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OPERATION VARIABLES INFLUENCE ON STRUCTURAL INTEGRITY OF MINING HAUL TRUCK'S CHASSIS

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Abstract. *Mining haul trucks operate in severe conditions, transporting large payloads along unpaved roads during full-day services. These conditions induce premature failures in truck's chassis, requiring corrective maintenance or even early fleet renewal, causing financial losses or decreasing mine productivity due to truck's unavailability. Several operation parameters, such as speed, road design and conditions, amount and arrangement of payload, affect the chassis structural integrity, but is difficult to know which of them are most harmful, since they act simultaneously, preventing us from knowing their individual contribution to failures. This paper proposes an analysis methodology of chassis structural behavior of mining haul trucks, submitted to different operation variables, allowing the evaluation of their individual influences and harmfulness. Using concepts of fatigue life calculations, damage accumulation and vehicle dynamics, a haul truck chassis 3D model was subjected to several operational configurations, through a numerical method using a meshfree software. The results present a mapping of the 40 most critical spots in a commercial haul truck's chassis and a failure ranking between them. In addition, this paper shows a comparative analysis of fatigue life consumption effect of different operation variables such as uphill and downhill grades, lateral road slope (super-elevation), curvatures radii, traffic speed and payload balance. Knowledge about the individual influence of these operation variables on the chassis service life allows truck's users and manufacturers to better evaluate the harmfulness of different mine sites, create engineering actions and good practice manuals to mitigate the effects of most injurious operations and have a better failure predictability.*

Keywords: *mining haul truck, structural integrity, fatigue life, operation variables*

1. INTRODUCTION

Mining haul trucks lifetime is limited by its chassis durability, set to 70.000 hours for commercial truck models. However, severe operational conditions, such as large payload transportation along unpaved roads during full-day services, induce premature failures in truck's chassis (cracks), requiring corrective maintenance or even early fleet renewal (Srilatha, 2017).

The truck operates on a very dynamic path, with different grades of uphills and downhills, in curves with different radii and directions, with its bucket loaded and unloaded, with different speeds, etc. All of these variables contribute to create variant mechanical stresses on chassis along the operation, accelerating its fatigue damage. However, among all these evolved variables, it is not known for sure which ones are more harmful to chassis fatigue life consumption, as they often act simultaneously or are not monitored.

1.1 Objective and scope of work

The primary objective of this research is to present the most critical spots in a commercial haul truck chassis, creating a fatigue failure ranking between them. Then, evaluate the individual influence that each operational variable has on structural integrity of these critical spots on chassis, creating a ranking of most harmful operations. After a better understanding of fatigue life consumption by each operational variable, practical solutions can be developed by truck manufacturers and user in order to mitigate the harmful effects of these variables in different mine sites, improving chassis lifetime and structural reliability, in addition to reducing corrective maintenance expenses.

2. BACKGROUD

In a mining operation, the material removed from the pit area needs to be transported to a crusher or storage piles, an operation normally carried out by haul trucks. The loading and transporting stages (loaded and empty) are the most critical phases in the mine's production cycle, as they represent more than 60% of the operating cost among all mine stages, motivated by the high-cost equipment acquisition, high fuel consumption and maintenance costs (Çetin, 2004). Haul trucks play an important role in these costs, as they can cost up to U$6mi and commonly present premature failures in their chassis, increasing maintenance costs and causing financial losses due to the equipment unavailability. These failures usually happen due to the mechanical fatigue, and occur in the truck chassis through the formation of cracks, caused by cyclical efforts coming from different load sources to which the truck is submitted (Srilatha, 2017). The chassis geometry and mechanical properties, as the common operational variables in haul truck services are presented below.

2.1 Haul truck chassis

The haul truck adopted in this work is a commercial model with a payload limit of approximately 233.000 kg and an operating gross weight of 384.000 kg. Its chassis is manufactured using a laminated and a cast steels, welded together, as shown in figure 1. The mechanical properties of both materials are presented in table 1, using data from a real chassis collected through metallographic, traction and fatigue tests (Gandra, 2017). It is possible to observe that, although they are different materials, their mechanical properties are very similar.

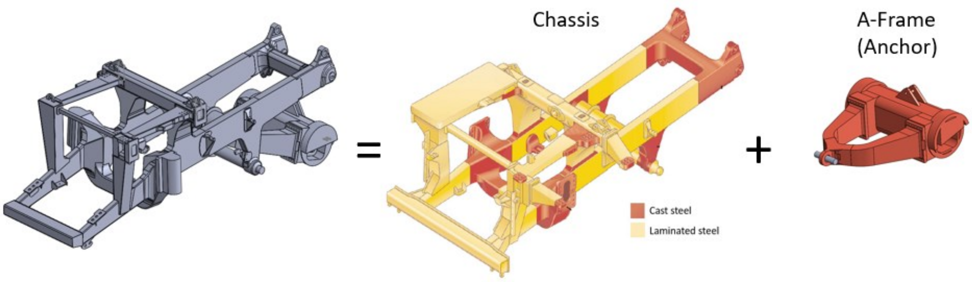

Figure 1: Haul truck chassis schematic figure

Table 1: Mechanical properties of haul truck chassis materials

Material	Yield Stress	Tensile strength limit	Elongation	Endurance limit
Laminated steel	339 MPa	488 MPa	31 %	NA
Cast steel	331 MPa	509 MPa	28 %	260 MPa

The chassis limits haul truck's lifetime since, while other items such as tires, engine and suspension are changed after reaching their lifecycle, the chassis does not allow this possibility. Its estimated lifetime is 70,000 hours, however, before reaching this time, it is common to occur premature failures, such as cracks at various spots, caused by fatigue. To prevent these cracks from being catastrophic, mining companies added to their maintenance checklists, inspection and corrective maintenance, applying electrode welding on cracks, reducing their growth, as shown in figure 2.

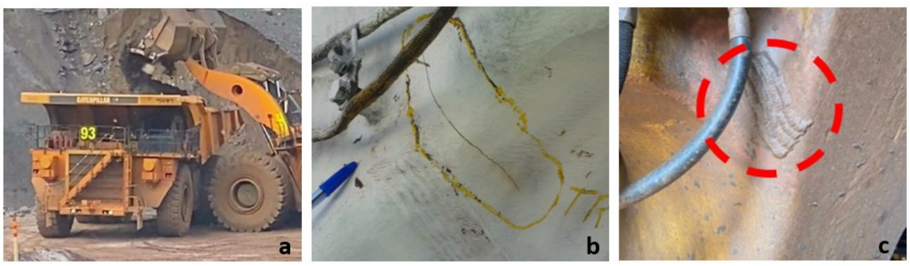

Figure 2: Haul truck in service (a), its premature failures (cracks) (b) and corrective maintenance applied (welding) (c)

2.2 Haul truck operational variables

Haul truck operating conditions are very severe, as it travels on unpaved roads in long journeys and with high load in its bucket, reaching up to 400 ton of payload in larger trucks. The reference haul truck of this work, transports up to approximately 233 ton, with a gross operating weight (truck and payload weight) of 384 ton. Haul trucks use is very intense, as it happens 24 hours a day, 7 days a week, and, although this is not a reality at all mines, it is a trend, aiming a better equipment use. In addition to the heavy payload and constant use, in open-pit mines, haul trucks travel on unpaved roads, under the action of sun and rain, with many uphills, downhills and curves, which characterizes a severe traffic condition.

According to (Spinelli, 2017), a vehicle is a dynamic system that experiences a very broad spectrum of vibrations, with numerous excitation sources. For haul trucks, some of these sources come from road irregularities, road geometry and driving mode (lateral/frontal inclinations and curves), mechanical components and basket loading/unloading operations. These load applications have distinct amplitudes and frequencies and, therefore, induce different damage to haul truck chassis. Loads caused by road irregularities or mechanical components usually have low amplitude and are absorbed by the tires elastic deformations or by vibration isolating devices (hydraulic and elastomeric pads), not being transferred to chassis. Excitations generated in loading and dumping stages, although inducing high stress caused by shock on bucket and stress release during dumping, occur once in each truck operational cycle, occurring in low frequency and, therefore, having little influence on chassis fatigue (Vieira and Torres, 2017). Contrarily, stress from road geometry variation, as uphill and downhill grades, curvature radii and lateral road inclination (camber/cross-fall), constantly occur in haul truck services, modifying, more severely, the stresses on chassis, as they cause the body to rotate in lateral and longitudinal directions (roll and pitch angles), changing load positions. In addition, speed is also an important variable because, in curved sections, speed can intensify the body roll angle, also modifying the load condition. Therefore, the operational variables covered in this work are those who change significantly the load status on chassis, described below:

- Uphill and downhill grade
- Curvature radius
- Camber/cross-fall (road lateral inclination)
- Superelevation (banking on curvature)
- Speed
- Payload distribution

After defined the haul truck model studied in this work, its chassis geometric and material characteristics, the structural problem of this component and possible operational variables responsible for this damage, a evaluation methodology of chassis structural behavior when in operation is presented below.

3. METHODOLOGY

Figure 3 presents the methodology flowchart adopted in this work, which has three main outputs, namely: The creation of a ranking of the most critical points on truck chassis; Creation of a ranking of the most critical daily haul truck operations, from the point of view of fatigue analysis; Definition of which payload distribution on the haul truck bucket is most critical to the chassis structural integrity.

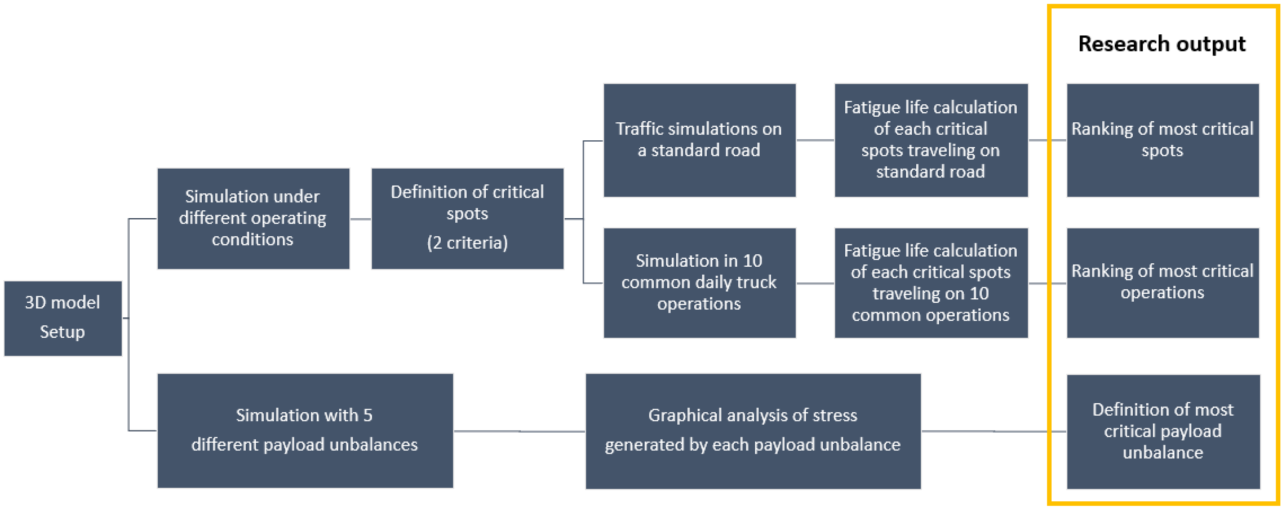

Figure 3: Work methodology flowchart

3.1 3D model and analyses set-up

All structural analysis presented in this work were carried out by computer software. The 3D model dimensions were collected from a real haul truck chassis scan, having a high level of detail (Gandra, 2017). Some simplifications were made, removing flanges and supports, in order to reduce computational processing time without changing its structural rigidity, using Solidworks. Structural analyses were performed using the software Simsolid, which uses meshfree calculation method, creating mathematical equations through a point cloud (nodes), spread throughout the model and its contours, without dividing it into elements, just as it is done in finite element method (meshes), bringing more reliability in complex assemblies with large deformations and reducing processing time (Altair Engineering Inc., 2020). The results obtained from a meshfree software are suitable for this work, because it is a primary analysis of a complex theme. To improve results accuracy and have greater reliability, its necessary to use calculations methodologies with higher order mathematical functions, however, when using commercial software such as Simsolid, this is not possible, due to closed source code.

In the 3D model setup for structural analysis, material mechanical properties, restriction conditions and damping condition (suspensions) were inserted. In addition, static loads were included, that is, loads always applied on haul truck structure, such as chassis weight, and also mechanical components weight such as engine, radiator, transmissions, fuel and oil tank, among others.

In addition to static loads, variable loads were also inserted, that is, those coming from payload amount and position on bucket. The payload loads are not transferred homogeneously to chassis, but punctually and unevenly at the bucket/frame coupling points. There are 6 coupling points where bucket lean on chassis, through which is transferred the empty bucket weight (33.189 kgf), added to payload weight (232.711 kgf) totaling 265.900 kgf.

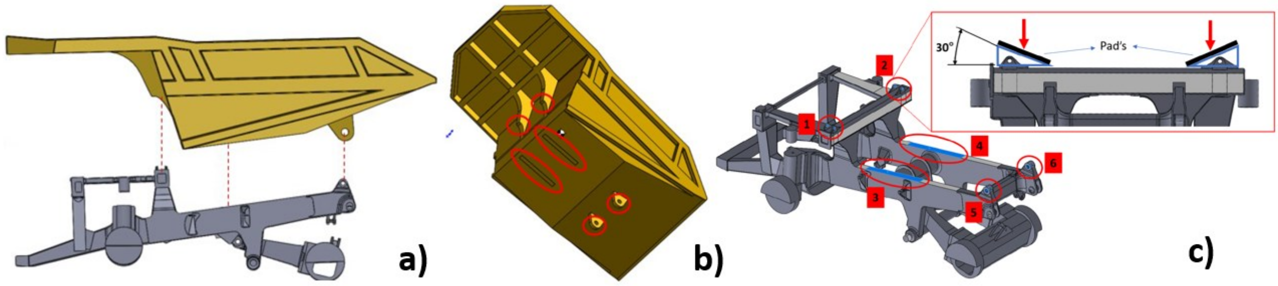

Figure 4: Bucket/chassis coupling points (a), bucket contact points (b) and chassis contact points (c)

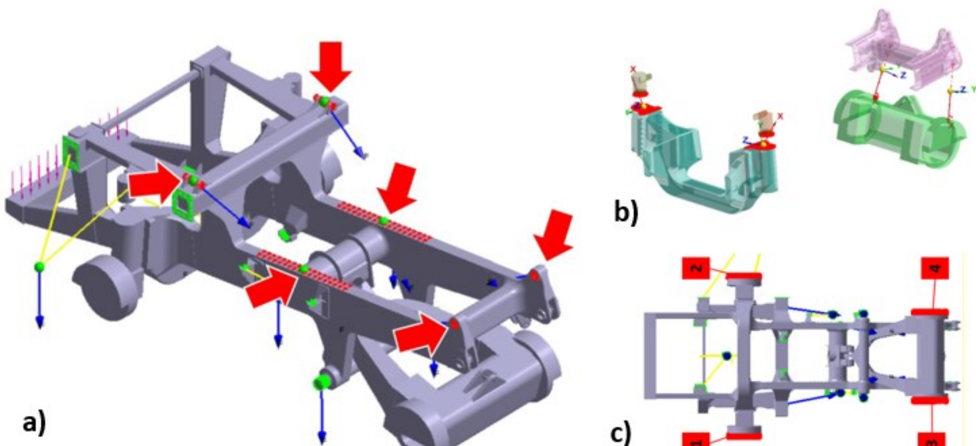

Figure 5: Chassis structural analysis setup, inputing loads (a), bumpings (b) and movement restrictions (c)

The 3D model and analysis set-up were an important pre-processing step for all following methodologies, as they were performed in a virtual simulation environment. Using this set-up, several chassis structural analyses operating under different conditions were carried out, as described in the methodologies below.

3.2 Evaluation of chassis most critical points

The different loads to which the chassis is subjected throughout its operation create unequal stresses in the chassis and, therefore, some regions are more prone to fatigue failure than others. The spots most susceptible to failure are those that present very high stress values (high mean stress) in addition to greater variation of these stresses along the time (high alternating stresses). This work analyzes which points of the haul truck chassis are more susceptible to fatigue failure (critical points), creating a ranking of the most critical ones.

To define which chassis points are critical, Von Mises stress values were collected from 20 structural analysis of the truck with different payload distribution on its bucket and on different floor slopes, in order to obtain a wide spectrum of loads. Five payload positions were simulated, as shown in image 6, and for each of them, the haul truck was simulated on a different floor inclination, namely: Flat floor; Camber 3% (lateral inclination); 12% uphill; 12% downhill;

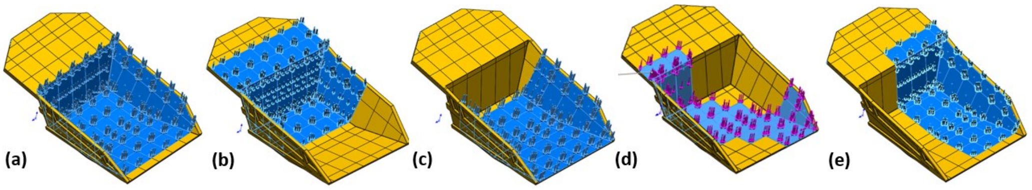

Figure 6: Payload distribution types – Balanced (a) and also the front (b), rear (c), diagonal (d) and lateral (e) unbalances

From the Von Mises stresses of these analyses, the critical points were defined based on two criteria, one numerical and other visual. To be defined as a critical point, the analyzed region must meet one or both of the criteria described below:

- Numerical criteria: Spots where Von Mises stress is greater than or equal to 1/3 of material yield stress
- Visual criteria: Spots with cracks in a used haul truck chassis analyzed by dye penetrant inspection (Gandra, 2017)

After defining the critical points, chassis is subjected to other structural analyses simulating truck traveling on a standard mining road. For this, a virtual standard track was created, composed by different segments, according to figure 7. Three levels of severity are created for this standard track, called track 1, 2 and 3 and the differences between them are:

- Track 01: Track with low severity, where operational variables such as speed, curve radii, slope of uphills/downhills and superelevation angles follow the values suggested by one mining road manual (Thompson, 2011).
- Track 02: Track with medium severity, where uphills and downhills have variable inclination grades, higher speed in some track segments and some curves without superelevations. All these changes tend to get worse the truck's operating conditions, harming its chassis structural integrity.
- Track 03: Track with high severity, where the parameters of track 02 were kept, except for the speed, which was increased, harming even more the operating conditions in some track segments.

For these three tracks, the haul truck travels on each of them with the bucket fully loaded and then unloaded, in sequence. Thus, the route through the 3 tracks loaded and unloaded is named as one full cycle, and is used as a parameter for critical points ranking creation.

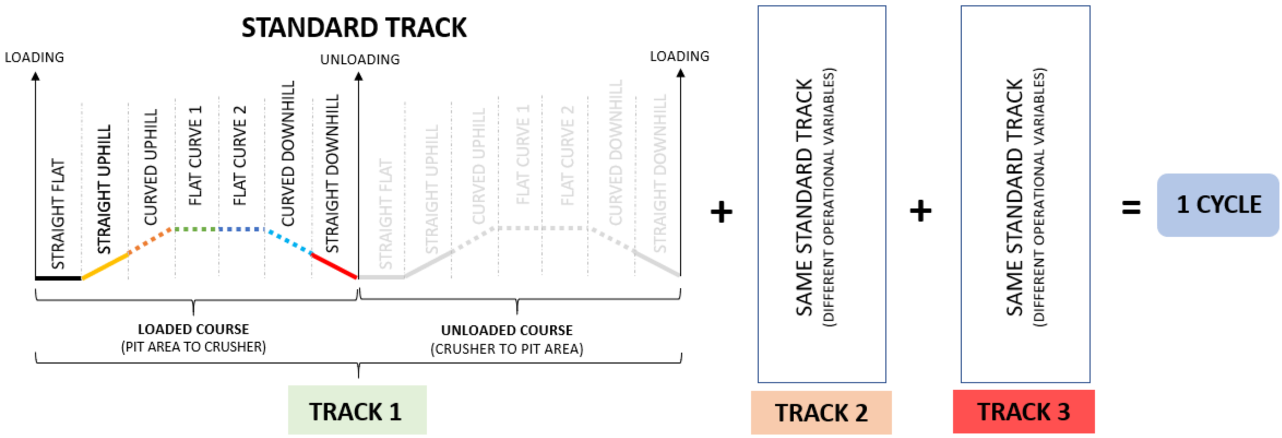

Figure 7: Standard track, its parts and three variations (track 1, 2 and 3), creating one full cycle

For each standard track segment, a static structural simulation with a dynamic aspect (quasi-static) was performed, that is, analytically, calculate the pitch and roll angles induced by operating variables in each track segment, and reposition the loads with the corrected inclination angle on a static structural analysis. In this way, it was possible to obtain the dynamic stress response of each critical point which, although collected from a static analysis, address a dynamic operating condition. The choice of a quasi-static analysis was adopted for this work in order to reduce processing time, as the amount of analysis is very high, and performing them all dynamically would take a long time. As this work is an introductory analysis to truck chassis fatigue topic, quasi-static analysis is an adequate method, as it presents, even less precisely and without realistic numerical results, sufficient basis to define the most critical spots and operations to truck chassis. Future works adopting dynamic analysis (multiple and flexible bodies) can increase the results precision and reliability, although increasing computational processing time, including analyzing other dynamic loads that change chassis fatigue life, such as mechanical components vibrations or loads from track irregularities (holes and corrugations).

For uphill and downhill track segments, the inclination grade is adopted as the pitch angle. On the other hand, for segments of straight curves, where there is a load lateral unbalance, the body roll angle is calculated according to the formulation of Gillespie (1992), which defines the roll angle as a function of mass transported, speed, curve radius, axle/suspension geometry and vertical/rolling suspension's stiffness. Tires lateral displacements are disregarded. On curved uphill/downhill segments, a resulting body inclination from pitch and roll angle is calculated. Lateral inclinations of straight or curved sections from camber angles or curves superelevation are also considered in the truck body resulting slope.

As a sum, 50 structural analyses were carried out, each one representing a track segment with its respective operational variables and with loads positioned according to pitch and roll angles calculated analytically. The Von Mises stress for each of the critical points were collected, creating a stress history along the standard track traffic (1 cycle). Using the Rain Flow fatigue cycle counting method (Matsuishi and Endo, 1968), the number of fatigue-inducing loads along the cycle were counted, and then, fatigue damage accumulated in one cycle was calculated through the Palmgreen-Miner theory (Palmgren, 1924), obtaining the number of cycles that each critical point can perform until failure, that is, the number of times the truck can travel along the standard track until crack. Data were organized in ascending order of damage, creating a ranking of critical points, showing which points are more sensitive to fatigue failure, presented in the results section of this work.

3.3 Evaluation of haul truck most critical operations to chassis structural integrity

In addition to knowing the chassis most critical points from a fatigue analysis, this work also seeks to rate which operations during haul truck's services on mining roads cause more fatigue damage to its chassis. For this, 10 common haul truck operating conditions were selected, summarized in table 2 and, to each one of them, the fatigue damage was calculated, summarized in the form of a ranking of most critical operations to truck's chassis.

The parameters highlighted in green on table 2 show operational variables modified in relation to the previous track segment, indicating exactly what comparison is made between one track segment and the other (e.g., between segment 1 and 2, the difference is the uphill slope from 8 to 10%). Thus, when comparing fatigue damage between these segments, it is possible to know the influence that this operational variable has on chassis fatigue behavior.

Table 2: 10 common mining roads geometry traveled by haul trucks and its operational variables

Segment	Type	Longitudinal grade (%)	Speed (Km/h)	Curve Radius (m)	Superelevation (%)
1	Straight uphill	8	8	-	-
2	Straight uphill	10	8	-	-
3	Curved uphill	10	8	200	-
4	Straight downhill	-8	16	-	-
5	Straight downhill	-10	16	-	-
6	Curved downhill	-10	16	200	-
7	Straight curve	-	16,33	30	-
8	Straight curve	-	16,33	200	-
9	Straight curve	-	42,16	200	-
10	Straight curve	-	42,16	200	7

Just like in critical points ranking methodology, the operational variables used in this work section such as speeds, curve radii, slope of uphills/downhills and superelevation angles are based on values suggested by one manual of mining roads (Thompson, 2011). Evaluating the damage caused by each operation of table 2, it was possible to discover a comparative influence of these operational variables on chassis structural behavior.

To conduct this comparative analysis, it was necessary to create an equal methodology for the simulation of all operations. So, a standard traffic condition was created, where the truck always starts from a straight flat road (most stable operating condition) to the track segments represented in table 2. Then, Von Mises stress values were collected, creating a stress history of two loads in sequence (straight flat floor and studied operation), but always starting from the same benchmark (straight flat floor), enabling a comparative fatigue analysis. Then, the fatigue life expectancy of each 40 critical points were calculated, that is, the number of times each point withstands until the failure induced by this operation occur, using the Soderberg fatigue failure criterion (Budynas and Nisbett, 2011). The ranking of most critical operations was obtained through the average of fatigue life expectancy of 10 less resistant points in order to create a ranking with points that are more likely to fracture.

3.4 Definition of most critical payload distribution to chassis structural integrity

This work also presents a chassis comparative structural analysis when the haul truck is loaded on a flat floor with five different payload positionings, namely, one uniformly distributed load and four types of unbalanced load, as shown in Figure 6. Simulations were conducted statically using the Simsolid software, and Von Mises stresses of each situation were graphically analyzed, allowing to define which payload distribution is the most critical for chassis structural integrity.

4. RESULTS AND DISCUSSION

The results obtained from three methodologies presented before are described below:

4.1 Ranking of most critical spots

Following the criteria for critical points definition described above, 40 critical points were obtained, 22 attended the numerical criteria, 10 attended the visual criteria and 8 points met both criteria, as described in figure 8.

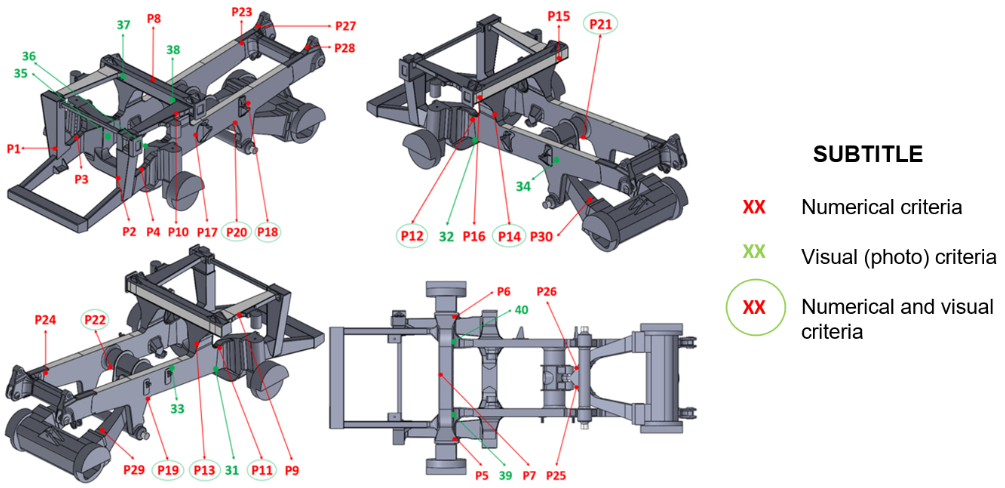

Figure 8: 40 critical points of haul truck chassis and which criteria they attend

It is observed that critical points are well spread throughout the entire chassis structure, on both equipment sides, ensuring a complete structure analysis. Figure 9 presents the critical points fatigue ranking and their respective number of cycles until failure.

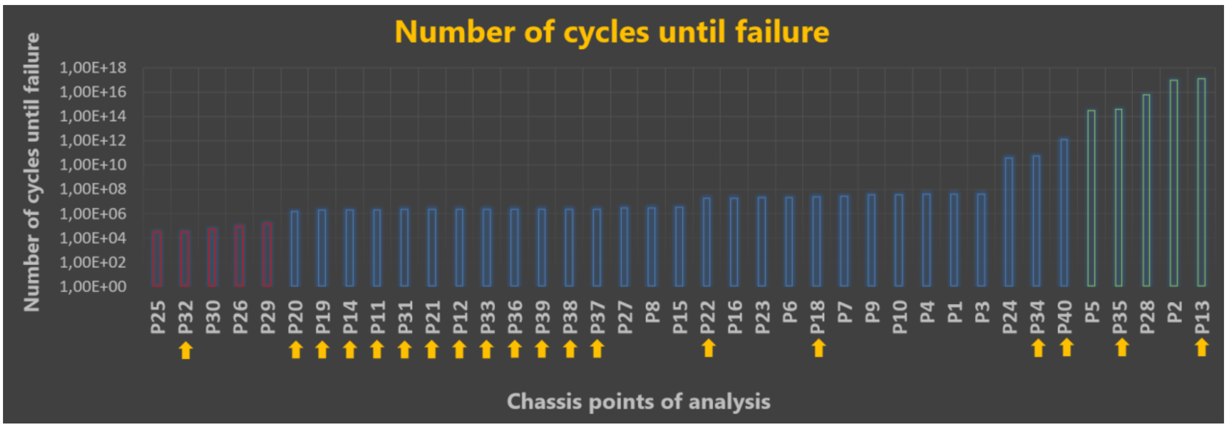

Figure 9: Ranking failure of haul truck chassis critical points

Among the 5 most critical points, highlighted in red in figure 9, 4 are located in the truck's rear region (points 25, 30, 26 and 29), at the A-frame component (anchor), supporting between 10.000 and 100.000 cycles of traveling through the standard track until fail. A-frame is a critical component because, when the truck is loaded, the payload induces very high efforts on it, even when in stable operating conditions, due to payload high weight concentrated in this region. When unloaded, there is a very large stress reduction, increasing the alternating stress in the historical load of these spots, which also increase the damage accumulation, accelerating fatigue life consumption.

Point 32, although not in the rear region, is the second most critical point and deserves attention, as the points 11, 20 and 21. As shown in Figure 10, stress formation in these points is strongly influenced by operations in curved sections, causing load lateral unbalance, and raising stress amplitude. In addition, the figure 10 shows the stress history of some of the chassis most critical points (according to ranking) when traveling on the standard track and, it is possible to see a very large stress amplitude difference when the truck's bucket is loaded vs. unloaded, proving the theory that points most susceptible to failure presents large stress amplitude variation (high alternating stress).

The points highlighted with yellow arrows represent those that presented cracks in the real chassis analyzed by dye penetrant inspection (visual criteria), and it is possible to observe an agreement between these regions and the most critical points in this ranking, demonstrating the results reliability of this ranking. Points 25, 30, 26 and 29 are not marked with arrows because they belong to the A-frame, which was not analyzed by dye penetrant inspection, only the chassis.

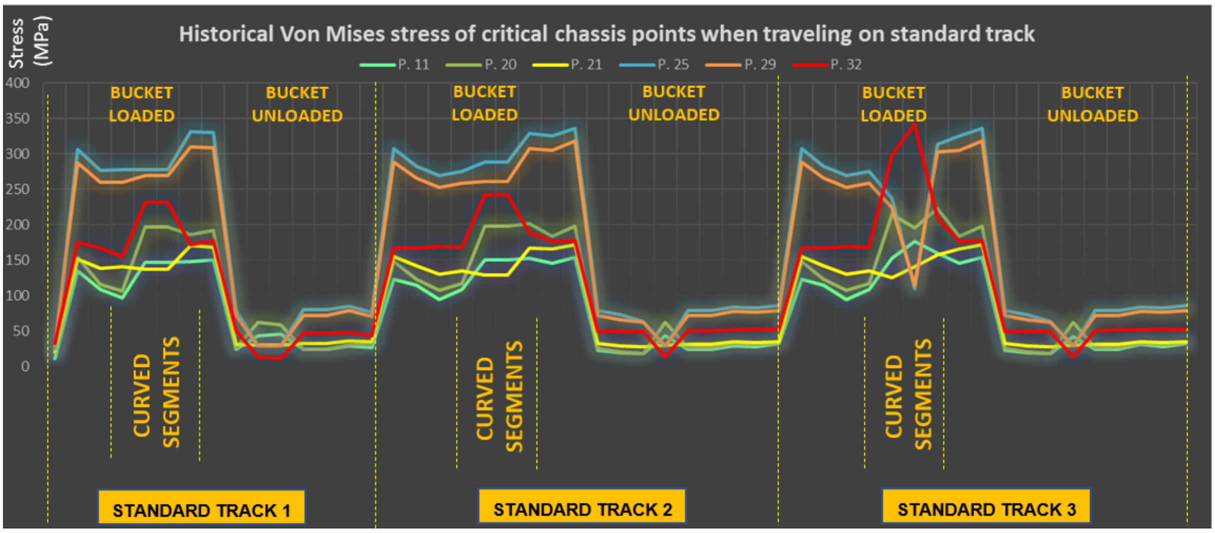

Figure 10: Stress history of some chassis critical points when traveling through standart track

Some of the critical spots are located in welded joints or near it, where mechanical properties are expected to be different in relation to base material. However, this difference was not adopted in this paper, since it is a preliminary analysis of spots most susceptible to failure, without numerically and absolutely quantifying the moment of failure. So, considering the welded joints mechanical properties equal to base materials is acceptable. Future studies addressing true mechanical properties and concepts of welded joints failure will bring greater results reliability.

4.2 Ranking of most critical operations

Figure 10 presents the fatigue failure ranking of 10 common haul truck operations, using the comparative method described in the methodology.

The three most critical operations (7, 9 and 10) are flat curves, motivated by the high roll angle that occurs in curved sections with high speed or small radii, creating a load unbalance (single side overload). Operations 7 and 9, although are curves with different radii and speeds, presented equal damage, because the speed chosen was the maximum indicated by the manufacturer according to the curve radius, demonstrating that fatigue is linked to the relation between radius and speed and consequently, to the roll angle. Operations 10 and 9 are flat curves with the same operating parameters, however, operation 10 has a 7% superelevation, resulting in 30 times longer life expectancy, demonstrating that the use of this geometry is beneficial to chassis durability. The 4th most critical operation is the curved downhill (operation 6), which has a life expectancy 70% greater than a curved uphill (operation 3), due to speed on downhill be higher than on uphill, creating a greater roll angle. Comparing a curved downhill (operation 6) to a straight downhill (operation 5), or comparing a curved uphill (operation 3) to a straight uphill (operation 2), observe that curved operations induce more fatigue life consumption, also due to body rolling. It is also concluded that there is a proportional relationship between the fatigue damage and uphill/downhill slopes, since the operations with 10% of inclination (operations 5 and 2) causes more damage than when an inclination is 8% (operations 1 and 4, respectively). Finally, the operation that presented the least criticality was a flat curve with a radius of 200m and a speed of 16 km/h (operation 8), which, due to its very low speed for the curve radius, presented a low roll angle and a low damage, proving again that damage is directly linked to the radius/speed ratio.

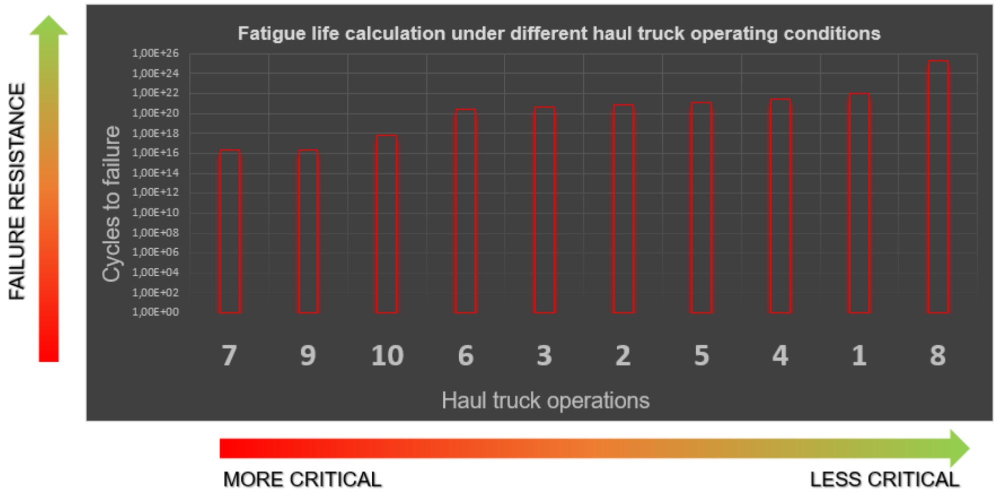

Figure 11: Ranking of most critical haul truck operations

4.3 Definition of most critical payload unbalance

Figure 11 presents the result of chassis static structural analyses subjected to 5 payload positioning types, loaded with maximum capacity and on a flat floor. As can be noted, when the payload is balanced in the haul truck's bucket, the load remains well distributed along the chassis, except for the A-frame, which constantly presents overstresses because of the high payload weight transferred to it. When rear unbalance occurs, overstresses in the A-frame intensify even more, as well as in other rear spots. On the other hand, in front payload unbalance, there is a stress relief in the rear, but the load transfer to the front doesn't generate overstresses, because of high rigidity of front reticulated structure, creating a better weight distribution. In diagonal payload unbalance, although the load is diagonally distributed, the loads remain well distributed in the chassis, slightly higher on one of the sides, but the overstress on A-frame remains. However, among all unbalance types, the most critical is the lateral one. This is because stresses appear high along the entire chassis main spar (one side - for which the unbalance occurs), on chassis tail and also on upper frame beam, in addition to overstresses on A-frame too. After a graphical comparative analysis of these stresses, it can be concluded that the lateral unbalance compromises more the structural integrity of the chassis, becoming the most critical payload unbalance.

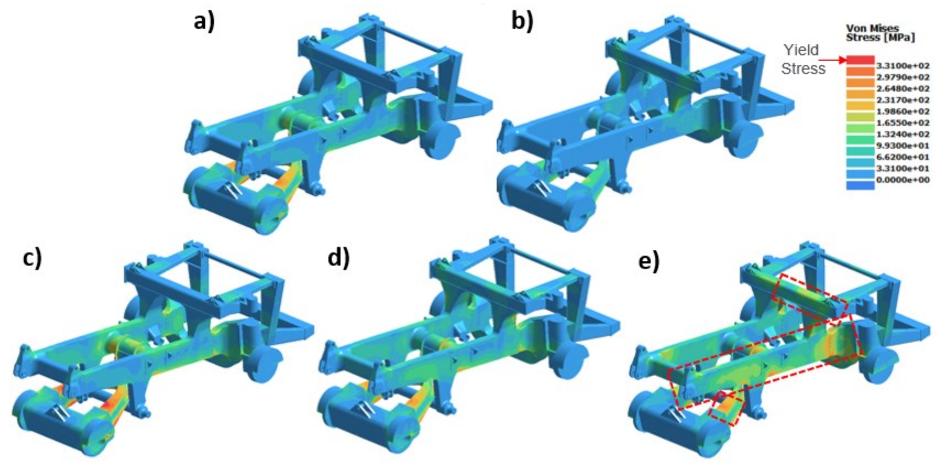

Figure 12: Chassis structural analyses under 5 payload positionings – Balanced (a) and also the front (b), rear (c), diagonal (d) and lateral (e) unbalances

5. CONCLUSIONS

The methodology applied in this work and the results obtained allowed the evaluation of which are the most critical points, in view of fatigue failure, of a haul truck chassis, presenting them in a ranking. These points are more concentrated in the rear region (specially at the a-frame), which is a heavily overloaded region by the payload weight, even in stable operating conditions. In addition, there are some other specific points on chassis, such as point 32, 11, 20 and 21 (and its symmetric points) which presents high sensitivity when operating in curved road sections. A common characteristic among the most critical points in the ranking is a big difference between stress amplitude while the truck is loaded vs. when it is unloaded, inducing more severe fatigue cycles in the chassis.

In addition, it was possible to evaluate in this work which operations are more critical to the chassis fatigue life, comparing 10 common daily operations during truck service, ordering them in the form of a criticality ranking. It can be concluded that the most critical operations are those that generate greater roll angle in the truck body, that is, curves with very high speed (eg flat curves), or small radii curves. In these sections, the use of camber is advantageous, reducing body roll angle and increasing life expectancy up to 30 times. It is also concluded that curved uphill and downhill are more critical than straight uphill and downhill, since the curved sections induce roll angles. In addition, the uphill and downhill angle of inclination is directly proportional to the fatigue damage, because the greater the angle, the more concentrated the loads are in some areas of chassis, increasing the stresses.

This work also compared 5 different payload positioning influence on haul truck chassis structural integrity. It is concluded that lateral unbalance is the most harmful type as it causes severe unilateral torsion on chassis, creating several overstress areas along it, mainly in the main side beam and its couplings with other parts. In addition, the incidence of lateral unbalance is greater in relation to other unbalances, as it is more common to occur due to some difficult factors in loading the bucket by the shovel loader, such as the truck maneuvering position, shovel turning area, operator's range of view and material accommodation after each deposited pass.

6. ACKNOWLEDGEMENTS

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