Study of The Derailment Potential of Railway Cargo Vehicles as a Function of the Loading Characteristics

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Abstract
Railway bogies of the Y25 family are the most common type used in freight wagons in Europe. This family of bogies presents poor curving performance and a history of derailments. While it is not feasible to overhaul the entire family of bogies, it is possible to assess the limits of safe operation of the wagons equipped with these bogies. This requires a deeper understanding of the effect of the loading characteristics in the derailment potential of freight vehicles equipped with bogies of the Y25 family, in realistic conditions. In this thesis, the safety against derailment of a laden freight wagon fitted with Y21 bogies is evaluated, using the derailment of a freight train in a Portuguese railway line as a case study. This requires the development of models, using the commercial multibody program VAMPIRE and the in-house program MUBODyn. To model the friction suspension elements of the freight vehicles, VAMPIRE offers line friction elements, while MUBODyn allows the use of imperfect kinematic joints. These vehicle models are simulated under potential derailment scenarios and the derailment assessment quantities are determined. Despite the good agreement between the two programs in the nominal case, the results differ in more adverse scenarios due to the different modelling approaches. Amongst the scenarios considered, asymmetric loading plays the biggest influence in the derailment potential of the wagon.

Keywords
Railway Dynamics; Freight Bogies; Derailment Assessment; Multibody Systems; Imperfect Kinematic Joints; Friction Modelling

1. Introduction
The railway dynamics involves the interaction between the two main structures that compose the railway systems: the rolling stock and the track. Different requirements led to the development of different railway vehicles to transport passengers and goods. The transport of passengers requires high levels of comfort and safety. Thus, passenger vehicles are equipped with more complex suspensions that may include viscous dampers and air springs. On the contrary, the movement of cargo only requires safety at low to medium speeds, without comfort considerations. Therefore, friction-damped suspensions [1] are commonly used in freight wagons to reduce maintenance costs, at the expense of vehicle stability [2]. Bogies of the Y25 family are equipped with Lenoir links combined with friction dampers in the primary and secondary suspensions, that play a key role in the dynamic behaviour of the bogie [3]. The understanding of the dynamic behaviour of these bogies, in the context of active safety, is addressed in this work.
Multibody simulations are used to assess the safety against derailment of railway vehicles [4–6]. The multibody simulation of the railway dynamics involves a model of the vehicle, a model of the track and a suitable wheel-rail contact method [7,8]. The vehicle model consists of a group of bodies connected by force elements and joints. Kinematic joints restrict the relative motion between the bodies and may be used to represent most mechanical systems, including railway vehicles [9]. Imperfect kinematic joints [10–12] can be used to model the clearances and friction effects [13]. The use of imperfect joints requires the selection of normal and tangential contact force models to represent the forces transmitted by the bodies [10,14,15]. The modelling of friction suspension elements is challenging from the computational point of view, because of the need to deal with impacts and friction effects that lead to stiff numerical problems.

Several criteria have been developed to evaluate the derailment potential of railway vehicles. Nadal formulates a single-wheel derailment criterion based on the idea that flange climb is prone to occur under conditions of high lateral contact forces combined with reduced vertical wheel load [16]. This criterion is related to the \( Y/Q \), which is the ratio of lateral wheel-rail contact force \( Y \) and vertical contact force \( Q \). The Nadal criterion defines the limit value to this ratio as a function of the wheel-rail coefficient of friction and the wheel profile. This criterion provides a basis for the limit values defined in standards, EN 14363 and UIC 518, that regulate the testing and numerical simulations required for the acceptance of the running behaviour of railway vehicles.

Most frequently, derailments are the combined result of several effects [5], such as faulty vehicle and track conditions, possibly related to defective maintenance and management, poor vehicle-track compatibility, human factors such as errors of drivers and other personnel, and adverse environmental conditions. The D-RAIL project includes the study of the influence of parameter variation, skew loading, wheel and suspension failures, isolated track defects and sloshing on the derailment potential of a single freight wagon with Y25 bogies [17].

2. **Wheel Flange Climb Derailment**

Wheel flange climb occurs when a flanging wheel climbs on top of the rail, leading to the loss of lateral guidance. This derailment mechanism is associated with situations where the flanging wheel is subjected to a high lateral force impulse combined with a drop in the vertical force that supports the wheel. The ratio of lateral contact force \( Y \) to vertical contact force \( Q \) on a wheel is commonly called \( Y/Q \). Increases in the lateral contact force are usually associated with high angles of attack. In turn, the vertical wheel load may be reduced by the negotiation of track irregularities, canted track and vehicle body roll resonances. Reductions in the vertical wheel load can also be caused by asymmetric loading.

Several flange climb derailment criteria have been developed to study the likelihood of derailment occurring when there is contact between the flange and the rail. Most commonly, these criteria assume derailment occurs when the \( Y/Q \) ratio exceeds a certain limit. The first structured effort to explain flange climb derailment was proposed by Nadal [16], based in the idea that the climbing of the flanging wheel is favoured by a combination of high lateral contact force and reduced vertical contact force. The railway vehicle is assumed to negotiate a perfectly smooth curve in quasi-static conditions, i.e., constant forward
velocity and subjected to constant contact forces. The flanging wheel is assumed to be in two-point contact, with the flange contact point leading, as shown in Figure 1. The wheel rolls about the instant centre of rotation at the tread contact point, and the tangential velocity of the flange at the point of contact is oriented downwards, as depicted in Figure 1 (b).

![Flanging wheel diagram](image)

Figure 1 – Top and side view of the flanging wheel.

The derailment criterion proposed by Nadal is defined in two dimensions by the ratio of lateral force $Y$ and vertical force $Q$ at the flange contact point, represented in Figure 2. $Y$ and $Q$, defined in the inertial reference system, are transformed into the lateral creep force $T_y$, tangential to the rail profile and oriented in the direction opposite to the sliding velocity at the flange contact point, and $N$, normal to the rail at the point of contact.

![Forces diagram](image)

Figure 2 – Forces at the flange contact point.

Nadal proposed wheel climb occurs when the flange ceases to slide on the rail, due to the sliding friction saturating on the flange contact point. The wheel is assumed to instantaneously pivot around the flange contact point. The friction saturation condition renders:

$$T_y = \mu_{w,r} N$$

(1)

where $\mu_{w,r}$ is the sliding friction coefficient at the wheel-rail interface. The limiting value of $Y/Q$ over which derailment is likely to occur, according to the single wheel criterion by Nadal, is defined by the relation between the contact forces, expressed by:

$$\frac{Y}{Q} = \frac{\tan \delta - \mu_{w,r}}{1 + \mu_{w,r} \tan \delta}$$

(2)

where $\delta$ is the angle of the plane of contact, measured relative to the horizontal plane.
Despite more recent developments on the study of flange climb derailment, the single-wheel Y/Q limit by Nadal is still widely used by the academia and the industry as a first approximation to assess derailment safety. Several vehicle safety acceptance standards, such as standard UIC 518 and EN 14363 refer to the Y/Q criterion of Nadal and define limits on its basis.

3. Multibody Formulation

The dynamic analysis of a multibody system involves the study of its motion and of internal and external forces developed during a given time period. The kinematic joints constrain the relative motion between the bodies, while the force elements represent the internal forces that develop between the bodies due to their relative motion. In this section, some of the features of the multibody formulation, required to model railway vehicles, are presented from the perspective of MUBODyn.

3.1. Equations of Motion

In the framework of using Cartesian coordinates, the equations of motion of a multibody system combined with the second time derivative of constraint equations are expressed as [18]:

\[
\begin{bmatrix}
    M & \Phi_q^T \\
    \Phi_q & 0
\end{bmatrix}
\begin{bmatrix}
    \ddot{q} \\
    \lambda
\end{bmatrix} =
\begin{bmatrix}
    g \\
    y - 2\alpha\Phi - \beta^2\Phi
\end{bmatrix}
\]

(3)

where \(M\) is the mass matrix, \(\ddot{q}\) is the vector of the system accelerations, \(g\) is the force vector, \(\Phi_q\) is the Jacobian matrix associated to the kinematic constraints, \(\lambda\) is the vector of Lagrange multipliers related to the joint reaction forces, \(y\) is the right-hand side of the acceleration constraint equations, \(\Phi\) is the first time derivative of the kinematic constraint \(\Phi\), and \(\alpha\) and \(\beta\) are parameters associated with the Baumgarte Stabilization. All these matrixes and vectors result from assembling individual contributions of bodies, joints and force elements.

3.2. Perfect Kinematic Joints

The relative motions of the bodies that form a mechanical system are limited by kinematic joints. These joints are described mathematically by a set of algebraic constraint equations that define the kinematic relations between the spatial coordinates that describe the state of the system. These kinematic joints are commonly used in multibody systems and are used to develop the railway vehicles models presented in this work. The mathematical description of the revolute joint is described by a set of \(n\) algebraic equations:

\[\Phi^{(n)} = 0\]

(4)

involving the kinematic quantities of the bodies of the system. The second time derivative of the previous equation can be written in the form:

\[\Phi = 0 \Rightarrow \Phi_q \dot{q} = y\]

(5)

where \(\Phi_q\) and \(y\) are terms of the equations of motion of the multibody system.

3.3. Imperfect Kinematic Joints

Real mechanical systems present local compliances and clearances that allow the correct fitting between the mechanical components. Imperfect joints, that are able to represent clearances, are implemented in
MUBODyn according to the formulation defined in [19]. This formulation follows a common mathematical description with the perfect kinematic joints, from the point of view of the algebraic operations that are required.

Contrary to perfect kinematic joints, that define kinematic constraints between bodies in the form of non-linear algebraic equations that contribute to the Jacobian matrix, imperfect joints implicitly impose kinematic constraints through the contact forces caused by the relative displacements and interferences between the bodies. Thus, the formulation of bushing/clearance joints is divided into two problems: the definition of the relative displacements/rotations; and the determination of the associated penetrations, with which the determination of the resultant normal and tangential contact forces are possible, using normal and tangential contact force models. The forces and equivalent moments are applied on the bodies through their summation to the force vector of the system, \( \mathbf{g} \).

4. **Train Derailment in the Portuguese Rail Network**

The scope of this thesis is the result of an inquiry on the root causes leading to a train derailment which occurred in a Portuguese railway line in 2017. The last wagon of a freight train loaded with sheet metal coils derailed while passing through a railway station at a speed of 100 km/h (27.78 m/s). This station is located on a curve with a mean radius of 601 m. Physical evidence on the track showed the wagon climbed the inner rail on the full curved section. The wagon proceeded until a collision with a crossing forced the wagon to climb the two rails and overturn to the right side of the track, as depicted in Figure 3.

![Figure 3 - Rear view of the train, showing the last wagon overturned to the right side of the track.](image)

5. **Modelling Approaches: VAMPIRE vs. MUBODyn**

The models of the freight wagon follow the general multibody formulation. The freight wagon is modelled in two different Multibody Dynamics (MBD) programs, namely VAMPIRE and MUBODyn. VAMPIRE is a commercial software used in the industry to simulate the railway vehicle dynamics, while MUBODyn is a general MBD analysis software developed at IST, which includes railways dynamics applications [7,8]. Thus, two distinct models of the wagon are developed to explore the modelling elements and functionalities available in each program.
MUBODyn and VAMPIRE differ greatly in how the interaction between suspension components is modelled, such as kinematic constraints and friction forces. In VAMPIRE, guides that limit the motion of components such as axleboxes are modelled with bumpstop elements, and friction forces are generated by friction elements. These types of elements require the definition of static loads and allow to establish dynamic load dependencies with external elements such as other stiffness, bumpstop or shear spring elements. Conversely, MUBODyn allows the use of perfect and imperfect 3D kinematic joints to constrain the relative motions between bodies. Imperfect joints also enable the modelling of clearances and friction between components to increase the complexity of the model. The transmission of forces in MUBODyn is obtained exclusively through kinematical relations between the suspension elements, rather than by the definition of static and dynamic load components, as is the case for VAMPIRE. On the one hand, the use of VAMPIRE line elements to define the constraints between components is a simpler and more numerically efficient method to model the vehicle. On the other hand, the use of MUBODyn kinematic joints is more accurate and dismisses the definition of static and dynamic components of the forces in several elements, that may differ or be incorrectly calculated.

6. Identification of Potential Derailment Scenarios

The VAMPIRE and MUBODyn models of the vehicle are simulated under different scenarios. In each scenario, a set of characteristics of the vehicle are modified and the derailment assessment quantities are determined. The quantities selected to assess the potential of flange climb derailment are the $Y/Q$ ratio.

6.1. Comparison of Results: VAMPIRE vs. MUBODyn

Both the VAMPIRE and MUBODyn models consist of two coupled vehicles in the nominal condition, running in the track with irregularities. $Y/Q$ in the leading outer wheel of the rear bogie of the rear vehicle is presented in Figure 4. The results from VAMPIRE and MUBODyn show a reasonable agreement and both capture the peaks of $Y/Q$ in the most adverse segment of the track. The maximum $Y/Q$ is equal to 0.715 according to VAMPIRE, while MUBODyn reports a value of 0.636. This discrepancy of over 10% may be attributed to the different description of the track irregularities, distinct wheel-rail contact methods and different approaches to model the friction elements in the suspensions.

![Figure 4 – Comparison of $Y/Q$ in wheel W3R of VAMPIRE vs. MUBODyn.](image-url)
6.2. Influence of Friction Coefficients on the Vehicle Behaviour

The values of the friction coefficients show large variations during the operation of railway vehicles [1]. The results of the simulations show that the variation of the friction coefficient in the suspension has a small effect on the contact forces and derailment assessment quantities, under the conditions considered.

6.3. Influence of the Failure of a Lenoir Link on the Derailment Potential

After the derailment, two Lenoir links were missing from the outer wheels of the trailing wheelsets of both bogies. The failure of a Lenoir link causes the loss of friction damping in the suspension. The results show that when a Lenoir link fails, the static vertical loads of the wheels of the bogie are redistributed: the vertical load in the respective wheel and the diagonally opposite wheel decrease, while the vertical wheel load in the other wheels increase. This causes an increase in the wheel load in the front outer wheels, where \( Y/Q \) is nominally higher, reducing the potential for derailment.

6.4. Influence of the Loading Characteristics on the Derailment Potential

A set of simulations were run to assess the impact of asymmetric loading in the derailment assessment quantities by positioning the coils with a predetermined lateral deviation. Table 1 shows the scenarios considered, where \( \Delta y \) represents a deviation of the coil to the outer side of the curve. Equivalent scenarios deliver the same results and are highlighted with the same colour. For this reason, five simulations represent all the combinations of lateral deviations of the coils.

<table>
<thead>
<tr>
<th>( \Delta y ) Rear Coil</th>
<th>( \Delta y ) Front Coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>-150mm</td>
<td>R-150F-150</td>
</tr>
<tr>
<td>0</td>
<td>R-150F0</td>
</tr>
<tr>
<td>150mm</td>
<td>R-150F150</td>
</tr>
</tbody>
</table>

Asymmetric loading causes a difference in vertical load between the inner and outer wheels. In the scenarios of asymmetric loading there is a superposition of effects: cant deficiency in the curve causes the inner wheels to unload and the outer wheels to load; lateral deviations of the coils to the inner side of the curve oppose this effect, while lateral deviations of the coils to the outer side further contribute to the asymmetry of vertical wheel loads. Scenario R-150F-150 delivers the most adverse conditions in the outer wheels. The maximum values of \( Y/Q \) in the outer wheels are shown in Figure 5. The lateral deviation of the coils to the outer side of the curve reduces the maximum values of \( Y/Q \) in the outer wheels. Conversely, lateral deviations of the coils to the inner side of the curve lead to the increase of the maximum \( Y/Q \) values.

The maximum \( Y/Q \) values reported by MUBODyn in the outer wheels are presented in Figure 6. Scenarios R150F150 and R-150F-150 are not included, because the simulation crashed before completion. The magnitudes of the maximum \( Y/Q \) values differ substantially when compared with Figure 5. Nonetheless, the \( Y/Q \) results from MUBODyn also allow drawing the conclusion that the lateral deviation of the cargo to the inner side leads to the increase of \( Y/Q \) in the outer wheels.
Figure 5 – Maximum values of \( Y/Q \) in the outer wheels using VAMPIRE.

Figure 6 – Maximum values of \( Y/Q \) in the outer wheels using MUBODyn.

Figure 7 clarifies the effect of asymmetric loading in the contact forces of wheel W3R when traversing the severe track irregularity at approximately 510 m. It is clear from Figure 7 (b) that asymmetric loading mainly affects the vertical force \( Q \) and has a small impact in the lateral force \( Y \). Therefore, the increase in \( Y/Q \) is attributed to the severe unloading of the wheel. Asymmetric loading has a significant influence on the safety against flange climb derailment of the vehicle. The correct positioning of the cargo reduces the unbalance of vertical forces in the left and right wheels.

Figure 7 – Comparison between nominal and worst case of asymmetric loading: (a) \( Y/Q \); (b) \( Y \) and \( Q \) in wheel W3R using VAMPIRE.

6.5. Review of MUBODyn Simulations

Some simulations did not finish due to numerical difficulties. The simulations fail in three distinguishable sections of the track. This fact raises the doubt on whether the failure of the simulations is related to track irregularities. The failure of the simulations may be related to different problems. The track model used in the simulations is rigid, resulting in increased peak values of the wheel-rail contact forces. The track
irregularities may also influence the capacity of the program to handle the simulations. High magnitudes and the combined effect of the track irregularities result in poor running behaviour of the vehicle. Additionally, discrete track irregularities, such as rail joints, introduce large instantaneous variations in the wheel-rail contact conditions that may prevent contact detection. A complementary cause for the numerical instabilities of the simulation may be related to the numerical integration method, which may not be robust enough to deal with the highly non-linear simulations, with a large number of imperfect joints with clearances subjected to dynamic forces, including impacts and friction forces.

7. Conclusions

This work presents a computational study on derailment safety of a freight wagon equipped with Y21 bogies. This series of bogies is equipped with Lenoir link suspensions, which offer a low-cost, low-weight and low-maintenance alternative to other bogie designs. However, these bogies present poor performance and are associated with history of derailments. Despite the suspension comprising simple elements, such as friction surfaces and joints with clearance, their combined effect results in a non-linear behaviour of the vehicle. Therefore, the accuracy of the simulation depends on the modelling decisions. In this work, the freight wagon is modelled using two different multibody analysis programs, namely VAMPIRE and MUBODyn. The modelling approaches used in each program are different. In VAMPIRE, the modelling of clearances and load-dependent friction involves a simplification of the suspension of the vehicle, whereas MUBODyn allows the use of imperfect kinematic joints to model the suspension more realistically.

Freight wagon safety is analysed with a case study from a real derailment. The assessment quantities used are the derailment potential \( Y/Q \), and the wheel unload \( \Delta Q/Q \). The results from VAMPIRE and MUBODyn of simulations with two coupled vehicles running under the nominal condition are compared and a good agreement is observed. Subsequently, alternative scenarios are simulated using the two programs, to identify likely causes for the derailment. The scenarios considered are irregular values of the coefficient of friction in suspension components, failure of a Lenoir link in the suspension, asymmetric loading of the vehicle, and abnormal values of the friction coefficient in the surfaces that support the cargo. The scenario with the most severe influence in \( Y/Q \) is the asymmetric loading of the vehicle, with the cargo shifted laterally to the inner side of the curve. In opposition to the physical evidence on the track, none of the scenarios studied show a tendency for the vehicle to climb the inner rail. The results of the simulations using VAMPIRE and MUBODyn differ significantly in the most adverse scenarios. The model developed in MUBODyn provides a more accurate vehicle description in conditions of large displacements, including in derailment scenarios.

References


