Quantification of Railway Track Safety with an Inertial Vehicle Response Identification

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Abstract

A new method for track inspection was developed to complement the traditional geometric methods. An inertial measuring system installed on the vehicle is used to acquire the vehicle’s response to irregular track input. A specialized data treatment method is used to evaluate railway track safety, observed from the vehicle dynamic performance point of view. System equations for the inverse vehicle dynamic problem are solved to estimate the wheels driving forces which are directly correlated with the vehicle’s safety when travelling over track unevenness. Results of a measuring campaign on a railway wagon are used to evaluate the present system, by direct positional comparison with track geometry measurements. Also, data collected and treated are compared with the lateral to vertical dynamic loading safety (L/V) ratio measured with instrumented wheelsets installed on the wagon. The results of the quantified track safety present good agreement with the traditional measuring methods. This confirms the ability of the method to detect the location of the potentially most hazardous regions, for optimised railway track maintenance purposes.

Keywords: safety, railway, track, quality, inertial, dynamic, vehicle.

1 Introduction

The quality of a railway track is quantified by its structural strength and geometric parameters deviation. The inspection is performed with a specialized vehicle which measures and records the variations of the track gage, vertical and lateral alignments, and cross-level. Measured values are compared to standardized limits. Usually, only short to medium wavelength irregularities are detected. Additionally, the cross-level variation per meter (track twist) can be calculated depending on the data sample rate.
A poor vehicle dynamic performance frequently occurs in locations such as curve entries or exits, severe track irregularities, or misalignments which promote yaw instability or hunting. Therefore, a bad vehicle performance may point out areas of track which need maintenance. Conversely, there are some track locations which exceed track geometry standard limits but do not cause poor vehicle performance.

Safety diagnosis is the ability to identify on which region of the line the vehicle dynamic performance is poor or dangerous. To meet security aspects, the evaluation must also consider the victim of the lack of safety; the vehicle which effectively derails. As the track and the vehicle form a naturally mutual dependent system, the vehicle’s behaviour reflects its own properties and forced movements, which are directly affected by the track geometry input, track stiffness, and train speed [2].

The track safety concept is the ability to promote the non-dangerous traffic of vehicles and trains. A vehicle transporting goods obviously depends on the track’s structural integrity, an efficient train operation, and the vehicle’s performance to reach a minimal probability of derailment. The only way to guarantee effective track quality, focusing on safety, is to objectively contemplate all these aspects, including vehicle behaviour.

Track properties are mainly described by their geometric parameters as curvature, transition curve form and length, and super-elevation. Track deformation also affects the passing vehicle as a result of its stiffness. The track irregularities are the variations around the nominal geometry, which may be a random or a periodic variation [6]. Regardless of the type of irregularities, the fact is that the track shape, with varying geometry, imposes a range of load distribution to the wheels and their sum imposes a variation on the vehicle’s kinematics. Therefore, the wheel acting forces produce the bogie directioning and the vehicle accelerations to negotiate the curves. The objective safety of the system is associated with the vehicle’s derailment, traditionally quantified with the $L/V$ factor. This well-known and widely accepted factor derives from the wheel/rail system characteristics. This means the vehicle’s response is as a result of the track irregularities input. Therefore, the whole system must be evaluated simultaneously to objectively quantify the track quality, from the point of view of safety [1].

An instrumented iron-ore wagon was proposed by Darby [9] 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 an instrumented wheel-set is another method to evaluate the effect caused by the track’s irregularity over the vehicle’s 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 [11] and, therefore, the vehicle’s safety. Also, the use of portable accelerometers is employed for passenger comfort measurements [11] 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 used, in particular, in automotive control systems. Examples of use of this new technology can be found in Feldmann [12] who proposes to detect the vertical track settlement and deterioration by using frequency domain transformation from the inertial measurements of the vehicle's behaviour. Weston [13] uses rate gyros and lateral acceleration for track curvature and alignment monitoring. Xia [14] used an inverse vehicle model to estimate high-frequency wheel/rail contact forces from the 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 as a result of high frequency movements of the body with reduced weight (ex. wheelset, side frame, etc.). However, at low frequencies, vehicle mass has predominance over the system's movements and can be used for a particular application, which is the object of this work. Hung [15] reports 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 unsafe vehicle conditions. Heirich [16] uses 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 [17] proposes 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. However, the use of the transfer function related to the parameters of the track (Track Geometry Assessment TGA, EN 14363) [18] is restricted to only two translational directions (vertical and lateral) and a wavelength range of 3-25 m, and does 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 cars or wagons which use it. During its service life, a perfect track develops irregularities which cause vehicle oscillation. In an 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 (DNV Report [19]). Focusing on the track geometry defects, structural elasticity, vehicle suspension characteristics, and train speed, all of these are potential, possible contribution causes and should, therefore, be evaluated together to minimize hazard risk, improving the safety of traffic. As can be observed, all the systems described are mainly based on only geometric aspects of the track.

Generally speaking, there are three types of relevant, unsafe vehicle conditions. The first type is the wheel-climb derailment. It may occur at low speed in sharp curves and is particularly related to vehicle suspension stiffness and wheel load distribution conditions. The second type is mainly related to large movements of the vehicle’s main body. This condition can be associated with the vehicle’s unsprung mass dynamic movements and directioning bogie/wheelset properties. The third type is relative to a syntonized train speed and a particular type of track irregularity. This
last one is associated with the dominant track evenness wavelength, the vehicle’s natural frequencies, and specific train speed. Although there are other types of unsafe conditions, including vehicle instability, accidental, and component failure, the second type here described, is mainly related to the vehicle body low frequency movements and small energy dissipation.

Our proposed methodology to quantify track safety through inspection is based on the detection of signs of unsafe railway vehicle performance, mainly associated with the second and third types of unsafe conditions, when travelling along the track unevenness. These signs are used to identify the exact location along the track and to prioritise the pertinent track geometry correction to the most harmful irregularities for the vehicle’s safety.

The metric adopted to identify the potential harmful location on the track associated with the vehicle’s safety is the traditional L/V ratio between the wheel lateral (L) and vertical (V) contact force. The wheel forces are quantified from the measurement of the vehicle’s attitude and its overall dynamic behaviour. This task is performed with an inverse vehicle dynamic model, fed with data acquired from the instrumented vehicle during the transit journey. The vehicle’s instrumentation is composed of an inertial measuring unit (IMU) with nine high-resolution transducers and an inertial navigation system (INS) for attitude recognition, and a GPS positioning signal [3].

2 Track vehicle interaction

The track geometry is the input to the vehicle’s dynamics on a moving train. Its curve circular radius, cant, and transition length generally describes track variation. In addition to the long geometry profile, a small wavelength irregularity is usually present. The maximum irregularity over the nominal geometry are usually limited to the track class (e.g. gage, level, alignment, cant, twist, etc.) as described by normative standards (e.g. FRA, UIE, etc.). Some types of irregularity do affect the modal vehicle’s behaviour (e.g. bounce vibration as a result of long-wave track level or lower sway mode as a result of track alignment). Other track irregularities are absorbed by the vehicle’s suspension (e.g. short wave-length track twist).

The wheel/rail contact force (L and V), as a result of the vehicle’s dynamic behaviour, is a function of the roughness of the track which the vehicle is travelling on. To identify the acting contact forces which produce the vehicle’s directioning movements, it is necessary to solve an inverse dynamic problem. The vehicle’s dynamics are described by a set of differential equations obtained from the Newton-Euler theorems applied to a model of the vehicle considered as a rigid body. This equation is valid for a fixed reference frame N (OXYZ) as presented in Figure 1. For the translational movements, the following differential equations relate to accelerations and external forces in an earth fixed reference frame [3]:

\[ m \ddot{x} = \sum F_{ext} \]  
(1)
This equation does not consider the drag and Coriolis effects from the earth rotations as a result of the irrelevant magnitude faced by the vehicle's acceleration. The external forces are mainly as a result of wheel contact forces and gravitational effects, as shown in Figure 1.

\[ m \overset{N}{\ddot{a}}_G = \sum \overset{\text{wheel}}{\bar{F}} - m \overset{N}{\bar{g}} \quad (2) \]

The equation can also be expressed in the body reference frame (Gxyz) using a rotational transformation matrix T, composed of the three Euler angles (roll \( \phi \), pitch \( \theta \), yaw \( \psi \)) as identified in Figure 1, from which the accelerations are to be measured and the forces computed:

\[ m T_{N}^{B} \left( \overset{N}{\omega} \overset{N}{\ddot{a}}_G + \overset{N}{\bar{g}} \right) = T_{N}^{B} \sum \overset{\text{wheel}}{\bar{F}} \quad (3) \]

When the measuring system is fixed at a 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 equation:

\[ \overset{\text{B}}{\bar{a}}_G = \overset{\text{B}}{\bar{a}}_P + \overset{\psi}{\omega} \wedge (G - P) + \overset{\phi}{\omega} \wedge (G - P) \]

\[ \overset{\omega}{\Omega} = \overset{\phi}{\Omega} \overset{\phi}{I} + \overset{\theta}{\Omega} \overset{\theta}{J} + \overset{\psi}{\Omega} \overset{\psi}{K} \]

where the angular velocity is composed by the body roll rate \( \overset{\phi}{\Omega} \), the pitch rate \( \overset{\theta}{\Omega} \), and the yaw rate \( \overset{\psi}{\Omega} \).
For the rotational movements described in a moving reference frame attached to the vehicle, the following differential equations relate angular accelerations $\alpha$ and body angular velocity $\omega_b = [\omega_x \ \omega_y \ \omega_z]^T$ and external moments with respect to the same pole:

$$\begin{bmatrix} J \end{bmatrix}_b \{\alpha\} + [\omega_b] \times [J]_b \{\omega_b\} = \{M^e\}$$  \hspace{1cm} (5)

The body external contact forces arising from each wheel (Hi, Li, Vi) are shown in Figure 1. The body external moments (MG) as a result of the wheel forces are obtained from the carbody dimensions as shown in Figure 1. To work out the contact forces solving the system equation, it is necessary to know the vehicle’s 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 2. Finally, the bodies angular attitude must be identified to solve torsion Equation 6.

The system has six equations and twelve contact force unknowns. Disregarding the longitudinal effects, one equation is removed and four longitudinal contact forces are ignored (no acceleration or breaking effects are evaluated). As a result of the system being hyperstatic, the contact lateral forces in each wheelset are summed. To solve the system with five equations and six unknown forces, an additional suspension torsion equation is disclosed to access each vertical force relationship, completing the system compatibility.

The vehicle longitudinal torsion, as a result of track twist, mainly affects 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 on the vehicle’s suspension stiffness, length and width of the vehicle, and magnitude and wavelength of track twist.

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

$$\Delta V = -k_p \frac{D}{2b} \delta$$  \hspace{1cm} (6)

To estimate the track twist from the overall vehicle inclination, a special filter is used to recover the local track superelevation ($\alpha$). However, the IMU coupled to the body measures the absolute vehicle roll angle referred to the earth plane ($\phi$). The total or earth referred body angle, as shown in Figure 2, is composed by the track cant angle ($\alpha$) added to the relative vehicle roll angle ($\beta$) as a result of suspension movements and inertial mass center height (hG):

$$\phi = \alpha + \beta$$  \hspace{1cm} (7)

The track cant angle ($\alpha$) 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 along the length (S) from:

$$\delta = \frac{d\alpha}{dS}$$  \hspace{1cm} (8)

![Figure 2: Track and vehicle roll angles](image)

To identify the angular accelerations, the vehicle’s angles and attitude, a specialized data treatment method based on an inertial navigation algorithm (INS) aided with extended Kalman filter is used as a multivariable estimator [3]. With all this information, it is possible to solve the vehicle’s inverse dynamic equations to evaluate the driving contact forces and calculate the traditional safety ratio force L/V.

To solve the inverse identification problem, the vehicle model has to be known, have a unique existing solution, and have continuous data of the measuring system available. Therefore, the requirements for the solution of the inverse problem are available using a complete measuring system, continuously monitoring vehicle body movement and its attitude dynamic behaviour (INS). A safety index (SI) is used to quantify track quality \(SI = 1 - \frac{L}{V}\) [3].

3 Measuring results and comparison

The safety index (SI) calculated with the system strapdown inertial recovery (SIR) algorithm, were compared with: a) the measured track geometry and b) the measured
bogie L/V wheel forces ratio (instrumented wheelsets (IWS)). A test campaign performing track inspection measuring track safety was carried out on a selected 25 kilometres track section with 1.6 metre gage located in the north region of Brazil. The typical iron-ore wagon was a 120 ton gondola GDT, with “7×11” and ride-control bogies.

The track geometry and irregularities were measured with a specialized measuring car (Plässer EM-100) in the same track location. The measurements were the variation of the track gage, vertical and lateral rail alignments (left and right), and track section cant. Additionally, it identifies track curvature and track twist.

The L/V wheel force ratio was also measured during the test campaign with two instrumented wheelsets (IWS) installed on the leading bogie of the wagon. For compatible comparison with SIR results, the bogie L/V value is calculated from the sum of the lateral load of each wheel divided by the sum of the vertical measured loads.

A special test train was prepared to travel on a selected track section. The train was formed with two locomotives (one at each end), four iron-ore loaded wagons and two laboratory cars. The instrumentation SIR system was installed underneath the first wagon, as can be observed in Figure 3. The two instrumented wheelsets (IWS) are installed in the leading bogie of this wagon. Additionally, a GPS is used to identify the speed of the train and position of the instrumented wagon.

Figure 3: Instrumented Wheelsets (yellow) and Measuring System (red)
Several tests were conducted at controlled speed (30, 50, 60, 70 and 75 km/h) in the eastbound direction (mine to port). The test at 75 km/h was selected for a closer analysis. The train speed was expected to be constant but as a result of a restriction near a bridge, the real speed varies around programmed values and its time history is presented in Figure 7. The track Safety Index (SI) values determined in function of kilometric position are presented in the upper graph of Figure 4. The lower graph in this figure shows the measured heading of the wagon.

![Safety Index Graph](image1)

**Figure 4:** Safety Index (km 35+000 until km 10+000)

The track geometry of this section, as measured with the EM-100 measuring car, is presented in Figure 5.

The upper graph (of Figure 5) shows the track super elevation along the kilometric position and the lower graph the track curvature. It can be observed in this section that there is a left curve of 860 meters of radius between km 16+800 and km 15+150. The bridge is identified at around 18 km (red vertical lines at Figure 5). The bogie L/V for the leading bogie, calculated from measured values of the two wheelsets, is presented in Figure 6.
Figure 5: Track Measured Geometry (EM-100 Measuring Car)

Figure 6: Leading Bogie L/V Results
The subsection between 27+000 km to 25+500 km was analysed in detail. This is a tangent track region as can be observed on the wagon absolute heading on Figure 8b measured with the SIR system installed on the vehicle.

Figure 8: Safety Index (leading bogie) and wagon heading
Figure 9: Measured L/V (leading bogie)

Figure 10 to Figure 12 show the track geometry measured with the Passer car. One can observe that there is a localized super elevation of 28 mm on 26+200 km, almost linearly rising and suddenly lowered as measured with the EM-100 car shown in Figure 10.

Figure 10: Track super elevation and curvature (EM-100)
In the same region, the track twist (5.0 metre chord) varies around ±15 mm (Figure 11). Additionally, the rail levelling goes up to −15 mm as shown in Figure 12.

Figure 11: Track Twist (chord length 5 m 3.5 m and 1.75 meters)

Figure 12: Track Levelling (left and right rail on 5 metre chord)
The safety index (SI) reached a lower value of 40%, as shown in Figure 8. In the same region, the L/V measured with the instrumented wheelsets was distinguishable from others with severe variation (Figure 9).

4 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, at 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 change, but location remains as a result of the damping factor of the suspension. The vehicle's response to track excitation is magnified by the vehicle frequency response function - FRF [2]. Therefore, cause and effect are related to this function.

Inspecting the sensor values, it is possible to identify which vehicle-moving mode contributes more to the SI values. Therefore, the type and magnitude of track wavelength roughness which is more harmful is identified and may be eliminated with maintenance intervention. Location without a GPS signal (e.g. long tunnels) can be complemented with a tachometer installed on the vehicle or an extrapolation performed from the INS algorithm. One limitation of the system is the precision and noise of the sensors which degrade the quality of the estimative.

This method is based on a simplified vehicle model which is complex enough to characterise the vehicle's low frequency behaviour, associated with the track long wavelength events and, therefore, can quantify safety between medium to high operation speeds (type 2 and 3 unsafety mode). Although a more sophisticated model, including suspension travel, can be realized [4, 8] to include medium to high frequency related to short wavelength roughness (first unsafety mode), the instrumentation, which must include the bogie and its inertial properties, will be much more complex.

The possibility of evaluating other types of wagon in different load conditions, or even passenger's car fleets, is possible providing that the model describes adequately the vehicle (inertial properties). This option is easily performed by only changing the installation of the measuring device. The data measured can also be used to evaluate passenger comfort using the vertical and lateral accelerometer signals in accordance with the comfort standard (e.g. ISO 2631), or even the vehicle modal quantification.
Differing from other systems which use only a few sensors or statistical information from them [5], the present new system is MISO which takes into account the complete vehicle multisignal input (tridirectional acceleration and angular rate) and delivers a single output index directly correlated to the objective safety condition (L/V value) revealing the novelty of this system.

5 Conclusions

An inertial measuring system and a specialized data treatment method to perform the railway track quality and safety quantification observed from the vehicle performance point of view is presented. With a strapdown inertial recovery (SIR) method, the system measures the vehicle’s dynamic movements and attitude during its transit along the irregular track using nine high-resolution transducers. The values measured are used to identify the full vehicle attitude, including angular positions and accelerations. The vehicle system equations for the inverse dynamic problem, augmented by the suspension torsion equation, is solved to directly calculate the wheels driving forces. The safety L/V contact force ratio at low frequency is identified. A safety index (SI) directly correlated with the vehicle safety, is determined based on the railway L/V safety limits. Values obtained are used to qualify the most harmful track locations for maintenance purposes.

A field test program inspecting the track was conducted on a special train travelling at controlled speed. The SIR was installed on a loaded iron ore wagon and the train ran on a selected track section at various speeds. The track safety index (SI) quantification was directly compared with local track measured geometry. Additionally, the results are also compared with measurements of the instrumented wheelset (IWS). Results show good agreement between both systems. The GPS signal simultaneously captures the train speed and the exact georeferenced location of the most potentially hazardous regions for track maintenance purposes.

The better classifying of the most harmful track locations allows prioritising of the track intervention strategy. The complementary combination of new and traditional monitoring track inspection techniques [7] can help to better understand asset behaviour and produce effective investment efficiency in railway track maintenance, being a promising technique.

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References


