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Evaluation of road roughness and its influence on operating parameters in open-pit mines

Avaliação da rugosidade de estradas e sua influência em parâmetros operacionais em minas a céu aberto

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Pedro Guilherme Cipriano Silva
ORCID: https://orcid.org/0000-0003-3193-2911
Secretaria de Meio Ambiente do Estado do Rio Grande do Sul, Brasil
E-mail: Pedro-silva@fepam.rs.gov.br
Hernani Mota de Lima
ORCID: https://orcid.org/0000-0002-5595-4149
Universidade Federal de Ouro Preto, Brasil
E-mail: hernani.lima@ufop.edu.br
Vidal Félix Navarro Torres
ORCID: https://orcid.org/0000-0001-9084-9195
Instituto Tecnológico Vale, Brasil
E-mail: vidal.torres@itv.org
Leandro Geraldo Canaan Silveira
ORCID: https://orcid.org/0000-0003-3298-4457
Vale S.A., Brasil
E-mail: leandro.silveira@aluno.ufop.edu.br
Felipe Ribeiro Souza
ORCID: https://orcid.org/0000-0002-6068-1288
Universidade Federal de Ouro Preto, Brasil
E-mail: felipe.souza@ufop.edu.br

ABSTRACT

Hauling ore and waste rock is a major cost factor in open-pit mines, encompassing both road maintenance and off-road truck operation. Road maintenance costs are directly influenced by traffic volume and the size of trucks using the roads. Off-road truck operating costs are impacted by various factors, including those affecting their movement, such as the direct interaction between tires and the road surface. Tire-road interaction significantly affects rolling resistance. Rougher surfaces with deeper grooves caused by track sinks lead to higher rolling resistance. This study employed laser profiling to characterize the surface roughness of five mine haul roads in two large Brazilian iron ore mines. This study evaluated the impact of these road irregularities on various operating parameters for 240-ton off-highway trucks, including rolling resistance, average travel speed, travel time, productivity, and unit transport cost. The results indicate that a 10 cm increase in road surface roughness can lead to a significant increase in rolling resistance (up to 5%), a substantial decrease in average speed (25%), a notable increase in travel time (26%), a decrease in productivity (19%), and a corresponding increase in unit transport cost (21%).

Keywords: Haul Road mine; Rolling resistance; Roughness; Productivity; Cost of transport

RESUMO

O transporte de minério e estéril é um importante fator de custo em minas a céu aberto, envolvendo tanto a manutenção de estradas quanto a operação de caminhões fora-de-estrada. Os custos de manutenção de estradas de mina são diretamente influenciados pelo volume de tráfego e pelo tamanho dos caminhões que utilizam as vias. Os custos operacionais dos caminhões fora-de-estrada são impactados por vários fatores, incluindo aqueles que afetam seu movimento, como a interação direta entre os pneus e a superfície da estrada. A interação pneu-estrada afeta significativamente a resistência ao rolamento. Superfícies mais rugosas com sulcos mais profundos levam a uma maior resistência ao rolamento. Este estudo empregou perfilagem a laser para caracterizar a rugosidade superficial de cinco estradas de transporte de minério em duas grandes minas brasileiras de minério de ferro. O estudo avaliou o impacto dessas irregularidades da estrada em vários parâmetros operacionais para caminhões fora-de-estrada de 240 t, incluindo resistência ao rolamento, velocidade média de viagem, tempo de viagem, produtividade e custo unitário de transporte. Os resultados indicam que um aumento de 10 cm na rugosidade da superfície da estrada pode levar a um aumento significativo na resistência ao rolamento (até 5%), uma redução substancial na velocidade média (25%), um aumento notável no tempo de viagem (26%), uma redução na produtividade (19%) e um correspondente aumento no custo unitário de transporte (21%).

Palavras-chave: Estrada de mina; Resistência ao rolamento; Rugosidade; Produtividade; Custo de transporte

INTRODUÇÃO

In open-pit mines, the haul road network is a critical component directly impacting production efficiency and cost. Haul road quality significantly affects mine productivity through factors like trafficability for off-road haul trucks and equipment longevity, ultimately influencing productivity, economics, and safety (Hustrulid et al., 2013; Reis et al., 2014; Tannant & Regensburg, 2001).

The trend towards larger haul trucks for economies of scale has led to an increase in overall truck weight and payload capacity. While this offers potential benefits, it can also compromise haul road performance and lead to higher total road user costs. These costs manifest directly as increased cost per ton hauled and indirectly as reduced production rates, shortened service life of vehicles and components (Tannant & Regensburg, 2001), and decreased equipment availability, all contributing to higher life-cycle costs.

Compared to drilling, blasting, and loading operations (Hustrulid et al., 2013; Reis et al., 2014; Tannant & Regensburg, 2001; R. Thompson, 2010a, 2010b), truck haulage can account for up to 50% of a surface mine's total operating costs. Therefore, any cost savings achieved through improved haul road design and management directly benefit the mining company by reducing the cost per ton of material hauled.

The wearing course, or top layer of material on a mine haul road, plays a critical role in tire-soil interaction. It resists vertical and horizontal forces generated by vehicle traffic and provides sufficient grip for truck tires. Therefore, maintaining a smooth surface is crucial. This involves controlling rolling resistance by characterizing (measuring and analyzing) existing road roughness and evaluating its economic impact on ore and waste material transport by off-road trucks.

Regular maintenance helps eliminate small reductions in vehicle speed and increases in cycle times, both of which negatively affect hourly and annual production (Soofastaei & Fouladgar, 2022; R. Thompson, 2010a, 2010b; R. J. Thompson & Visser, 2006).

Several factors contribute to road deterioration, including weather conditions, time, and heavy traffic volume. These factors increase surface roughness, making proper characterization of a road's longitudinal profile essential. Characterization is crucial for effective road maintenance and for ensuring a ride safety and comfort for vehicles, and a reduced dynamic load on vehicles and the road surface.

Roughness is a key factor influencing vehicle operating costs, vehicle dynamics (handling and stability), and drainage (water removal from the road surface) (Múčka, 2016). According to the American Society for Testing and Materials (ASTM) standard E 867, road roughness refers to the deviations of a pavement surface from a perfectly flat plane, with specific characteristic dimensions. A road profile, on the other hand, represents the vertical elevations of the pavement surface measured along a defined travel path (Chang et al., 2009).

The International Roughness Index (IRI) is the globally recognized standard for characterizing longitudinal road roughness, used extensively in road management systems. IRI serves as a single metric for both road surface performance and ride quality. It has a strong correlation with overall vibration levels experienced by vehicles and the pavement itself (Sayers & Karamihas, 1998). A smooth road surface offers several benefits beyond passenger comfort. It can also lead to reduced fuel consumption, lower vehicle maintenance costs, and decreased road noise.

This paper describes the process of characterizing the surface roughness of five mine haul roads using laser profiling. It then analyzes the impact of these irregularities on the operating parameters of two large iron ore mines in Brazil. The analysis focuses on 240-ton off-highway trucks, evaluating factors such as rolling resistance, average transport speed, travel time, productivity, and unit transport cost.

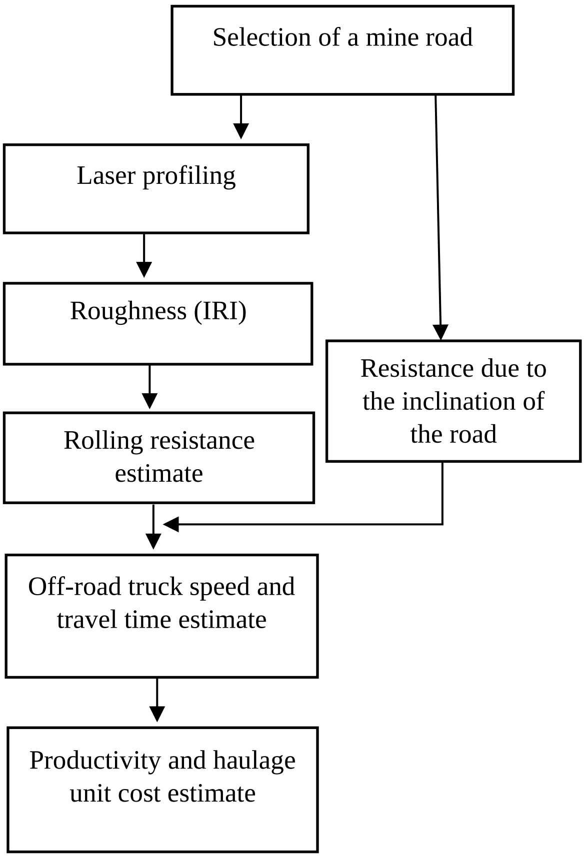
Materials and methods

Figure 1 presents a flowchart summarizing the steps followed in this case study. The process began with selecting a mine haul road for analysis.

Laser profiling using a specialized vehicle was then conducted to measure the surface roughness of the pavement. This roughness data was fed into a mathematical model to estimate the rolling resistance experienced by the vehicles. The model also factored in the resistance due to road inclination to determine the maximum achievable speed for a 240-ton off-highway truck on that specific road section.

Finally, the model was used to estimate the productivity and unit hauling cost associated with operating the off-highway truck. To understand the impact of road roughness, the process was repeated with varying levels of simulated roughness on the mine road.

Figure 1. Case study steps and sequencing.



Roughness measurement

This study employed laser profiling to measure the surface roughness of the mine haul road. This technique involves a profilometer mounted on the front of a moving vehicle. The profilometer utilizes laser sensors to record the vertical displacement between the vehicle body and the pavement surface as the vehicle travels at a constant speed. An accelerometer is often included to account for vehicle bounce (Chatti & Zaabar, 2012; de Blasiis et al., 2020; Graham, 1974; Hettiarachchi et al., 2023; Holman & St Charles, 2006; Holmberg et al., 2017; Múčka, 2016; Zaabar & Chatti, 2010).

The International Roughness Index (IRI), expressed in meters per kilometer (m/km), is used to quantify the roughness based on the measured vertical deviations from a reference plane (Chatti & Zaabar, 2012; de Blasiis et al., 2020; Fakhri et al., 2021; LaClair, 2006; Richardson & McIver, 2015; Šroubek et al., 2021; Zaabar & Chatti, 2010).

The vertical displacement is typically measured along the wheel tracks created by vehicles. This data is then translated into a longitudinal profile, a graph that visually represents the road's surface irregularities along its horizontal distance.

Rolling resistance estimate

Rolling resistance was estimated using a mathematical model called the Highway Development and Management Model, or HDM-4. This model is widely adopted globally due to its extensive validation and modification for various transportation conditions across different countries since its initial development in Australia (Coffey et al., 2018).

The HDM-4 model relies on a set of equations (Equations 1, 2, 3, 4, 5, 6, and 8) and accompanying tables (Tables 1-3) to conduct the calculations.

$$Fr = CR2 \times FCLIM \times (b11 \times Nw + CR1 \times (b12 \times M + b13 \times v^2 \quad \text{..................(1)}$$

Where:

Fr is the rolling resistance (N);

CR2 is the rolling resistance surface factor;

FCLIM is the climatic factor;

$b11$, $b12$ and $b13$ are rolling resistance parameters;

Nw is the number of wheels;

CR1 is the rolling resistance tire factor (Table 1); and

M is the vehicle weight (kg), and *v* is the vehicle speed (m/s).

$$CR2 = Kcr \times (a0 + a1 \times Tdsp + a2 \times IRI + a3 \times DEF \quad \text{.............................(2)}$$

Where:

Kcr2 is the calibration factor (Table 2);

$a0$, $a1$, $a2$ and $a3$ are model coefficients (Table 3);

Tdsp is the texture depth using the sand patch method;

IRI is the international roughness index (m/km); and

DEF is the Benkelman beam rebound deflection (mm);

$$FCLIM = 1 + 0{,}003 \times PCTDS + 0{,}002 \times PCTDW \quad \text{.....................................(3)}$$

Where:

PCTDS is the percent driving under snow conditions and

PCTDW is the percent driving under wet conditions.

$$b11 = 37 \times Dw \quad (4)$$

$$b12 = \frac{0{,}067}{Dw}\text{, old tires} \quad (5)$$

$$b12 = \frac{0{,}064}{Dw}\text{ latest tires} \quad (6)$$

$$b13 = 0{,}012 \times \frac{Nw}{Dw^2} \quad (7)$$

Where:

Dw is the diameter of the wheels (m).

Table 1 – Rolling resistance tire factor.

Tire types	CR1
Radial	1.00
Cross-ply bias	1.30

Fone: Adapted from Chatti & Zaabar (2012).

Table 2 – Calibration factor for rolling resistance force

Vehicle class	Tare weight (t)	Kcr2
Medium car	1.46	0.50
Sport utility vehicle	2.50	0.58
Van	2.54	0.67
Light truck	3.70	0.99
Articulated truck	13.60	1.10

Fonte: Adapted from Zaabar & Chatti (2010) e Chatti & Zaabar (2012)

Table 3 – Rolling resistance surface factor coefficients

Surface class	Vehicle mass							
	<= 2.5 (t)				> 2.5 (t)			
	*a*0	*a*1	*a*2	*a*3	*a*0	*a*1	*a*2	*a*3
Asphalt	0.50	0.02	0.10	0.00	0.57	0.04	0.04	1.34
Concrete	0.50	0.02	0.10	0.00	0.57	0.04	0.04	0.00
Unsealed	0.80	0.00	0.10	0.00	0.80	0.00	0.10	0.00

Fonte: (adapted from Worldbank (Chatti & Zaabar, 2012; Zaabar & Chatti, 2010).

Resistance due to the inclination of the road estimate

The laser profiling data, containing the x, y, and z coordinates of points along the road layout, was used to characterize each section. The following properties were determined for each section:

- Length (meters)
- Slope (percentage)
- Rolling resistance coefficient due to road inclination (percentage)
- Classification (uphill, downhill, or horizontal)

Horizontal sections are defined as having an inclination between 0 and 2%. The equation used to calculate the rolling resistance coefficient due to road inclination (fθ) is provided in Equation (8).

$$f_\theta = \sin(\theta) \quad (8)$$

Where θ is the road inclination (°).

Off-road truck speed and travel time estimate

A truck requires tractive effort (pulling force) to overcome various resistances and propel itself forward. This tractive effort needs to be greater than the combined resistance forces but less than the grip force between the tires and the road for the truck to move effectively. Equation (10) was used to calculate the theoretical maximum speed achievable by the truck on each road section, considering these resistance forces.

For simplicity, air resistance was neglected. Inertial resistance, arising from the truck's mass and need to accelerate, was factored in by applying a velocity reduction factor. This factor accounts for the decrease in achievable speed compared to ideal conditions (Holman & St Charles, 2006; Hustrulid et al., 2013).

$$V_m = \frac{270 \times Pot \times E_t}{W \times (f_r + f_\theta} \quad (9)$$

Where:

Vm is the maximum speed (km/h);

Pot is the engine power (hp);

E_t is the coefficient relative to the transmission efficiency;

W is the mass of the truck (kg);

f_r is the rolling resistance coefficient; and

f_θ is the resistance coefficient due to the slope of the road.

Finally, the average speeds for loaded (outbound) and empty (return) trucks on each road were calculated. This involved weighting the average maximum speeds for each section by their corresponding lengths. Equation (10) was then used to determine the round-trip times for each haul road.

The total travel time for a complete round trip was obtained by summing the outbound and return travel times for each road section.

$$T_v = \frac{D_i}{V_i \times 16{,}66} + \frac{D_v}{V_v \times 16{,}66} \quad (10)$$

Where:

T_v is the variable transport time (min);

D_i is the distance of the outward path (m);

D_v is the distance of the return trip (m);

V_i is the average speed loaded (km/h); and

V_v is the average empty speed (km/h).

Productivity and haulage unit cost estimate

Productivity and haulage unit cost were estimated according to Eqs. (11) and (12) (Holman & St Charles, 2006; Reis et al., 2014). The efficiency factor of the operation was 0.70.

$$P = \frac{60 \times C \times E}{T_c} \quad (11)$$

Where:

P is the productivity (t/h);

C is the actual load capacity of the truck body (t);

E is the combined factor of operator efficiency and equipment condition; and

T_c is the truck cycle time (min).

$$C_{unit} = \frac{\sum C_{op}}{P} \quad (12)$$

Where:

C_{unit} is the operating unit cost ($/t) and

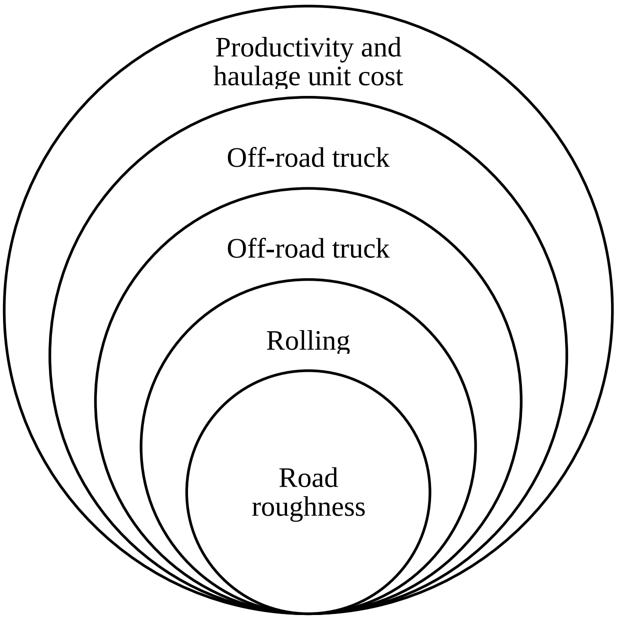
C_{op} is the sum of the transportation operating costs (US$/h).

Analysis of haul road roughness effects on haulage operational parameters

This study focuses on surface roughness of mine haul roads as a key control variable in managing transportation operating parameters. Road roughness is a critical input for the rolling resistance estimation model, HDM-4, and it directly impacts a chain of subsequent variables (Figure 2). It's important to note that various rolling resistance estimation models exist in the literature, and the chosen model will influence the results.

For this simulation, the roughness range was set between 0 mm/m and 100 mm/m.

Figure 2. Roughness as a control variable for haulage operating parameters.



Case Study: Large-scale ore mine roads

This case study was conducted at two large iron ore mines in northern and southeastern Brazil, referred to as Mine 1 and Mine 2, respectively. For each mine, key haul roads were chosen based on their strategic importance in handling high volumes of material. The selection process considered data from Table 4 and Figure 3. Only Caterpillar 793D off-highway trucks with a 240-ton capacity were included in the analysis, as they constitute most of the truck fleet in both mines.

Table 4 – Roads selected for the case study.

Road	Length (km)	Width (m)	Origin	Destiny
A (mine 1)	5,450	35	Mining front	Crusher
B (mine 1)	4,070	35	Mining bench	Waste pile
C (mine 2)	4,990	30	Mining bench	Crusher
D (mine 2)	6,960	43	Mining bench	Crusher
E (mine 2)	4,120	30	Mining bench	Waste pile

Figure 3. Roads A, B, C, D and E.

Road A

Road B

Road C

Road D

Road E

Results and Discussion

Roughness and rolling resistance

Figure 4 illustrates the average road surface roughness for the analyzed sections. Road B exhibits a roughness value 2 mm higher than Road A, along with a greater spread of data points. This increased roughness is likely due to the lower soil compaction in the waste rock discharge area (Road B) caused by the constant activity of material unloading and stacking.

Roads C and D show significant differences in roughness compared to Road E. Road D has the smoothest and most consistent surface (low roughness dispersion). This can be attributed to its construction following Vale's Mine Road Manual recommendations, including specific structural layers and other requirements.

Road E, designated for waste rock transport, has the highest roughness values, exceeding Roads C and D by approximately 16.0 mm/m and 30 mm/m, respectively. Additionally, it exhibits a wider range of roughness measurements.

Figure 4. Ninety-five percent confidence interval for the average roughness on each road.

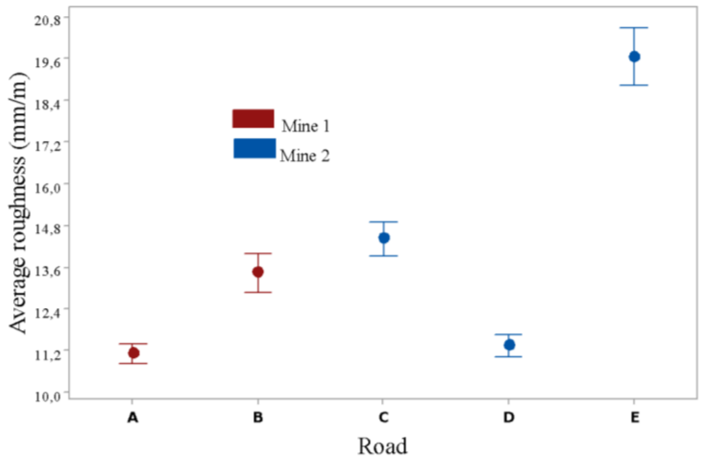
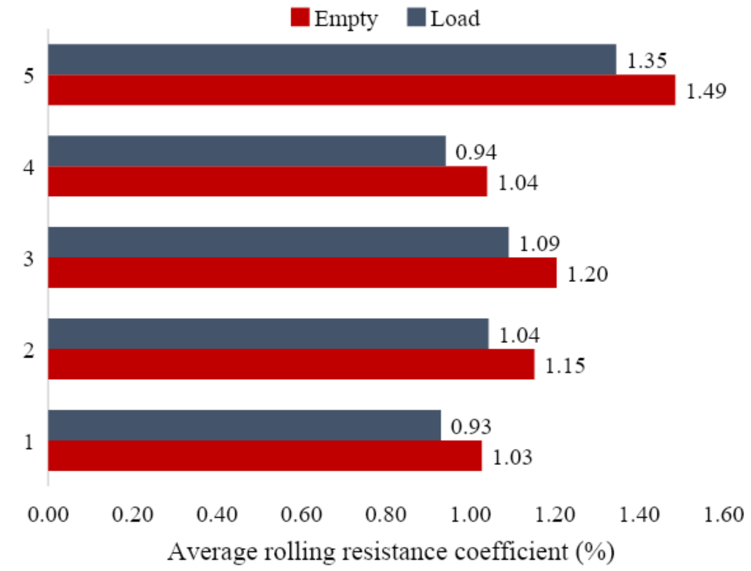


Figure 5 presents the average rolling resistance coefficient for loaded and empty trucks on each road. Interestingly, the coefficient is higher for unloaded trucks.

This phenomenon can be explained by the relationship between load, tire temperature, and rolling resistance. Under a heavier load, the tire experiences increased energy dissipation, leading to a rise in temperature. As the temperature rises, the air particles within the tire move more erratically, causing an increase in internal pressure. This pressure increase results in a stiffer tire with less deformation. Consequently, the hysteresis loss coefficient, which represents the energy dissipated within the tire material due to its cyclic deformation, decreases. This decrease in hysteresis loss translates to a lower rolling resistance coefficient for loaded trucks (LaClair, 2006).

Figure 5. Rolling resistance results.

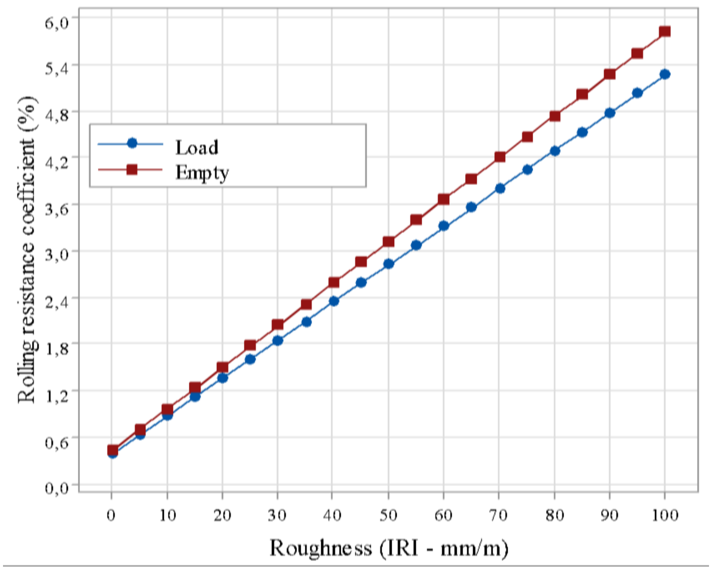


Influence of roughness on the haulage operating parameters

Figure 6 confirms a linear relationship between road surface roughness and the rolling resistance coefficient. For every 10 cm (100 mm/m) increase in roughness, the coefficient increases by 4.90 percentage points for loaded trucks and 5.40 percentage points for empty trucks. This trend suggests that empty trucks are more sensitive to road irregularities.

It's noteworthy that the difference in the rolling resistance coefficient between loaded and empty trucks also widens with increasing roughness.

Figure 6. Influence of roughness on the rolling resistance coefficient.



The influence of the 10 cm (100 mm/m) variation in the roughness on the speed, travel time, productivity and unit transport cost for each mine road is presented in Table 5. Considering the average results of each parameter, the 10 cm increase in roughness results in a 5-percentage point rolling resistance increase, 25% reduction in the speed, 26% increase in the travel time, 19% reduction in the productivity and increase in the haulage unit cost by 21%.

Table 5 presents the impact of a 10 cm (100 mm/m) increase in road roughness on various operating parameters for each mine haul road. Analyzed on an average basis across all roads, this roughness increase translates to:

- a 5% increase in rolling resistance
- a 25% reduction in average speed
- a 26% increase in travel time
- a 19% decrease in productivity
- a 21% increase in unit transport cost

Table 5. Impact of road roughness on haulage operational parameters at Mines 1 and 2.

Road	Length (km)	Δ Rolling resistance (%)		Δ Average speed (km/h)	Δ Travel time (min)	Δ Productivity (t/h)	Δ Haulage unit cost (US$/t)
A	5.45	4.90 (load)	5.40 (empty)	5.12	9.51	49.24	-
B	4.07			4.56	5.35	48.49	-
C	4.99			7.62	9.66	83.94	0.72
D	6.96			5.02	8.03	44.09	0.60
E	4.12			4.02	4.90	51.55	0.36

Conclusions

This study investigated the impact of haul road roughness on the operating parameters of off-highway trucks in two open-pit iron ore mines. The findings demonstrate a clear correlation between increased road roughness and higher rolling resistance experienced by the vehicles. This, in turn, leads to a series of negative consequences for mine haul truck operations.

The Key issues observed were the Roughness and Rolling Resistance Relationship; and the Impact on Operating Parameters (including the reduced average speed, the increased travel time, the decreased of productivity, and the increased unit transport cost).

The study quantified the impact of a 10 cm increase in road roughness on various operating parameters. This roughness increment resulted in:

- 5% Increase in Rolling Resistance
- 25% Decrease in Average Speed
- 26% Increase in Travel Time
- 19% Decrease in Productivity
- 21% Increase in Unit Transport Cost

The study also revealed that empty trucks are generally more sensitive to road roughness compared to loaded trucks. This can be attributed to the influence of load on tire behavior and rolling resistance.

Maintaining smooth haul roads is crucial for minimizing operating costs and maximizing productivity in open-pit mines. By regularly monitoring road surface conditions and implementing timely repairs to address roughness issues, mine operators can achieve significant economic benefits. This includes reduced fuel consumption, lower engine wear and tear, improved haul truck efficiency, increased mine production output and lower unit transport costs.

This study emphasizes the economic importance of maintaining good road quality in open-pit mines. Regular monitoring and proper maintenance of haul roads are essential for optimizing haul truck performance, minimizing operating costs, and maximizing overall mine productivity.

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