Monitoring railway track quality and safety using dynamic inertial response of the carbody and truck

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ABSTRACT: Modern sustainable cities are searching for cleaner transportation alternatives to reduce traffic congestion and decarbonise energy supply. Therefore the interest on railways as a sustainable and energy-efficient urban mass transportation mode is renewed. To provide passengers comfort, operational safety and effective track maintenance, a systemic low-cost monitoring process may be used. An inertial measuring system installed in the carbody and trucks, is developed to evaluate the passenger comfort, the railway track quality and safety, observed from the vehicle dynamic performance point of view. The system measures the dynamic movements of the carboy and extended to observe also the truck attitude and suspension torsion due to irregular track geometry. The values measured are used in an inertial navigation algorithm with a *Kalman* filter, to identify the full vehicle and truck attitude, including angular positions and accelerations. System equations for the inverse carbody and truck dynamic problem, augmented with the suspension torsion equation, is solved to directly estimate the wheels driving forces that are directly correlated with the vehicle safety. Values obtained are used to quantify track harmful locations. The results of two test campaign travelling on the irregular track in a conventional train, identifies the full vehicle and trucks attitude and the suspension torsion angular movement. The safety index and the location of the most potential hazard region for track maintenance purposes were identified. Good correlation between safety index and measured *L*/*V* and track geometry is observed, being this method a promising technique.

1 INTRODUCTION

Modern sustainable cities are searching for cleaner transportation alternatives to reduce traffic congestion and decarbonize energy supply. Therefore the interest on railways as a sustainable and energy-efficient urban mass transportation mode is renewed. However, turning railways again into the backbone of a sustainable and multimodal transportation system, requires guaranteeing track quality for safety operation and comfort for passengers. The rail infrastructure managers periodically inspect tracks with special vehicles that record track geometry parameters. Although track geometry directly impacts vehicle safety, the track quality indices used by infrastructure managers to assess tracks seldom consider vehicle dynamics (*Costa*, *Ambrósio* et al., 2023). In fact, the track geometry properties, namely the wavelength of the irregularities, affects the vehicle dynamic behaviour, altering the wheel-rail contact forces. The most recognized index for quantifying vehicle safety is the *Nadal's* well-known lateral to vertical (L/V) contact force ratio. The railway track is expected to be reliable, available for use and easy to maintain. To guarantee safe traffic conditions also, the operator should kept track geometry standards at the highest quality possible, for an inspection time interval. The current track assessment process is carried out with only a geometric focus, limiting tolerable millimetric deviations around the design layout, in an isolated fashion from the vehicle performance, as illustrated on the upper part of Figure 1. The standards for track geometry (*EN*-13848 or *FRA* Regulations), establishes the dimensional acceptable limits depending on the track quality level, for each operation permitted speed range.

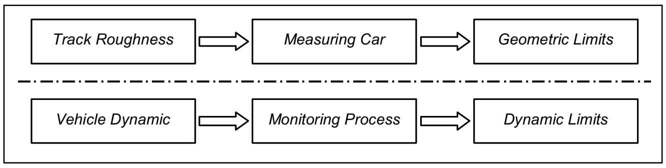

Figure 1 – Tradicional Independent Evaluation Process

The current vehicle dynamic performance assessment process is carried out monitoring the vehicle dynamic performance, as illustrated on the lower part of Figure 1. The international standards for vehicle acceptance (*EN*-14363 or *AAR* Chapter-

XI) establishes the acceptable inertial limits depending on operational speed. Therefore it is not really observed any dynamic vehicle-track correlation on this two traditional assessment method. Railways also seek how to establish explicit processes for decision-making regarding various activities to be undertaken to keep the track infrastructure in satisfactory condition or within desirable/required condition/operational limits. Geometric track parameters of a railway networks are usually sampled every 0.25 m (or 1 ft). Track Quality Indices (*TQIs*) is used to assess the track quality through a numerical value that characterizes the quality of a track section. Commonly, *TQIs* involve the standard deviations (SDs) of the geometry parameters (*Offenbacher* et al. 2020). Typical vehicle performance parameters are the passenger comfort (*ISO*-2631 or *EN*-513), limits for accelerations in certain manoeuvres (EN-14363) and the safety against derailment (*L*/*V* quotient described in *EN*-14363 or *AAR* Chapter XI). All parameters are clearly related with the dynamic performance of the vehicle. The more usual type of vehicle dynamic monitoring is to measure the vertical acceleration on the axlebox (*Li* et al, 2017). Different types of data treatment with specific purpose, are proposed by different authors like feed forward neural network (*Gadhave* and *Vyas*, 2022) and deep learning techniques (*Hao* et al, 2023). The vehicle suspension health can be also evaluated throughout on board instrumentation (*Russo* et al., 2022). More recently in Switzerland a monitoring system was developed to predicts the lateral forces optimised for curves to assess running safety of tilting trains (*Walther* et. al., 2022). A good inspection/ monitoring policy can lead to more accurate and reliable fault detection. However, one obstacle is how to deal with the data provided by the monitoring equipment or inspection vehicle, as well as the choice of suitable methods to translate the data into useful information for maintenance planning and prioritisation. Recent research has indicated that, though observed irregularities and its quality indicators may still lie within limit values established by current standards, without the consideration of wavelength content along with dynamic wheel-rail forces, it might be difficult to detect geometric defects that may potentially influence vehicle safety. Recent study (*Costa* et. al., 2021) explores the use of Wavelet Analysis (WA) in the statistical modelling of railway track irregularities (longitudinal level, alignment, gauge and cross-level). After reconstruction of signals using WA, the impact on *Y/Q* through vehicle dynamics simulations is measured and probabilities of derailment based on *Nadal's* criterion are computed through Importance Sampling. Observed results suggest that *Y/Q* values are sensitive to the scale/frequencies of the track defects, hence, investigating the effects of varying wavelength defects in the force transmissions between vehicle and rail may be beneficial for better condition monitoring and track maintenance prioritisation. (*Costa* et. al., 2021). The vehicle/track interaction is monitored with an on board acceleration monitoring system (*Tsunashima*, 2022) and data treatment based on *wavelet* and *Hilbert* transformation on time–frequency analysis is performed to detect track irregularities. The proposed method was applied to data obtained by regular measurement of in-service vehicles, and its effectiveness was examined and confirmed. Also, the use of on board instrumentation is employed for track geometric irregularities identification (*Xiao* et al, 2020). A numeric algorithm based on Kalman filter treat the signs of on board accelerometers to reconstruct track irregularities. The numerical results indicate that the proposed algorithm is capable of identifying the track irregularities using the on-board measurement signals, even polluted by high-level noise, at constant speed and with longitudinal acceleration.

2 METHODOLOGY

The methodology adopted to quantify "TRACK QUALITY" is to identify where it is more aggressive to the "VEHICLE SAFETY". The specific circumstance for this scenario is three general types of vehicle unsafe conditions. The first condition is the wheel-climb derailment at a low speed on sharp curves. Another such condition is related to vehicle main body large movements. The latter condition is relative to a specific speed and a particular type of track irregularities. The first condition is mainly related with vehicle suspension stiffness and load distribution. The second is related with the vehicle unsprung mass dynamic movements and the directioning truck/wheelset properties. The third is related to the track evenness wavelength, the vehicle natural frequencies and train speed. Although there are other types of unsafe conditions, including the accidental and component failure ones, those here described are only related to the vehicle body low frequency movements and small energy dissipation. The methodology proposed is based on detection of signs of unsafe railway vehicle performance, mainly related to the second and third described types, when travelling on the track evenness. The vehicle has its oscillations movements registered and recorded in a storage media. Data is treated with a inverse dynamic algorithm and safety index is identified based on the known safety function *L*/*V* which is the traditional ratio between the wheel lateral (*L*) and vertical (*V*) forces proposed by *Nadal* (1908), as illustrated on the diagram on

Figure 2. Different from traditional methods (see Figure 1) this new proposition involves simultaneously the track irregularities, vehicle dynamic response and train speed. The quality signs are used to identify the location on the track and prioritise the pertinent track geometry correction for the most harmful irregularity to the vehicle safety.

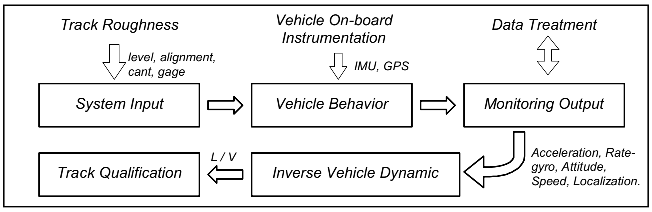

Figure 2 – Closed System Performance Evaluation

For this purpose, the metric adopted to identify the potential harmful location is associated with the vehicle safety. The wheel forces are quantified from the measurement of the carbody and trucks acceleration and attitude due to its overall dynamic behaviour. Additionally the vertical wheel relieve due to suspension torsion is also taken into account (*Barbosa*, 2021). Using four inertial measuring devices (*IMU*) with ten high-resolution transducers and a *GPS* signal, the safety index (*SI*) can be directly estimated from the wheel driving forces and suspension torsion. This task is performed with an inverse vehicle dynamic model, fed with data acquired from complete vehicle instrumentation, during the transit journey and an inertial navigation algorithm (*INS*) for attitude recognition.

3 VEHICLE DYNAMICS MODEL

The wheel-rail contact force, due to the vehicle dynamic behaviour, is a function of the track roughness where the vehicle is travelling on. To identify the acting contact forces that produce the vehicle directing movements, it is necessary to solve an inverse dynamic problem (*Barbosa*, 2016). The vehicle dynamics is governed by a set of differential equations obtained from the *Newton-Euler* theorems applied to the car body (considered as a rigid body) valid for a fixed reference frame ***N*** (*OXYZ*) presented in Figure 3. For the translational movements, the following differential equation relate accelerations and external forces in an earth fixed reference frame (*Newton's* law), not considering the drag and coriolis effects from the earth rotations due the irrelevant magnitude faced to the vehicle accelerations:

$$m\,{}^{N}\vec{a}_G = \sum \vec{F}_{wheels} - m\,{}^{N}\vec{g} \tag{1}$$

The external forces are mainly due to wheel contact forces and gravitational effects as shown in Figure 3. The equation also can be expressed in the body reference frame (*Gxyz*) using a rotational transformation matrix ***T***, composed with the three *Euler* angles (roll ϕ, pitch θ, yaw ψ) as identified in Figure 3. When the measuring system is fixed at particular point *P*, not coincident with the vehicle centre of gravity ***G***, the measured acceleration must be projected according to the field acceleration equation, to be used by the *Newton's* equation:

$$\vec{a}_G = \vec{a}_P + \dot{\vec{\omega}} \wedge (G-P) + \vec{\omega} \wedge [\vec{\omega} \wedge (G-P)] \tag{2}$$

For the rotational movements described in a moving reference frame ***Gxyz*** attached to the vehicle, the following differential equations relates angular accelerations and velocities (roll rate $\omega_x = \dot{\phi}$, pitch rate $\omega_y = \dot{\theta}$, yaw rate $\omega_z = \dot{\psi}$) and external moments is used:

$$[J]_G \{\dot{\omega}\} + [\tilde{\omega}] \cdot [J]_G \{\omega\} = \{M_G^{ext}\} \tag{3}$$

The body external contact forces due to each wheel (H_i, L_i, V_i) are shown in Figure 3. The body external moments (M_G) due to the wheel forces are obtained from the carbody dimensions as shown in Figure 3. To work out the contact forces solving the system equation, it is necessary to know the vehicle body accelerations, as stated in equation 1. Additionally, it is also necessary to measure the angular velocity and to estimate the angular acceleration, needed to solve equation 3. Finally, the body angular attitude must be identified to solve the suspension torsion equation 4, that identifies the vertical wheel load relieve due to track twist. The system has six equations and twelve contact forces unknowns. Disregarding the longitudinal effects, one equation is removed and four longitudinal contact forces are ignored (no acceleration or breaking effects).

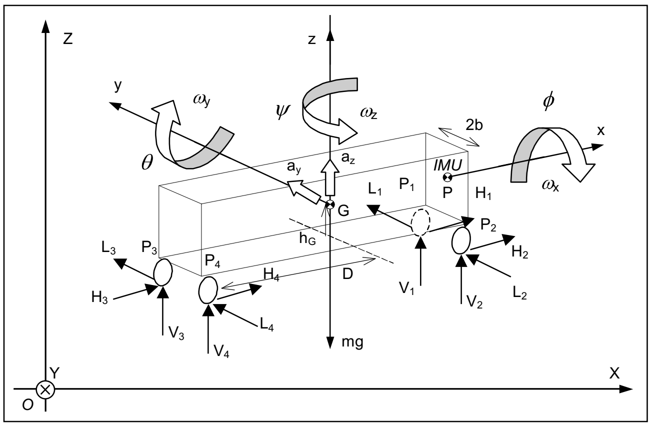

Figure 3 – Vehicle Attitude and Forces distribution on the wheels

Due to the system being hyperstatic, the contact lateral forces in each wheelset are summed. To solve the system with five equations and six unknowns, an additional suspension torsion equation is disclosed to access each vertical force relationship, completing the system. Finally the contact wheel forces (L_i, V_i) are related to the measured accelerations and angular velocities, masses and inertia moments. The vehicle longitudinal torsion due to the track twist (ϕ_{track}) affects mainly the vertical wheel load distribution. Considering the car structure as a rigid body, the track twist deflects the vehicle suspension unloading the diagonal wheels. This effect is internal (not inertial) and depends upon the suspension stiffness, length of the vehicle, track gage and magnitude and wavelength of track twist. An extended version of the measuring system (*Barbosa*, 2021), has two additional instrumentation installed in each truck, that can quantify the relative inclination. The *IMU* installed in each truck, allow to identify the relative *roll* angle (δ_i) between the trucks and vehicle body as shown in Figure 4, with the aid of the *INS* algorithm. The vertical wheel load relieve may be related directly to suspension stiffness or to a normalized angular rotation limits (*APTA*, 2017).

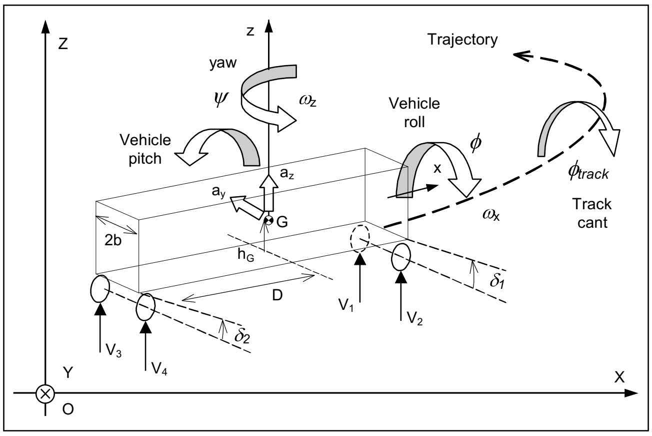

Figure 4 – Relative Vehicle/trucks roll angles

Considering the axle moving as the track on the vertical direction and only the vehicle primary suspension, the expression for the vertical load variation as a function of the track angular twist per meter (ϕ_{track}) is related to a body dimensions proportion ($D/2b$) and suspension torsional stiffness (k_ϕ) stated as: $\Delta V = -k_\phi (D/2b) \phi_{track}$ (4)

To identify the angles and attitude, the inertial navigation algorithm (*INS*) based on extended *Kalman* filter is used. With all this information, it is possible to solve the vehicle inverse dynamic equations to evaluate the driving contact forces and calculate the Safety Index (*SI*) on each wheel. The Safety Index (SI) is defined as the *L/V* ratio limit established by the standards (*UIC*, *AAR*) minus the measured and worked out L_i/V_i value for each wheel individually:

$$SI = 1 - \left\lfloor (L_i/V_i)_{measured} \Big/ (L/V)_{\text{Standard Limit}} \right\rfloor \tag{5}$$

4 MEASURING SYSTEM AND DATA TREATMENT

Typically the measuring system consists of two/four inertial measurement units, being two fixed on the vehicle and eventually two fixed on the trucks. The inertial measurement unit, or simply *IMU*, is a micro-electro-mechanical system (*MEMS*) that measures and reports the body movement. It utilizes a set of tri-orthogonal accelerometers to measures the vehicle accelerations ${}^{B}\vec{a}_G$ and angular speed device to measure the attitude variation ${}^{B}\vec{\omega}$. A *GPS* identifies the vehicle speed and position expressed in the geographic-referenced latitude and longitude. All these information are synchronized, digitalized, anti-aliasing filtered, and recorded in the on-board microcontroler. To recover the complete vehicle and trucks attitude to calculate the *SI* index, a process based on inertial navigation algorithm (*INS*) is used to treat rough data from the sensor and identify vehicle external loads. Vehicle and trucks accelerations and angular attitudes are the main information to recover from the accelerometers, rate-gyros and magnetometers information. To this end, a strapdown inertial recovery algorithm and a local level frame identification must be involved for vehicle and trucks angular attitude recognition. An integrated navigation system on terrestrian movement's methodology should combine state data, generated by the dynamic equations, with independent redundant data in a *Kalman* filter algorithm.

5 VALIDATION PROCESS

The validation process of the proposed system were based on the comparison of the safety index (*SI*) calculated with the strapdown inertial recovery algorithm, with the measured track geometry and measured truck *L/V* wheel forces ratio obtained with an instrumented wheel set (*IWS*). Two test campaigns were performed: one in an iron ore wagon at Carajas Railway from VALE (at São Luiz do Maranhão, Brasil) and another in a passenger car of a commuter train from Companhia Paulista de Trens Metropolitanos (*CPTM*) at Sao Paulo city. The track geometry and irregularities were measured with a specialized measuring car (*Plasser* EM-100).

5.1 Test Campaign in a Gondola Wagon

A special test train was prepared (see upper photo in **Figure 5**) to travel in a selected track section of the Carajas Railway. The train was formed with two locomotives (one at each end), four iron-ore 120 ton loaded wagons and two laboratory passenger cars. The measuring system was installed underneath the first wagon, as can be observed in Figure 5 (red small box).

Figure 5 – Train - IWS (yellow) and IMU(red)

The two instrumented wheelsets (*IWS*) are installed in the leading truck of this wagon (yellow colored). The selected 25 kilometres track section goes from km 35 to km 10 (in the east sense) of the Carajas railway located in the North Region of Brazil. There are some curves and a bridge over a sea firth. This railway is 1.6 meter gage with almost 900 km connecting the Carajas Mine to the Sao Luiz port. The typical iron-ore wagon is a 120 tons gondola GDT, with 7”×11” ride-control trucks.

5.2 *Test Campaign in a Passenger Car*

The evaluation test of the system was performed in the train of the series 8000, similar to the Figure 6, travelling on the line 8 of *CPTM* in the west side of Sao Paulo city in Brazil. The test was performed on the track #2 in the west direction. The test was performed outside business hours, with all the cars of the train empty. The instrumentation implemented on the vehicle consists of four boxes with high precision accelerometers and *GPS*, installed on the car saloon and *IMUs* installed on the trucks, as presented in upper photo of **Figure 7**. Each truck receive an instrumentation box with *IMUs* fixed on the structure, detailed shown in lower photo of **Figure 7**. Additionally a *GPS* receiver is used to acquire the speed and the georeferenced position and kilometric distance. All data measured is time synchronized and stored in a solid-state media (micro SD-card) for pos-processing analysis.

Figure 6 – Train series 8000 from CPTM

Figure 7 – Instrumentation

5.3 Wagon Test Results

The test performed at 75 km/h was selected for a closer analysis. The sub-section between kilometer 31+500 and 30+500 is a tangent segment of the track. At km 31 +100, a Safety Index (*SI*) of at least 80% is identified, as shown in Figure 8. A sudden change is noticed in the super-elevation value to 23 mm at km 31+080, as shown in Figure 9. At this point, the track twist reached ± 23 mm (see Figure 8). Therefore, the poor geometry is correspondently identified with the measuring system. The safety at this point is confirmed with the L/V measured with the instrumented wheelsets of 0.15, as shown in Figure 10.

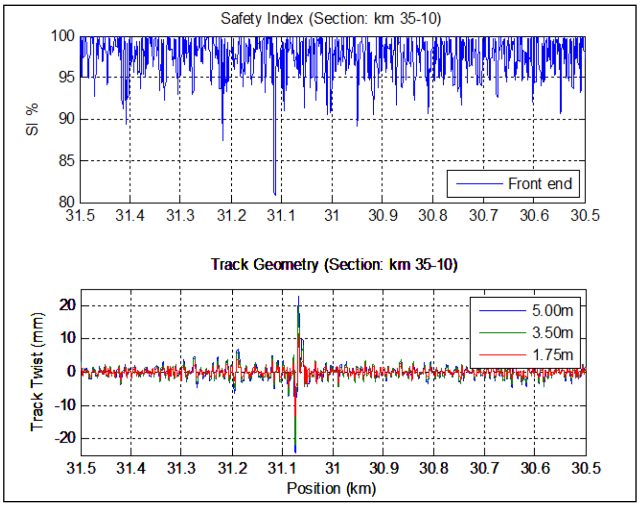

Figure 8 – Track Safety and Twist

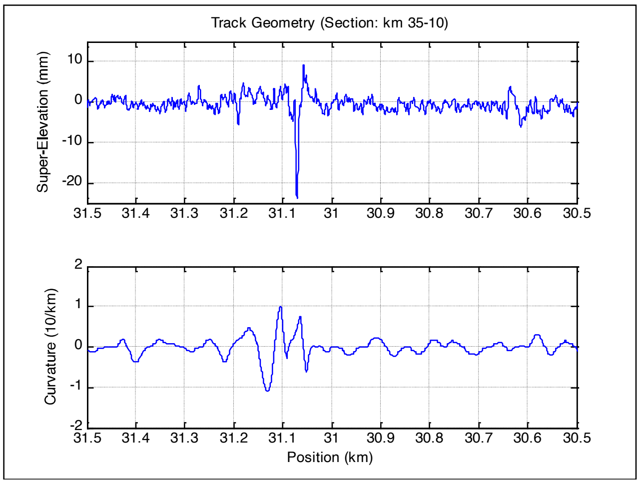

Figure 9 – Track Superelevation and Curvature

The complete test results can be detailed appreciated at the final reporter published in an international journal (*Barbosa*, 2016)

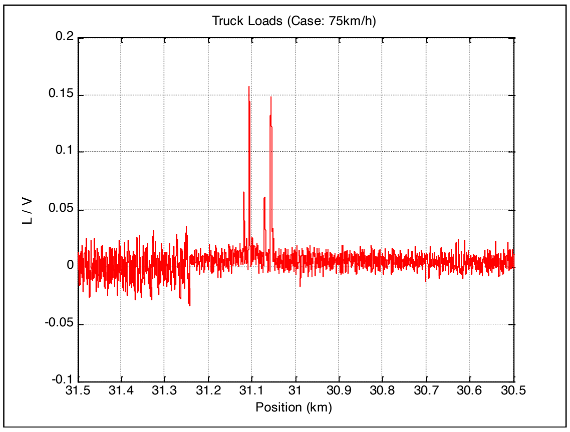

Figure 10 – Leading Truck Measured L / V

5.4 Passenger Car Test Results

The test was performed on the track #2 of line 8 in the west direction, between Station Osasco (km 15+946) and Station Comandante Sampaio (km 18+253). The results obtained from the test was treated according to the methodology presented in item 4, with the purpose to identify the safety along the track length. A particular section that contains a reverse curve, between km 16+900 and km 18+300, was separated for a deeper analysis. This section contains a reverse curve with 211 and 330 meters of radius (superelevation of 173 and 153 mm) respectively, as quantified with the measuring car (*Plasser* EM-100 form *CPTM*) as presented in the Figure 11.

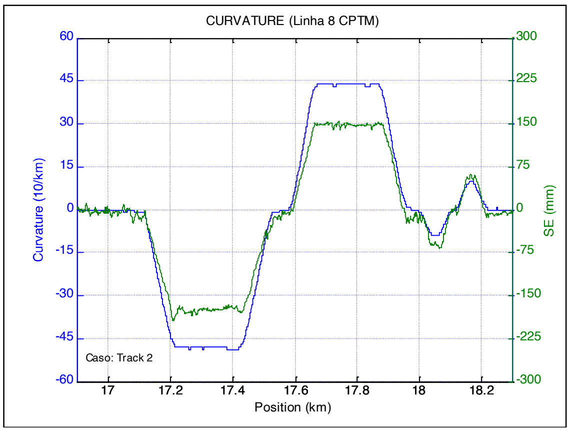

Figure 11 – Measured Track Geometry (curvature and superelevation)

The test train passed through this section with a speed of around 25 km/h. The vehicle dynamic behaviour including accelerations, angular speeds and vehicle attitudes were acquired and stored for post-processing analysis.

Torsion Analysis - The sensors in each truck and in the car, measure longitudinal rotation based on an *INS algorithm* (item 4) that are presented in the Figure 12 for the carbody (black line) and for each truck (front and rear truck). These values are precise and stable enough to identify the angular suspension torsion (see Figure 13). This value is used to quantify the wheel load relieve during suspension torsion analysis as presented on item 3. Using the maximum allowed torsion presented in item 4, the calculated percentual vertical wheel load relieve is presented in Figure 14. This dynamic vehicle behaviour may be confronted in the space domain with the geometric measurements performed with the measuring car (see Figure 15). It is observed a good agreement between the on board car inertial measurements (see Figure 14) and the geometric as presented in Figure 15

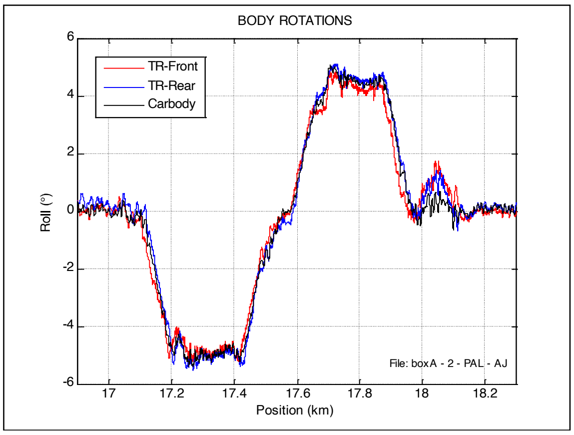

Figure 12 – Truck and Car Roll

To compute the wheel loads, it is measure the translational acceleration and angular velocity, to identify the angular accelerations and the car body *Euler* angles as described in item 3. Values for the *safety index* (*SI*) can be determined at any vehicle extremity. Adopting an *L/V* limit of 1.2, the resulting values for the *safety index* of the carbody front end and rear end, are presented in **Figure 16**. Finally the calculated values of the *GLOBAL SAFETY INDEX* (*GSI*) including the carbody and truck inertial effects and suspension torsion is presented in Figure 16, showing the worst safety condition of *GSI* = 0.86 at track location on km 17+200 that clearly identifies the influence of the reversed curves and reveals the good quality of this track section. The train operating speed is variable depending on the style of the driver, trainload, signalisation, climatic variations and any speed restrictions existing on the line. However in different speeds, forced movements will change its magnitude, modifying the values measured, but keeping the location identified.

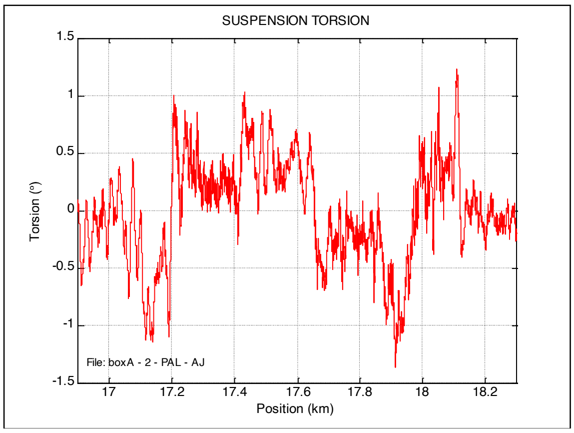

Figure 13 – Suspension Torsion (IMU)

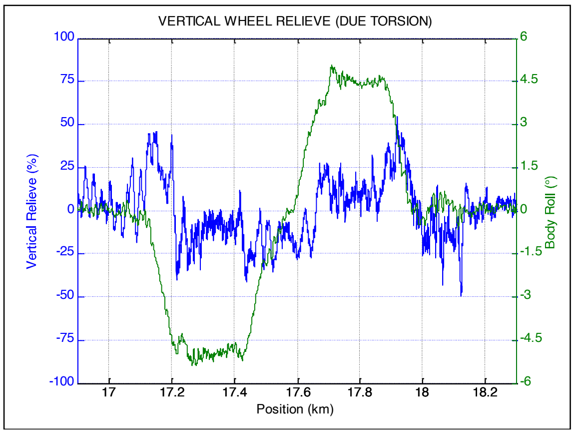

Figure 14 – Vertical Wheel Load Relieve

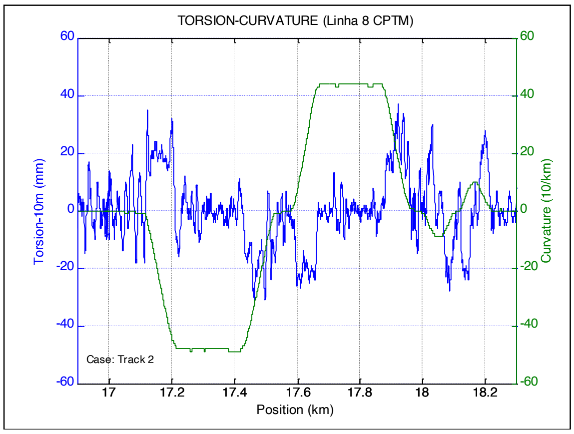

Figure 15 – Track Torsion and Curvature

Even the natural movements induced by periodic irregularities changes, but location remains due to the damping factor of the suspension. Differently from the other systems that uses only statistics information from few sensors, this measuring system is Multiple-Input Single-Output (*MISO*) that takes into account the complete vehicle multisignal input and delivers a single output index (*SI*) directly associated to the safety condition.

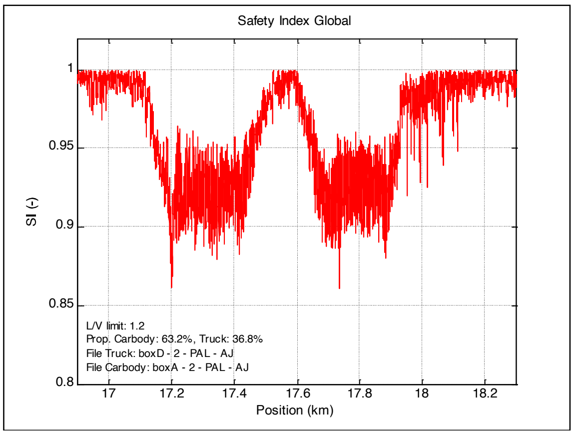

Figure 16 – Global Safety Index

The full results of this test in detail can be appreciated in *Barbosa* (2021).

6 CONCLUSIONS

The system measures the carbody dynamic and trucks movements, with four inertial devices, including suspension torsion, during its transit along the irregular track. The values measured are used in the strapdown inertial recovery algorithm with an extended *Kalman* filter, to identify the full carbody and trucks attitude, including angular positions and accelerations. The vehicle and truck system equations for the inverse dynamic problem, augmented by suspension torsion equation, is solved to directly calculate the wheels driving forces. Values obtained are used to qualify track harmful locations. The full vehicle attitude and movement, including vertical wheel load relieves identification due to suspension torsion, and calculations of the safety index (*SI*) are performed. The values obtained for the *SI* drop down to almost 86%, probably due to track twist in the end of the first curve of the reverse, that promote vertical wheel load relieve of the vehicle. The *GPS* signal simultaneously captures the exact georeferenced location and train speed of the most potential hazard region. The test results were compared to the measured track geometry and a good correlation was observed and the most harmful location was identified for track maintenance purposes. Due to its simplicity and low cost, the measuring system can be easily installed in any vehicle and operate with any load condition and variable travelling speed, without the traditional traffic disturbance. The system can be applied to any specific vehicle fleet, travelling in any track section, in the usual operational speed and detect the most harmful location for this specific track, to complement the geometric measuring methods. The analyses can also be focused to compute different priority criteria (passenger comfort, minimal dynamic vertical load applied to the track, instantaneous safety indicator, etc.) according to the user interests. The better classification of the most harmful track locations, allows prioritising the track intervention strategy.

7 ACKNOWLEDGEMENTS

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