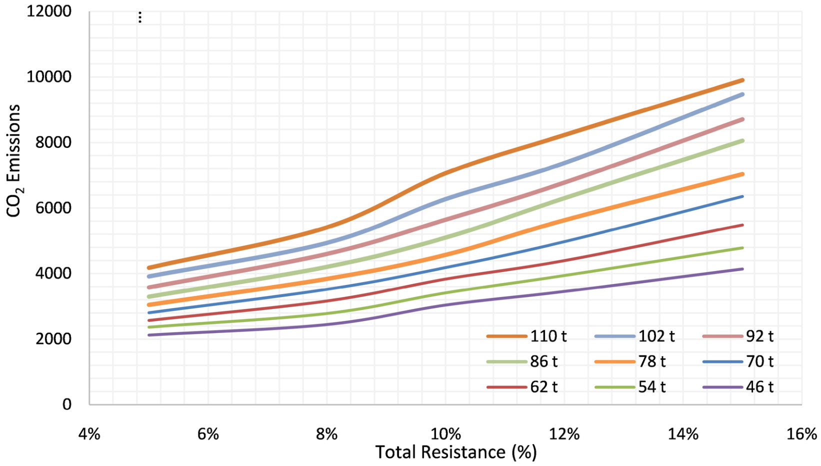

Figure 5. Relationships between CO_2 emissions, F_{tu} and R_r for the 775G model. Source: Authors.

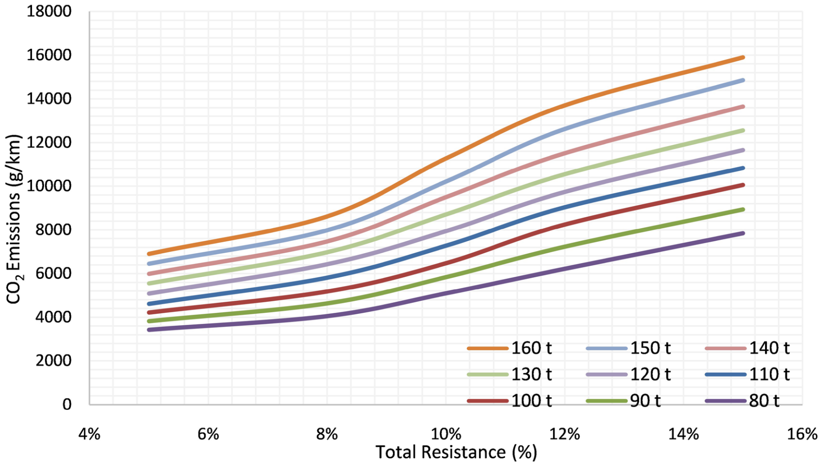

Figure 6. Relationships between CO_2 emissions, F_{tu} and R_r for the 777G model. Source: Authors.

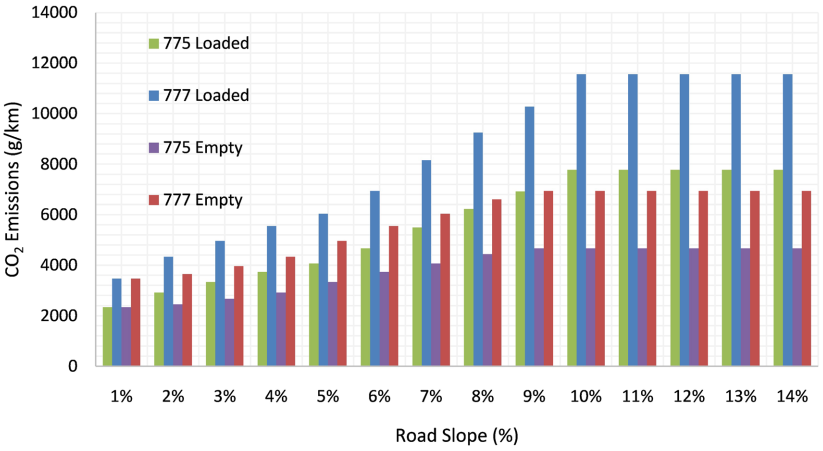

Figure 7. Conceptual relationships between the CO_2 emissions of 775G and 777G trucks and the slope of the road. Source: Authors.

CO_2 emissions are related to the equipment size, power, rolling resistance and track slope. The larger the size of the truck is, the greater the CO_2 emissions. Fuel consumption has a strong correlation with the engine power and load factor. It was determined that a 10% reduction in the load factor can significantly decrease fuel consumption, CO_2 emissions and operating costs.

4. Conclusion

The models developed for the optimization of transportation routes for mining are an important complement to analyses of productivity and costs. Models optimized to quantify productivity costs are extremely important tools for maximizing productivity and minimizing the costs of transporting ore and waste in open pit mining. It can be concluded that both productivity and costs are affected by the slope of the track and the rolling coefficient since these parameters directly affect the speed by altering the truck cycle times.

Specific factors include track slope, rolling resistance, payload, speed and truck engine characteristics. By reducing the resistance of a truck during a transport cycle, the overall fuel efficiency can be improved without affecting the cycle or the productivity parameters, reducing CO_2 emissions.

This study presents a comprehensive and integrated model that is crucial for the analysis of CO_2 emissions from off-highway trucks, filling a significant gap in the understanding of the contributions of these vehicles to global greenhouse gas emissions. Off-highway trucks play a vital role in key industrial sectors, such as mining, construction and agriculture, although their CO_2 emissions have been underestimated due to the inherent complexity of their operations.

By combining detailed operational data, vehicle characteristics, load profiles and specific emission factors, the proposed model offers an accurate and adaptable tool for comprehensively assessing the environmental impacts of these trucks. The consideration of certain factors, such as transported load, track slope, average speed and mechanical efficiency, allows for a highly accurate calculation of CO_2 emissions. It is notable that the integration of these elements provides a holistic assessment of the environmental impacts of off-highway trucks.

The relevance of the accurate modeling of CO_2 emissions in this context is highlighted, as these analyses are crucial for formulating mitigation strategies and adopting sustainable operating practices. The optimization of haulage methods, considering certain factors, such as track slope and rolling coefficient, is proven to be an effective approach for improving productivity and reducing transportation costs in mining. In addition, the reduction in rolling resistance over transport cycles can boost fuel efficiency, resulting in reduced CO_2 emissions.

In summary, we offer valuable insights for informed decision-making in industrial sectors that rely on off-highway trucks. The proposed model and operational considerations highlight the interconnection between efficiency, productivity and environmental impact, providing a practical and sustainable approach for addressing the challenges in CO_2 emissions that are associated with these essential vehicles.

Despite the robustness of the model presented and the theoretical basis used, the lack of empirical validation through field tests is recognized as a limitation. The practical application of the model in real scenarios, with direct monitoring of operational parameters via on-board sensors (on-board telemetry), is essential to confirm the accuracy of the estimates of fuel consumption and CO_2 emissions. Therefore, future studies that contemplate this validation stage are suggested, in order to strengthen the reliability of the results and expand the applicability of the model in different operational contexts and types of equipment.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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