Railway wagon dynamics subjected to wind, in-train forces and track geometry defects

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Abstract

A running railway wagon can be subjected to forces from in-train dynamics, wind, track curving, and track geometry irregularities and defects at the same time. However, there is no standard that sets appropriate dynamics criteria under a combination of these loads. This paper takes into account longitudinal train dynamics, lateral coupler forces, wagon dynamics, and the effects of track irregularities/defects to study railway wagon dynamics to determine acceptable operational conditions. A case study has been presented and the results show that the safe wind speed limit is 20 m/s for the simulated wagon running on a section of FRA class 5 track with a combination of track geometry defects and in-train forces.

Keywords: Wagon dynamics; Wind; Coupler force; Track geometry defects; Track irregularities

1. Introduction

Considering a single wagon, there are three primary excitation sources to take into account for vehicle system dynamics, namely track excitations, coupler forces and wind forces. Even for an ideal track that can be described by design parameters, excitations are generated by track gradients and curvature. In reality, there are two other types of track excitations: track irregularities and track defects. Both of these can be defined as deviations of the actual track geometry from the designed geometry. They are usually grouped into four types: gauge, horizontal alignment, top and twist [1]. Track irregularities are of comparatively small amplitudes (e.g., 5mm), while track defects have significantly larger amplitudes (e.g., 30mm). Track irregularities exist even in tracks of high standard and cannot be avoided; they are random in nature and mainly originate from the tolerances associated with the manufacture of track components and the processes of construction and maintenance of the track. Track defects, on the other hand, mainly result from the loadings imposed by train operations. Track defects are of major concern in maintaining safe interaction between vehicles and track [1].

Lateral coupler forces are conventionally neglected for single-vehicle system dynamics due to small coupler angles. However, with the overall mass and length of modern heavy haul trains having increased significantly, the resulting in-train forces are obviously much larger. The conventional assumption that lateral components of in-train forces are negligible can therefore no longer be assumed. In addition, wagon instability due to lateral components of coupler forces, especially on curved track, has become an issue of concern [2]. Derailments caused by excessive lateral in-train forces have been reported upon in [3-5]. In regard to the issue of crosswind effects, derailments where crosswind was found to be the primary contributing factor have clearly indicated the need for wagon stability studies under crosswinds (see examples in [6,7]).

While the potential is low for the three excitation sources mentioned above to all act on a wagon simultaneously, the risk is not one that can be ignored. However, current studies and acceptance procedures mainly focus on compliance with criteria for individual excitation sources. Hence there is now an interest in gaining an understanding of wagon stability under the combined effects of the various excitation sources. Motivation for this study also comes from the need for improvement of wagon acceptance procedures. In comparison with other international standards, the relevant Australian Standard (AS/RISSB7509.2 [8]) is focused on wheel unloading criteria for wind loading and overturning in curves without any track irregularity. AS/RISSB7509.2 does not include wind load calculations, but refers to the UK standard GM/RT2142 [9]. However, the GM/RT2142 requirements are only applicable to tangent track. Therefore, the corresponding results do not apply for curves. This paper presents a methodology to study wagon stability by considering: (1) wind forces, (2) track irregularities, (3) track curvature, (4) in-train forces, and (5) track defects. The enabling techniques include longitudinal train dynamics [10], coupler angle calculation [11], wagon

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dynamics [12], a wagon model acceptance procedure [13], and modelling of track irregularities and track defects.

2. Simulation Methodology

As shown in Fig. 1, the proposed methodology requires a collection of knowledge concerning longitudinal train dynamics, coupler angle calculations, wagon dynamics, track irregularities, track defects, and wind force simulations. The methodology was developed to cope with the following research gaps:

**The lack of Australian or international standards for assessment of wagon stability under the combination of these factors to minimise the risk of rollover derailment;**

**Complications with wagon dynamics under the implications of lateral coupler forces, combined track defects, and curvature effects.**

The methodology commences with a simulation of longitudinal train dynamics during which coupler angles over the full train trip are also calculated so as to determine the lateral and longitudinal in-train forces. Wagon dynamics models are developed and verified by referring to a wagon model validation procedure based on Australian standards as presented in [12]. Track irregularities and defects are specified according relevant standards. Wind forces are calculated according to the side area of the wagons and the running speed of the train. Finally, wagon dynamics simulations are executed considering a number of combinations of wind speeds and track geometry defect types.

![Figure 1. Methodology for investigation regarding the combination of factors affecting wagon stability](image)

![Figure 2. Relationship between wind angle and resultant wind angle [14]](image)

![Figure 3. Vehicle configuration during curving [15]](image)
2.1. Crosswind Modelling

Modelling of wind forces starts with a consideration of vectors of wagon velocity along the track, \( u \) and crosswind velocity, \( u_w \). Knowing the wind angle, \( \phi \), a resultant wind velocity vector with respect to the wagon, \( u_v \), can be determined along with the resultant wind angle, \( \Psi \), shown in Fig. 2. The implications of the asymmetric aerodynamic force are modelled by six aerodynamic forces and moments: drag force \( F_d \), side force \( F_s \), lift force \( F_l \), rolling moment \( M_r \), pitching moment \( M_p \), and yawing moment \( M_y \).

The aerodynamic forces and moments are defined as [14]:

\[
F_i = 0.5 \rho C_i A u_v^2
\]

\[
M_i = 0.5 \rho C_M A u_v^2 H
\]

where \( F_i \) indicates the aerodynamic drag (D), lift (L), and side (S) forces; \( M_i \) indicates the aerodynamic rolling (R), pitching (P), and yawing (Y) moments; \( \rho \) is air density; \( C_i \) indicates the D/S/M force coefficients; \( C_M \) indicates the R/Y/P moment coefficients; \( A \) is the wagon side area (m\(^2\)); \( u_v \) is the crosswind velocity (m/s); and \( H \) is reference height of the wagon (m) [9].

2.2. Longitudinal Train Dynamics and Coupler Angle Calculations

Longitudinal train dynamics has commonly assumed the simplification that there are no lateral and vertical movements for vehicles, i.e., only the longitudinal freedom is considered. For this study, force elements considered for the longitudinal train dynamics analysis are: propulsion resistance, curving resistance, gravitational components, traction forces, dynamic brake forces, air brake forces and in-train forces. Modelling of these elements has been extensively discussed previously [2,10] and are not discussed in this paper.

As an extension of [14], where only a lateral track defect on tangent track was studied, a curve with a radius of 300 metres has been chosen in this paper. Therefore, calculations of coupler angles and subsequent determination of lateral in-train forces are required. Modelling of coupler angles can be found in [15] and the geometrical layout is shown in Figure 3, with the angle between the two vehicles being \( \theta \). The calculation process is expressed as:

\[
\phi = (1 + (\alpha + \gamma) - O_{v2} \times \theta)/D
\]

\[
L = O_{v2} + O_{v2} + C_1 + C_2
\]

\[
\alpha = A_1/R_1
\]

\[
\beta = A_2/R_2
\]

\[
\gamma = L/2/R_2
\]

\[
\theta = \alpha + \beta + 2\gamma
\]

\[
D = C_2 + C_2
\]

where \( \phi \) is the coupler angle of vehicle 1; \( \alpha, \beta, \gamma \) are chord angles as shown in Figure 3; \( O_{v1}, O_{v2} \) are the overhang lengths of vehicles 1 and 2; \( C_1, C_2 \) are the coupler lengths of these vehicles; . Having determined the in-train forces and coupler angles from the longitudinal train dynamics simulation, the longitudinal and lateral coupler force components respectively can be determined as follows:

\[
F_{c,kx} = F_{c,k} \times \cos(\phi)
\]

\[
F_{c,ky} = F_{c,k} \times \sin(\phi)
\]

where \( F_{c,k} \) is the coupler force; \( F_{c,kx} \) is the longitudinal component of the coupler force; \( F_{c,ky} \) is the lateral component of the coupler force.

A hypothetical heavy haul track including many curved sections over a total length of about 50km has been considered as shown in Figure 4. The simulated train has a configuration of 1 head end locomotive hauling 66 wagons; the locomotive has a mass of 120 tonnes and all wagons have empty and loaded masses of 20 tonnes and 106 tonnes respectively. Combining the results of longitudinal train dynamics simulation and coupler angle calculation, the maximum lateral coupler force on 300m radius curves was determined as 13.146 kN.

2.3. Wagon Modelling

A multibody wagon model has been developed in Gensys [16] and its parameters are presented in Table 1. The AS60 kg/m rail profile and ANZRU wheel profile have been used in the model, both being for the "as new" condition without any wear. The coefficient of friction at the wheel-rail contact patches is taken as 0.4, corresponding with dry weather conditions. The numerical integrator used is a modified Heun method with the step-size of 1 ms.
Figure 4. Operational data for train simulation [12]

Table 1. Wagon model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car body mass (empty)</td>
<td>11901 kg</td>
</tr>
<tr>
<td>Car body roll inertia</td>
<td>706126 kg-m²</td>
</tr>
<tr>
<td>Car body pitch inertia</td>
<td>85342.12 kg-m²</td>
</tr>
<tr>
<td>Car body yaw inertia</td>
<td>85342.12 kg-m²</td>
</tr>
<tr>
<td>Mass of bolster</td>
<td>894.2 kg</td>
</tr>
<tr>
<td>Bolster roll inertia</td>
<td>324.1 kg-m²</td>
</tr>
<tr>
<td>Bolster pitch inertia</td>
<td>32.7 kg-m²</td>
</tr>
<tr>
<td>Bolster yaw inertia</td>
<td>186.9 kg-m²</td>
</tr>
<tr>
<td>Mass of sideframe</td>
<td>715.4 kg</td>
</tr>
<tr>
<td>Sideframe roll inertia</td>
<td>116.6 kg-m²</td>
</tr>
<tr>
<td>Sideframe pitch inertia</td>
<td>182.5 kg-m²</td>
</tr>
<tr>
<td>Sideframe yaw inertia</td>
<td>161.5 kg-m²</td>
</tr>
<tr>
<td>Mass of wheelset</td>
<td>1087.5 kg</td>
</tr>
<tr>
<td>Wheelset roll inertia</td>
<td>322.7 kg-m²</td>
</tr>
<tr>
<td>Wheelset pitch inertia</td>
<td>100 kg-m²</td>
</tr>
<tr>
<td>Wheelset yaw inertia</td>
<td>322.7 kg-m²</td>
</tr>
<tr>
<td>Bogie spacing (half)</td>
<td>2.655 m</td>
</tr>
<tr>
<td>Side bearing lateral spacing (half)</td>
<td>0.43 m</td>
</tr>
<tr>
<td>Wheelset spacing (half)</td>
<td>0.9145 m</td>
</tr>
<tr>
<td>Wheel radius</td>
<td>0.46 m</td>
</tr>
</tbody>
</table>
2.4. Track Irregularities and Defects

The single-vehicle dynamics simulations are undertaken with the wagon running over a section of track with the designed track geometry presented in Table 2; the track includes US Federal Railroad Administration (FRA) Class 5 track irregularities [17]. Track defects for gauge, horizontal alignment, top and twist are defined by referring to the Australian Rail Track Corporation’s track geometry standard [1] which indicates that each defect considered individually would not require immediate rectification for the safety of freight trains operating at a speed below 60 km/h. The magnitudes of the track geometry defects are also listed in Table 2 and their individual positions along the track within the 300 m radius curve are shown in Fig. 5. All four track geometry defects are superimposed over the designed track geometry so that they are experienced by the wagon at the same time.

3. Simulation Cases and results

Twenty simulation tests have been conducted in the GENSYS simulation software package to assess the combined
effects of the following loading regime used for this study:
** Crosswind speeds: 0, 10, 15 and 20 m/s;
** The simultaneous combination of gauge, horizontal alignment, top, twist defects;
** Constant wagon speed: 45 km/h;
** Maximum lateral coupler force: 13.146 kN.

The wagon stability assessment is based on the main acceptance criteria specified in Australian Standard AS/RISSB7509.2 [8] concerning dynamic behaviour of freight rolling stock as presented in Table 3. Note that there is no requirement specified in AS7509.2 in regard to gauge defects, and that all these criteria are set in isolation from each other with no requirements specified regarding assessing their combined effects.

Based on the results of the twenty simulation cases, it has been found that the criteria for the maximum lateral accelerations are not seriously affected by the chosen values for crosswind speed, lateral coupler force and track defects (calculated maximum lateral accelerations do not exceed ±0.3g). More complex outcomes can be observed for the individual wheel L/V (lateral to vertical) ratios, sum L/V axle ratios and wheel unloading. Those results have been analysed for the individual track geometry defects and for the combination of all of them and the maximum values are presented in Figure 6.

The results show that, with individual defects, the dynamics performance of the wagon satisfies the standard. While individual L/V and sum L/V axle ratios increase their values with the increase of crosswind speed, those ratios do not exceed their respective limits. In the combined defects case, the general trend of the criteria values is the same, but the limits of individual L/V and sum L/V axle ratios are exceeded when the crosswind speed reaches 20 m/s.

Table 3. Acceptance Criteria in AS/RISSB7509.2

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Acceptance criteria (limits)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Item_1</td>
<td>Negotiation of isolated track irregularities: vertical and lateral</td>
<td>Maximum vertical acceleration: ±0.8g; maximum lateral acceleration: ±0.5g; maximum wheel unloading sustained for 50ms should be 90%; maximum sum L/V axle ratio sustained for 50ms should be 1.5.</td>
</tr>
<tr>
<td>Item_2</td>
<td>Transition curve negotiation</td>
<td>Maximum sum L/V axle ratio sustained for 50ms should be 1.5; maximum wheel L/V ratio sustained for 50ms should be 1.0.</td>
</tr>
<tr>
<td>Item_3</td>
<td>Longitudinal forces in curves</td>
<td>Maximum wheel unloading 100%; flange climb lifting the centre of the tread off the rail head less than 10mm.</td>
</tr>
<tr>
<td>Item_4</td>
<td>Wind load considerations</td>
<td>Maximum wheel unloading 90% for one side of any bogie.</td>
</tr>
</tbody>
</table>

Figure 6. Simulation results – maximum parameter values for various track defect categories
Wheel unloading also increases with the increase of wind speed, but remains well below its 90% limit value. As expected, vertical acceleration results show high values in the case of top defects with these being very close to the limits, thus contributing to vertical acceleration results in the case of combined defects. Based on the results of this study, the use of individual L/V and sum L/V axle ratios as the primary criteria for combined defects is recommended. However, the results presented in this paper should only be taken as preliminary as the probability of meeting such combined defects in reality is low. Further investigations on combined defects should be performed on the basis of field data, and then the proposed methodology can be used to study wagon safety and stability issues for the specific vehicle design and track quality involved.

4. Conclusion

This paper describes a method to study wagon dynamics when subjected to a combination of excitations: in-train forces, track curving, track irregularities, track defects and wind forces. The method can be used to improve the existing Australian Standard AS/RISSB7509.2 in which there are currently no specific requirements specified in regard to combined defects. Individual L/V and sum L/V axle ratios can be used as criteria for combined defects. The simulation results provided indicate that the wind speed limit is 20 m/s for the simulated wagon running on Class 5 track with combined geometry defects. Further research should be performed with more variation of input parameters and using real track data on combined defects.

References


[http://www.gensys.se/ref_man.html](http://www.gensys.se/ref_man.html)