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# Development of a New Wear Model for the Study of Wheel and Rail Profile Evolution on Complex Railway Networks

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## 1. Introduction

The prediction of wheel and rail wear is a fundamental issue in the railway field, both in terms of vehicle stability and in terms of economic costs (wheel and rail profile optimization from the wear viewpoint and planning of maintenance interventions).

In this work the Authors present a model for the evaluation of the wheel and rail profile evolution due to wear specifically developed for complex railway networks. In this case the computational load needed to carry out the exhaustive simulation of vehicle dynamics and wear evaluation turns out to be absolutely too high for each practical purpose. To overcome this critical issue of the wear prediction models, the Authors propose a new track statistical approach to reach relevant results in a reasonable time; more specifically the Authors suggest to replace the entire railway network with a discrete set of $N_c$ different curved tracks (classified by radius, superelevation and traveling speed) statistically equivalent to the original network. The new approach allows a substantial reduction of the computational load and, at the same time, assures a good compromise in terms of model accuracy.

The architecture of the new wear model is made up of two mutually interactive but separate units: the vehicle model for the dynamical analysis and the model for the wear evaluation (Figure 1.1). The first one consists of two parts that interact online during the dynamic simulations: a 3D multibody model of the railway vehicle (implemented in SIMPACK) and an innovative 3D global contact model for the detection of the contact points between wheel and rail and for the calculation of the contact forces (implemented in a C/C++ user routine of SIMPACK) [1][2].

The wear model (entirely implemented in MATALB) starts from the outputs of the dynamic simulations (position of contact points, contact forces and global creepages) and calculates the pressures inside the contact patches through a local contact model (FASTSIM algorithm); then the material removed by wear is evaluated (by means of experimental laws correlating the friction power produced by the tangential contact forces and the removed material) and the worn profiles of wheel and rail are obtained by means of an innovative update strategy [2][3][4]. The new updated wheel and rail profiles (one mean profile both for all the wheels of the vehicle and for all the rails of the considered tracks) are then fed back as inputs to the vehicle model and the whole model architecture can proceed with the next discrete step of the procedure. In this work adaptive discrete steps (function of the wear rate and obtained imposing suitable threshold values $D^{w}_{step}$ and $D^{r}_{step}$ on the maximum of the removed material quantity on wheels and on rails) have been chosen to update the wheel and rail profiles, and to correctly follow the nonlinear behavior of the system.

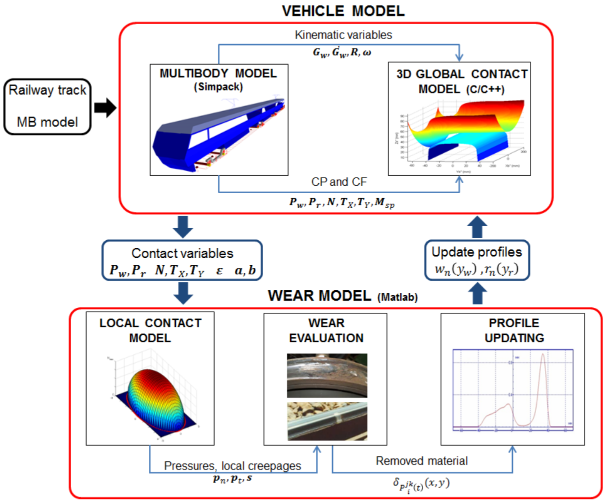

*Figure 1.1: Architecture of the model.*

## 2. Simulation Strategy

The wheel and rail wear progress evolve according to different time scales and a fully simulation of such events would require a too heavy computational effort. For this reason the following specific algorithm has been adopted for updating the profiles:

1) the wear evolutions on wheel and rail have been decoupled because of the different scales of magnitude:

a) while the wheel wear evolves, the rail is supposed to be constant: in fact, in the considered time scale, the rail wear variation is negligible;

b) the time scale characteristic of the rail wear evolution, much greater than the wheel wear evolution one, causes the same probability that each discrete rail profile comes in contact with each possible wheel profile. For this reason, for each rail profile, the whole wheel wear evolution (from the original profile to the final one) has been simulated.

2) to have a good compromise between calculation times and result accuracy a suitable number of discrete steps both for the wheel and for the rail steps have been chosen, $n_{sw} = 20$ and $n_{sr} = 5$. The wheel wear threshold

$D^{w}_{step}$ has been fixed equal to 0.2 mm, while the rail wear threshold $D^{r}_{step}$ has been set equal to 0.8 mm to obtain an appreciable rail wear during the simulations.

## 3. Statistical Description of the Railway Track

The statistical track description is an essential task to make possible and rationalize the approach and the simulation work on a complex railway line. In the present work a new statistical approach has been exploited to draw up a virtual track of the Aosta-Pre Saint Didier line. The basic idea is to substitute the simulation on the whole track with a set of simulations on short curved tracks statistically equivalent to the original network [4].

More precisely, the curve tracks are obtained dividing the whole track into $n_{class}$ curve radius intervals $[R_{min} - R_{max}]$; each of these is then divided again into $n_{class}$ superelevation subclasses $[h_{min} - h_{max}]$. For each radius class, a representative radius $R_c$ is calculated as the weighted average on all the curve radii, by using the length of the curve as weighting factor. Similarly, for each superelevation subclass, the correspondent representative superelevation H is chosen as the weighted average on all the curve superelevations, by using the length of the curve as weighting factor. For each representative curve a speed value V is chosen as the minimum value between the maximum line speed allowable in curve and the vehicle speed calculated by imposing an upper limit to the non-compensated acceleration [4]. Finally a weighting factor $p_k$ is introduced for each subclass to take into account the frequency of a certain matching radius-superelevation in the track and to diversify the wear contributions of the different curves.

## 4. Results

To evaluate the accuracy, the numerical efficiency and the sensitivity to parameters of the new approach, the results obtained from the exhaustive simulations performed on all the railway network have been compared to those achieved on the set of curved tracks statistically equivalent to the network. Both the exhaustive and the statistical approaches have been validated in collaboration with Trenitalia S.p.A. and Rete Ferroviaria Italiana (RFI), which have provided the technical documentation and the experimental results concerning the Aosta-Pre Saint Didier railway line and the vehicle ALSTOM DMU Aln 501 Minuetto (data related to three different vehicles, conventionally called DM061, DM068, DM082, have been measured); this scenery is quite critical and exhibits serious problems in terms of wear. Three reference parameters evolution FH (flange height), FT (flange thickness) and QR quota (see Figure 4.1a), capable of estimating the wheel profile evolution due to wear without necessarily knowing the whole profile shape, are considered. An additional control parameter QM (that estimates the rail head height) is then introduced to evaluate the evolution of rail wear (see Figure 4.1b).

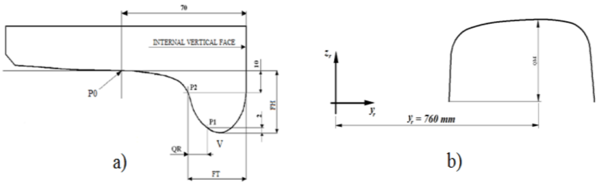

*Figure 4.1: Definition of the wear control parameters.*

### 4.1. Complete Aosta Pre-Saint Didier Railway Line

The results obtained studying the whole Aosta-Pre Saint Didier line are presented and compared with the experimental data.

By way of example the progress of QR dimension, for the $n_{sr}$ discrete steps of the rail, is shown in Figure 4.2 as a function of the mileage; as it can be seen, the decrease of the dimension is almost linear with the traveled distance except in the first phases, where the profiles are still not conformal enough.

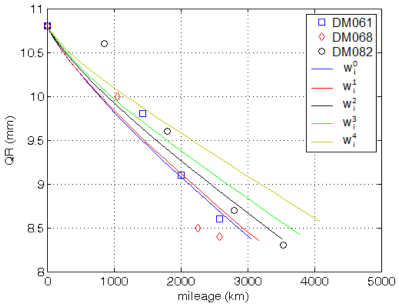

*Figure 4.2: Complete track: QR progress.*

The wear evolution on the wheel profiles is presented in the Figure 4.3 (for reasons of brevity only the profiles evolution related to the first rail step is represented). The figure shows the main localization of the removed material on the wheel flange due to the quite sharp curves that characterize the Aosta-Pre Saint Didier line. In Figure 4.4 the evolution of the rail profile is shown.

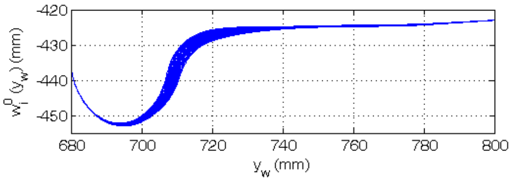

*Figure 4.3: Complete track: $w_i^0$ evolution.*

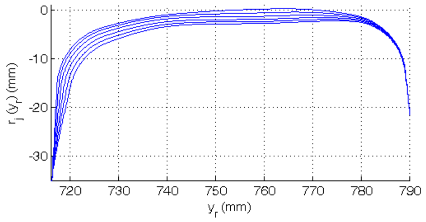

*Figure 4.4: Complete track: rail evolution.*

### 4.2. Statistical Analysis Results

The results obtained with the statistical analysis approach are presented. A suitable value of the curved classes number $n_{class}$ have to be supposed. For the Aosta-Pre Saint Didier line the value $n_{class} = 10$ represents a good compromise among track description, result accuracy and computational effort; in fact a $n_{class}$ too high would increase the result accuracy but would increase the computational time too and would lead to a high number of curve classes quite difficult to be statistically treated.

By way of example the Figure 4.5 presents the evolution of QR parameters. It can be seen the same qualitatively trend obtained with the complex railway approach both concerning the conformity considerations and the localization of the worn material on the wheel flange.

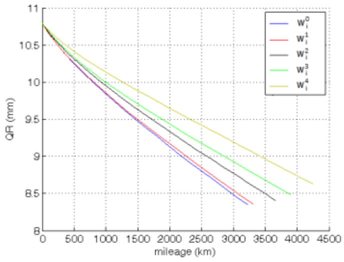

*Figure 4.5: Statistical approach: QR progress.*

As it can be seen in Figure 4.6, 4.7, the evolution of the wheel (related to the first rail step) and rail profiles are qualitatively in agreement with the complete railway approach and the same considerations of section 4.1. are valid.

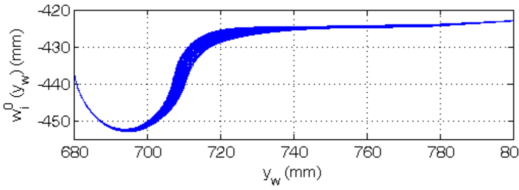

*Figure 4.6: Statistical analysis: $w_i^0$ evolution.*

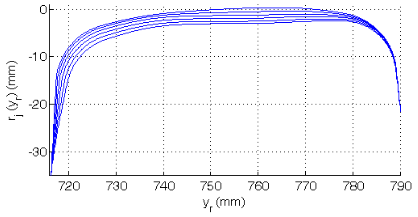

*Figure 4.7: Statistical analysis: rail evolution.*

### 4.3. Comparison between the Complete Railway Line and the Statistical Analysis

A quantitatively comparison between the results obtained with the complete railway line and the statistical approach with $n_{class} = 10$ is carried out. In Table 4.1 the final values of the QR dimension for all the $n_{sr}$ rail step (each of length $km_{tot}^{i}$) are presented. The increase of the QR quota indicates a shift of the material removed towards the wheel tread due to the variations of the contact conditions as explained in previous sections. The QR comparison shows a good consistency between the two investigate approaches with a maximum error e ≈ 1.0%.

*Table 4.1: Evolution of the wheel quotas.*

| | **Complete Railway** | **Statistical Description** $n_{class}$=10 | |
|---|---|---|---|
| | QR (mm) | QR (mm) | e (%) |
| $km_{tot}^{0}$ | 8.38 | 8.35 | 0.4 |
| $km_{tot}^{1}$ | 8.35 | 8.36 | 0.1 |
| $km_{tot}^{2}$ | 8.37 | 8.41 | 0.5 |
| $km_{tot}^{3}$ | 8.43 | 8.48 | 0.6 |
| $km_{tot}^{4}$ | 8.57 | 8.63 | 0.7 |

The Table 4.2 displays the evolution of the step length $km_{tot}^{i}$ as a function of the $n_{sr}$ rail steps and shows a good consistency between the two considered procedures: the increase of the mileage travelled by the vehicle as the rail profile is more and more worn indicates a decrease of the wear rate explained by a better conformity between wheel and rail surfaces. In the Table 4.3, 4.4 the comparison of the parameters QM and the total vehicles number traveled on the track $N_{tot}$ needed to evaluate the rail wear are shown.

*Table 4.2: Evolution of the total mileage $km_{tot}^{i}$.*

| | **Complete Railway** | **Statistical Description** $n_{class}$=10 | |
|---|---|---|---|
| | $km_{tot}$ (km) | $km_{tot}$ (km) | e (%) |
| $km_{tot}^{0}$ | 3047 | 3219 | 5.6 |
| $km_{tot}^{1}$ | 3163 | 3306 | 4.5 |
| $km_{tot}^{2}$ | 3515 | 3659 | 4.1 |
| $km_{tot}^{3}$ | 3772 | 3893 | 3.2 |
| $km_{tot}^{4}$ | 4080 | 4244 | 4.0 |

*Table 4.3: Evolution of the QM quota.*

| **Complete Railway** | **Statistical Description** $n_{class}$=10 | |
|---|---|---|
| QM (mm) | QM (mm) | e (%) |
| 32.31 | 32.00 | 0.6 |

*Table 4.4: Total vehicle number $N_{tot}$.*

| | **Complete Railway** | **Statistical Description** $n_{class}$=10 | e (%) |
|---|---|---|---|
| $N_{tot}$ | 2957850 | 3076200 | 4.0 |

### 4.4. Sensibility Analysis of the Statistical Approach

A sensibility analysis of the statistical approach with regard to the class number $n_{class}$, i.e. the most important parameter of the track discretization, is presented. The variation range studied is $n_{class} = 4 \div 10$. By analyzing the data relative to the wheel presented in Table 4.5, for each value of $n_{class}$ investigated, the trend of the wheel parameters shows an increase both of the wheel flange thickness FT and the QR quota in according to the variation of the contact conditions explained in the previous sections. Analogously the $km_{tot}^{i}$ evolution trend is the same for each of the statistical analysis considered and also the mileage increases as the rail wear increases, indicating the more and more conformal contact between wheel and rail surfaces. The error e presented in Table 4.5 is referred to the complete railway approach and shows less and less consistency between the results of the whole railway approach and of the statistical analysis as the $n_{class}$ parameter decreases: in particular small $n_{class}$ values, corresponding to a rough discretization of the track, lead to an important underestimation of the removed material highlighted by the increasing mileage traveled. The less accuracy of the model and the underestimation of the worn material as the track description is more and more rough is found also by analyzing the rail control parameter and the number of the train evolving on the track (see Table 4.6).

*Table 4.5: Evolution of the wheel parameters.*

| **Statistical Description** | | FT mm | e % | QR mm | e % | $km_{tot}$ km | e % |
|---|---|---|---|---|---|---|---|
| $n_{class}$=4 | $km_{tot}^{0}$ | 28.02 | 1.0 | 8.29 | 1.0 | 3775 | 23.9 |
| | $km_{tot}^{1}$ | 28.16 | 0.7 | 8.25 | 1.2 | 3967 | 25.4 |
| | $km_{tot}^{2}$ | 28.19 | 0.9 | 8.28 | 1.1 | 4267 | 21.4 |
| | $km_{tot}^{3}$ | 28.26 | 0.9 | 8.35 | 1.0 | 4521 | 19.9 |
| | $km_{tot}^{4}$ | 28.35 | 1.0 | 8.47 | 1.2 | 4793 | 17.5 |
| $n_{class}$=6 | $km_{tot}^{0}$ | 28.06 | 0.8 | 8.31 | 0.8 | 3620 | 18.8 |
| | $km_{tot}^{1}$ | 28.18 | 0.6 | 8.28 | 0.9 | 3743 | 18.5 |
| | $km_{tot}^{2}$ | 28.23 | 0.7 | 8.29 | 0.9 | 4038 | 14.9 |
| | $km_{tot}^{3}$ | 28.31 | 0.8 | 8.36 | 0.9 | 4237 | 12.3 |
| | $km_{tot}^{4}$ | 28.40 | 0.8 | 8.48 | 1.1 | 4569 | 12.0 |
| $n_{class}$=8 | $km_{tot}^{0}$ | 28.10 | 0.7 | 8.33 | 0.6 | 3431 | 12.6 |
| | $km_{tot}^{1}$ | 28.19 | 0.6 | 8.30 | 0.5 | 3529 | 11.6 |
| | $km_{tot}^{2}$ | 28.26 | 0.6 | 8.31 | 0.7 | 3903 | 11.0 |
| | $km_{tot}^{3}$ | 28.35 | 0.6 | 8.37 | 0.8 | 4092 | 8.5 |
| | $km_{tot}^{4}$ | 28.44 | 0.7 | 8.49 | 0.9 | 4445 | 8.9 |
| $n_{class}$=10 | $km_{tot}^{0}$ | 28.43 | 0.5 | 8.35 | 0.4 | 3219 | 5.6 |
| | $km_{tot}^{1}$ | 28.50 | 0.5 | 8.36 | 0.1 | 3306 | 4.5 |
| | $km_{tot}^{2}$ | 28.56 | 0.4 | 8.41 | 0.5 | 3659 | 4.1 |
| | $km_{tot}^{3}$ | 28.62 | 0.4 | 8.48 | 0.6 | 3893 | 3.2 |
| | $km_{tot}^{4}$ | 28.75 | 0.4 | 8.63 | 0.7 | 4244 | 4.0 |

*Table 4.6: Rail control parameters evolution.*

| **Statistical Description** | QM mm | e % | $N_{tot}$ | e % |
|---|---|---|---|---|
| $n_{class}$=4 | 31.58 | 2.3 | 3797900 | 28.4 |
| $n_{class}$=6 | 31.69 | 1.9 | 3543500 | 19.8 |
| $n_{class}$=8 | 31.83 | 1.5 | 3309800 | 11.9 |
| $n_{class}$=10 | 32.00 | 1.0 | 3076200 | 4.0 |

The mean computational times relative to each discrete step of the whole model loop are schematically summarized in Table 4.7 ($t_{wt}$, $t_{rt}$=$n_{sw}$*$t_{wt}$ are the total simulation times for wheel and rail respectively and $t_T$=$n_{sr}$*$t_{rt}$ is the total simulation time). The huge computational effort that affects the complete railway line simulation, makes this approach hardly feasible to the wear evolution studies typical of the railway field. On the contrary the statistical track description (see Table 4.5-4.7) shows a high saving of computational load and at the same time a not excessive loss of model accuracy; in particular, with a number of curve classes $n_{class}$ = 10, wear evaluation results are qualitatively and quantitatively in agreement with the complete line approach (a maximum error e ≈ 5% on the mileage traveled by the vehicle has been found). In conclusion the innovative wear model, developed for the study of complex railway networks using a statistical track description approach, is capable of simulating the wear evolution both on the wheel and on the rail surfaces with reasonable computational time and leads to a good result consistency if compared to the considered experimental data.

*Table 4.7: Computational time.*

| **Railway approach** | | **Computational time** | | |
|---|---|---|---|---|
| | | Wheel wear evaluation $t_{wt}$ | Rail wear evaluation $t_{rt}$ | Total simulation time $t_T$ |
| Complete track | | 5d 50m | 4d 50h 40m | 24d 7h 20m |
| Statistical analysis | $n_{class}$=4 | 12m | 4h | 20h |
| | $n_{class}$=6 | 19m | 6h 20m | 1d 7h 40m |
| | $n_{class}$=8 | 25m | 8h 20m | 1d 16h 40m |
| | $n_{class}$=10 | 34m | 11h 20m | 2d 8h 40m |

## 5. Conclusion

In this work the Authors presented a complete model for the wheel and rail wear prediction in railway applications specifically developed (in the collaboration with Trenitalia S.p.A and Rete Ferroviaria Italiana (RFI)) for complex railway networks, where the exhaustive analysis on the complete line is not feasible because of the computational load required.

Future developments will be based on further validations of the whole model through new experimental data always provided by TI and on a better investigation of the statistical approach. In this way further improvements of the statistical analysis (mainly related to tracking and braking actions, impulsive events such as the track switches and weather conditions) will be possible.

## 6. References

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