J Braz. Soc. Mech. Sci. Eng.
DOI 10.1007/s40430-015-0471-9

REVIEW

New method for railway track quality identification through the safety dynamic performance of instrumented railway vehicle

Roberto Spinola Barbosa[1]

Received: 30 January 2014 / Accepted: 9 December 2015
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Abstract Track geometry locations that exceed geometry-standardized limits do not necessarily cause poor vehicle performance. However, there are locations under geometric limits that promote unsafe dynamic vehicle performance. To handle this dichotomy, a new method for track inspection is proposed to complement the traditional ones. An inertial measuring system and a specialized data treatment method is presented to evaluate the railway track quality, observed from the vehicle dynamic performance point of view. With inertial devices the system measures the vehicle dynamic movements during transit along an irregular track. Values measured are used in an inertial navigation algorithm with a Kalman filter, to identify the full vehicle attitude, including angular positions and accelerations. System equations for the inverse vehicle 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. An adimensional Safety Index (SI) is proposed to evaluate track quality. Values obtained are used to quantify track harmful locations. Results of two test campaign travelling on the irregular track in a conventional train identify the full vehicle attitude and movement. The SI and the location of the most potential hazard region for track maintenance purposes were identified. Good correlation between SI and measured track geometry is observed being a promising technique.

Keywords Railway · Track · Quality · Safety · Vehicle · Dynamic

1 Introduction

Railway companies seek to operate transport systems with greater confidence. Tracks should be reliable, available for use and easy to maintain (reliability–availability–maintainability and safety—RAMS as defined by the European Union—UIC). To guarantee safe traffic conditions, the operator should keep track geometry standards at the highest quality possible, for an inspection time interval. This maintenance process is expensive due to tamping, ballast cleaning or renewal, sleeper replacement, joint repair, rail grinding or replacement and substructure treatment and other maintenance interventions. Railways also seek 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. Jovanovic [19] proposed a track maintenance management system where the Track Quality Index (TQI) is one of the conditions to be met, to apply maintenance resource more effectively. The Track Expert Group of UIC reveals in the report "Future of railway monitoring in Europe" [27] an increasing vehicle-based measuring systems rather than trackside or manual that will enable comparison and trend identification, leading to deeper understanding of asset behaviour: "This can help optimise maintenance strategy".

Track quality is traditionally quantified with a specialized-on-moving measuring car that measures track geometric basic parameters. Usually, the inspection car measures and records the variation of the track gage, vertical and lateral alignments and cross-level (angular variation on a track

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✉ Roberto Spinola Barbosa
spinola@usp.br

[1] Depto. Eng. Mecânica, POLI - USP, Escola Politécnica da Universidade de São Paulo, São Paulo, SP 05508-900, Brazil

Published online: 22 December 2015

section—cant or super elevation). Additionally, the cross-level variation per meter (track twist) can be calculated depending on the data sample rate. Some systems also use the three-point middle-chord technique as a device for particular measurement [14]. Values recorded are confronted with standard recommended limits and harmful regions are identified for maintenance planning. These measuring techniques are focused on measuring the track geometry and local irregularities and compare values to normalize limits. The average geometric variation associated with track quality is also used for track classification purposes (e.g. [13] or [9]). To assess track geometry quality, Li et al. [23] use the dynamic track–vehicle simulations on the spectra wave-length irregularity spectral domain to access the track–vehicle dynamic and indicate the use of second-order derivatives of track vertical irregularity for assessing track geometry quality [24].

Most of the track measuring systems identify only the track geometry variation within short wavelength identification (3–25 m, [16]). Also these systems do not deform the track during the measuring process. Therefore, the real deformed track geometry with the vehicle fully loaded is not recovered. An initiative to overcome these restrictions is the Track Machine Guidance project (TMG) developed by the UIC committee. For this purpose, requirements for a real-time machine guiding system were established based on absolute references and co-ordinate-based definition of the track geometry, using satellite positioning. The primary benefit is cost reduction for measurements absolute positioning, levelling, lining and tamping of the tracks [11]. Another complementary technique employed is the Ground Penetrating Radar (GPR) to evaluate the track substructure.

In addition to the well-known geometric measuring methods, researches related to the vehicle response characterization, when travelling over the track irregularities, are observed. Correlation metrics between the track roughness characteristic and the dynamic vehicle behaviour is the key for these methods. Several researchers [22, 28] discuss the detection of rail track irregularities, based on the measurements of the bearing box vertical acceleration during the operation of rail vehicles. Wilson and Ketchum [32] develop a performance-based track geometry (PBTG), an inspection method based on an accelerometer installed on a conventional track geometry inspection vehicle. The method calculates the vehicle behaviour in real-time based on the measured track geometry input. Kawazaki and Youcef-Toumi [20], Czop et al. [6], Sun et al. [29] and Tsunashima et al. [30] proposed a procedure-based system identification technique that solves an inverse dynamic problem, estimating track irregularities from the measured acceleration applied to the vehicle model of the frequency domain. English and Moynihan [8] also used a real-time processing inverse wagon linear model excited with measured track frequency content to predict wheel–rail contact forces.

An instrumented iron-ore wagon was proposed by Darby et al. [7] to measure the suspension spring deflection, lateral side frame acceleration, brake pipe pressure, inter-car separation, longitudinal wagon acceleration; coupler force and structural stress. Despite using various sensors, it is essentially a simple captive system, based only on measurements of deflection and some particular accelerations of a wagon to indirectly evaluate the track quality.

The use of instrumented wheel-set is another method to evaluate the effect caused by the track irregularity over the vehicle behaviour in traffic. In spite of being an expensive and laborious instrument, the quantification of the wheel-rail contact force ratio is an indication of track quality [15] and, therefore, the vehicle safety. Also portable accelerometers are employed for passenger comfort measurements [2] based on the ISO-2631 and UIC-513 Standards.

Inertial measurement devices (IMU) are new technologies developed in the aerospace industry with widespread application in military equipment. These devices are now available in the automotive industry and are particularly used in automotive control systems. Examples of use of this new technology can be found in Feldmann et al. [12] who propose to detect the vertical track settlement and deterioration using frequency domain transformation from the inertial measurements of the vehicle behaviour. Weston et al. [31] uses rate gyros and lateral acceleration for track curvature and alignment monitoring. Xia et al. [33] used an inverse vehicle model to estimate high-frequency wheel–rail contact forces from measurements of sensors installed in a track-recording car. One can observe in the temporal results, the difficulty of vehicle dynamics correlation with the wheel forces due to high-frequency movements of the body with reduced weight (e.g. wheelset, side frame, etc.). However. at low frequencies vehicle mass has predominance over the system movements and can be used for a particular application, which is the object of this work. Hung et al. [18] report that peak threshold of the pitch angular rate and the integral threshold of the roll angular rate of the vehicle truck frame are closely related to vehicle unsafe conditions. Heirich et al. [17] use an inertial device in the vehicle to infer the track features such as bank, bank change, slope, slope change, relative heading, curvature and basic track elements. Luber et al. [25] propose a method for track geometry assessment taking into account the vehicle/track interaction. The method is supported with vehicle vertical and lateral transfer function used for the prediction of the vehicle reaction forces. The results show a significant enhancement of the correlation between the track assessment quantities and the vehicle reaction forces. Although use of transfer function related to the parameters of the track (Track Geometry Assessment TGA [10, 16]) is restricted to only two translational directions (vertical and lateral) and a wavelength range of 3–25 m, and not include rotational aspects. These aspects reinforce the need to broaden the spectrum of evaluation that is the proposal here presented.

Track geometry should be designed to meet the requirements of the fleet of car or wagons that uses it. During its service life, a perfect track develops irregularities that cause vehicle oscillation. In the extreme case, the vehicle can lose its guidance. Defects and failure of the track superstructure and vehicle dynamic performance may be mixed and cause these undesirable derailment events [11]. Focusing on the track geometry defects, structural elasticity, vehicle suspension characteristics and train speed, all these are potential possible contribution causes and should therefore be evaluated together to minimize hazard risk improving safe traffic.

Conversely, track geometry locations that exceed the standardized limits often do not cause obligatory poor vehicle performance. On the contrary there are good track locations under geometric limits that promote unsafe dynamic vehicle performance [21]. Additionally track stiffness does affect the passing vehicle dynamic. The larger the irregularities, the stronger the dynamic interaction effects. This process is auto propelled and increases the track defects at each passing vehicle. Additionally, depending on the train speed, a particular track roughness wavelength excites the vehicle modal resonance that substantially magnifies the dynamic effect. Safety is a complex phenomenon and depends simultaneously on the vehicle dynamic characteristics and on the track system response and geometry. To optimise track maintenance, would be of interest to include vehicle performance on the track evaluation method. It would be of interest to also identify the problems as they arise rather than waiting for the scheduled inspection campaign.

To handle this subject a new method for track inspection is proposed to complement the traditional ones. Track irregularities excite vehicle vibrations main modes and produce translational and angular movements. Wheel/rail contact forces that support the vehicle vertical load and produce the lateral directioning guiding forces cause these movements. The guiding forces are directly related to the vehicle accelerations. Hence, the results of the vehicle dynamic behaviour can be employed to evaluate the track geometry adequacy. Complementarily to the traditional measuring method, the vehicle dynamic performance can be used to identify the potential place of low safety on the track. The evaluation of these results can be used as metrics to prioritise location of maintenance on the already measured track geometry. This methodology can even more optimise maintenance intervention and improve the vehicle traffic safety.

2 Methodology

The methodology adopted to quantify track quality is to identify where it is more aggressive to 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 directioning bogie/wheelset properties. The third is related to the track evenness wavelength, the vehicle natural frequencies and train speed [4]. Although there are other types of unsafe conditions, including the accidental and component failure ones, those described here are only related to the vehicle body low frequency movements and small energy dissipation.

The new methodology proposed and presented here 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. These signs are used to identify the location along the track and prioritise the pertinent track geometry correction in the most harmful irregularity to the vehicle safety.

For this purpose, the metric adopted to identify the potential harmful location is associated with the vehicle safety. This adimensional index is directly correlated to the traditional ratio between the wheel lateral (L) and vertical (V) contact force. The wheel forces are quantified from the measurement of the vehicle attitude and its overall dynamic behaviour. Using an inertial measuring device (IMU) with ten high-resolution transducers and a GPS signal, the Safety Index (SI) can be directly estimated from the wheel driving forces. 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

The wheel-rail contact force, due to the vehicle dynamic behaviour, is a function of the track roughness where the vehicle is travelling above. To identify the acting contact forces that produce the vehicle directioning movements, it is necessary to solve an inverse dynamic problem. 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 Fig. 1. For the translational movements, the following differential equations relate accelerations and external forces in an earth fixed reference frame (left upper index, mean the reference frame used):

$$m\,{}^{N}\vec{a}_G = \sum \vec{F}^{\text{ext}} \tag{1}$$

This equation does not consider the drag and coriolis effects from the earth rotations due the irrelevant magnitude faced to the vehicle accelerations. The external forces are mainly due to wheel contact forces and gravitational effects as shown in Fig. 1.

$$m\,{}^{N}\vec{a}_G = \sum \vec{F}_{\text{wheels}} - m\,{}^{N}\vec{g} \tag{2}$$

The equation also can be expressed in the body reference frame $B(G_{xyz})$ using a rotational transformation matrix $\boldsymbol{T}$ (where the right underscript N states for the fixed reference frame and the right superscript B states for the body fix moving reference frame), composed with the three Euler angles (roll ϕ, pitch θ, yaw ψ) as identified in Fig. 1, where the accelerations are to be measured and the forces computed:

$$m\,T_N^B\left({}^{N}\vec{a}_G + {}^{N}\vec{g}\right) = T_N^B \sum \vec{F}_{\text{wheels}} \tag{3}$$

When the measuring system is fixed at particular point P, not coincident with the vehicle center of gravity $\boldsymbol{G}$, the measured acceleration must be projected according to the field acceleration equation, to be used by the Newton equation:

$$\vec{a}_G = \vec{a}_P + \vec{\alpha} \wedge (G-P) + \vec{\Omega} \wedge \left[\vec{\Omega} \wedge (G-P)\right] \tag{4}$$

where the angular velocity is $\vec{\Omega} = \dot{\phi}\,\vec{I} + \dot{\theta}\,\vec{J} + \dot{\psi}\,\vec{K}$ compose by the roll rate $\dot{\phi}$, the pitch rate $\dot{\theta}$ and the yaw rate $\dot{\psi}$. For the rotational movements described in a moving reference frame attached to the vehicle, the following differential equations relates angular accelerations α and body angular velocity $\omega_B = [\,\omega_x\ \omega_y\ \omega_z\,]^{\mathrm{T}}$ and external moments with respect to the same pole:

$$[J]_G\{\alpha\} + [\omega_B] \wedge [J]_G\{\omega_B\} = \left\{M_G^{\text{ext}}\right\} \tag{5}$$

The body external contact forces due to each wheel (H_i, L_i, V_i) are shown in Fig. 1. The body external moments (M_G) due to the wheel forces binary are obtained from the carbody dimensions as shown in Fig. 1. To work out the contact forces solving the system equation, it is necessary to know the vehicle body accelerations, as stated in Eq. 1. Additionally, it is also required to measure the angular velocity and to estimate the angular acceleration, needed to solve Eq. 5. Finally, the body angular attitude must be identified to solve the torsion Eq. 6.

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). 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.

The vehicle longitudinal torsion due to track twist affects mainly the vertical wheel load distribution. Considering the car structure as a rigid body, the track twist deflects the suspension unloading the diagonal wheels. This effect depends upon the vehicle suspension stiffness, length and width of the vehicle and magnitude and wavelength of track twist.

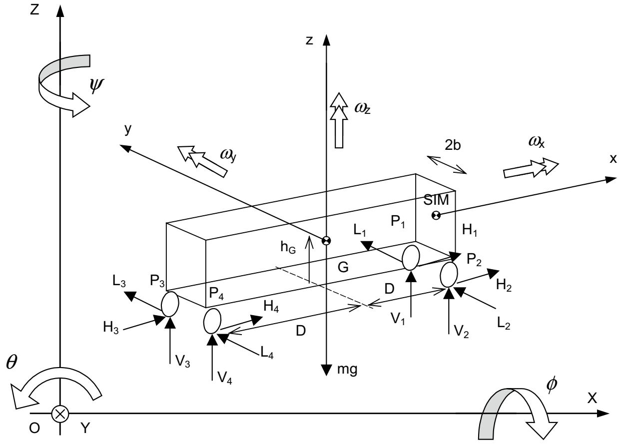

Fig. 1 Body attitude and forces distribution on the vehicle

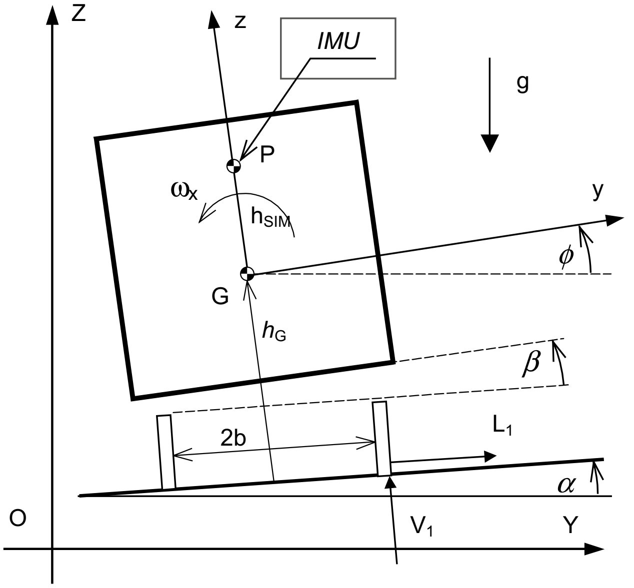

Fig. 2 Track and vehicle roll angles

Namely, the expression for the vertical load variation as a function of the track angular twist per meter (δ) is related to a body geometry proportion ($D/2b$) and suspension torsional stiffness (k_φ) stated as:

$$\Delta V = -k_\phi \frac{D}{2b}\delta \tag{6}$$

To estimate the track twist from the overall vehicle inclination, a special filter is used to recover the local track superelevation (α). However, the IMU coupled to the body measures the absolute vehicle roll angle referred to the earth plane (ϕ). The total or earth referred body angle, as shown in Fig. 2, is composed by the track cant angle (α) added to the relative vehicle roll angle (β) due to suspension movements and inertial mass center height (h_G):

$$\phi = \alpha + \beta \tag{7}$$

The track cant angle (α) can be measured with an additional IMU installed on the wheelset. If this value is not available, another identification method is necessary. Disregarding any small vehicle suspension roll, the twist variation can be obtained from:

$$\delta = \frac{\mathrm{d}\alpha}{\mathrm{d}S} \tag{8}$$

Finally to identify the angles and attitude, the inertial navigation algorithm (INS) based on extended Kalman filter is used for multivariable estimator.

With all this information, it is possible to solve the vehicle inverse dynamic equations to evaluate the driving contact forces and calculate the SI on each wheel. The SI is the difference between the L/V adopted limit and the module worked out L/V value for each wheel [3].

$$\mathrm{SI} = \left|\frac{L}{V}\right|_{\mathrm{Limit}} - \left|\frac{L_i}{V_i}\right|_{\mathrm{measured}} \tag{9}$$

4 Measuring system and data treatment

The measuring system consists of an inertial measurement unit fixed on the vehicle, a GPS and a computer for command actions, data acquisition and storage media. 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 ${}^B\vec{\omega}$. Additionally a tri-orthogonal magnetometer set and a precision barometer measures the orientation ${}^B\vec{m}$ based on the earth magnetic filed and the relative level. All the sensors are mounted in the vehicle and measurement the three-dimensional movements. A GPS identifies the vehicle speed and position expressed in the geographic-referenced latitude and longitude. All this information is anti-aliasing filtered, digitalized and recorded in the on-board control computer.

To recover the complete vehicle 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 accelerations and angular attitude are the main information to recover from the accelerometers, rate-gyros and magnetometers information. To this end, a strapdown inertial recovery (SIR) algorithm and a local level frame identification must be involved for vehicle 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.

The vehicle translational motion expressed in a fixed reference frame $\boldsymbol{N}$ is described by:

$$m\,{}^N\vec{a}_G = \sum {}^N\vec{F}_i^{\mathrm{ext}} \tag{10}$$

The vehicle attitude relative to an inertial reference frame $\boldsymbol{N}$, is described by three Euler angles denoting vehicle roll angle ϕ, elevation angle θ and heading angle ψ as shown in Fig. 1. The absolute position of a point in the vehicle is described by the vector ${}^N\vec{r}$ expressed in the inertial reference frame $\boldsymbol{N}$ and its time rate of change are:

$${}^N\vec{r} = T_B^{N\,B}\vec{r} \quad \text{and} \quad {}^N\dot{\vec{r}} = T_B^{N\,B}\dot{\vec{r}} + \dot{T}_B^{N\,B}\vec{r} \tag{11}$$

where the left superscript N over the vector states for the fixed reference frame and the left superscript B states for the body fix moving reference frame. T_B^N is the direction cosine matrix (DCM) formed with the three Euler rotation angles, which leads to the transformation matrix in terms of the three successive sequential body rotations (sequence 3–2–1, according to NASA Standard, Baruh):

$$T_B^N = \begin{bmatrix} c\theta\, c\psi & c\theta\, s\psi & -s\theta \\ -c\theta\, s\psi + s\phi\, s\theta\, c\psi & c\theta\, c\psi + s\phi\, s\theta\, s\psi & s\phi\, c\theta \\ s\phi\, s\psi + c\phi\, s\theta\, c\psi & -s\phi\, c\psi + c\phi\, s\theta\, s\psi & c\phi\, c\theta \end{bmatrix} \tag{12}$$

the prefix "*s*" and "*c*" stands for sine and co-sine for the respective angle.

The velocity vector ${}^N\vec{V}$ expressed in the inertial fixed frame $\boldsymbol{N}$ is defined in terms of position ${}^B\vec{r}$ expressed in rotating body fix reference $\boldsymbol{B}$, as:

$${}^N\vec{V} = T_B^{N\,B}\dot{\vec{r}} \quad \text{and its time derivative as } {}^N\vec{a} = \dot{T}_B^{N\,B}\dot{\vec{r}} + T_B^{N\,B}\ddot{\vec{r}} \tag{13}$$

The relation between the body angular velocities ω_B (roll rate, pitch ate and yaw rate) and the vehicle attitude rate Ω_N (rate in bank, attitude and heading) is described by [5]:

$$\begin{Bmatrix}\omega_x\\ \omega_y\\ \omega_z\end{Bmatrix} = \begin{bmatrix}1 & 0 & -s\theta\\ 0 & c\phi & s\phi\, c\theta\\ 0 & -s\phi & c\phi\, c\theta\end{bmatrix}\begin{Bmatrix}\dot{\phi}\\ \dot{\theta}\\ \dot{\psi}\end{Bmatrix} \tag{14}$$

and the time rate of change of the transformation matrix $\dot{T}_N^B$ is:

$$\dot{T}_B^N = T_B^N\ \omega_B \quad \text{where} \quad \omega_B = \begin{bmatrix}0 & -\omega_z & \omega_y\\ \omega_z & 0 & -\omega_x\\ -\omega_y & \omega_x & 0\end{bmatrix} \tag{15}$$

where ω_i are the three angular speeds components described in the skew symmetric rotating matrix expressed on the body reference frame.

The problem of attitude determination involves determining the transformation matrix that maps the on-board sensed information with model transformation to the geographic frame magnetic and gravity field components. For the body-referenced magnetic sensor to match the local geographic-referenced magnetic field, and for the body-referenced accelerometer sensor to match the local geographic-referenced acceleration then:

$${}^N\vec{m} = T_B^N\,{}^B\vec{m} \quad \text{and} \quad {}^N\vec{a}_G = T_B^N\,{}^B\vec{a}_G \tag{16}$$

Assuming these two vectors are not parallel, a third orthogonal vector can be produced by the cross product. The matrix formed using these three vectors as columns (superscript T over the vector states for transposed vector) can be associated to:

$$\left[{}^N\vec{m}^{\mathrm{T}}\ \ {}^N\vec{a}^{\mathrm{T}}\ \ \left({}^N\vec{m}\wedge{}^N\vec{a}\right)^{\mathrm{T}}\right] = T_B^N\left[{}^B\vec{m}^{\mathrm{T}}\ \ {}^B\vec{a}^{\mathrm{T}}\ \ \left({}^B\vec{m}\wedge{}^B\vec{a}\right)^{\mathrm{T}}\right] \tag{17}$$

The matrix on the left-hand side is composed by known geographic-referenced information. The matrix on the right-hand side is composed by sensed information. Therefore, the unknown DCM orthogonal matrix can be obtained from:

$$T_B^N = \left[{}^B\vec{m}^{\mathrm{T}}\ \ {}^B\vec{a}^{\mathrm{T}}\ \ \left({}^B\vec{m}\wedge{}^B\vec{a}\right)^{\mathrm{T}}\right]^{\mathrm{T}}\left[{}^N\vec{m}^{\mathrm{T}}\ \ {}^N\vec{a}^{\mathrm{T}}\ \ \left({}^N\vec{m}\wedge{}^N\vec{a}\right)^{\mathrm{T}}\right] \quad \text{and} \quad T_N^B = \left(T_B^N\right)^{\mathrm{T}} \tag{18}$$

A better refined estimative for the DCM matrix to identify body attitude is obtained using a Kalman filter technique [26]. Typical integration accumulated drifts errors, such as heading vehicle attitude, are to be corrected with multiple cross sensor information. With the accelerometers and the magnetometer a level frame is to be determined. Based on this error difference, an extended Kalman filter algorithm, merge multi sensor data, to correct and stabilize the rate-gyros orientation calculations as shown in Fig. 3. Complementary GPS data allows estimating the vehicle speed, alignment and the curvature of the trajectory [1].

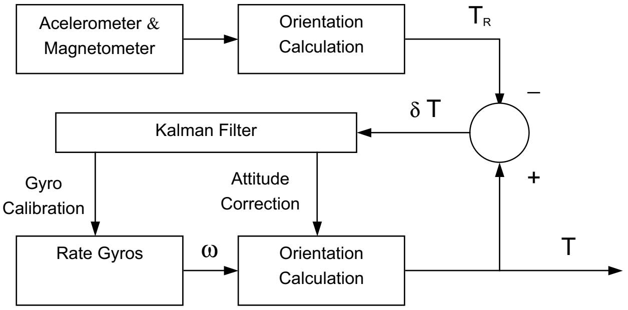

Fig. 3 Block diagram

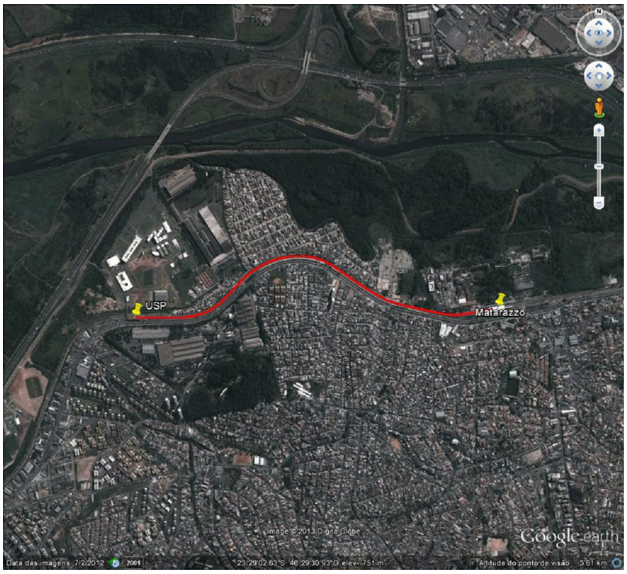

Fig. 4 Path travelled (satellite photo)

The angular description can be on the Euler form or Quaternion form, depending on the need to solve the singular problems due to angular quantification. With the accelerations, angular rate and attitude angles, the vehicle guiding force is calculated with aid of a strapdown inertial recovery (SIR) algorithm that allows to determine the SI. Data is filtered with a low-pass 15 Hz FIR filter.

5 Field measurements

Two field tests were performed with a passenger car equipped with the measuring system installed in the middle of the first passenger car. The first on-traffic-performance-concept proof was performed on the train on line 12 of the Companhia Paulista de Trens Metropolitanos (CPTM) from Bras Station to Calmon Viana Station in the east of Sao Paulo city, Brazil.

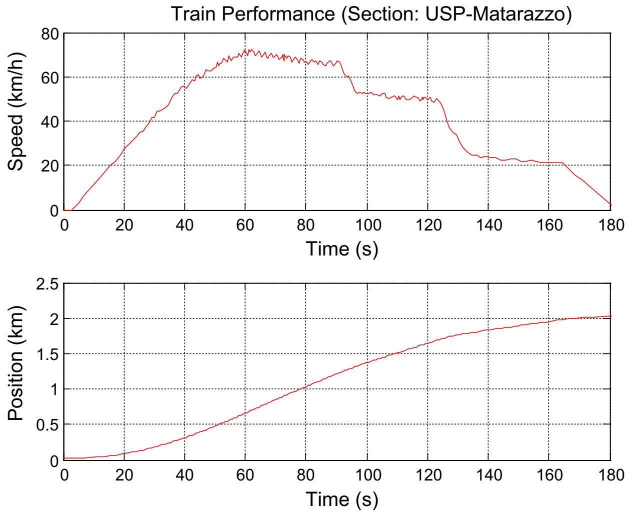

Fig. 5 GPS information

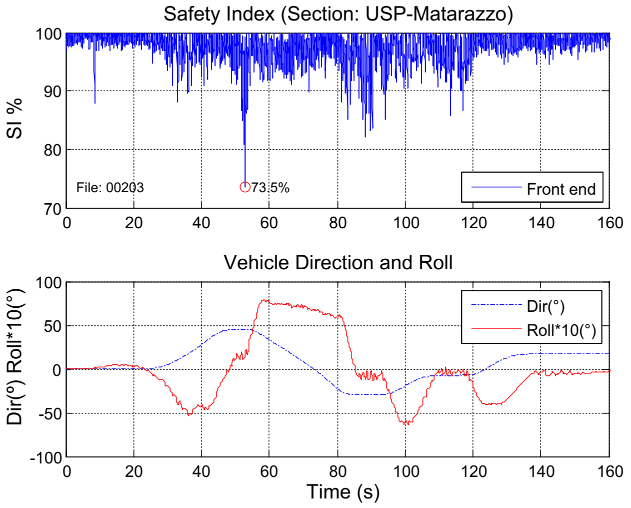

Fig. 7 Safety Index for the car front end—SI

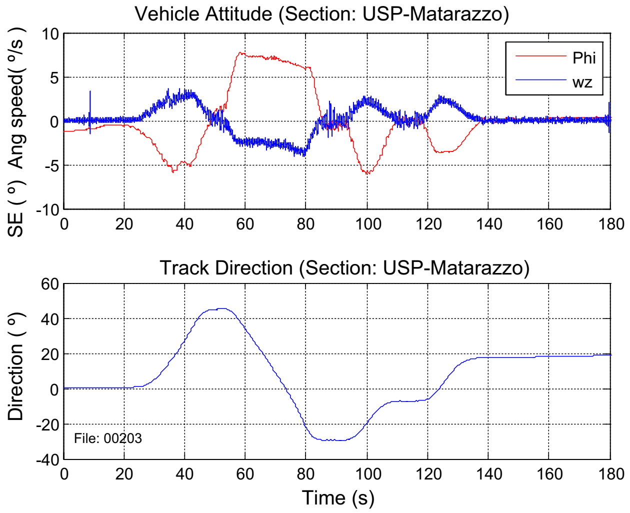

Fig. 6 Vehicle attitude

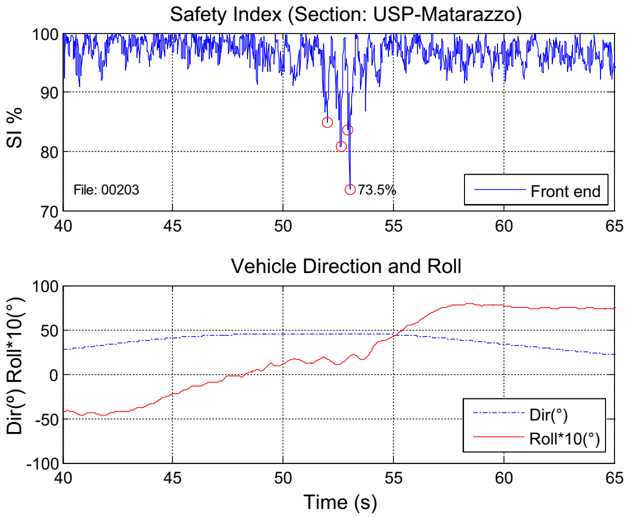

Fig. 8 Detail of the smallest values of the SI

A slice of path travelled, with a reversed curve, is selected for visualization and analysis. This section is between two stations (USP and Matarazzo) as can be observed in Fig. 4, which presents the satellite photo of the region (path travelled in red). After the USP station, the first short left curve can be observed (train moves to east), then the long right curve and two short left curves before the Matarazzo station. The train was conducted at the normal operational speed along this line, which is almost 50 km long. Particularly, the section between the two stations is around 2 km long and the train performance can be observed in Fig. 5 (speed and position).

The results of the rough measurements are presented in Fig. 6. The upper graph shows the vehicle angular yaw speed (ω_z) and the roll angle (Phi angle). The lower graph of Fig. 6 presents the car body or track direction (Psi angle). The long right curve of the section, between 50 and 55 s, can be clearly observed, when the train speed is around 67–69 km/h.

6 Analysis of data

To compute the wheel loads, it is necessary to 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 SI can be determined at any vehicle extremity. Adopting an *L*/*V* limit of 1.0, the resulting values for the SI of the vehicle front end are presented in Fig. 7. The upper graph presents the SI values and the

Fig. 9 Photo from satellite

lower graph, the vehicle movements. Reduced SI values are observed in the first reversed curves before the long right turn.

Figure 8 presents a closed look of the most critical region. The upper graph presents the SI and the extreme values are identified (red circles). As can be seen, the smallest SI value is 73.47 % at time 53.03 s, probably due to track twist in the straight track between the first reversed curves that promote roll movement oscillations of the car body. Other large values are observed next to 52.95; 52.63 and 52.00 s (SI values of 83, 7, 80.9 and 84.9 % respectively). This method point out exactly the place of reduced safety of the track, from the vehicle point of view and reinforces the recommendation for track maintenance on the geometric and irregularity properties in this location.

The exact location of the critical region is: Latitude: −23.484347° (23°29′3.65″S); Longitude: −46.496272° (46°29′46.58″O); Altitude: 737.949 m; Speed: 68.0 km/h; Heading: 43.45°; Time: 2013-02-20 T12:20:30Z (minus 3 h in this country).

The second test was performed at line 11 from Luz Station at Sao Paulo center to Guaianazes Station also on the east bound of the city. On this evaluation results measured were compared to the real track geometry measurements performed with a specialized car (EM-100 from Plasser).

In the section from km 10+800 to km 11+200 near Station Vila Matilde which exact geo-referenced location is shown in the satellite photo presented in Fig. 9, it is identified a reduced SI. The quantified value was 79 %, as shown in Fig. 10. At the bottom of the same figure is shown the direction of the passenger car in this region. Immediately after the critical point, there is a curve with a transition until km 11+100 after a circular curve with radius of approximately 650 m.

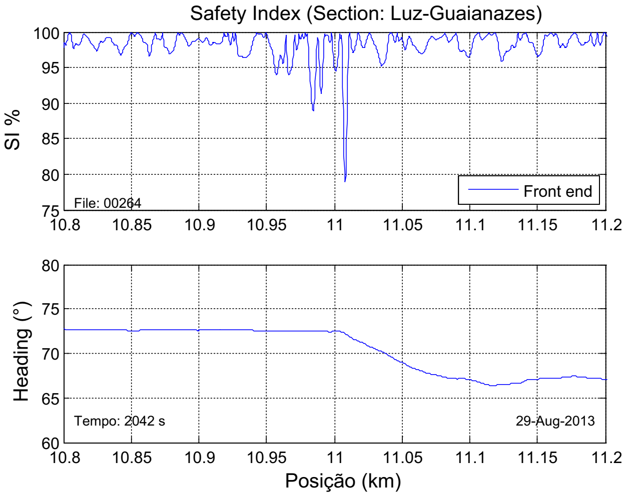

Fig. 10 Safety Index (km 11+000)

The track geometry and irregularities measured with the EM-100 vehicle are presented in the following figures. The track alignment shows a local variation before the transition curve as can be observed in Fig. 11. Also the track

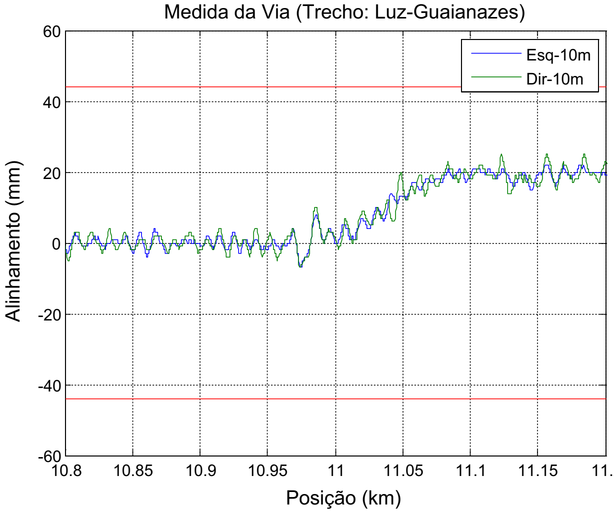

Fig. 11 Track alignment

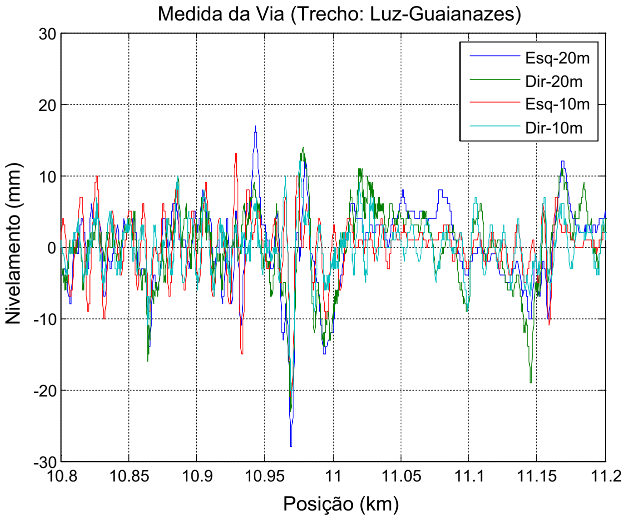

Fig. 12 Track leveling

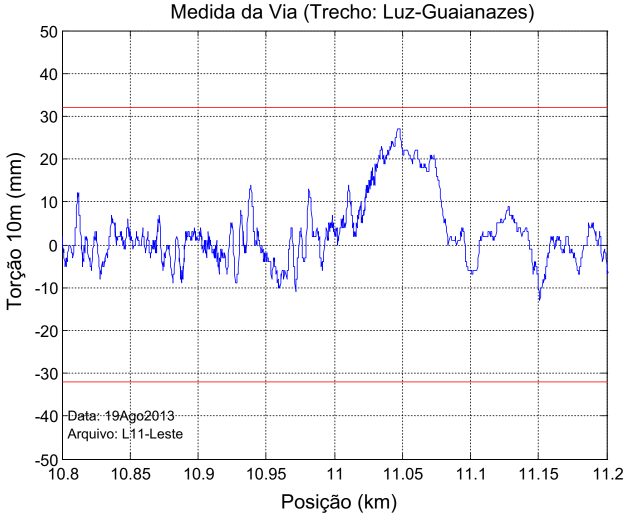

Fig. 13 Track twist (chord length 10 m)

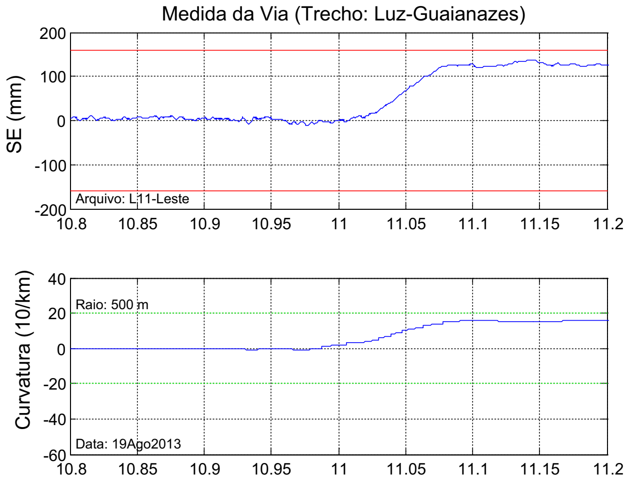

Fig. 14 Track cant and curvature

levelling presented in Fig. 12 shows abrupt variations. The track twist and track can and curvature are presented in Figs. 13 and 14 respectively.

It can be observed that all the track geometry measurements are below the FRA Class 3 level (red line on the graphs). At position km 11+010 inside the transition curve segment, there is small levelling deviation (Fig. 12) but not the highest value, and a twist in the transitions curve entrance (Fig. 13). Exactly on this position a reduced SI of 79 % was identified.

7 Comments

Albeit unnecessary from the point of view of track quality, this method takes into account the non-stationary longitudinal coupler forces effects. This action does affect the wheel load distribution, particularly in curves where its projection affects the lateral acceleration and the angular yaw body acceleration. Therefore, this jerk phenomenon is characterized with the body angular accelerations covered accordingly with this approach.

The results are related to the speed of the train during the journey. The operating speed is variable depending on the style of the driver, train load, climatic variations and any speed restrictions existing on the track. However, in different speeds, forced movements will change its magnitude, modifying the values measured, but keeping the location identified. Even the natural movements induced by periodic irregularities changes, but location remains due to the damping factor of the suspension.

The repeatability of the system is confirmed with different passenger cars of the same fleet. The possibility of evaluating similar vehicles in various load conditions or distinct passengers car fleets is easily performed, only by changing the installation of the measuring device. The data measured can also be used to evaluate passenger comfort using the vertical and lateral accelerometers signals in accordance with the comfort standard (ISO 2631) or even the vehicle modal quantification.

Differently from the other systems that use only statistics information from few sensors, the present new system is MISO that takes into account the complete vehicle multisignal input and deliver a single output index directly correlated to the safety condition.

8 Conclusions

A new inertial measuring system and a specialized data treatment method are presented to perform the railway track quality quantification, observed from the vehicle performance point of view. With an inertial device, the system measures the vehicle dynamic movements and attitude during its transit along the irregular track. The values measured are used in the strapdown inertial recovery (SIR) algorithm with an extended Kalman filter, to identify the full vehicle attitude, including angular positions and accelerations. The vehicle system equations for the inverse dynamic problem, augmented by suspension torsion equation, is solved to directly calculate the wheels driving forces Also the safety *L*/*V* contact force ratio in the low frequency region is identified. The SI directly correlated with the vehicle safety is determined based on the traditional railway *L*/*V* ratio. Values obtained are used to qualify track harmful locations.

The results of a preliminary test campaign travelling on the irregular track in a conventional train are presented. The full vehicle attitude and movement identification as far as the calculations of the SI is performed. Values obtained for the SI drop down to almost 75 % probably due to track twist in the straight track between the reversed curves that promote roll movement oscillations of the vehicle. The GPS signal simultaneously captures the exact georeferenced location and train speed of the most potential hazard region for track maintenance purposes. The second test results were compared to the measured track geometry and a good correlation was observed and the most harmful location was identified. The new method developed is direct and objectively identifies the location of undesirable track geometry and irregularities, through the unsafe dynamic vehicle behaviour.

This quantification is not unique but may complement the other existing geometric tools. Due to its simplicity and low cost, the new 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 user interests. The better classification of the most harmful track locations, allows prioritising the track intervention strategy. The complementary combination of new and traditional monitoring track inspection techniques can help to better understand asset behaviour and produce effective investment efficiency in railway track maintenance, being a promising technique. Future development aims to extend this concept to a system with a full sensor in each rigid body, all of them time synchronized, and with the correspondent set of equations of motions.

Acknowledgments The author would like to thank the Mechanical Department of the Polytechnic School of São Paulo University (EP-USP) for the support to this research and Companhia Paulista de Trens Metropolitanos—CPTM, in São Paulo, Brazil that made available the resources for the railway measurements.

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