Advances in reliability assessments of axles

Mac-Lan NGUYEN-TAJAN
Xavier LORANG
SNCF, Innovation & Research Department

1st October 2014, TC24, Milan

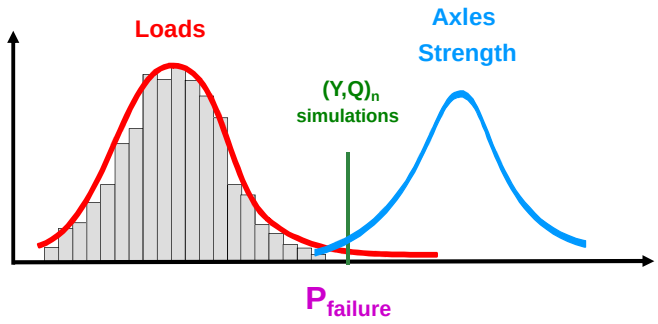
Overall objectives of the WP2/WP3

*"Euraxles aims at monitoring more effectively the **axles fatigue reliability** within a context of possible evolutions of the usages (progressive market opening, traffic escalation, velocities increase, etc.) and the introduction of innovations"*

*WP2/WP3 concentrated on the **design methods**.*

The process for homologating an axle consists in:
- a method to calculate forces acting on the axle
- a method to calculate stresses in different sections of the axle
- the definition of allowable stresses

Overall objectives of the WP2/WP3



WP2

Loads
Simulations
Reliability approach

WP3 : fatigue limits

Overall objectives of the WP2/WP3

The work performed in WP2/WP3 consisted in :

✓ developing a **methodology to characterize the real in-service loads severities** and compare them to the normative loads

✓ developing **numerical models using finite element analyses** for the stress evaluation, developing a commonly accepted numerical validation process and giving recommendations for a future revision of the standard EN1310X

✓ characterizing the **fatigue limits of the steel grades A1N and A4T**

✓ developing a **methodology which estimates the probability of failure** of an axle, taking into account the load variability and the components' strength scattering

Specific activities led by SNCF

1. Load analysis
2. Reliability assessments

Load analysis

A. Load database

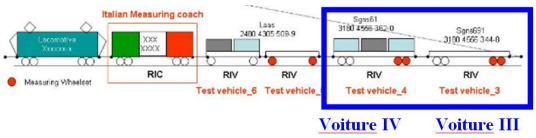
B. Load analysis method
and application to a passenger coach axle

A. Load database

3 test campaigns were available:

- **Dynotrain (DB, SNCF, TrenItalia, BT, Alstom, FP7 project)**

- FP7 project for virtual homologation of trains.
- On-track tests carried out in October 2010
- Analysis of running behaviour of a vehicle running on different networks (7500 km in **Germany, France, Italy, Switzerland** → 300 km of data).



5 types of vehicle:
• Locomotive BR 120-510-2
• Passenger coach Bim 547.5 in empty condition
• 4-axle freight wagon Sgns 691 in empty condition
• 4-axle freight wagon Sgns 691 in fully loaded condition
• 2-axle freight wagon Laas in empty condition

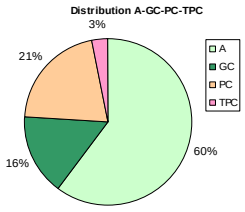
Vmax=200km/h or 120 km/h

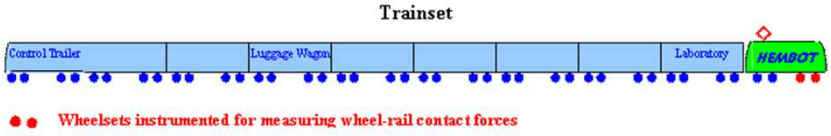
A. Load database

- **Hembot (TrenItalia, AnsaldoBreda)**

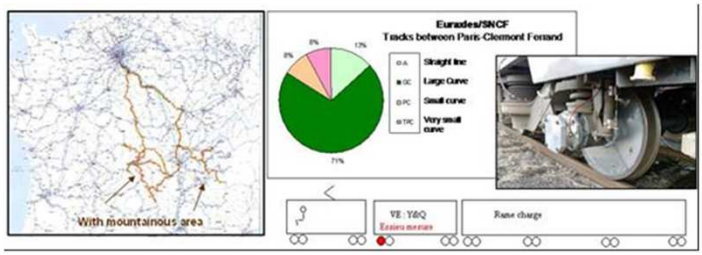
European project (1997-2003)

Locomotive E402 138 equipped with Hembot bogies
21,25 tons/axle,
Vmax=220km/h
76 km of acquisition (Firrenze-Arrezzo)





- **Euraxles (SNCF)**

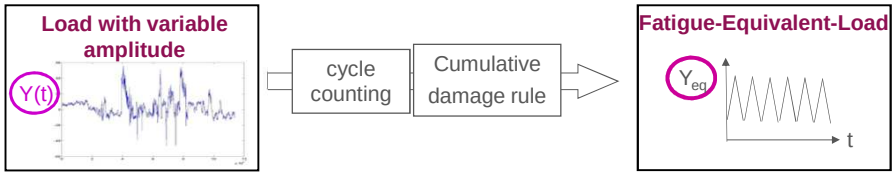


Non-powered axle of a passenger coach running from Paris to Clermont-Ferrand
Maximum speed of V=160 km/h. , Axle load 14t
4 weeks of acquisitions (**2000 km**)

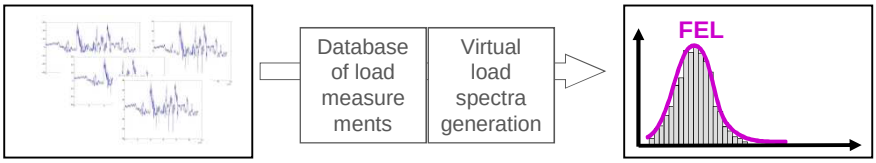
The measured wheel/rail forces on the left and right wheel were low pass filtered with a cut off frequency of 20 Hz for Q and 10 Hz for Y

B. Load analysis method

1. **Definition of a fatigue load/a fatigue cycle**
2. **Method to analyze a measured load with variable amplitudes and define a cyclic equivalent load**

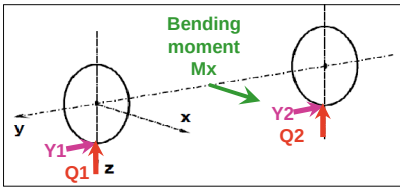


3. **Method to characterize the in-service axle usages variability**



1. Definition of a fatigue load/a fatigue cycle

+ Braking forces
+ Inertia forces

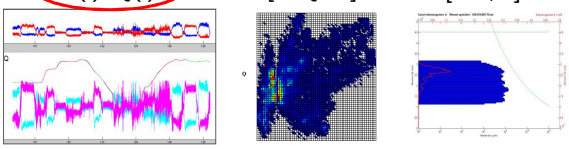


Assumptions :

Intertia forces
Bending moments My, Mz can be neglected

Only the bending moment Mx is considered

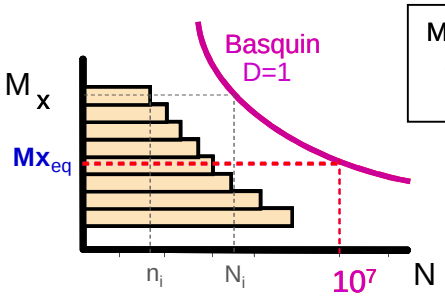
Y(t), Q(t) ⇨ [Yi,Qi,ni] ⇨ [Mxi,ni]



Each axle revolution generates a fatigue cycle

From Y and Q forces measurements, a **bending moment spectrum** can be derived

2. Definition of a cyclic equivalent-load



MINER damage accumulation
$D = \Sigma(n_i/N_i)$

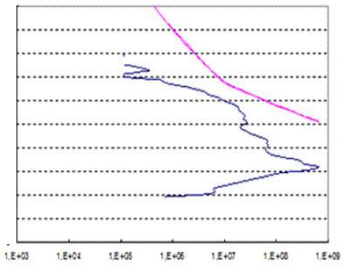
$$\forall i \quad N_i.M_i^m = N_{eq}.M_{eq}^m$$

$$D = \sum_i \frac{n_i}{N_i} = \frac{1}{N_{eq}} \sum_i \frac{n_i.M_i^m}{M_{eq}^m}$$

$$D = 1 \quad \Rightarrow \quad M_{eq} = \left(\frac{1}{N_{eq}} \sum_i n_i.M_i^m \right)^{1/m}$$

- Basquin with one slope
- Damage law with 2 slopes, Haibach rule (k/2k-1)
- Konsequent Miner rule

Application of FEL to the Hembot load spectrum



Kref	1.E7	7.E6	4.E6
EN13103	80 kNm	80 kNm	80 kNm
Basquin 1 slope (b=8)	85,7 kNm	82,0 kNm	76,5 kNm
Basquin 2 slopes (b=8;15)	71,2 kNm	69,4 kNm	66,7 kNm
Konsequent Miner rule	67,5 kNm	66,4 kNm	66,6 kNm

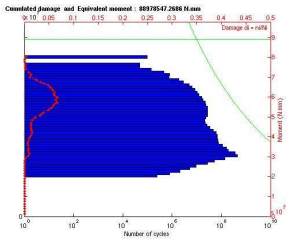
- The Miner rule with a Basquin law with one slope is definitely too severe.
The Miner rule with a Basquin law with two slopes gives results close to the KMR.
The KMR gives lower FEL than the traditional Miner rules, as expected.

- The equivalent-load of the measurement is much lower than the normative load defined as according to standards EN13103/13104 (except with the one slope curve).

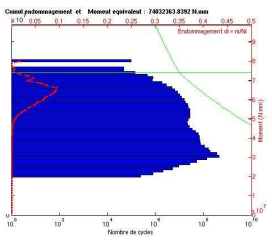
Parametric analyses

Effect of the train velocity
Effect of the mass carried by the axle
Effect of the axle's lifetime
Effect of the signals filtering
Effect of the cumulative damage law…

Effect of Basquin law with 1 or 2 slopes:



Mx_{eq} = 89 kN.m



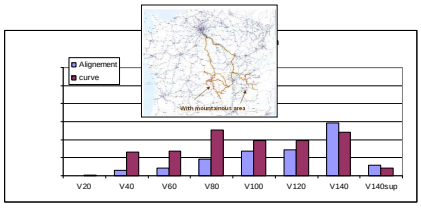
Mx_{eq} = 74 kN.m

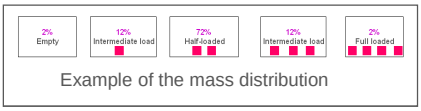
3. Usage variability : decomposition of the load measurements into classified elementary load spectra

According to previous work of RSSB and DeltaRail, the main sources of variability are:

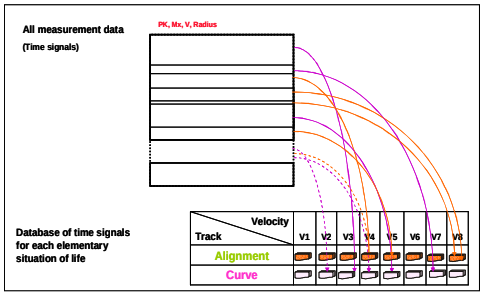
- track characteristics (curvatures and quality)
- train velocity
- position of the axle in the vehicle (in front or at the rear)
- mass supported by the vehicle

Parameters for classification into elementary situations of life

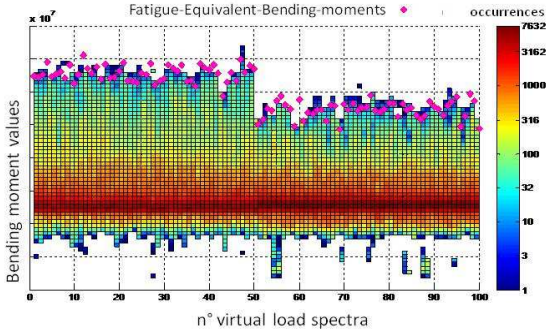




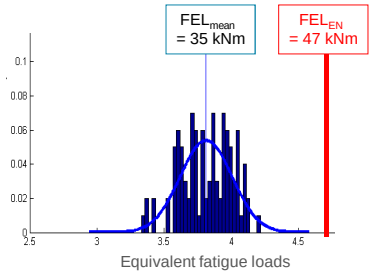
Example of the mass distribution



3. Usage variability : Generation of virtual load spectra and calculation of FELs



Axle lifetime : 7. 10^6 km
Damage rule : Konsequent Miner rule



FEL_{mean} = 35 kNm
$M_{x,EN13103}$ = 47 kNm
→ $\mathcal{S}(M_{x,EN13103}) = 1{,}5.10^{-3}$

Specific activities led by SNCF

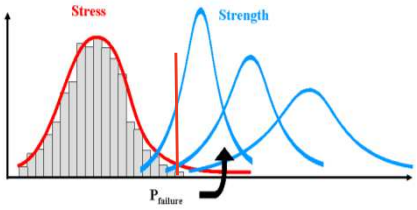
1. Load analysis
2. Reliability assessment

Reliability assessments

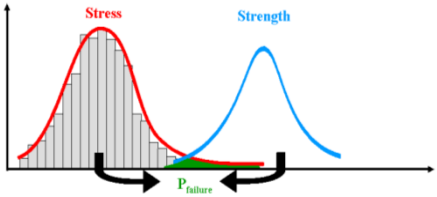
A. The Stress Strength Interference Analysis method

B. Application to an SNCF passenger coach axle

A. The Stress Strength Interference Analysis method for reliability assessment



SSIA for specification



SSIA for validation

Load analysis :

- classification into elementary situations of life of the measured loads
- generation of various new load spectra
- transformation into a cyclic equivalent load
- Defination of a simple cyclic design load (standard load) : the designer doesn't have to handle the variable amplitude load issue

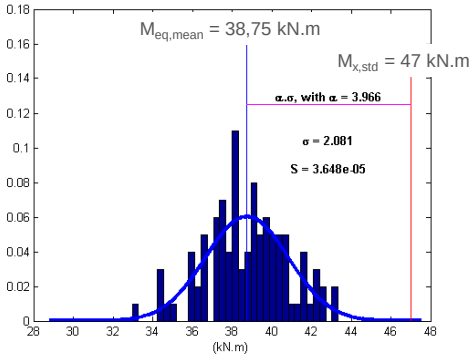
Fatigue limits characterization

Probability of failure calculation

B. Application to a passenger coach axle

Load distribution

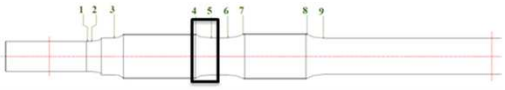
Final set of parameters for A1N (feb. 2014) :
k= 18.8 ; D = 0,5 ; Ne = 2.2e6 and Kref = 7e6 kms



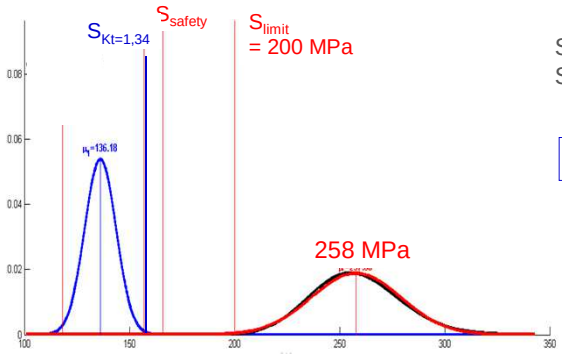
The coefficient of variation of the load severity distribution that is found is CV = 5,4%.

$M_{x,std}$ = 47 kN.m
Prob(Meq>Mxstd) = 3,6e-5

Probability of failure of the studied axle



Kt=1.34 (calculated with FEA)



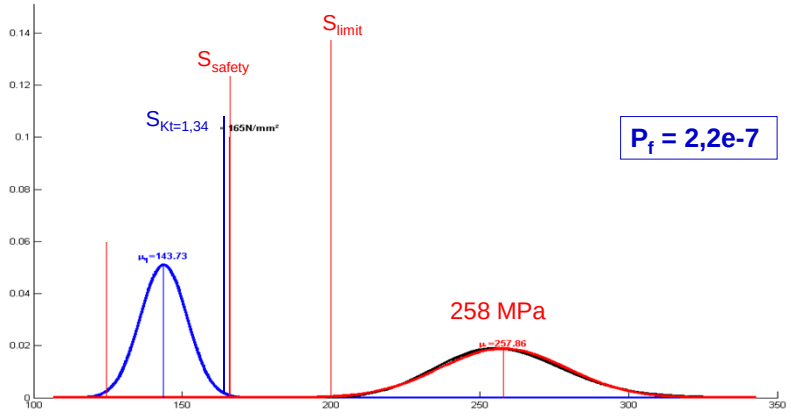
$S_{Kt=1,34}$=157 MPa
S_{safety} =166 MPa

P_f = 3,02e-8

$$P_f \in [8.8e-12 ; 1e-5]$$

depending on the parameters that are taken for the calculations

Probability of failure of an axle at the limit of the standard requirements



P_f = 2,2e-7

Conclusions

Load analysis

- Database of in-service loads
- Recommendations for future :
  - Additional load measurements are necessary
  - Multi-body simulations can complement the data
- Method to analyze a variable load from measurements
  - Agreement on the method to calculate a cyclic fatigue-equivalent load
    Konsequent Miner Rule or Haibach rule, parameters to be carefully identified (A1N and A4T
  - Proposal for classification into elementary situations of life
  - Proposal for generation of new load spectra taking account of the variability of axle usages
  - Application to real load spectra and comparison to standard loads
- Recommendations for future :
  - Information from track geometry/operation conditions is a key-point

Reliability assessments

- Stress Strength Interference Analysis method is used to estimate the probability of failure and measure the severity of the standard load
- Applications to real axles give realistic probabilities of failure
- Sensitivity to parameters
  - Agreement on the material parameters for A1N and A4T
  - Importance of the distribution of the fatigue limits (mean value but also scatter)
  - Load distribution coefficient of variation in the range of usual values

  Future work :
  - Applications to other axles (with available load data) : are the standard loads and the probabilities of failure almost the same for all existing axles ?

Thank you for your attention