WEAR AND RCF BEHAVIOUR OF CONVENTIONAL AND HARD RAILS IN DIFFERENT CONTEXTS

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ABSTRACT

Automated measurements made with specialized measuring cars allow to get a large number of reliable data at short intervals over long distances on many infrastructure parameters. The correlation of rail wear with traffic indicators (MGT or time) is shown in this paper, leading to important optimisation considerations that may dramatically reduce maintenance costs. The implications on data processing and trackworks organization are analysed in for two main lines. RCF defects are analysed as well.

INTRODUCTION

Rail wear is common on all curves with radius lower than typically 700~800 m and rail replacement / grinding is one of the greatest expenditures in rail track maintenance.

A number of measures are typically employed in order to try to reduce rail wear: increase of superelevation, speed reduction, lubrication, improved rail materials.

In the last years, RFI conducted a long experimental test on a particularly curvy line in the North-East of Italy. The preliminary outcomes of this activity were presented at Railway Engineering 2007 conference [1] together with some preliminary conclusions on the behaviour of three different types of rail steels. Rail wear was mainly analysed in that occasion on the basis of manual precision rail wear measurements. As it will be shown in the paper, wear appears to be a rather varying phenomenon within many curves, leading to the need of assessing this parameter by using continuous measurements taken by measuring trains.

Italian infrastructure owner (RFI, *Rete Ferroviaria Italiana*, a public company belonging to the holding FS SpA, *Ferrovie dello Stato*) classified the importance of lines on the basis of traffic. Different measuring trains and different frequencies of measurement are therefore planned depending on the line category.

The analyses presented in 2007 were complemented with the results from the analysis of other sets of data coming from measurements on a different line in central Italy with peculiar characteristics in terms of length of the curves, speed and number of trains per day and different maintenance approaches.

The final results obtained in both the situations are critically analysed and compared, obtaining general guidelines to maintenance and operation of conventional and hard rails. A general approach regarding the use of hard rails was defined on the basis of the historical data available from measuring coaches with contactless (laser-camera) systems.

AVAILABLE DATA AND GENERAL CONSIDERATIONS

Wear at 45° is measured by means of a laser-optical (contactless) systems that acquires simultaneously both rail profiles every 0.5 m. The measuring units are installed on the dedicated RFI measuring train *Archimede* that runs continuously over the main lines of the entire RFI network.

Acquired profiles are then processed in order to find the desired parameter (wear at 45°) referred to the position along the like (PK) together with many other track and infrastructure parameters (e.g. rail vertical and lateral wear, track cant, gauge, alignment, etc.)

Data are stored on hard disk on the measuring train in a proprietary format and can be processed / printed for later use. A typical screenshot of some data recovered by the *Archimede* train software is shown in Figure 1.



Figure 1. Typical screen dump of the output generated by *Archimede* software. Data of interest in this paper are wear at 45° on left and right rails (*Us.* 45° *Sx* and *Us.* 45° *Dx* respectively, i.e. the 5th and 6th diagram). "Us." is the shortened Italian word "usura" (=wear).

For the present activity data were transformed to ASCII files for the analysis with Matlab. As an example that will be discussed later in more detail when describing the line, Figure 2 shows all the measurements collected on and in the vicinity of a particular curve on the Prato-Bologna line.

A large degree of variability of wear along the curve is evident, including "slow" variation (a sort of drift in the average value of wear) and large amplitude variations on a short basis. This plot is rather different from the *Archimede* screenshot, showing that plotting includes some post-processing or filtering of acquired (raw) data. These variations are confirmed, with increasing amplitude, during a rather long period (21 months), excluding possible bias errors of the measuring system. It is evident that these features are characteristics of the curve and are probably originated by a combination of geometric initial features of the track and of dynamic phenomena originated by passing trains. It is known that the amplitude of dynamic stresses in increased by local defects, amplifying probably initially acceptable irregularities.

Spectral analysis conducted on one set of data is shown in Figure 2, where peaks at 17.07 m, 32 m and 64 m are evident. Considering that resolution in the wavelength domain is inversely proportional to the wavelength (while it is constant in the spatial frequency – or wave number – domain), these peaks therefore contain the wavelengths of 18 m, 36 m and 72 m respectively. These lengths are characteristic

of 144 mm rails obtained by flash butt welding of 18 m and 36 m rails (a process that was usual before long rails of 108 m or 120 m were available on the market).



Figure 2. Rail wear at 45° on the right rail of the Prato-Bologna line around km 19.2 (left) and Power Spectral Density distribution, where peaks with higher energy content are highlighted (right).

As maintenance is planned on the basis of *Archimede* printouts, it was therefore necessary to filter out unwanted wavelengths. It is worth to remind that any kind of digital filter, either IIR or FIR, introduces a different phase shift on different wavelengths (so called *phase distortion*) also for the signal components that are in *bandpass region*, i.e. those wavelengths for which the filter gain is unity (=+0 dB).

In this work a non-causal filter, implemented in Matlab with the *filtfilt* command, was applied. This filtering procedure has the peculiarity that the order of the filter is doubled but that the phase shift is null for all frequency (or wavelength) components. This leads to preserving the relative angular position (phase) of all the signal components that can be superimposed in a straightforward way. Local space features are therefore affected as usual by the filter but without any further distortion. Figure 3 shows the effect of filtering with different cut-off wavelengths, respectively 5 m and 50 m. While in the first case filtering is mainly needed to remove local, extremely short phenomena (spikes), in the second case filtering returns a signal shape that is much more similar to *Archimede* printouts.



Figure 3. Space-domain data of 45° rail wear high-pass filtering wavelengths with cut-off wavelengths of 5 m (left) and 50 m (right).

A quantification of the "lost" part of signal due to filtering can be done by simply zooming on the signal filtered above 5 m wavelength (Figure 4). It is clear how differences of $4\div5$ mm on a 10 m length basis are almost completely lost.



Figure 4. Zoom on the previous figure (filter cut-off wavelength=5 m). Variations of the wear at 45° in the order of 4÷5 mm over 10 m can be observed.

This observation lead to a possible explanation of apparently contradictory results of measurements collected during the campaign reported in [1]: taking measurements at short time intervals with a positioning error of just a few metres led to *negative wear*, i.e. a decrease of the absolute value of wear.

In the rest of this paper only data filtered on wavelengths above 50 m are considered. It is worth anyway to highlight that with this approach local wear phenomena may be largely underestimated, neglecting potentially important local wear features. In particular, it could be possible to consider as acceptable and safe for service rails that actually are worn above allowed limit (i.e. 15 mm).

WEAR MECHANISM AND WEAR RATE CLASSIFICATION

Wear mechanism appears to be of adhesive type as there are no contaminants or other agents (like sand) that may involve abrasive wear.

As wear progresses with time, it proved to be useful to classify wear rate in categories as follows (lowercase=right curve, uppercase=left curve):

- Negligible wear rate for $w_{45} \le 0.5 \text{ mm/year}$ (green colour, code **n** or **N**);
- Moderate (of "physiological") wear rate for $0.5 < w_{45} \le 2$ mm/year (yellow colour, code **m** or **M**);
- Severe wear rate for $w_{45}>2$ mm/year (red colour, code s or S);
- presence of hard rails: additional code **h** or **H** (see appropriate column for rail type).

CASE STUDY 1 - GENOVA-RAPALLO, SOUTHBOUND (ODD) TRACK

This line was described in [1] and it is characterized by limited maximum speeds, in the order of 90 km/h with low radius curves. Track stability issues led in the past to the reduction of lateral forces by reducing both the speed and the cant, especially in very tight tunnel.

The line was in fact built more than one century ago and it represented a very challenging tasks. The worldwide famous "Via dell'Amore" (love path) in the Cinque Terre region, a narrow footpath on the rocks just a few metres above sea level, was in fact the only way to bring dynamite to excavate tunnels. Its parameters are certainly to be considered as out-of-date in modern times; nevertheless it constitutes a strategic line connecting the South of France and the Genoa harbour, one of the most important in the Mediterranean sea, to Central and South Italy.

In this line rails of R260 (UTS=900 MPa), R320Cr (UTS=1100 MPa) and R350HT (UTS=1200 MPa) types (the latter types only for testing) according to EN 13674-1:2003 are installed.

Available data

From the point of view of the activities described in this paper, the line was measured by *Archimede* train only until 2006, when the measuring train was subsequently used to make measurements on the high speed Italian railway network that was at that time under construction. Only automated wear measurements are considered here, complementing the information supplied in [1]. RCF damage will be reported on the basis of local visual inspections on hard and conventional rails.

Available data are rail wear at 45° (w_{45}), gauge, cant, curvature between Genova Brignole and Rapallo (PK 4+000 to PK 29+600) on the following dates:

- 1. (t=0) November 2004
- 2. (t=7 months) June 2005
- 3. (t=12 months) November 2005
- 4. (t=15 months) February 2006

Data analysis consisted of the following steps:

- PK and w_{45} data synchronization on the basis of curvature data and fixed points;
- curve numbering following official RFI tables;
- plotting of w_{45} data vs. official RFI line tables, with identification of hard rail positions;
- wear classification and wear type definition.

Figure 5 shows as an example an excerpt of track and wear properties measured between PK 12+000 e 18+000. Rotating the page by 90° counter clockwise, it is possible to "see" the track as the virtual driver of a train. Location, curve severity and wear amplitude can then readily be observed.

Correlation between rail wear, curvature and rail hardness

A spreadsheet was compiled with the main parameters (curve number, maximum curvature and PK, wear, rail steel type, presence of RCF defects, wear type) and an printout sorted with increasing curve radius is shown in Figure 6 to highlight the importance of curve radius on w_{45} . Consider that most of the curves with R \leq 450 m have the high rail made of hard steel; note that these rails were changed very often (sometimes more often than once per year!) before installing hard rails.

It can be concluded that:

- wear rate is always **severe** for curves with $R \le 450$ m and R260 steel;
- wear rate is always **moderate** for curves with around 450<R≤1200 m;
- wear rate is **negligible** for R>1500 m;
- wear rate is always **negligible** (except for Rapallo curve #59) where hard rails are used.

It is worth to note that maximum observed wear values were 12 mm and 14 mm in only two cases, suggesting an early removal of rails.

The estimation of the wear rate was made on the basis of rails lay down date and the wear measured by means of transverse profile measurement made with the manual instrument MiniProf. The limited time spanned by automated measurements (15 months) was not sufficient to determine with the *Archimede* train a sufficiently reliable estimation of the wear rate, that being a finite difference is mostly affected by relative error resulting from the difference of two very similar values.



Figure 5. Example of data plotting for the Genova-Rapallo line. From top to bottom: curve numbering; *Archimede* curvature and PK measurement with indication of maximum curvature; left rail wear; track curvature (with indication of the position of hard rails); right rail wear.

| Nº curva | Binario | Curva a | PK di max curvatura da | Curvatura massima da | Raggio | Tipo usura Tipo rotaie | Rotaie dure? |
|----------|---------|---------|---------------------------|-------------------------|--------|---------------------------|-----------------|
| | | | Archimede | Archimede | | | aare. |
| 33 | Dispari | SX | 12.090 | -0.03 | -33333 | N | |
| 10 | Dispari | SX | 4.380 | -0.04 | -25000 | N | |
| 63 | Dispari | SX | 26.550 | -0.20 | -5000 | N | |
| 23 | Dispari | SX | 9.209 | -0.21 | -4762 | N | |
| 40 | Dispari | SX | 13.420 | -0.26 | -3846 | N | |
| 61 | Dispari | SX | 25.790 | -0.30 | -3333 | N | |
| 19 | Dispari | SX | 7.652 | -0.49 | -2041 | N | |
| 16 | Dispari | SX | 6.830 | -0.65 | -1538 | N | |
| 29 | Dispari | SX | 11.050 | -1.18 | -847 | M | |
| 12 | Dispari | SX | 4.953 | -1.26 | -794 | M | |
| 31 | Dispari | SX | 11.470 | -1.29 | -775 | M | |
| 60 | Dispari | SX | 25.210 | -1.56 | -641 | M | |
| 15 | Dispari | SX | 6.638 | -1.62 | -617 | N | |
| 21 | Dispari | SX | 8.242 | -1.82 | -549 | M | |
| 18 | Dispari | SX | 7.292 | -1.98 | -505 | M | |
| 26 | Dispari | SX | 9.653 | -2.05 | -488 | M | |
| 57 | Dispari | SX | 20.620 | -2.21 | -452 | S | |
| 53 | Dispari | SX | 18.360 | -2.27 | -441 | NH | 1200 |
| 28 | Dispari | sx | 10.530 | -2.39 | -418 | S | |
| 64 | Dispari | sx | 27.050 | -2.46 | -407 | S | |
| 55 | Dispari | SX | 18.950 | -2.55 | -392 | NH | 1200 |
| 35 | Dispari | SX | 12.650 | -2.58 | -388 | NH | 1200 |
| 44 | Dispari | SX | 14.650 | -2.73 | -366 | NH | 1100 |
| 49 | Dispari | SX | 16.490 | -2.79 | -358 | NH | 1200 |
| 46 | Dispari | SX | 15.300 | -2.85 | -351 | NH | 1100 |
| 59 | Dispari | sx | 21,600 | -3.06 | -327 | S+NH | 1200 |
| 56 | Dispari | dx | 19.590 | 2.62 | 382 | nh | 1200 |
| 66 | Dispari | dx | 28.640 | 2.62 | 382 | mh | 1100 |
| 58 | Dispari | dx | 21.370 | 2.58 | 388 | nh | 1200 |
| 37 | Dispari | dx | 12.940 | 2.51 | 398 | nh | 1100 |
| 43 | Dispari | dx | 14.370 | 2.48 | 403 | nh | 1100 |
| 54 | Dispari | dx | 18.550 | 2.45 | 408 | n | |
| 48 | Dispari | dx | 16.280 | 2.42 | 413 | nh | 1100 |
| 50 | Dispari | dx | 17.000 | 2.42 | 413 | nh | 1100 |
| 27 | Dispari | dx | 10.300 | 2.34 | 427 | S | |
| 22 | Dispari | dx | 8.664 | 2,18 | 459 | m | |
| 34 | Dispari | dx | 12.210 | 2,13 | 469 | m | |
| 45 | Dispari | dx | 14.990 | 1.83 | 546 | nh | 1100 |
| 30 | Dispari | dx | 11.240 | 1.82 | 549 | m | |
| 52 | Dispari | dx | 17.920 | 1.82 | 549 | m | |
| 9 | Dispari | dx | 4 114 | 1.70 | 588 | m | |
| 62 | Dispari | dx | 26.260 | 1.60 | 625 | m | |
| 41 | Dispari | dx | 13,780 | 1.01 | 990 | n(m) | |
| 14 | Dispari | dx | 5.376 | 0.99 | 1010 | m | |
| 17 | Dispari | dx | 6.960 | 0.83 | 1205 | m | |
| 39 | Dispari | dx | 13 310 | 0.44 | 2273 | p | |
| 42 | Dispari | dx | 13,950 | 0.10 | 10000 | n | |

Figure 6. Genova-Rapallo table ordered by increasing curve radius. For colours and symbols see text body.

Identification and counting of RCF defects

It was possible to visit only 41% and 54% of the curves where R320Cr (1100) and R350HT steel were respectively used. In any case, these data were thought to be sufficient for a first global evaluation of wear phenomena. As head checks were not visible on R260 rails, they will not be further considered here. The following colour codes were assigned to checked locations (Si = Yes):



Figure 7 and Figure 8 show the average yearly wear rate for R320Cr and R350HT rails respectively. The numerousness of categories, the distributive and cumulative wear functions are shown in Figure 9. The average yearly wear rate vs. curve radius is shown in Figure 10.

| PK | Num. | Località | Binario | Data | Curva | GPS Nord | GPS Est | R [m] | Tipo | s | h | Head | anc | V | Mesi | Usura a | Usura |
|--------|---------|----------------------------|---------|---------|-------|-----------|------------|-------|----------------|------|------|----------|---------|----------|----------|------------|------------|
| | Curva | | | di posa | | | | | di rotaia | [mm] | [mm] | Checks? | Rango C | fiancata | dalla | 45°[mm] | mm/anno |
| | REI | | | | | | | | | | | | [m/s^2] | | posa | 2007-06-24 | |
| - | - | | - | - | - | - | - | • | T. | - | - | - | - | - | • | - | _ t |
| 13+037 | 37 | Bogliasco | Dispari | mar-02 | dx | 44 22,746 | 009 03,999 | 10000 | 1100 | 1439 | 84 | Si | -0.50 | 95 | 63 | 0.114 | 0.022 |
| 27+005 | 64 | Santa Margherita Ligure | Pari | gen-03 | dx | 44 20,203 | 009 13,086 | 529 | 1100 | 1444 | 95 | Si | 0.41 | 85 | 53 | 0.432 | 0.098 |
| 28+974 | 66 | Rapallo | Dispari | feb-03 | dx | 44 21,060 | 009 13,614 | 561 | 1100 | 1434 | 113 | Si | 0.22 | 85 | 52 | 0.878 | 0.203 |
| 15+174 | 46 | Pieve Ligure | Pari | gen-04 | dx | 44 22,336 | 009 05,497 | 1000 | 1100 | 1440 | 60 | Si | 0.15 | 85 | 41 | 0.775 | 0.227 |
| 28+570 | 66 | Rapallo | Dispari | apr-04 | dx | 44 20,886 | 009 13,454 | 505 | 1100 | 1444 | 119 | Si | 0.30 | 85 | 38 | 0.742 | 0.234 |
| 26+973 | 64 | Santa Margherita Ligure | Pari | gen-03 | dx | 44 20,198 | 009 13,062 | 421 | 1100 | 1447 | 129 | Si | 0.45 | 85 | 53 | 1.078 | 0.244 |
| 28+721 | 66 | Rapallo | Pari | gen-03 | SX | 44 20,966 | 009 13,485 | 410 | 1100 | 1439 | 90 | Si | 0.75 | 85 | 53 | 1.299 | 0.294 |
| 12+909 | 37 | Bogliasco | Pari | mar-02 | SX | 44 22,746 | 009 03,949 | 382 | 1100 | 1443 | 156 | Si | 0.76 | 95 | 63 | 1.627 | 0.310 |
| 26+917 | 64 | Santa Margherita Ligure | Pari | gen-03 | dx | 44 20,197 | 009 13,020 | 421 | 1100 | 1448 | 82 | Si | 0.77 | 85 | 53 | 1.394 | 0.316 |
| 15+2/1 | 46 | Pieve Ligure | Pari | gen-04 | dx | 44 22,335 | 009 05,570 | 343 | 1100 | 1439 | 85 | SI | 1.05 | 85 | 41 | 1.085 | 0.318 |
| 29+041 | 66 | Rapallo | Dispari | teb-03 | dx | 44 21,072 | 009 13,662 | 438 | 1100 | 1440 | 145 | SI | 0.28 | 85 | 52 | 1.592 | 0.367 |
| 29+250 | 66 | Rapallo | Dispari | teb-03 | dx | 44 21,088 | 009 13,822 | 448 | 1100 | 1440 | 130 | INO | 0.36 | 85 | 52 | 1.768 | 0.408 |
| 15+211 | 46 | Pieve Ligure | Pari | gen-04 | dx | 44 22,341 | 009 05,527 | 613 | 1100 | 1445 | 85 | 51 | 0.33 | 85 | 41 | 1.570 | 0.460 |
| 28+639 | 66 | Rapallo | Dispari | apr-04 | dx | 44 20,927 | 009 13,452 | 505 | 1100 | 1439 | 118 | 51 | 0.30 | 85 | 38 | 1.483 | 0.468 |
| 12+946 | 37 | Bogliasco | Dispari | mar-02 | dx | 44 22,750 | 009 03,927 | 400 | 1100 | 1439 | 105 | 51 | 1.03 | 95 | 63 | 2.529 | 0.462 |
| 16+016 | 64 | Easte Marsharita Ligura | Pari | mag-03 | SX | 44 00 197 | 000 12 025 | 400 | 1100 | 1441 | 115 | 51 | 0.61 | C0 20 | 49 | 2.010 | 0.492 |
| 26+937 | 49 | Santa Margnerita Ligure | Pari | gen-03 | dx | 44 20,107 | 009 13,035 | 421 | 1100 | 1451 | 119 | 51 | 0.52 | C0 20 | 53 | 2.360 | 0.534 |
| 16+130 | 40 | Diava Ligura | Pari | mag-05 | SX | 44 22,317 | 009 06,237 | 400 | 1100 | 1445 | 07 | 01 | 0.44 | 00 | 49 | 2.200 | 0.539 |
| 20+419 | 40 | Preve Ligure | Diepari | fob 03 | dy. | 44 22,343 | 009 05,540 | 454 | 1100 | 1440 | 134 | Siliovi | 0.32 | 96 | 41 62 | 2.436 | 0.544 |
| 28+770 | 66 | Rapallo | Diepari | apr-04 | dx | 44 21,004 | 009 13,940 | 434 | 1100 | 1442 | 154 | Sillevi | 0.32 | 85 | 38 | 2.430 | 0.502 |
| 28+906 | 66 | Papallo | Diepari | feb-03 | dv | 44 20,000 | 009 13 574 | 410 | 1100 | 1440 | 128 | Si | 0.34 | 85 | 52 | 3 204 | 0.739 |
| 12+930 | 37 | Bogliasco | Pari | mar-02 | ex | 44 22 745 | 009 03 974 | 382 | 1100 | 1442 | 144 | Si | 0.23 | 95 | 63 | 3 906 | 0.733 |
| 28+800 | 66 | Banallo | Pari | gen-03 | ey . | 44 20 999 | 009 13 522 | 410 | 1100 | 1444 | 146 | Si | 0.37 | 85 | 53 | 3 292 | 0.745 |
| 12+987 | 37 | Bogliasco | Dispari | mar-02 | dx | 44 22 749 | 009 03 959 | 600 | 1100 | 1446 | 165 | Si | 0.04 | 95 | 63 | 3,991 | 0 760 |
| 16+158 | 48 | San Rocco viadotto di Sori | Pari | mag-03 | SX | 44 22 327 | 009 06 217 | 400 | 1100 | 1444 | 140 | Si | 0.44 | 85 | 49 | 3.261 | 0.799 |
| 28+705 | 66 | Rapallo | Dispari | apr-04 | dx | 44 20,960 | 009 13 470 | 410 | 1100 | 1442 | 150 | Si | 0.34 | 85 | 38 | 2,560 | 0.808 |
| 28+686 | 66 | Rapallo | Pari | gen-03 | SX | 44 20,950 | 009 13,467 | 410 | 1100 | 1447 | 156 | Si | 0.30 | 85 | 53 | 3.628 | 0.821 |
| 15+258 | 46 | Pieve Ligure | Pari | aen-04 | dx | 44 22,338 | 009 05,561 | 343 | 1100 | 1444 | 102 | Si | 0.93 | 85 | 41 | 2.983 | 0.873 |
| 29+488 | 66 | Rapallo | Dispari | feb-03 | dx | 44 21,050 | 009 13,990 | 461 | 1100 | 1446 | 136 | Si lievi | 0.29 | 85 | 52 | 3.877 | 0.895 |
| 28+844 | 66 | Rapallo | Dispari | apr-04 | dx | 44 21,020 | 009 13,534 | 406 | 1100 | 1444 | 150 | Si | 0.35 | 85 | 38 | 2.897 | 0.915 |
| 12+991 | 37 | Bogliasco | Dispari | mar-02 | dx | 44 22,748 | 009 03,962 | 600 | 1100 | 1444 | 165 | Si | 0.04 | 95 | 63 | 4.904 | 0.934 |
| 29+105 | 66 | Rapallo | Dispari | feb-03 | dx | 44 21,086 | 009 13,707 | 438 | 1100 | 1446 | 140 | Si | 0.32 | 85 | 52 | 4.213 | 0.972 |
| 28+618 | 66 | Rapallo | Pari | gen-03 | SX | 44 20,911 | 009 13,474 | 505 | 1100 | 1450 | 135 | Si | 0.19 | 85 | 53 | 4.528 | 1.025 |
| 29+158 | 66 | Rapallo | Dispari | feb-03 | dx | 44 21,091 | 009 13,747 | 500 | 1100 | 1445 | 128 | Si | 0.25 | 85 | 52 | 4.694 | 1.083 |
| 28+878 | 66 | Rapallo | Pari | gen-03 | SX | 44 21,028 | 009 13,560 | 406 | 1100 | 1446 | 133 | Si | 0.47 | 85 | 53 | 5.438 | 1.231 |
| 29+353 | 66 | Rapallo | Dispari | feb-03 | dx | 44 21,078 | 009 13,894 | 448 | 1100 | 1444 | 130 | No | 0.36 | 85 | 52 | 5.627 | 1.299 |
| 29+291 | 66 | Rapallo | Dispari | feb-03 | dx | 44 21,087 | 009 13,849 | 448 | 1100 | 1444 | 130 | Si lievi | 0.36 | 85 | 52 | 5.914 | 1.365 |
| 29+033 | 66 | Rapallo | Pari | | SX | 44 21,072 | 009 13,651 | 438 | 1100 | 1446 | 130 | Si | 0.39 | 85 | | 3.135 | |
| 29+011 | 66 | Rapallo | Pari | | SX | 44 21,065 | 009 13,643 | 550 | 1100 | 1445 | 122 | Si | 0.19 | 85 | | 1.849 | |
| 28+953 | 66 | Rapallo | Pari | | SX | 44 21,052 | 009 13,604 | 561 | 1100 | 1448 | 150 | Si | -0.02 | 85 | | 3.046 | |
| | | | D | 11 | | | C D | 220 | \overline{a} | • 1 | | 1 0 | • | • | | | |

Figure 7. Genova-Rapallo: average wear of R320Cr rails sorted for increasing wear rate.

| PK | Num. | Località | Binario | Data | Curva | GPS Nord | GPS Est | R [m] | Tipo | S [mm] | h [mm] | Head | anc | V | Mesi | Usura a | Usura |
|--------|------|--------------|---------|----------|-------|-----------|------------|-------|-----------|-----------|-----------|----------|---------|---------|------|------------|------------|
| | RFI | | | ui posa | | | | | ui rotaia | [iiiiii] | [inni] | CHECKS: | [m/s^2] | nancata | posa | 2007-06-24 | mmanno |
| - | - | • | | • | - | - | - | - | 7 | - | - | - | - | - | - | - | _ t |
| 14+900 | 44 | Pieve Liqure | Pari | ago-04 | dx | 44 22.371 | 009 05.291 | 1000 | 1200 | 1435 | 48 | Si | 0.23 | 85 | 34 | -0.055 | -0.019 |
| 21+774 | 59 | Camoqli | Dispari | gen-04 | SX | 44 20,878 | 009 09,415 | 667 | 1200 | 1440 | 64 | No | 0.40 | 85 | 41 | 0.109 | 0.032 |
| 19+172 | 55 | Mulinetti | Pari | set-03 | dx | 44 21.693 | 009 08 095 | 1000 | 1200 | 1439 | 96 | No | -0.10 | 85 | 45 | 0.169 | 0.045 |
| 19+122 | 55 | Mulinetti | Pari | set-03 | dx | 44 21,691 | 009 08,059 | 461 | 1200 | 1438 | 114 | No | 0.43 | 85 | 45 | 0.371 | 0.099 |
| 18+917 | 55 | Mulinetti | Pari | set-03 | dx | 44 21,689 | 009 07,991 | 461 | 1200 | 1440 | 98 | No | 0.54 | 85 | 45 | 0.457 | 0.122 |
| 21+926 | 59 | Camogli | Dispari | gen-04 | SX | 44 20,835 | 009 09,510 | 2500 | 1200 | 1447 | 64 | No | -0.21 | 85 | 41 | 0.427 | 0.125 |
| 21+795 | 59 | Camogli | Dispari | gen-04 | SX | 44 20,872 | 009 09,429 | 600 | 1200 | 1440 | 81 | No | 0.38 | 85 | 41 | 0.523 | 0.153 |
| 18+825 | 55 | Mulinetti | Pari | set-03 | dx | 44 21,699 | 009 07,925 | 424 | 1200 | 1439 | 110 | No | 0.56 | 85 | 45 | 0.583 | 0.155 |
| 20+260 | 56 | Recco | Pari | mar-02 | SX | 44 21,574 | 009 08,864 | 508 | 1200 | 1442 | 115 | Si lievi | 0.32 | 85 | 63 | 0.930 | 0.177 |
| 19+995 | 56 | Recco | Pari | mar-02 | SX | 44 21,696 | 009 08,756 | 1031 | 1200 | 1437 | 65 | Si lievi | 0.10 | 85 | 63 | 0.938 | 0.179 |
| 19+964 | 56 | Recco | Dispari | ago-04 | dx | 44 21,716 | 009 08,739 | 1031 | 1200 | 1437 | 54 | No | 0.17 | 85 | 34 | 0.522 | 0.184 |
| 21+840 | 59 | Camogli | Dispari | gen-04 | SX | 44 20,860 | 009 09,459 | 468 | 1200 | 1445 | 82 | No | 0.63 | 85 | 41 | 0.710 | 0.208 |
| 14+850 | 44 | Pieve Ligure | Pari | ago-04 | dx | 44 22,383 | 009 05,265 | 700 | 1200 | 1443 | 126 | No | -0.06 | 85 | 34 | 0.589 | 0.208 |
| 19+664 | 56 | Recco | Dispari | ago-04 | dx | 44 21,782 | 009 08,541 | 400 | 1200 | 1441 | 122 | No | 0.56 | 85 | 34 | 0.599 | 0.211 |
| 14+818 | 44 | Pieve Ligure | Pari | ago-04 | dx | 44 22,377 | 009 05,236 | 459 | 1200 | 1443 | 133 | No | 0.31 | 85 | 34 | 0.602 | 0.212 |
| 20+231 | 56 | Recco | Pari | mar-02 | SX | 44 21,589 | 009 08,853 | 508 | 1200 | 1439 | 120 | Si lievi | 0.28 | 85 | 63 | 1.120 | 0.213 |
| 21+884 | 59 | Camogli | Dispari | gen-04 | SX | 44 20,851 | 009 09,488 | 1000 | 1200 | 1445 | 82 | No | 0.00 | 85 | 41 | 0.796 | 0.233 |
| 14+767 | 44 | Pieve Ligure | Pari | ago-04 | dx | 44 22,384 | 009 05,195 | 459 | 1200 | 1442 | 100 | No | 0.53 | 85 | 34 | 0.721 | 0.254 |
| 20+044 | 56 | Recco | Pari | mar-02 | SX | 44 21,681 | 009 08,787 | 900 | 1200 | 1443 | 100 | Si lievi | -0.06 | 85 | 63 | 1.424 | 0.271 |
| 19+905 | 56 | Recco | Pari | mar-02 | SX | 44 21,729 | 009 08,708 | 402 | 1200 | 1441 | 140 | Si lievi | 0.43 | 85 | 63 | 1.427 | 0.272 |
| 20+173 | 56 | Recco | Pari | mar-02 | SX | 44 21,619 | 009 08,838 | 508 | 1200 | 1444 | 118 | Si lievi | 0.30 | 85 | 63 | 1.472 | 0.280 |
| 18+725 | 55 | Mulinetti | Pari | set 03 | dx | 44 21,718 | 009 07,857 | 600 | 1200 | 1438 | 100 | No | 0.25 | 85 | 45 | 1.055 | 0.281 |
| 19+771 | 56 | Recco | Dispari | ago-04 | dx | 44 21,772 | 009 08,619 | 437 | 1200 | 1441 | 124 | No | 0.43 | 85 | 34 | 0.801 | 0.283 |
| 14+640 | 44 | Pieve Ligure | Pari | ago-04 | dx | 44 22,419 | 009 05,114 | 374 | 1200 | 1442 | 126 | No | 0.63 | 85 | 34 | 0.887 | 0.313 |
| 21+667 | 59 | Camogli | Pari | ott-01 | dx | 44 20,923 | 009 09,366 | 667 | 1200 | 1436 | 74 | Si | 0.33 | 85 | 68 | 1.828 | 0.323 |
| 14+701 | 44 | Pieve Ligure | Pari | ago-04 | dx | 44 22,406 | 009 05,157 | 374 | 1200 | 1442 | 120 | No | 0.67 | 85 | 34 | 0.932 | 0.329 |
| 12+589 | 35 | Bogliasco | Dispari | apr-04 | SX | 44 22,769 | 009 03,669 | 450 | 1200 | 1439 | 93 | Si | 0.91 | 95 | 38 | 1.057 | 0.334 |
| 14+578 | 44 | Pieve Ligure | Pari | ago-04 | dx | 44 22,441 | 009 05,082 | 374 | 1200 | 1444 | 126 | No | 0.63 | 85 | 34 | 0.962 | 0.340 |
| 14+578 | 44 | Pieve Ligure | Pari | ago-04 | dx | 44 22,441 | 009 05,080 | 374 | 1200 | 1444 | 126 | No | 0.63 | 85 | 34 | 0.964 | 0.340 |
| 19+861 | 56 | Recco | Pari | mar-02 | SX | 44 21,746 | 009 08,684 | 402 | 1200 | 1442 | 150 | Si lievi | 0.37 | 85 | 63 | 1.802 | 0.343 |
| 19+665 | 56 | Recco | Pari | mar-02 | SX | 44 21,774 | 009 08,544 | 400 | 1200 | 1442 | 138 | Si lievi | 0.45 | 85 | 63 | 1.872 | 0.357 |
| 20+300 | 56 | Recco | Dispari | ago-04 | dx | 44 21,561 | 009 08,874 | 750 | 1200 | 1436 | 70 | Si | 0.27 | 85 | 34 | 1.076 | 0.380 |
| 20+104 | 56 | Recco | Pari | mar-02 | SX | 44 21,652 | 009 08,813 | 420 | 1200 | 1446 | 140 | Si lievi | 0.38 | 85 | 63 | 2.074 | 0.395 |
| 19+869 | 56 | Recco | Dispari | ago-04 | dx | 44 21,749 | 009 08,686 | 406 | 1200 | 1442 | 125 | No | 0.52 | 85 | 34 | 1.126 | 0.397 |
| 20+272 | 56 | Recco | Dispari | ago-04 | dx | 44 21,576 | 009 08,869 | 508 | 1200 | 1441 | 100 | SI | 0.42 | 85 | 34 | 1.240 | 0.438 |
| 19+759 | 56 | Recco | Pari | mar-02 | SX | 44 21,765 | 009 08,612 | 437 | 1200 | 1444 | 140 | Silievi | 0.32 | 85 | 63 | 2.340 | 0.446 |
| 21+578 | 59 | Camogli | Pari | ott-01 | dx | 44 20,942 | 009 09,298 | 420 | 1200 | 1441 | 120 | SI | 0.51 | 85 | 68 | 2.738 | 0.483 |
| 20+089 | 56 | Recco | Dispari | ago-04 | dx | 44 21,669 | 009 08,810 | 420 | 1200 | 1442 | 110 | Silievi | 0.58 | 85 | 34 | 1.407 | 0.497 |
| 20+172 | 56 | Recco | Dispari | ago-04 | dx | 44 21,628 | 009 08,839 | 508 | 1200 | 1440 | 108 | Silievi | 0.36 | 85 | 34 | 1.428 | 0.504 |
| 20+232 | 56 | Recco | Dispari | ago-04 | dx | 44 21,597 | 009 08,860 | 508 | 1200 | 1441 | 100 | Si | 0.42 | 85 | 34 | 1.540 | 0.544 |
| 12+650 | 35 | Bogliasco | Dispari | apr-04 | SX | 44 22,750 | 009 03,706 | 380 | 1200 | 1439 | 164 | Si | 0.71 | 95 | 38 | 1.745 | 0.551 |
| 12+763 | 35 | Bogliasco | Dispari | apr-04 | SX | 44 22,744 | 009 03,785 | 429 | 1200 | 1436 | 150 | SI | 0.60 | 95 | 38 | 1.792 | 0.566 |
| 21+570 | 59 | Camogli | Pari | ott-01 | dx | 44 20,951 | 009 09,310 | 420 | 1200 | 1443 | 140 | Si | 0.38 | 85 | 68 | 3.435 | 0.606 |
| 12+612 | 35 | Bogliasco | Dispari | apr-04 | SX | 44 22,759 | 009 03,680 | 380 | 1200 | 1439 | 165 | SI | 0.71 | 95 | 38 | 1.987 | 0.627 |
| 12+788 | 35 | Bogliasco | Dispari | apr-04 | SX | 44 22,746 | 009 03,807 | 600 | 1200 | 1439 | 130 | SI | 0.27 | 95 | 38 | 2.002 | 0.632 |
| 14+968 | 45 | Pieve Ligure | Pari | ago-04 | SX | 44 22,3/1 | 009 05,343 | 519 | 1200 | 1442 | 80 | SI | 0.53 | 85 | 34 | 2.356 | 0.832 |
| 14+988 | 45 | Pieve Ligure | Pari | ago-04 | SX | 44 22,363 | 009 05,358 | 519 | 1200 | 1444 | 100 | SI | 0.39 | 85 | 34 | 2.639 | 0.931 |
| 12+822 | - 37 | Bogliasco | Dispari | | SX | 44 22,746 | 009 03,833 | 1000 | 1200 | 1438 | 59 | SI | 0.29 | 95 | | 0.729 | |

Figure 8. Genova-Rapallo: average wear of R350HT rails sorted for increasing wear rate.



Figure 9. Genova-Rapallo: distributive and cumulative functions of average yearly wear rate for R320Cr (1100) and R350HT (1200) rails.



Figure 10. Genova-Rapallo: average yearly wear rate for R320Cr rails (38 measurements) and R350HT rails (47 measurements).

Conclusions on Genova-Rapallo measurements

The analysis of these results shows that:

- wear distribution is much different for the two types of hard rails used, being mostly concentrate at low values for R350HT rails (more than 25% of occurrences in the class 0.2÷0.3 mm/year), while it is very dispersed for R320Cr rails (there are six values out of seven greater than 10% in range 0.2÷0.9 mm/year) (Figure 9 left);
- the cumulative diagram obviously reflects this distribution, having the 80% of R320Cr rails an average wear rate of 0.8÷0.9 mm/year vs. an average wear rate of 0.4÷0.5 mm/year of R350HT rails (ratio≈2) (Figure 9 bottom right);
- supposing, although not very likely, a constant wear rate and aiming at reach a useful life of 20 years before reaching the alarm limit w_{45} =14 mm (=0.7 mm/year), only 55% of R320Cr rails reach this goal compared to 96% of R350HT rails;

- apparently, there is not a simply relationship between the curve radius and average wear rate, as low wear rates were observed not only for large radii (as expected) but also for small radii (Figure 10);
- R320Cr rails are extensively affected by RCF phenomena, being head checks visible on almost all visually checked rails (Figure 7);
- R350HT rails are affected by head checks only where wear is bigger (Figure 8). This seems to be contrary to the widely accepted competing mechanisms of wear and crack growth. It should be clarified, anyway, that only the head shoulder was affected by head checks while the area mostly subject to wear is the (originally vertical) gauge face. Crack removal may prove harder where wear is lower. Another possible interpretation is that, having normally very low cant deficiency, lateral forces are relatively low and both wear and crack nucleation are prevented. Where forces are higher, it appears that crack growth is bigger than wear even if the latter is high.

Some limits to this analysis are the non exactly equally distribution of measuring points due to some points difficult or impossible to reach (for example inside tunnels) and the only visual analysis of RCF defects.

CASE STUDY 2 – PRATO-BOLOGNA, NORTHBOUND (EVEN) TRACK

This line, opened in the '30s, is called *Direttissima* and is a part of the Milan-Rome railway line. It is characterized by a very intense traffic of both passenger and freight trains. The section considered, around 17 km long between Prato and Vernio-Montepiano-Cantagallo, can be run at 110÷120 km/h without intermediate stops. On next 14 Dec. 2009, the high speed line between Firenze and Bologna will be opened shunting this line for most of the passenger traffic. This will be the last section of the high speed network connecting Turin-Milan-Bologna-Florence-Rome-Naples-Salerno.

Measurements with *Archimede* covered a longer period. No hard rails were installed in this line during the whole activity reported here. For short, only outputs from the measuring train will be reported and commented here.

Available data

ASCII files available contained only w_{45} data for both the rails in the Prato Centrale – PC Precedenze section (from PK 16+800 to 46+800) (note: only the last measurement contained cant, gauge and curvature data) collected on:

- 1. (t=0) January 2006
- 2. (t=5 months) June 2006
- 3. (t=9 months) October 2006
- 4. (t=17 months) June 2007
- 5. (t=21 months) October 2007

Data analysis consisted of the following steps:

- PK and w_{45} data synchronization obtained from the comparison of different w_{45} measurements;
- curve progressive numbering starting from the first (PK 16+800) after Prato Centrale station;
- plotting of w_{45} data;
- wear rate classification.

Due the absence of official RFI documents and to the length of some curves (some more than 1 km long), measurements were plotted curve by curve only on the high rail, the one that is influenced by the maximum wear w_{45} .

It was observed that, for the nominal speed of 110÷120 km/h, non compensated acceleration a_{nc} is always close (except for more gentle curves) to $a_{nc}=1$ m/s², contrary to what happened near Genova.

Wear trend in long curves

A recurrent behaviour was identified on a large portion of the curves, consisting of a progressive increase of w_{45} along the curve. This phenomenon applies in a more or less consistent way on all curves of sufficiently high length.

The extension of the phenomenon is such that transient effects due to vehicle dynamics after transition curve are believed to be completely exhausted, i.e. the phenomenon also happens in constant radius curve. As kinematic conditions are therefore stationary, the only possible reason for such progressive wear is linked to friction conditions, i.e. to variation of lubrication conditions. It seems that the train enters the curve with well lubricated locomotive wheel flanges (no trackside lubricators are active) and then that the protection offered by the lubricant is gradually lost. A global overview of this phenomenon is shown in Figure 11, and one of the curves shown there (i.e. curve 3) was already shown in Figure 2.



Figure 11. Prato-Bologna curves that suffer progressive wear indicated with SI' (=YES), 1/2 and NO depending on the presence of the phenomenon.

Correlation between rail wear rate and curvature

Wear rate classification was based on the same criteria described above. As rails were somewhere changed in between the first and the last considered measuring run, a set of information had to be considered including the maximum wear measured on each rail before change and possibly different wear classes. Information can be extracted from Figure 12, Figure 13 and Figure 14.

| N° | Curva | PK di max | Curvatura | Raggio | R | ∆Usura | tempo 1 | ∆Usura 1 | Usura finale | Cambio | ∆usura | tempo 2 | ∆Usura 2 | Usura | Tipo di | Note |
|-------|-------|--------------|------------|--------|------|--------|---------|-----------|--------------|---------|--------|---------|----------|--------|---------|----------|
| curva | а | curvatura da | massima da | | | 1 | [mesi] | [mm/anno] | o pre- | rotaie? | 2 | [mesi] | [mm/anno | finale | usura | |
| | | Archimede | Archimede | | | | | - | cambio | | | | 1 | | | |
| 17 | dx | 31.540 | 1.66 | 602 | 602 | 0.0 | 6 | 0.0 | 9 | Sì | 4 | 12 | 4.0 | 5.0 | n+s | Nota 5 |
| 3 | SX | 19.370 | -0.62 | -1613 | 1613 | 0.9 | 21 | 0.5 | 6 | | | | | | N | Nota 6 |
| 7 | SX | 22.330 | -0.97 | -1031 | 1031 | 1.0 | 21 | 0.6 | 4 | | | | | | М | Nota 5 |
| 6 | dx | 21.880 | 0.96 | 1042 | 1042 | 1.5 | 21 | 0.9 | 3 | | | | | | m | Nota 4 |
| 15 | SX | 30.220 | -0.94 | -1064 | 1064 | 1.5 | 21 | 0.9 | 5 | | | | | | М | Nota 5 |
| 12 | SX | 27.150 | -1.49 | -671 | 671 | 2.0 | 21 | 1.1 | 2 | | | | | | М | |
| 2 | dx | 18.360 | 1.29 | 775 | 775 | 1.0 | 9 | 1.3 | 8 | Sì | 1 | 4 | 3.0 | 1.0 | m+s | Nota 2 |
| 5 | SX | 20.940 | -1.74 | -575 | 575 | 1.0 | 8 | 1.5 | 6 | Sì | 0 | 4 | 0.0 | | M+N | Nota 6 |
| 9 | SX | 23.740 | -1.71 | -585 | 585 | 3.0 | 21 | 1.7 | 3 | | | | | | М | Nota 6 |
| 16 | SX | 31.010 | -1.71 | -585 | 585 | 3.5 | 21 | 2.0 | 6 | | | | | | S | Nota 6 |
| 8 | dx | 22.860 | 1.48 | 676 | 676 | 4.0 | 21 | 2.3 | 5 | | | | | | s | Nota 6 |
| 11 | SX | 25.650 | -1.67 | -599 | 599 | 4.0 | 21 | 2.3 | 7 | | | | | | S | Nota 5+6 |
| 10 | dx | 24.860 | 1.69 | 592 | 592 | 2.0 | 10 | 2.4 | 7 | Sì | 2 | 4 | 6.0 | 1.0 | s+s | |
| 18 | SX | 32.530 | -1.70 | -588 | 588 | 1.0 | 5 | 2.4 | 7 | Sì | 3.4 | 12 | 3.4 | 5.0 | S+S | Nota 6 |
| 14 | dx | 28.880 | 1.66 | 602 | 602 | 2.3 | 10 | 2.8 | 7 | Sì | 1.3 | 4 | 3.9 | 1.0 | s+s | Nota 9 |
| 1 | dx | 16.990 | 1.70 | 588 | 588 | 4.0 | 17 | 2.8 | 8 | Sì | 4 | 12 | 4.0 | 8.0 | s+s | Nota 1 |
| 20 | SX | 35.800 | -1.70 | -588 | 588 | 2.4 | 9 | 3.2 | 8 | Sì | 1 | 4 | 3.0 | 2.0 | S+S | |
| 13 | dx | 27.860 | 1.67 | 599 | 599 | 6.2 | 21 | 3.5 | 3 | | | | | | s | Nota 6+8 |
| 19 | dx | 33.700 | 1.69 | 592 | 592 | 6.3 | 21 | 3.6 | 12 | | | | | | s | Nota 8 |
| 4 | dx | 20 270 | 1 62 | 617 | 617 | | | | 11 | Sì | 3 | 16 | 23 | 3.0 | s | Nota 3 |

Figure 12. Prato-Bologna: wear properties sorted for final or pre-rail change wear.

| N° | Curva | PK di max | Curvatura | Raggio | R | ∆Usura | tempo 1 | ∆Usura 1 | Usura finale | Cambio | ∆usura | tempo 2 | ∆Usura 2 | Usura | Tipo di | Note |
|-------|-------|--------------|------------|--------|------|--------|---------|-----------|--------------|---------|--------|---------|----------|--------|---------|----------|
| curva | а | curvatura da | massima da | | | 1 | [mesi] | [mm/anno] | o pre- | rotaie? | 2 | [mesi] | [mm/anno | finale | usura | |
| | | Archimede | Archimede | | | | | | cambio | | | | ì | | | |
| 5 | SX | 20.940 | -1.74 | -575 | 575 | 1.0 | 8 | 1.5 | 6 | Sì | 0 | 4 | 0.0 | | M+N | Nota 6 |
| 9 | SX | 23.740 | -1.71 | -585 | 585 | 3.0 | 21 | 1.7 | 3 | | | | | | М | Nota 6 |
| 16 | SX | 31.010 | -1.71 | -585 | 585 | 3.5 | 21 | 2.0 | 6 | | | | | | S | Nota 6 |
| 18 | SX | 32.530 | -1.70 | -588 | 588 | 1.0 | 5 | 2.4 | 7 | Sì | 3.4 | 12 | 3.4 | 5.0 | S+S | Nota 6 |
| 1 | dx | 16.990 | 1.70 | 588 | 588 | 4.0 | 17 | 2.8 | 8 | Sì | 4 | 12 | 4.0 | 8.0 | s+s | Nota 1 |
| 20 | SX | 35.800 | -1.70 | -588 | 588 | 2.4 | 9 | 3.2 | 8 | Sì | 1 | 4 | 3.0 | 2.0 | S+S | |
| 10 | dx | 24.860 | 1.69 | 592 | 592 | 2.0 | 10 | 2.4 | 7 | Sì | 2 | 4 | 6.0 | 1.0 | s+s | |
| 19 | dx | 33.700 | 1.69 | 592 | 592 | 6.3 | 21 | 3.6 | 12 | | | | | | s | Nota 8 |
| 11 | SX | 25.650 | -1.67 | -599 | 599 | 4.0 | 21 | 2.3 | 7 | | | | | | S | Nota 5+6 |
| 13 | dx | 27.860 | 1.67 | 599 | 599 | 6.2 | 21 | 3.5 | 3 | | | | | | s | Nota 6+8 |
| 17 | dx | 31.540 | 1.66 | 602 | 602 | 0.0 | 6 | 0.0 | 9 | Sì | 4 | 12 | 4.0 | 5.0 | n+s | Nota 5 |
| 14 | dx | 28.880 | 1.66 | 602 | 602 | 2.3 | 10 | 2.8 | 7 | Sì | 1.3 | 4 | 3.9 | 1.0 | s+s | Nota 9 |
| 4 | dx | 20.270 | 1.62 | 617 | 617 | | | | 11 | Sì | 3 | 16 | 2.3 | 3.0 | s | Nota 3 |
| 12 | SX | 27.150 | -1.49 | -671 | 671 | 2.0 | 21 | 1.1 | 2 | | | | | | М | |
| 8 | dx | 22.860 | 1.48 | 676 | 676 | 4.0 | 21 | 2.3 | 5 | | | | | | s | Nota 6 |
| 2 | dx | 18.360 | 1.29 | 775 | 775 | 1.0 | 9 | 1.3 | 8 | Sì | 1 | 4 | 3.0 | 1.0 | m+s | Nota 2 |
| 7 | SX | 22.330 | -0.97 | -1031 | 1031 | 1.0 | 21 | 0.6 | 4 | | | | | | М | Nota 5 |
| 6 | dx | 21.880 | 0.96 | 1042 | 1042 | 1.5 | 21 | 0.9 | 3 | | | | | | m | Nota 4 |
| 15 | SX | 30.220 | -0.94 | -1064 | 1064 | 1.5 | 21 | 0.9 | 5 | | | | | | М | Nota 5 |
| 3 | SX | 19 370 | -0.62 | -1613 | 1613 | 0.9 | 21 | 0.5 | 6 | | | | | | N | Nota 6 |

Figure 13. Prato-Bologna: wear properties sorted for curve radius.

| N° | Curva | PK di max | Curvatura | Raggio | R | ∆Usura | tempo 1 | ∆Usura 1 | Tipo di | Note |
|-------|-------|--------------|------------|--------|-----|--------|---------|-----------|---------|----------|
| curva | а | curvatura da | massima da | | | 1 | [mesi] | [mm/anno] | usura | |
| | | Archimede | Archimede | | | | | | | |
| 16 | SX | 31.010 | -1.71 | -585 | 585 | 3.5 | 21 | 2.0 | S | Nota 6 |
| 18 | SX | 32.530 | -1.70 | -588 | 588 | 1.0 | 5 | 2.4 | S+S | Nota 6 |
| 1 | dx | 16.990 | 1.70 | 588 | 588 | 4.0 | 17 | 2.8 | s+s | Nota 1 |
| 20 | SX | 35.800 | -1.70 | -588 | 588 | 2.4 | 9 | 3.2 | S+S | |
| 10 | dx | 24.860 | 1.69 | 592 | 592 | 2.0 | 10 | 2.4 | s+s | |
| 19 | dx | 33.700 | 1.69 | 592 | 592 | 6.3 | 21 | 3.6 | s | Nota 8 |
| 11 | SX | 25.650 | -1.67 | -599 | 599 | 4.0 | 21 | 2.3 | S | Nota 5+6 |
| 13 | dx | 27.860 | 1.67 | 599 | 599 | 6.2 | 21 | 3.5 | s | Nota 6+8 |
| 14 | dx | 28.880 | 1.66 | 602 | 602 | 2.3 | 10 | 2.8 | s+s | Nota 9 |
| 8 | dx | 22.860 | 1.48 | 676 | 676 | 4.0 | 21 | 2.3 | s | Nota 6 |

Figure 14. Prato-Bologna: track and wear properties sorted for increasing curve radius (only relative to curves with severe wear, i.e. *all the curves with R from* 585 *m to* 602 *m*).

Wear rate appears to be, in this case, inversely proportional to a fractional power of curve radius. Figure 15 shows the trend of average yearly wear rate (where needed considering pre- and post-rail change).

It is evident how rail change leads to a sudden increase in the average yearly wear rate of rails, always resulting in the $3\div 6$ mm/year range, at least until wear rate are not restored to values typical of partly worn rails where forces are distributed over a large contact surface. It may be interesting to observe that

there are three curves that before rail change had moderate or negligible wear and that after have shown severe wear. These were curve 17 (R=602 m, w_{45} =4 mm/year), curve 2 (R=775 m, w_{45} =3 mm/year) and curve 4 (R=617 m, w_{45} =2.3 mm/year), although for the last only one pre-rail change measurement was available (and then it has not been possible to estimate pre-rail change wear rate).



Figure 15. Prato-Bologna: average yearly wear rate [mm/year] pre- and post-rail change vs. curve radius.

It is also interesting to check the absolute wear value at rail change: 1 rail at $w_{45}=6$ mm, 3 rails at $w_{45}=7$ mm, 3 rails at $w_{45}=8$ mm, 1 rail at $w_{45}=9$ mm, 1 rail at $w_{45}=11$ mm. It is clear that rail change is done much before rails reached wear limit; noticeable improvements look therefore possible to identify a finer maintenance strategy. It is worth to underline that all these calculations are made with *Archimede* curves filtered above 50 m wavelength, leading to potential errors in the range of around ± 2 mm on local wear value.

Conclusions on Prato-Bologna measurements

As line visits were not included in this activity, conclusions can only be drafted for rail wear. Generally speaking, extremely severe rail wear phenomena, in the order of 3÷6 mm/year, were found on the Prato-Bologna line also for curve radii where for Genova-La Spezia there were only moderate wear situations. For curves of radius around 600 m, the application of hard rails on Genova-La Spezia looks useless while it looks absolutely necessary for Prato-Bologna. Re-railing problems appear dramatic on this line, leading to incredibly high transient wear rate.

CONCLUSIONS

In this paper wear behaviour of conventional and hard rails were analysed for two different cases, being the most important differences the curve radius and the cant deficiency (non-compensated acceleration). Results show that very often wear in curves of constant radius is not constant and that an average wear figure can not be given on a curve by curve basis. Re-railing problems have shown dramatic wear problems, while RCF was extensively present on most of the higher hardness rails. Some mechanism were not fully understood and will be investigated more in detail in a following work.

Problems with rolling stock wheel flange wear after rerailing (especially with hard rails) were not addressed in this paper and will be discussed in a future work.

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