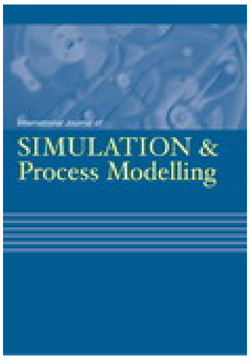

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Study of vehicle dynamics response to collision in windrows of mine access roads through computer simulation

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Abstract: The study presents an ore transport vehicle in simulated collision against the protection windrow (berm), located on the side of the roads, in order to prevent the vehicle from escaping in transit on the road. The work presents a study developed through computer simulation to validate the safety of access roads to mines owned by MRN. The objective is to dimension a windrow that it guarantees the safety of employees who travel with heavy-duty vehicles within the mine's operating fields. The computational simulations were carried out using the software EDEM and motion view to simulate granular particles through the discrete element method (DEM) methodology and the theory of vehicle dynamics respectively. The information for the elaboration of the works was provided by MRN and complemented through scientific studies developed by the Naves Engenharia team. The results presented satisfactory data to the conditions required initially.

Keywords: simulation; computer aided engineering; discrete element method; DEM; vehicular collision simulation.

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Biographical notes: Elyton Naves is the Director of Naves Engenharia (a Brazilian engineering company), which has been developing researches in computational simulation field involving vehicle dynamics, multibody simulations with flex bodies, finite and discrete elements. He has more than five years of experience in computational simulation in mechanical engineering field. He obtained his Master's in Mechanical Engineering from Catholic University of Minas Gerais (PUC-MG, Brazil). He is mainly focused in the field of automotive industries, decided to explore others disciplines involving multidisciplinary subjects, that not only automotive engineering is present but also mining, construction and others.

João Lucas Diniz Oliveira is graduated in Mechanical Engineering through the Catholic University of Minas Gerais and Hochschule Schmalkalden (Thüringen, Germany). Currently, he is studying his Master's in Universidade Federal de Minas Gerais (UFMG), Brazil in the field of Mechanical Engineering. He has experience in projects on the area of aerodynamics, mainly in aeroelasticity studies involving the flutter phenomenon. He holds interests in the field of CAE development and analysis of granular materials and simulations coupled with multibody dynamics.

André Rebelo Novais is a Geotechnical Civil Engineer for almost three years at Mineração Rio do Norte (a Brazilian mining company). For almost ten years he worked with the realisation and coordination of infrastructure projects (roads and railways). He is currently working with the management of road implementation projects, tailings dams and conveyor belts in engineering by the implementation directorate. He holds a degree in Civil Engineering from Universidade FUMEC in 2015 and a specialisation in geotechnics from PUC-MG in 2020.

1 Introduction

The interest in greater safety within the production area led to the search for a study methodology through computer simulations, in order to validate the dimensions of the windrows at the Teófilo-Cipó Mine, owned by MRN. This work presents the initial steps of intensive study to recreate different work environment conditions, including vehicle and mineral approaches through computer simulation.

The windrows, stabilising or protective berms, are safety elements that have the main function of preventing vehicles operating on the road from leaving the road, in addition to serving as an auxiliary element in the effective functioning of the surface drainage system (Filho, 2011). They are composed of materials found in the soil of the access roads of the mine, being redone or replaced due to the bad weather.

On access roads to the mines, ore transport vehicles travel at an average speed between 40 and 60 km/h, and due to the characteristics of the vehicle there is a high risk for the vehicle driver and other employees who transit the perimeter.

The standard that governs the minimum safety dimensions for windrows in Brazil is NR-22, citing the article shown on Figure 1.

Figure 1 Text extracted from Brazilian Standard NR22 – Occupational Health and Safety in Mining

STANDARD NR22 – Occupational Health and Safety in Mining

22.7.6 Transport in open pit mines must meet the following minimum requirements:

a) the external limits of the stands used as roads must be demarcated and clearly signposted during the day and at night
b) the minimum width of traffic lanes must be twice the width of the largest vehicle used, in the case of single lanes, and three times the width of the largest vehicle used, in the case of single lanes, and three times the width of the largest vehicle used, in the case of single lanes, and thee times the width of the largest vehicle used
c) on the sides of benches or roads where there is a risk of vehicles falling, windrows must be built with a minimum height corresponding to half the diameter of the largest vehicle tire that travels through them

Source: Ministry of Labor and Employment (2022)

To build a virtual behaviour model of the windrow, the DEM methodology, discrete element method (DEM) or distinct element method, which is part of the family of numerical computational simulation methods, was used. This methodology was first developed in the paper ‘A discrete granular modal for granular assemblies’ by Cundall and Strack (1979). Analysis using discrete elements, describes the interaction between granular elements and rigid bodies, e.g., mechanical equipment, DEM methodology can also be used to simulate a wide variety of granular flow and rock mechanics situations.

2 Materials and methods

To build the computational model, the conditions were divided into two main works:

- construction of the vehicle model with parameters and properties similar to those used by the access roads of the Teófilo-Cipó mine
- construction of the physical model for the windrow, following sizing and existing parameters such as area, density, grain size based on the granulometry studies provided and characterisation tests in the windrows of the Teófilo-Cipó Mine.

Data collection was carried out involving the types of vehicles that travel in the mine and the type of soil used for the preparation of the windrow (all data are considered for the construction of the virtual model), through data provided by the MRN. For a better understanding of the mine models built in Brazil, a partial study of projects of other mines in the region of Itabira, Minas Gerais, Brazil was realised (Reis et al., 2014).

In order to simplify the model, virtual models with plastic behaviour of the material that makes up the vehicle were not considered, that is, the impact suffered by the vehicle does not permanently deform its components.

2.1 Construction of the virtual model of the truck

For the elaboration of the virtual model for the truck, a study was realised to survey several parameters for 8 $\times$ 4 vehicles.

The subject of ‘vehicle dynamics’ is concerned with the movements of vehicles on a road surface. The movements of interest are acceleration and breaking, ride, and turning. Dynamic behaviour is determined by the forces imposed on the vehicle from the tyres, gravity and aerodynamics. The vehicle and its components are studied to determine what forces will be produced by each of these sources at a particular maneuver, and how the vehicle will respond to the forces. For that purpose it is essential to establish a rigorous approach to modelling the systems and the conventions that will be user to describe motions (Gillespie, 1992).

Figure 2 shows the actual dimensions for theoretical basis, while Figure 3 shows the appearance of the side view of the built virtual model and Table 1 shows the distribution of mass along the truck.

For the creation of the virtual model, a point of vital focus in the work is to keep the behaviour of the model in such a way as to respect the vehicular dynamics. Some basic concepts are necessary to understand the considerations made to analyse the dynamics of a vehicle. One of these concepts is the accumulated mass, since all the components present move together, the mass of the car can be considered in an enveloped form located in the centre of gravity (CG), taking into account the correct properties of mass and inertia (Naves, 2018).

Figure 2 Technical draw of the 8 × 4 truck – side view

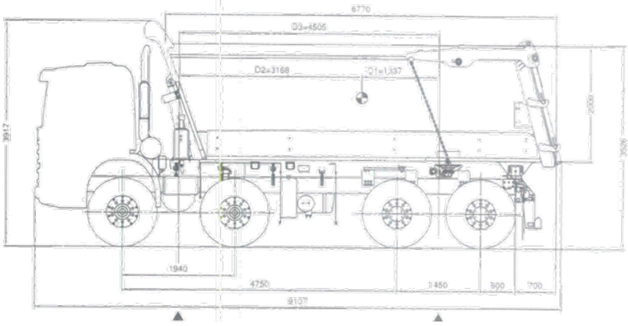


Figure 3 Virtual mode – side view (see online version for colours)

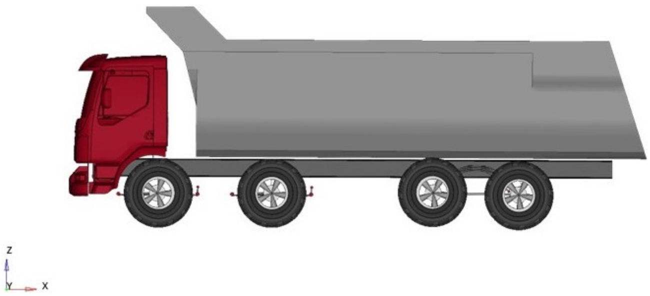


Table 1 Distribution of truck mass through its different components

8 × 4 rigid truck model	
Component	*Mass (kg)*
Bucket (loaded)	54,000.00
Chassis	7,880.00
Cabin	2,000.00
Tyres	840.00
Front axles	100.00
Rear axles	120.00
Suspension (shock absorbers and springs)	280.00
Total	65,220.00

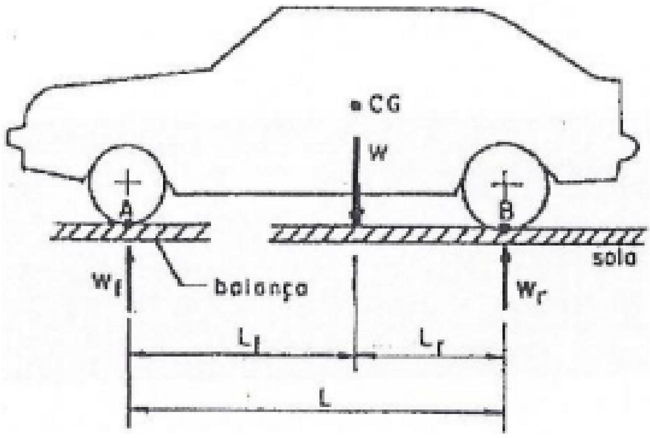
Understanding the positioning of the CG is of paramount importance for most vehicle dynamics analyses, in the case of vehicle simulation, for model adequacy. Figure 4 indicates the load on the front and rear axles, in addition to distances for positioning the CG in a simple vehicle model.

Through the knowledge of the vehicle mass (W), in addition to the distances between axles (L) and one of the loads (W_f or W_r), it is possible, longitudinally, to find the distance values L_f and L_r, according to the equations (1) and (2) between the axles and the vehicle's CG.

$$L_f = \frac{W_r}{W} \cdot L \tag{1}$$

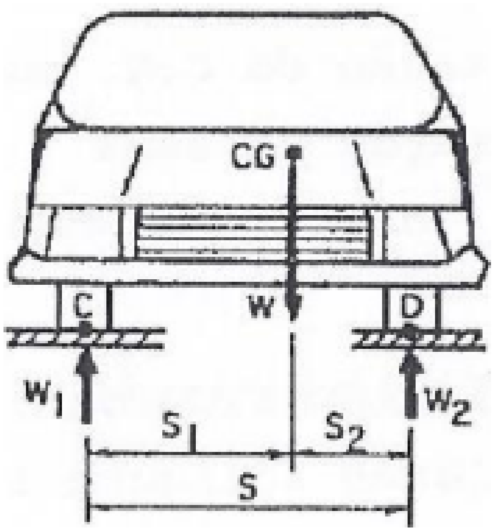
$$L_r = \frac{W_r}{W} \cdot L \tag{2}$$

Figure 4 Longitudinal positioning of the CG



Source: Canale (1989)

Figure 5 Transversal positioning of the vehicle CG



Source: Canale (1989)

Similarly, the transverse position of the CG is obtained. In Figure 5 we have the loads and distances to define the position of the transverse CG determined by the distances S_1 and S_2 calculated by the equations (3) and (4).

$$S_1 = \frac{W_2}{W} \cdot S \tag{3}$$

$$S_2 = \frac{W_1}{W} \cdot S \tag{4}$$

For the positioning of the vertical CG in addition to the moments of inertia found for the body components, the calculation is performed through the CAD model building software itself.

With the help of the literature and extracted from scientific databases, it was also possible to know the coefficients calculated for the truck's suspension system, both between the chassis and axles, and the cabin and chassis, determining for a better approximation of the dynamic behaviour of a truck real vehicle (Abdelkareem et al., 2021). Table 2 shows the distribution of stiffness along the truck elements.

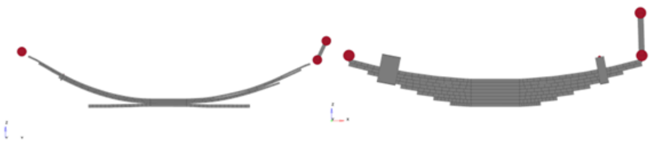
Table 2 Distribution of stiffness and damping values through the truck suspension system components

8 × 4 truck suspension system	
Spring stiffness	*kN/m*
Cab/chassis	145.00
Chassis/front axles	900.00
Chassis/rear axles	1,200.00
Damping coefficient	*kN · s/m*
Cab/chassis	5.50
Chassis/front axles	27.00
Chassis/rear axles	70.00

Springs are crucial suspension elements in cars, needed to minimise impacts and bumps due to road irregularities and create a comfortable ride. A leaf spring, especially of the longitudinal type, is a reliable and persistent element in automotive suspension systems. These springs are generally formed by stacking leafs of steel in progressively longer lengths on top of each other, so that the spring is thicker in the middle to resist bending and thin at the ends where it attaches to the body. A leaf spring must withstand various types of external forces, but the most important task is to resist varying vertical forces (Shokrieh and Rezaei, 2003).

For the elaboration of a virtual model for the damping system, it was necessary to have a detailed understanding of the functioning of the spring sheaf, equipment that constitutes the damping system of heavy vehicles, whose function is to increase the stiffness coefficient established between the tyre and the axle.

Figure 6 Virtual models for front and rear axle spring sheaf of the virtual model (see online version for colours)



Initially, the parameters for leaf springs in heavy vehicles were studied. For such models, we have that the front axles are composed of leaf springs with 3 or 4 steel beams while the rear axles are composed of 8 beams, shown in Figure 6.

The virtual models for spring sheaves, after being built virtually, were tested in a 'bench test' to verify and adjust the stiffness coefficient. The tests were carried out according to the principles established by Hooke's law, in which the stiffness coefficient of a body is obtained by applying an increasing force, and observing the deformation that the body undergoes (Ratajenski, 2009). Hooke's law is represented through formulation on equation (5).

$$F = -k \cdot x \tag{5}$$

where

- F – force applied (N)
- k – body stiffness coefficient (N/m)
- x – linear deformation of the body (mm).

After performing and verifying the stiffness coefficient obtained, the adjustment for the virtual spring beam is performed by changing the thickness of the plates. The greater the thickness of the leaves, the greater the stiffness coefficient see Figure 7.

Figure 7 Graphs with results for the 'bench test' performed virtually (see online version for colours)

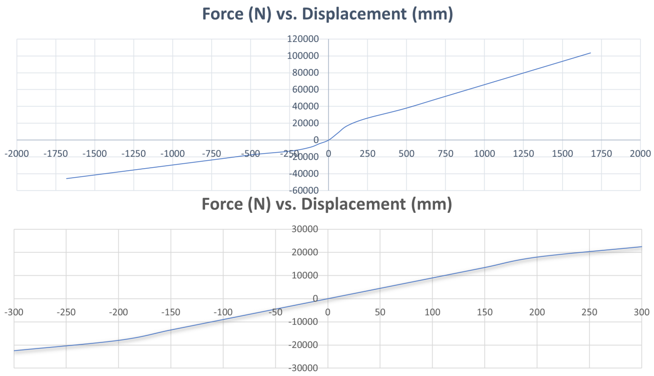
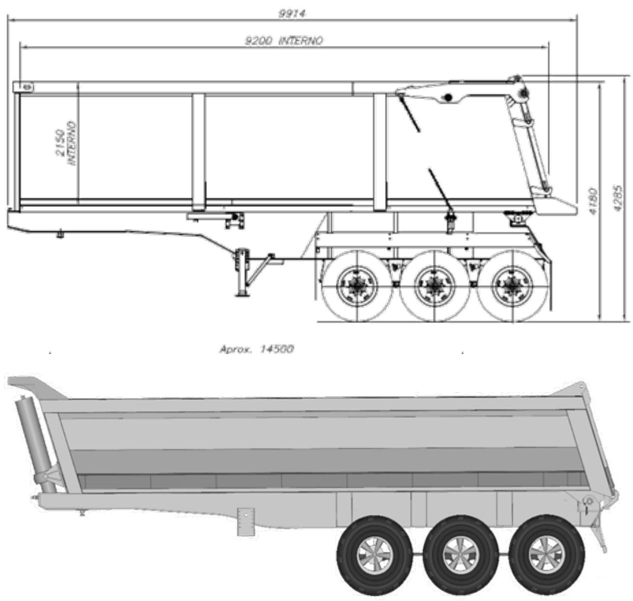


Figure 8 Technical draw and virtual model of the 8 × 4 truck implement – side view



For the construction of the second virtual model for a truck that transits the mine access roads, follow the model of the technical drawing shown on Figures 8 and 9.

To build the virtual model of the 8 × 4 truck with implement, defined in this article as 'articulated truck', the following mass values were considered, found in documents passed on by MRN, in addition to information considered by the software arranged on Table 3.

To determine the values of stiffness and damping coefficients for the suspension system, the values for the 8

× 4 truck of the previous virtual model were considered, followed by Table 4 values for the implement.

For the construction of the virtual vehicle model, some concepts of the same value were used, such as the virtual theoretical model of the tyre, in addition to the constituent materials of the chassis, the cabin, the connecting axles between the tyres and the bucket. Understanding the structural models of a high load capacity vehicle is equivalent to other models developed by the manufacture itself, thus providing a previously studied vehicle model (Sekulic and Dedovic, 2011).

Figure 9 Comparison between implement body from the technical draw and virtual model – rear view

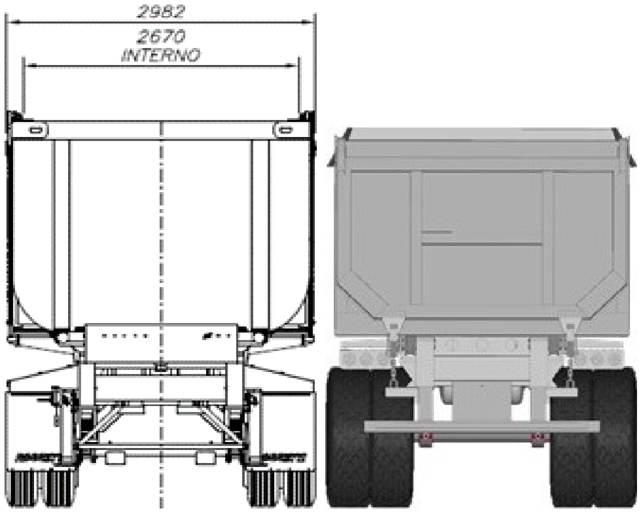


Table 3 Distribution of masses by the components of the 8 × 4 truck with implement

8 × 4 truck model with implement	
Component	*Mass (kg)*
Bucket (loaded)	89,900.00
Chassis	7,880.00
Cabin	2,000.00
Tyres	1,680.00
Front axles	100.00
Rear axles	120.00
Implement axes	180.00
Suspension (shock absorbers and springs)	420.00
Total	102,280.00

Material parameters are extremely important since, when recreating the real model in virtual scale, the type of behaviour caused by windrow impact differs between different materials. This behaviour is defined by the coefficients of friction and restitution between the materials (Zieher and Meywerk, 2015). The comparison between real and virtual model of the tyre is shown on Figure 10.

A fundamental aspect for computer simulation is the determination of friction coefficients, to define contact parameters, among them, the tyre and the ground. These parameters were based on literature. The tyre in contact with the ground generates a longitudinal force considered as rolling resistance formulated on equation (6) (Jazar, 2009).

$$F_r = \mu_r \cdot F_N \tag{6}$$

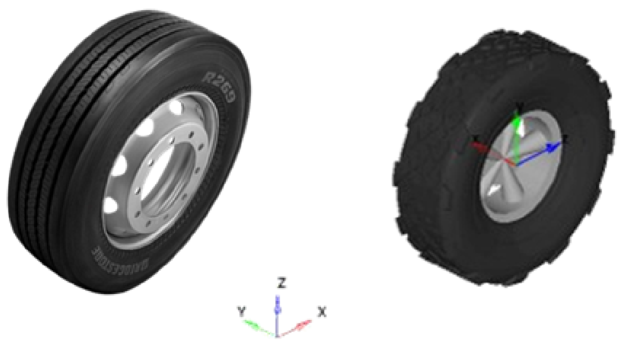
where

- F_r – rolling force (N)
- μ_r – rolling coefficient
- F_N – normal strength (N).

Table 4 Suspension system coefficient values for the 8 × 4 truck with implement

8 × 4 truck suspension system with implement	
Spring stiffness (individual value)	*kN/m*
Cab/chassis	145.00
Chassis/front axles	900.00
Chassis/rear axles	1,200.00
Implement chassis/axes	1,200.00
Damping coefficient (individual value)	*kN · s/m*
Cab/chassis	5.50
Chassis/front axles	27.00
Chassis/rear axles	70.00
Implement chassis/axes	70.00

Figure 10 Comparison between real and virtual model of Tire 295/80 R22.5 (see online version for colours)



When accelerating or braking the vehicle, longitudinal forces develop between the tyre and the ground, see Table 5. The friction force is determined as a longitudinal force that is proportional to the normal force of the body (F_N) formulated on equation (7) (Jazar, 2009).

$$F_X = \mu_f \cdot F_N \tag{7}$$

where

- F_X – longitudinal force (N)
- μ_r – coefficient of friction
- F_N – normal strength (N).

Table 5 Contact friction coefficient between tyre and ground

Coefficient	*Symbol*	*Quantity*	*Unit*
Dynamic friction	$\mu - f$	0.8	–
Rolling friction	$\mu - roll$	0.3	–

Source: Zieher and Meywerk (2015)

2.2 Construction virtual windrow model

Construction of the virtual model of the windrow required standard dimensions and size for MRN mine windrows, in addition to studies on soil composition and parameters for its construction.

For the virtual berm model the material comprising the berm and it is natural angle of repose significantly influence how the berm performs (Thompson, 2019).

Figure 11 Dimensions of the windrow

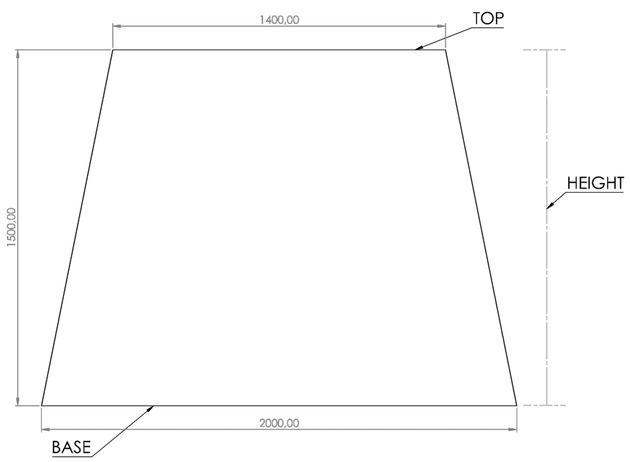


Table 6 Contact coefficients between surfaces and particles

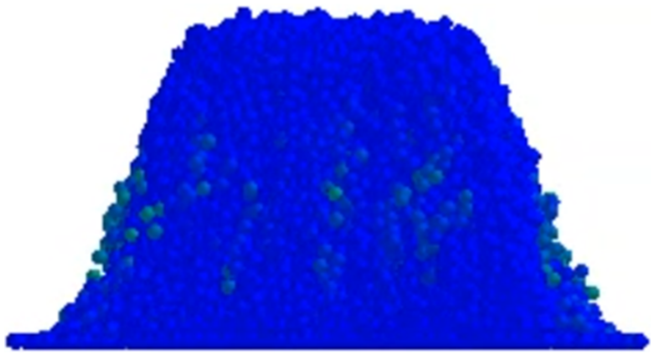
	Contact parameters				
Model/coefficient	*Poisson*	*Restitution*	*Kinetic friction*	*Rolling friction*	*Model elasticity*
Particle/particle	0.3	0.3	1	0.5	1.00E+10
Particle/soil	N/A	0.3	1	0.5	1.00E+10
Particle/truck tyre	N/A	0.6	1	N/A	1.00E+08
Particle/truck steel components	N/A	0.3	1	N/A	1.00E+08

As the information for the standard windrow dimension is confidential, for the purpose of the article, the geometry of a representative windrow is presented according to Figure 11.

Altair's software (EDEM) was used to simulate the behaviour of earth particles when colliding. This behaviour is calculated using the DEM.

When applying the DEM method to solve particle behaviour, different parameters for contact and mechanical behaviour between grains, found in literature, must be known (Thoeni et al., 2018). Among the parameters to be defined in the EDEM software to compose the simulation, we have the friction coefficient between the tyre and the windrow, as shown in Table 6.

Figure 12 Virtual model of windrow, built in EDEM software (see online version for colours)



To build a virtual windrow model, another fundamental parameter is the energy coefficient between the particles, which means, the amount of energy required to disperse particles compacted by gravity and body moisture. The EDEM software presents models for cohesion between particles, among which, according to the need, those that follow the principles of the Hertz-Mindlin model with Johnson-Kendall-Roberts (JKR) cohesion. The Hertz-Mindlin model with JKR cohesion is a contact-cohesive model that takes into account the influence of Van Der Waals forces within the contact zone and allows the user to model strongly adhesive systems such as dry powders or wet materials (Johnson et al., 1971). The necessity for this model was observed since, according to information provided by the MRN, the windrows suffer compaction after the rainy season. The Hertz-Mindlin model with JKR cohesion uses calculations for the following types of force:

- tangential elastic force
- normal dissipation force
- tangential dissipation force.

The normal force for cohesion JKR depends on the overlap between materials (δ) and the interaction parameter, surface energy (γ) as shown on equations (8) and (9).

$$F_{JKR} = -4\sqrt{\pi \cdot \gamma \cdot E} \cdot a^{\frac{3}{2}} + \frac{4E}{3R} \cdot a^3 \tag{8}$$

$$\delta = \frac{a^2}{R} - \sqrt{4 \cdot \pi \cdot \gamma \cdot \frac{a}{E}} \tag{9}$$

where

- F_{JKR} – normal cohesion force JKR (N)
- γ – surface energy (J/m^2)
- δ – overlap (m)
- E – Young's modulus of the material (GPa)
- a – particle contact length (m)
- R – radius of the particle (m).

The presented parameters for the DEM soil model represent in this case the dynamic behaviour for the grains. Each property, if altered, can result in a large set of different physical behaviours, concluding that, the correct parameterisation to each grain model must be conducted in order to ensure the correlation between real-virtual model.

The construction of the windrow virtual model shown on Figure 12 was followed by tests in order to reach proximity behaviour to reality. These tests were conducted based on scientific data collected from windrows constructed and physically tested (Giacomini and Thoeni, 2015). When it is observed that the dynamic behaviour of the virtual windrow approaches the behaviour studied in field, it is reached the conclusion of this stage of the work.

2.3 Definition of conditions to be simulated

As previously presented, the windrow geometries, vehicle models, collision angles, load types and speeds were varied in the simulations. These variations were made to better approximate the real model and better understand the impact of the parameter on the model result arranged on Table 7.

Table 7 Impact conditions for the simulations

Simulation	*Vehicle model*	*Angle of collision (°)*	*Speed (km/h)*
Leira_001 Leira_002 Naves models 1 to 3	Rigid truck 8 × 4 model	5, 10 and 15	30, 40 and 60
Leira_001 Leira_002 Naves models 1 to 3	Articulated truck 8 × 4 model	5, 10 and 15	40 and 60

Table 8 Comparative windrow dimensions

Windrow model	*Base (m)*	*Top (m)*	*Height (m)*
Leira_001	100%	100%	100%
Leira_002	167%	214%	169%
Naves_001	100%	143%	163%
Naves_002	120%	143%	163%
Naves_003	169%	229%	188%

Since the data for the windrow dimensions is classified due to legal boundaries, the information related to the windrow model is relative, considering the base dimensions of windrow Leira_001, according to Table 8.

2.4 Definition of basic parameters for analysis of results

Once the parameters for the physical and dynamic behaviour of the windrow components (soil, windrow geometry, earth compaction) and vehicle (mass, inertia, material components, connection between components and others) definition for interpretation of results. With this in mind, the solution according to the advance of the vehicle's first axis was proposed. This decision was made based on the fact that the windrow transposition only occurs after a certain percentage of the vehicle has been advanced. Aiming at the driver's safety, it is understood that when the vehicle falls and comes to a complete stop inside the access road, there is no risk of other accidents occurring inside the mine, since the environment is controlled. For a better understanding of the system, see Figures 13, 14 and 15.

Figure 13 Simplification for understanding the level of advance of the vehicle in the windrow (see online version for colours)

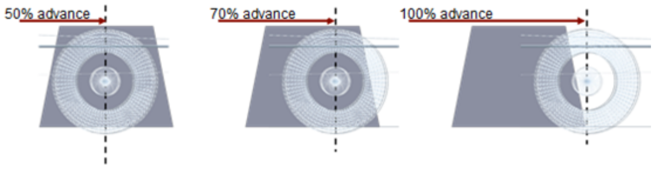


Figure 14 Example of simulation with failed conditions (see online version for colours)

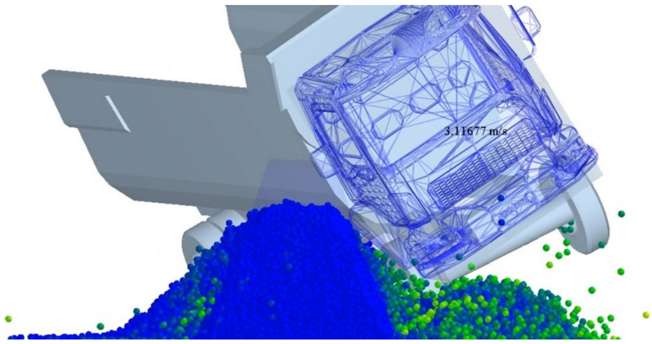
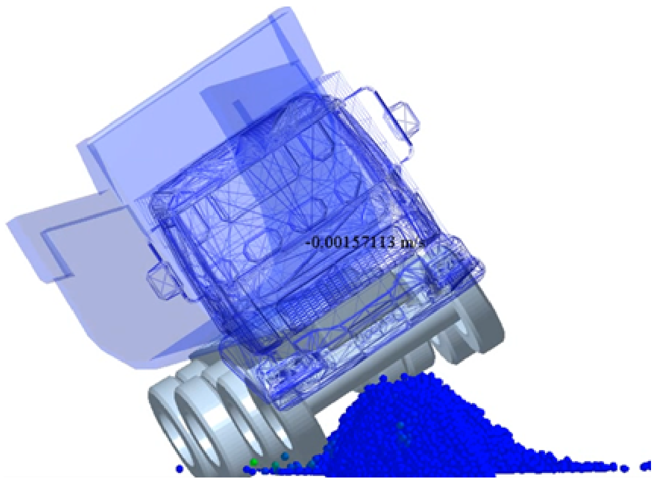


Figure 15 Example of simulation with approved conditions (see online version for colours)



3 Results

A total of 27 simulations were conducted to study and analyse the vehicle's dynamic behaviour. For the first 11, the conditions of speed and type of vehicle for collision in different geometric shapes of windrow were changed shown in Figure 16.

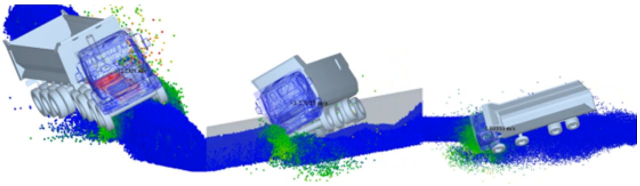


Figure 16 Collision simulation between vehicle and virtual windrow (see online version for colours)

It was concluded, with these simulations, that the geometry windrow named Leira_001, does not have the size and structure to resist the impact of vehicles, rigid and articulated, when in fully loaded conditions, speed of 40 km/h and a collision angle of 15°.

For Leira_002, with more robust geometry and size, there was a positive result, both at a collision speed of 40 km/h and at 60 km/h.

Aiming the economy of material and space occupied, simulations were realised with windrows of intermediate size. The intermediate-sized windrows were named Naves_001 to Naves_005. When completed, it was observed that Leira_002 was oversized, since Naves_005 met all the necessary safety conditions, with smaller proportions.

As the main reason of the study was to understand the safety conditions provided by Leira_001, simulations 12 to 27, a dedicated study was elaborated with different collision parameters to better understand the physical limits of the windrow.

Table 9 Windrow behaviour results table according to the simulated parameters

Speed (km/h)	*Angle of collision (°)*	*CURB*	*1/2 load*	*GVW*
30	5	Approved	Approved	Approved
	10	Approved	Approved	Approved
	15	Approved	Approved with remarks	Approved with remarks
40	5	Approved	Approved	Approved
	10	Approved	Approved	Disapproved
	15	Disapproved	Approved with remarks	Disapproved
60	5	Approved	Approved	Approved
	10	Approved with remarks	Disapproved	Disapproved
	15	Disapproved	Disapproved	Disapproved

With the final combined time of the simulations performed of approximately 965 hours of computer simulation, including the time for simulations of adaptation of the virtual model to reality was developed for Leira_001, the main reason for the study.

Among the 27 simulation models performed, we have five simulations that bring, with greater relevance, results to the analysis. Among them two simulations for better understanding of the windrow's energy absorption capacity at impact, see Figure 17.

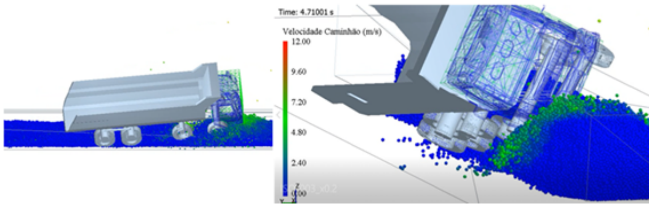


Figure 17 SIM_003 – Leira_002 – impact condition: speed 40 km/h – collision angle: 15° – GVW load condition (see online version for colours)

Simulation 003 presents Leira_002, with a more robust size, capable of interrupting the transfer of the fully loaded virtual vehicle model, see Figure 18.

Figure 18 SIM_010 – Naves_005 – impact condition: speed 60 km/h – collision angle: 15° – GVW load condition (see online version for colours)

Simulation 010 presents virtual windrow Naves_005, with intermediate size, between Leira_001 and Leira_002, capable of withstanding and being approved in conditions to ensured security according to the computational field collision with the fully loaded rigid vehicle model. This result broadened the understanding of the factors presented as determinants for greater windrow resistance capacity.

Two fundamental simulations for understanding the resistance capacity of Leira_001 were realised through the study directed on it, see Figures 19, 20 and 21.

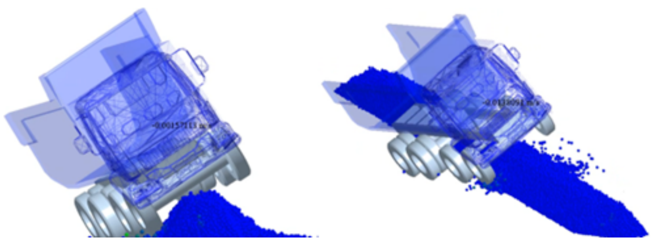


Figure 19 SIM_016 – Leira_001 – impact condition: speed 30 km/h – impact angle 15° – load condition CURB (see online version for colours)

The simulations presented above show the result of the computer simulations alternating in three vehicle load states. With the results presented in Table 9, the impact of the final weight of the vehicle is observed. It should be noted that, in addition to changes in weights, consequent changes, such as changes in the vehicle's CG and moment of inertia, led to the result presented. For future studies, a broader analysis is suggested, with variations on collision conditions and soil models, in order to optimise the study results.

Figure 20 SIM_018 – Leira_001 – impact condition: speed 30 km/h – impact angle 15° – load condition 1/2 load (see online version for colours)

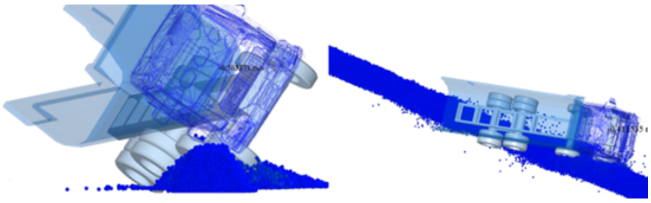


Figure 21 SIM_019 – Leira_001 – impact condition: speed 30 km/h – impact angle 15° – GVW load condition (see online version for colours)

4 Discussion

The project proved to be extremely important to demonstrate the impact of different variables for vehicle impact characteristics on windrows. Those variables include, speed, soil conditions and angle of collision.

It was understood that when changing the windrow dimensions, the parameter with the greatest impact is the top width, which means, as long as it is physically allowed to change this width (there is a limit, since the soil does not remain compacted). This parameter will have the greatest influence on the probability of the vehicle and its driver not having serious accidents.

It was also possible to observe an impact on the variation of the vehicle's loading condition. The vehicle in the empty loading condition, for example, presented worse results crossing the windrow in impact conditions similar to those of the fully loaded vehicle.

5 Conclusions

Every impact analysis requires extreme care and attention since each parameter plays a fundamental role in the simulation result. As presented in this article, different studies were conducted in order to portray in the simulation a result more consistent with reality.

The main challenge of the work was the research of parameters that approached the real coefficients of materials and vehicle components, since this information is highly confidential to manufacturers. Another challenge presented was the understanding of the impact of each parameter on the behaviour of virtual models, whether the vehicle or the windrow model. Each parameter was meticulously adjusted following previous studies, in addition to a detailed soil granulometry provided by MRN.

From the understanding of the dynamic behaviour of vehicles and the responses to the variation of established coefficients, it was possible to build a virtual model that more realistically represented the real model. From this realistic interaction model between vehicle and windrow, changes in parameters such as speed, windrow size and collision angle allowed the construction of a representative table of the results evaluation.

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