Modelling and simulation of damage mechanisms in railway vehicle-track interaction

F Ciuffini¹, F Favo¹, S Giulianelli¹, A Miele², G R Sitongia¹, S Strano²

¹RFI, Rome, Italy
²Department of Industrial Engineering University of Naples Federico II, Naples, Italy

Abstract. This paper focuses on the estimation of damage contribution that each type of railway vehicle produces on the line Pescara - Ancona. The results of the numerical simulations provides fundamental information to understand the railway vehicle properties mostly influencing track damage mechanisms. The results have clearly shown the influence of the wheelset vertical forces on the damage indicators. The analysis of the specific contribution on damage by a specific railway vehicle will be particularly important to modulate track access charges by vehicle type. Moreover, simulation results will allow to adjust the unit maintenance cost of the line on the class of train, whose volumes are known.

1. Introduction

The study on the damage dynamics of a railway infrastructure is one of the most interesting topics in the railway field in recent decades. The deterioration of the rails is mainly caused by the passage of the rolling stock and also, it depends on some characteristics of the vehicles such as the mass, the speed, the type of traction and the wheelset distance, and on some characteristics of the railway infrastructure, such as the curvature radius in the curve sections.

In general, rails are subject to damage due to the interaction forces exchanged by railway vehicles. This leads to maintenance and safety issues. The damage is often categorized as rolling contact fatigue (RCF), track settlement and wear of the rail [1]. This paper is focused on the estimation of damage contribution that rolling stocks produce on the line Pescara-Ancona. The plano-altimetric characteristics of this line are typical of a straight plain line, with few corners. It is a mixed traffic line with regional, long haul and freight trains: this line can be taken as the representative line of a large part of the Italian network.

Vehicles contribute to track deterioration in different way, depending on the different interactions between vehicle and track. These damages are the causes of maintenance actions such as tamping, rail treatment and rail replacement. Engineering models are generally used to modulate costs between different types of traffic, while these costs are recorded with other methods (econometric or allocative). On a new infrastructure, only engineering models can be used. The proposed method has the aim of comparing some significant wear parameters regarding the track, modulating a measure of damage obtained with other models. Infrastructure elements subject to wear during the passage of trains are shown in Figure 1 and the ordinary maintenance of these items is due to direct costs. A large part of the maintenance of tracks, junction, ballast could be carried out by the Infrastructure Managers (IMs) as extraordinary maintenance in the context of line renewals and the related costs are not attributable as direct costs.
In this model, items are divided into 2 categories: items subject to variations in the physical features of the train, such as mass, speed and number of axles, and items variable only in relation to the number of trains passing through. Focusing on track damage, an engineering damage function is investigated, given track geometry and train features, finding most significant ones, and as an output a wear damage level index.

In order to achieve that, the software SIMPACK® Rail has been used for the simulations. SIMPACK® Rail is the world-wide market leader for rail vehicles multi-body simulation with a wide dataset of specific components for the construction of railway vehicle models and for the detailed modelling of the wheel-rail contact [2]. In addition, the SIMPACK® Rail Wear add-on module has been used for the damage calculation. Simulations with this tools provided comparison of vehicle concepts concerning wear and the automated calculation of damages.

2. Damage mechanisms

To estimate the damage functions it is necessary to calculate 3 quantities: dynamic forces for single wheel, wheel/rail contact area and the specific friction energy. The dynamic force for single wheel is:

\[ Q(V) = a_Q \cdot V + b_Q \]  

where \( Q(V) \) is the dynamic vertical force at the wheel, \( V \) is the vehicle speed, \( a_Q \) and \( b_Q \) are coefficients that depend on vehicle and rail characteristics. The contact area \( A_{\text{wheel}} \) is calculated with dimensions of the two semi-axis of the ellipse \( a \) and \( b \):

\[ A_{\text{wheel}} = \pi \cdot a \cdot b \]  

Once the dynamic forces and contact area have been calculated, these are the inputs for the different damage laws that allow to calculate the damage indices \( D_1, D_2, D_3, D_{4.1} \) and \( D_{4.2} \). For the relationship between vertical dynamic force at wheel \( Q(V) \) and ballast damage / rail displacement it is assumed that \( D_1 \sim Q^3 \):

\[ D_1 = n_{RS} \cdot Q(V)^3 \]  

where \( n_{RS} \) is the number of wheelsets which contribute to damage. The maintenance activity associated with \( D_1 \) is tamping (levelling/straightening). The relationship between the dynamic vertical force at the wheel \( Q(V) \) and the rail defects on the straight track it is assumed that \( D_2 \sim Q^{1.2} \):

\[ D_2 = n_{RS} \cdot Q(V)^{1.2} \]  

The Traction power value \( (\text{Tpv}) \) is considered as an index of rolling contact fatigue caused by traction of the driven wheel.
\[ TPV = D_3 = \frac{P_{wheel}}{A_{wheel}} \]  \hspace{1cm} (5)

The specific energy of friction \( W_b \) in the wheel-rail contact is strictly related to rolling contact fatigue \( D_{4.1} \) and wear \( D_{4.2} \) [3].

The functions of \( D_{4.1} \) and \( D_{4.2} \) are:

\[
\begin{align*}
D_{4.1} &= 0 & \text{for } W_b < 15 \text{ N and } W_b \geq 175 \text{ N} \\
D_{4.1} &= n_{FW} \cdot (0.02 \cdot W_b - 0.3) & \text{for } 15 \text{ N} \leq W_b < 65 \text{ N} \\
D_{4.1} &= n_{FW} \cdot (-W_b + 175)/110 & \text{for } 65 \text{ N} \leq W_b < 175 \text{ N}
\end{align*}
\]

\[
\begin{align*}
D_{4.2} &= 0 & \text{for } W_b < 65 \text{ N} \\
D_{4.2} &= n_{FW} \cdot (W_b - 65)/110 & \text{for } W_b \geq 65 \text{ N}
\end{align*}
\]

where \( n_{FW} \) is the number of leading wheelsets. As can be seen, for high values of \( W_b \) the phenomenon of rail wear increases while contact fatigue due to rolling disappears [3]. The maintenance activities associated with \( D_2 \), \( D_3 \) and \( D_{4.1} \) are rail treatments like grinding or milling while rail replacement is related to \( D_{4.2} \).

The specific friction energy \( W_b \), also known as wear number, has been evaluated with MBS A multibody model of a passenger vehicle was generated starting from the wheel/rail contact up to the definition of the entire train, as can be seen in Figure 1 and Figure 2, specifying all interactions between the various components.

According to the dynamic simulations results, the trend of the wear number was determined in function of the variation of 4 parameters featuring rail infrastructure or rail vehicle. These parameters are curvature radius in the curve sections, mass of the vehicle, longitudinal stiffness of the primary suspension and the wheelset distance.

![Figure 2. Bogie dynamic model](image1)
![Figure 3. Train dynamic model](image2)

![Figure 4. Wear number trend](image3)
As can be seen in Figure 4, the wear number has different trends depending on which parameter is being varied. Each time only one parameter has been changed while the others remain constant. As the curvature radius increases, the $W_b$ decreases. The vehicle mass and the wheelset distance influence the $W_b$ trend in the same way. As the longitudinal stiffness increase, the $W_b$ trend remains almost constant.

3. Results

The test case track considered for the simulations is the Pescara-Ancona line. For this line track a dynamic model was generated in SIMPACK® considering the planoaltimetric profile, the rail inclination (1:40) and the cant in the curve sections. A model example can be seen in Figure 5.

![Track Pescara-Ancona: (a) planoaltimetric profile; (b) speed profile](image)

In this paper, 8 different passenger rolling stocks are considered, which represent 4 categories of service performed.

| Rolling Stock | Locomotives + Coaches | Average speed (km/h) | Total mass (t) | Average axle-load (t) | Service performed     |
|---------------|-----------------------|----------------------|----------------|-----------------------|-----------------------|
| Ale 501       | 3                     | 86                   | 123            | 15                    | Regional fast         |
| ETR 425       | 5                     | 86                   | 205            | 17                    | Regional fast         |
| E 414 + UIC Z1| 2 + 9                 | 153                  | 577            | 13                    | High speed            |
| E 444 + UIC Z1| 1 + 7                 | 128                  | 330            | 10                    | Intercity             |
| E 464 + UIC Z1| 1 + 5                 | 68                   | 322            | 13,5                  | Regional slow         |
| ETR 324       | 4                     | 86                   | 164            | 16,4                  | Regional fast         |
| ATR 220 tr    | 4                     | 68                   | 180            | 18                    | Regional slow         |
| ETR 500       | 2 + 11                | 153                  | 576            | 11                    | High speed            |
In Table 1 there are some characteristics of the trains considered in this paper. In the first column there is the composition of each train in terms of locomotives and coaches. In the second one there is the average speed calculated by speed profile of each train. The third one represents the mass of each train and the fourth column is the ratio between the mass of a train and the wheelsets number. The last column define the service performed by each vehicle.

In Figures 6 and 7, it is possible to observe the results in terms of damage indices from D$_1$ to D$_{4.2}$ for each train considered. D$_{1,str}$, D$_2$ and D$_3$ are the components of the damage on the straight sections while D$_{1,curv}$, D$_{4.1}$ and D$_{4.2}$ are the components of the damage on the curve sections.

![Figure 6. Damage on straight sections](image6.png)

![Figure 7. Damage on curve sections (r = 800 m)](image7.png)

The percentage values were calculated in relation to the total value of each damage index, caused by the transit of all trains on the entire line.

As can be seen, the most damaging vehicles are E414+UIC Z1 and ETR 500, which belong to high speed category. This can be due to the high mass and traction power that characterize them. For D$_1$, 

---

5
and $D_2$, which depend by maximum dynamic load for single wheel, and for $D_{4.1}$, the E444+UIC Z1 is more damaging than other vehicles considered (except high speed vehicles). For $D_3$, all non-high speed vehicles cause almost the same damage. Finally, for $D_{4.2}$, the damage caused by E444+UIC Z1 and E464+UIC Z1 is comparable to the damage caused by high speed vehicles.

4. Conclusions
The study presented in this paper has been focused on the incidence of some types of rolling stocks on the track damage. The analysis of the specific contribution on damage by a vehicle type will be more important in order to modulate track access charges by vehicle type. The simulation results will allow a dual purpose: on the class of train whose volumes are known on the line (in terms of trains*km or t*km) and to provide damage quantification, and therefore ordinary maintenance costs on the line, varying traffic volumes (train*km or t*km), train composition (% freight, regional, long haul) and vehicle parameters. As written in paragraph 2, maintenance activities are associated with damage indices; if the maintenance costs are known, it is possible to associate them with the damage functions by the use of some calibration coefficients ($k_i$) [4]. Therefore, these coefficients allow to establish the costs directly related to the passage of vehicles on the railway infrastructure in order to calculate the direct costs related to the entire route considered.

References
[1] Smith, A., Iwnicki, S., Kaushal, A., Odolinski, K., Wheat, P. Estimating the relative cost of track damage mechanisms: combining economic and engineering approaches (2017) Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 231 (5), pp. 620-636.
[2] Kuka, N., Verardi, R., Ariaudo, C., Pombo, J. Impact of maintenance conditions of vehicle components on the vehicle–track interaction loads (2018) Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 232 (15), pp. 2626-2641.
[3] M. Bond, "A bear called Paddington", Collins, London, United Kingdom, 1958.
[4] NZV-BAV_TP2017_Anleitung EN Verschleissfaktor Fahrbahn Federal Office of Transport (BAV), 3003 Bern, Finance department Published on BAV website
[4] ERRI B176. Bogies with steered or steering wheelsets” European Rail Research Institute (ERRI), 1989