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# ROLLING RESISTANCE ANALYSIS IN OPEN PIT MINING HAULING

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## ABSTRACT

In open pit mining hauling, the influence analysis of the geometric and operational parameters of the haul roads is still not very expressive. Thus, in this study, mathematical models are developed for productivity and transport costs, including a greater diversity ofhaul parameters. Geometric parameters such as the thoroughfare slope and curvature radius and operational parameters such as deformation and pressure, truck gross mass and speeds are found to be related in the calculation of rolling resistance and total resistance to movement, thus enabling general optimization models. An initial simulation with values obtained from a Brazilian iron mine makes it possible to validate the applicability and the great potential of the models in maximizing productivity and minimizing transport costs.



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# INTRODUCTION

Open pit haul roads play a key factor in productivity and cost management, and attention to the elements of productivity and cost functions has been increasing with studies that evaluate the phenomena involved in total resistance to movement (TR). According to Tannant and Regensburg (2001), the TR is defined by the sum of rolling resistance (Rr), established by the combination of forces that a vehicle must overcome to move on a specific flat surface, and the grade resistance (GR), determined by the combination of forces that a vehicle must overcome to move on a specific surface associated withthe gravitational force acting on the vehicle and the road grade. Thompson (2011) stated that truck performance is strongly related to rolling resistance. The author also reportedthat for every 1% increase in rolling resistance, the truck can undergo a speed reduction of approximately 10% on an uphill grade and up to 26% on a flat road due to the poor conditions of haul roads. From an economic point of view, Thompson (2011) notedthat approximately 50% of a mine's operating costs correspond to transport, which is affected by the quality of the road and, consequently, by the rolling resistance. Thompson, Peroni and Visser (2019) indicated some performance indicators that are also affected by rolling resistance: productivity, fuel consumption, tire replacement, emissions, maintenance and safety of haul truck operations in open pit mines. Figure 1 illustrates how varying rolling resistance affects operating costs in relation to increased fuel consumption as productivity declines. The three focal points of Rr analysis are the operating conditions, vehicle type and tire characteristics. In the literature, there are tests for Rr calculations that include the variables of tire pressure, tire temperature, road curvature radius, road super elevation, tire load, road roughness and speed (YDREFORS *et al.*, 2021). According to Bode and Bode (2013), for trucks, Rr can reach approximately 0.5% of the vehicle's gross mass. According to Nakajima (2019), tire heating is responsible for 90% of Rr energy losses. Rr hasalso been characterizedby several studies that consider theinternal variables, such as the track deformation (COUTERMARSH, 2007; GRAHN, 1991), tire deformation (XIONG *et al.* 2015), tire heating (WANG, 1998), tire pressure (TAGHAVIFAR; MARDANI, 2013) and aerodynamics (JUHALA, 2014). Direct Rr calculations do not include many variables and end up being unpredictive, which can directly and unexpectedly affect production and the nonachievement of goals as well as incurring higher operating costs than estimated. According to Alegre *et al*. (2021), another way to calculate Rr is through retro analysis dispatch systems data, generating models that estimate Rr in a certain operation case. This approach can be used to verify possible deficiencies in the Rr estimative and thus rectify them to provide greater fidelity. Rr directly impacts the developed speed of vehicles and is detrimental to low cycle times, not only affecting productivity but also adding costs per journey. The proposed modeling was used to theoretically evaluate productivity and cost mitigation, adhering and correlating diverse parameters involved in track geometries and equipment attributes, in addition to the characterization of each element in its due responsibility in the Rr function. In this way, it is possible to provide a better interpretation of the reality of the evaluated phenomena, where mathematical models can bevalidated in an iron mine for the CAT 793C off-road truck. The models were used to demonstrate, through sensitivity analysis, the most impacting parameters and were validated as am effective tool in decision making on which aspects should be improved and monitored on roads and equipment.

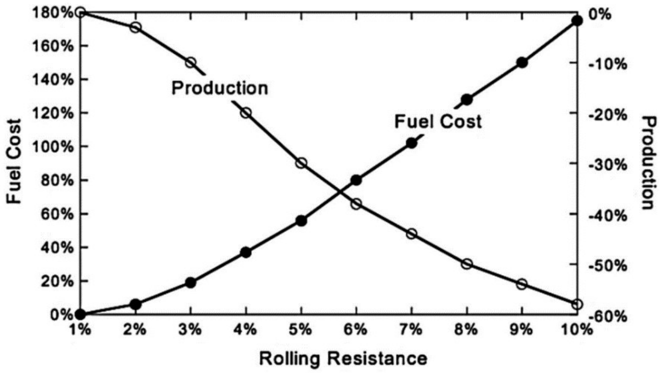



**Figure 1. Relationship between rolling resistance, production and fuel cost**

# MATERIALS AND METHODS

Aiming at broad control and monitoring of production and costs, Equation 1 is proposed for productivity ($P_t$), and Equation 2 is proposed for costs ($C_t$) with variables in common with each other. $P_t$ is expressed in tons transported per hour (t/h), and $C_t$ is expressed in US dollars per ton transported (US$/t).

$$P_t = \frac{60 \cdot C_e \cdot \rho_{re} \cdot E_t \cdot F_t}{T_f + \frac{1}{16.67}\left(\frac{d_i}{v_i} + \frac{d_v}{v_v}\right)} \quad (1)$$

where $C_e$ is the rated truck capacity (m³),$\rho_{re}$is the material density (t/m³), $E_t$is the combined factor of operator efficiency and equipment condition, $F_t$is the truck bed fill factor, Tfis the fixed time in minutes, $d_i$ and $d_v$are the round-trip distances (m), and $v_i$ and $v_v$are the round-trip speeds (km/h). Concurrently, Equation 2 for costs is described, where $C_{topex}$represents the OPEX transport costs in (US$/h) and$C_{mv}$is the road maintenance cost (US$/h).

$$C_t = \frac{\left(T_f + \frac{1}{16.67}\left[\frac{d_i}{v_i} + \frac{d_v}{v_v}\right]\right) \cdot (C_{t_{opex}} + C_{mv})}{60 \cdot C_e \cdot \rho_{re} \cdot E_t \cdot F_t} \quad (2)$$

Most dynamic parametersare associated with the speeds and distances that directly impact productivity and costs; these parametersare considered over time. Other variables have a significant impact; however, in good operational practices, they are partially immutable, such as the machine efficiency and material densities. In the following sections, a detailed mathematical model incorporating dynamic variables is presented to obtain general mathematical models of productivity and costs in transport.The distances to reach the maximum speed and a total stop have a significant impact on the average speeds employed by the machines. According to López Jimeno (2014), to reach the maximum speeds required, the behavior of the movement is uniformly varied and is governed by the Torricelli equation from classical physics. By means of a constant acceleration and relating to the developed power of the kinetic energy and time equations, the acceleration distances can be defined. Table 1 shows the distances and acceleration and deceleration times for the CAT 793C off-road truck, considering the respective maximum speed reached.The truck speed increase is strongly linked to the productivity increase. However, high speeds can reduce the tire lifetime, implying cost increases, and can even compromise safety. In addition, parameters such as temperature and tire pressure, when outside the recommended limits, can also compromise the lifetime.

**Table 1. Distance and acceleration and deceleration times for the CAT 793C**

| Parameters for the CAT 793C | | | | | |
|---|---|---|---|---|---|
| m (kg) | P (W) | v (km/h) | (m) | $T_a$ (s) | *$T_{da}$ (s) |
| 336,678 | 1,691,647 | 35 | 50.58 | 11 | 11 |

Therefore, monitoring tires and complying with the established standards are essential to obtain maximum productivity at the lowest cost and with maximum safety. Therefore, the maximum pressure adopted is 145 pounds per square inch (psi) and a maximum temperature of 71 degrees Celsius (°C) according to Bridgestone (2016) for the off-road truck CAT 793C.For López Jimeno *et al.* (2014), the available tractive effort of an off-road truck is the amount of force that the engine can deliver to the contact point of the drive wheels with the ground. This type of traction is independent of the contact relationship between the tires and the road; the problem can be studied with a free-body model, and a force equation acting on the truck can be described; thus, considering the decomposition of the forces acting on a truck on an inclined plane, the tractive effort for a truck operating in an open pit mine to overcome the total resistance can be expressed by Equation 3. López Jimeno *et al.* (2014) also presented Equation 4, which expresses the tractive effort available,where $E_t$ is the tensile effort (kgf), P is the off-road truck power (hp), $E_f$is the transmission efficiency, which varies from 0.7 to 0.8, and v is the off-road truck speed (km/h).

$$E_t = Rr \pm R_\theta + R_a + R_m + R_i (3)$$

$$E_t = \frac{270.24 \cdot P \cdot E_f}{v} \quad (4)$$

where $E_t$ is the total resistance (kgf), Rr is the rolling resistance, $R_\theta$ is the resistance due to the road slope, $R_a$ is the aerodynamic resistance, $R_m$ is the resistance due to the internal mechanical friction and $R_i$ is the resistance due to inertia. For trucks currently used in open pit mining, the resistances due to mechanical friction, aerodynamics and inertia are much smaller than the other resistances; that is, $Rr + R_\theta >> R_a + R_m + R_i$. Therefore, these other resistances are considered insignificant in this study and are not considered in the next steps.Rolling resistance represents the degree to whicha tire opposes truck displacement due to deformations suffered by the tire's contact surface with the road, including roughness and grooves. Part of the energy dissipated in these deformations is absorbed by the tire and manifests itself in heat form, increasing the tire temperature. Ofthe TR, Rr is the most important resistance to be evaluated, as it significantly affects productivity and costs. For a broad analysis and quantification of Rr, it is necessary to consider the three aspects of tires, tracks and trucks.For the tire parameters, to determine the rolling resistance, it is essential to consider the tire structure influence since the behavior of the tire's rubber impacts the viscoelastic characteristics due to the temperature and the excitation. When the rubber is cyclically excited, the energy is dissipated in heat form, which significantly influences Rr.The parameters that determine Rr (kgf) on off-road truck tires are the rolling resistance coefficient $f_r$ (kgf/t) and the load imposed on the tire $F_c$(t) as expressed through Equation 5. The coefficient rolling resistance can be expressed in terms of a percentage (%) or in terms of kgf/t.

$$Rr = f_r \cdot F_c (5)$$

Therefore, considering the rolling resistance and the resistance due to the slope of the road on Equation 5 in Equations 3 and 4, Equation 6 is obtained, which allows calculating the maximum speed of the truck for a maximum engine power, where $v_m$ is the maximum speed (km/h), fr is the rolling resistance coefficient (kg/t), $f_\theta$ is the grade resistance (kg/t), and $F_c$ is the truck gross mass (t).

$$v_m = \frac{270.24 \cdot P \cdot E_f}{F_c \cdot (f_r + f_\theta)} \quad (6)$$

Tire rubber compounds exhibit nonlinear viscoelastic behavior, whose mathematical formulation is considerably complex. However, linear viscoelastic modeling represents this phenomenon very well. The representation of the stress (σ) and strain (Ɛ) of the viscoelastic behavior of rubber shows a delay in the response of the material to an external excitation and, as a consequence, a lag between stress and strain. This lag, known as hysteresis in the stress–strain curve (Equation 7), is responsible for the dissipation of energy in the form of heat, where $E_f$ is the energy supplied by the motor, $E_d$is the dissipated energy, and $E_r$is the recovered energy.

$$E_f = E_d + E_r \tag{7}$$

The energy consumption of the truck caused by the tire's rolling resistance, which is the energy needed to keep moving, depends on the tire type, inflation pressure, applied load, material property, temperature, speed and road surface. According to ISO 18164:2005, the tire rolling resistance is the energy dissipated or consumed by a unit of distance traveled, which can be represented as the result of the product of the deformation magnitude, the material deformed volume and the material property loss expressed as a function of the phase angle, as shown in Equation 8.

$$\epsilon_\varepsilon = \pi(\sigma_0\varepsilon_0)(Sen\delta)V (8)$$

The modeling is based on the concepts discussed by Rhyne and Cron (2012), which focuses on the first term, the magnitude of deformation, for a compact pavement, adapting to the open pit reality for off-road truck operation. This pavement can be made of compact rock or material that exhibits ruts from tire rolling during transport. Initially, these ruts, which are oriented with the tire tread, produce approximately 50% of the total rolling resistance when considering compression and longitudinal shear forces. In this way, the resistance due to the formed grooves is considered.Equation 9 proposes the final model of the tire's hysteresis in an elastic way, mediated by the volume of deformed material V and the phase angle δ associated with the operating conditions, where E is the tire elastic modulus, $L_c$is the distance from the tread contact area to the road surface, r is the tire's metallic belt radius and P is the inflation pressure.

$$\epsilon_\varepsilon = \left(\frac{P^2}{E} + \frac{E{L_c}^2}{12r^2}\right)\pi sen(\delta)V \tag{9}$$

To define the total tire contact with the road ($L_c$), the conditions of tire flattening, defined by the manufacturer's manual equations, and the road sinking proposed by the Swedish formula (Mikkonen&Wuolijoki, 1975) are related, generating Equation 10, where the total tire contact with the road can be defined once the tread depths (z), tire load ($F_c$), width (l) and tire pressure (P) are known.

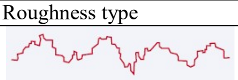
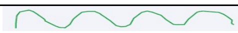
$$L_c = \frac{F_c}{Pl} + 1.62z \tag{10}$$

Inserting a road pavement roughness factor μ, the roughness factor is proposed on a scale of values according to four types of road profiles and is described in Table 2. Multiplication by 1000 for unit transformation purposes results in Equation 11, which represents the rolling resistance coefficient $f_r$ in kg/t for tires used for transport by off-road trucks in open pit mines.

$$f_r = 1000\left(\frac{P^2}{E} + \frac{E\left[\frac{F_p}{Pl}+1.62\ \right]^2}{12r^2}\right)\frac{\pi lhRsen(\delta)}{\mu F_c} \tag{11}$$

The phase angle (δ) characterizes the viscoelastic properties of materials. A value of 0 degrees corresponds to the characteristics of elastic materials, while 90 degrees corresponds to viscous behavior.Tire materials presentviscoelastic behavior with a phase angle between 0° and 90°. The performance of a tire is related to the mechanical-dynamic properties of the tread compound. When a certain amount of energy is supplied to this material, part is stored elastically, and part is dissipated in heat form. Wang (1997) characterized this behavior for viscoelastic materials, and Figure 7 presents the phase angle curves according to the stress temperature. The final model in Equation 11 is then applied in simulations for the equipment used in a Brazilian iron mine that uses the CAT 793C off-road truck. Table 3 discretizes the data related to the equipment. Table 4 presents geometric and operational characteristics for the tire model studied.To validate Equation 11, the following parameters are also considered: the tire elasticity modulus, with a maximum value of 7 megapascals (MPa), and a phase angle of 10° at a temperature of 20°C. For the analysis of the results of the Rr factor, or $fr$, the variation parameters are the roughness factor ranging from 0.1 to 0.9, compact groove dimensions ranging from 0.001 cm to 0.3 cm, implied speed ranging from 9 km/h to 47 km/h and tire inflation pressure ranging from 103 psi to 142 psi; productivity and costs are evaluated as a function of the Rr factor, $f_r$ ranging from 5 kg/t to 200 kg/t.

**Table 2. Road surface roughness factor proposed by the authors**

| Roughness type | Class | Description | μ |
|---|---|---|---|
|  | I | Very rough with a microrough and wet surface | 0.1≤ μ ≤0.3 |
|  | II | Slightly rough with a microrough surface | 0.5 <μ ≤0.7 |
|  | III | Very rough with a regular to fine surface | 0.3 <μ ≤0.5 |
|  | IV | Smooth with a fine to microrough surface | 0.7<μ ≤0.9 |

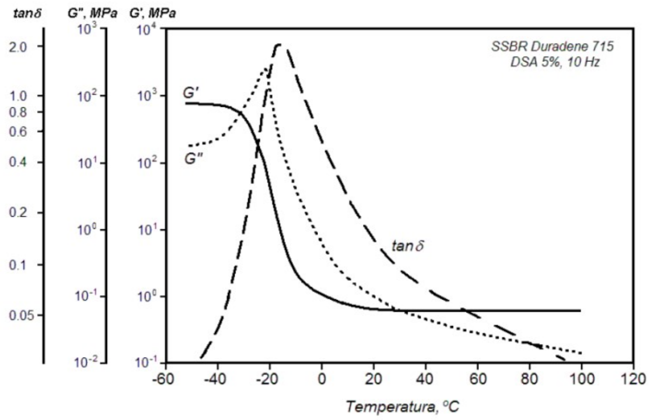



**Figure 2. Phase angle variability as a function of the tire temperature**

# RESULTS AND FINDINGS

The simulation results for 793C trucks and tires in Figure 3 show a parabolic behavior between the inflation pressure and the rolling coefficient, and for the loaded CAT 793C, the minimum Rr factor of 30.8 kg/t corresponds to 127.8 psi. In Figure 4, the roughness presents an asymptotic behavior and is inversely proportional to the Rr factor, since higher roughness values correspond to a smoother road. Another parameter included in this validation is the height or depth of the compact grooves in the transport path varying from 0 to 30 cm, in a directly proportional behavior in which a 10 cm groove can increase the rolling resistance by 6 kg/t, 20 cm by 13 kg/t and 30 cm by 52 kg/t, and a greater scope is presented in Figure 5. The traction effort $E_t$ is the junction of the rolling resistance, track slope and aerodynamic drag, so we cannot evaluate the influence of the Rr factor as a function of speed in isolation, but we can evaluate how the increase in speed affects the sum of resistances to movement, summarized here as the traction effort and presented graphically in Figure 6. Higher speeds decrease the traction effort, presenting a decrease in the sum of the movement resistances, including the rolling resistance.

**Table 1. Distribution of the weight, power and tire type for the CAT 793C truck**

| Truck | Weight (kgf) | | Unloaded weight distribution (%) | | Loaded weight distribution (%) | | Power (hp) | Speed (km/h) | Tire |
|---|---|---|---|---|---|---|---|---|---|
| | Unloaded | Loaded | Front | Rear | Front | Rear | | | |
| 793C | 113510 | 223168 | 47 | 53 | 33.6 | 66.4 | 2300 | 53.6 | 40.00R57 |

**Table 2. Tire characteristics, 4000R57**

| Tire | Maximum load(kgf) | | Metal band radius (m) | Tread width(m) | Tread thickness (m) |
|---|---|---|---|---|---|
| | Unloaded | Loaded | | | |
| 40.00R57 | 15040 | 55889 | 1.606 | 1.09 | 0.097 |

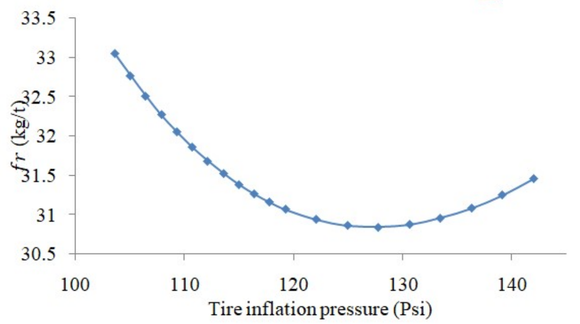



**Figure 3. Behavior of the Rr factor as a function of the inflation pressure**

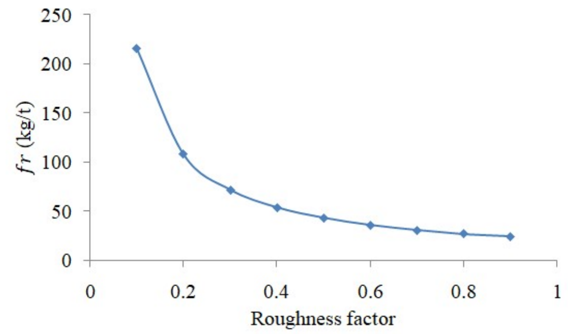



**Figure 4. Behavior of the Rr factor as function of the roughness**

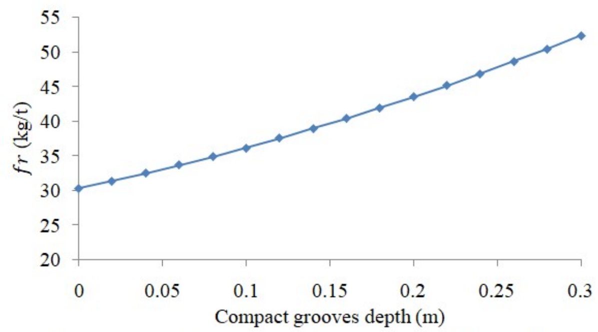



**Figure 5. Behavior of the Rr factor as a function of the groove depth**

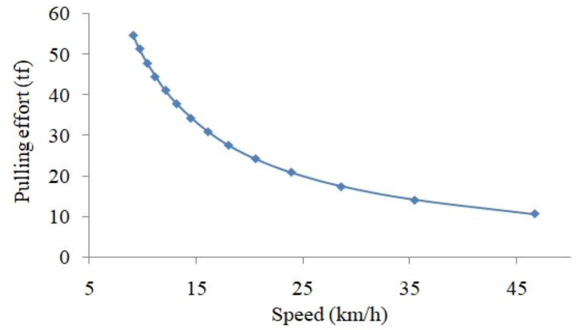



**Figure 6. Behavior of the tractive effort as functionof the speed**

The productivity and costs are also evaluated on the influence of the proposed model of tire deformation, using the equations of production (1), costs (2) and calculation of average speed per traction effort (13), yielding Equations 12 and 13.

$$P_t = \frac{60 * C_e * \rho_{re} * E_t * F_t}{T_f + 2(T_a + T_{da}) + \frac{1}{16{,}67}\left(\sum\frac{d_c}{v_R} + \sum\frac{d_l}{v_l}\right) + \frac{f_v+1}{4505 * P * E_f * f_v}\sum\left[d_i\left(F_c(f_r)\right)\right]} \quad (12)$$

$$C_t = \frac{1}{P_t}\cdot\left[C_{t-o} \quad + C_{mv}\right] (13)$$

where $T_a$ is the round-trip deceleration time (min); $T_{da}$is the deceleration time (min),$v_R$ is the truck speed in the curves (km/h),$v_l$ is the speed influenced by the width of the road (km/h), $d_c$ is the distance of the track on the curve (m), $d_l$ is the distance of the track with a width less than the minimum (m), and $f_v$ is the speed factor. Equation (13) allows calculation of the maximum speed developed by the truck. However, it is necessary to apply a speed factor according to the weight/power ratio (kg/hp) that varies according to the empty or loaded condition, according to Table 5. The respective factors presented agree with the values recommended by López Jimeno *et al.* (2014), proving their potential for practical application.

**Table 5. Speed ratio for CAT 793C**

| Speed | CAT 793C |
|---|---|
| Loaded (Vc) | 17.9 |
| Unloaded (Vv) | 29.9 |
| Speed factor ($f_v$=$V_v$/Vc) | 1.67 |

For the initial simulation of the productivity and cost models for a 300 m deep pit for the CAT 793C off-road truck, the database presented in Table 6 isused.

The validation uses 16 different values for Rr for the productivity and cost functions. Figures 7 and 8 present the behavior of the functions.

**Table 4. Data for initial productivity and cost equation validation**

| Parameter (variable) | Unit | CAT 793C |
|---|---|---|
| Ore mass (m) | t | 246.2 |
| Maneuvering time($t_m$) | min | 0.85 |
| Unloading time ($t_d$) | min | 0.95 |
| Loading time ($t_q$) | min | 3.38 |
| Waiting time ($t_e$) | min | 2.0 |
| Total fixed time ($T_f$) | min | 7.18 |
| Acceleration time ($t_a$) | min | 1.0 |
| Deceleration time ($d_a$) | min | 1.5 |
| Curve delay time ($t_c$) | min | 2.0 |
| Narrow zone delay time ($t_l$) | min | 0.0 |
| Engine power (P) | HP | 2300 |
| Pit height (H) | m | 300 |
| Loaded truck weight ($F_{ci}$) | kgf | 336678 |
| Unloaded truck weight ($F_{cv}$) | kgf | 113510 |
| Haul cost ($C_{topex}$) | US$/h | 631.6 |
| Maintenance cost ($C_{mv}$) | US$/h | 23.1 |
| Rolling resistance factor ($f_{ri}$) | | 0.031 |
| Speed factor ($f_v$) | | 1.67 |

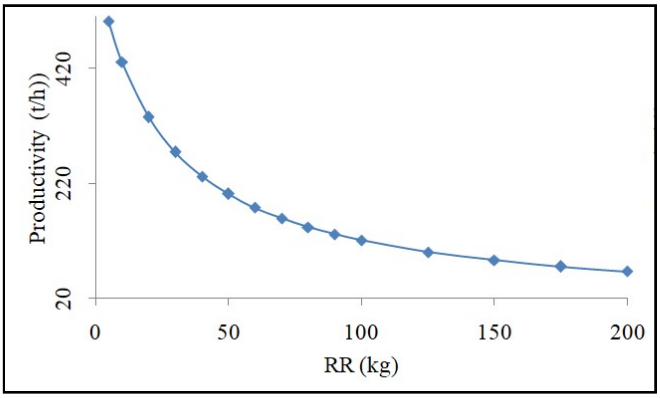



**Figure 7. Productivity behavior as a function of the Rr factor**

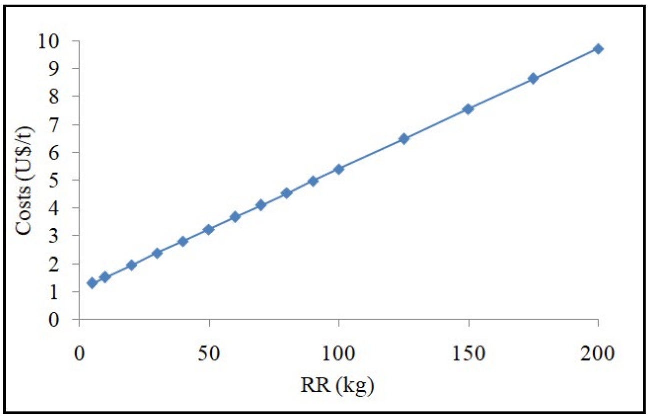



**Figure 8. Cost behavior as a function of the Rr factor**

# CONCLUSION

The parasitic condition implied by the rolling resistance due to tire deformation and interaction with the road is notable. The asymptote of productivity points to the great effect caused by a slight increment in the Rr factor, as well as in cost management, in which a direct proportion is pointed out.The analysis of the Rr factor and its most impacting parameters is crucial for maintenance planning of tracks and correct tire calibration for the associated traffic speed to reach the maximum capacity of the equipment and routes.The mathematical model developed shows great potential and applicability in optimizing productivity and transport costs based on the parameters of mine roads or roads. An important contribution of the developed model is to quantify the rolling resistance, the speed in curves, the influence of the width of the road below the minimum recommended by national and international standards and the speed as a function of the traction effort. Therefore, the mathematical model is an important tool for research related to transport routes.

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