Course on
High Speed Trains

Dynamic Response of Bridges for High Speed Trains

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1. Motivation

- Dynamic nature of railway loads

- High speed trains: TGV, AVE, ... Design speeds of 350 km/h

- New Spanish code for loads for design of railway bridges; International research: UIC, ERRI

- Study of resonant effects in real bridges in service.

- Dynamic factor? $\rightarrow$ Dynamic analysis!

2. Dynamic factor Φ

- Magnifies the effects of static loads:

$$\mathcal{S}_{\text{din}} \leq \Phi \mathcal{S}_{\text{sta}}$$

- Takes into account (as an envelope) the dynamic nature of the loads and vibration effects in the structure;

- Does not take into account **resonance effects**;

- Applies only for speeds $v \leq [220]$ km/h (cfr. EC-1 part. 3)

2. Dynamic factor Φ (cont.)

♠ Section resultants proportional to displacements (δ)

$$\Phi \cdot \delta_{\text{sta,lm}} \geq \delta_{\text{din,real}}$$

where,

$\delta_{\text{din,real}}$ maximum dynamic deflection under the real trains crossing the bridge within project's velocities range ($0 - v$ km/h);

$\delta_{\text{sta,lm}}$ maximum static deflection under the selected static model.

3. Mechanical models

- Travelling load models (TLM);

- Vehicle-bridge interaction models (VBIM);

  - Detailed interaction model (DIM)

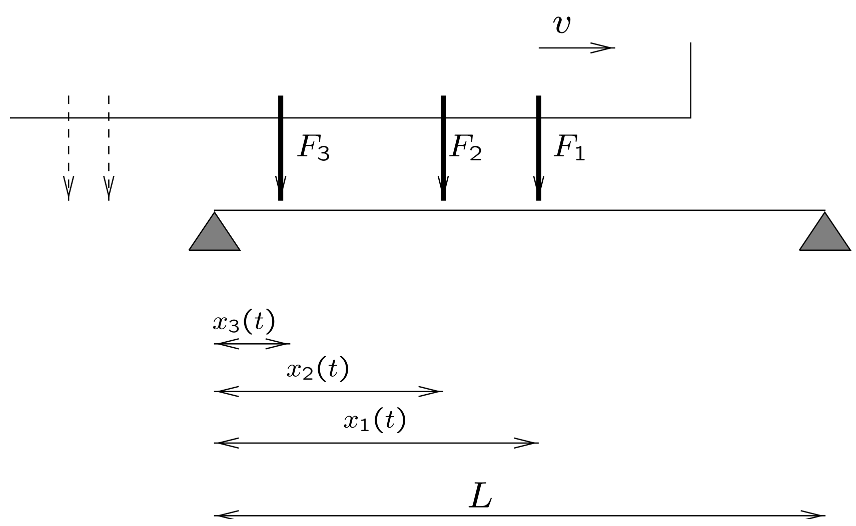
  - Simplified interaction model (SIM)

- Track-deck interaction models;

- Other models: ballast mast, soil interaction...

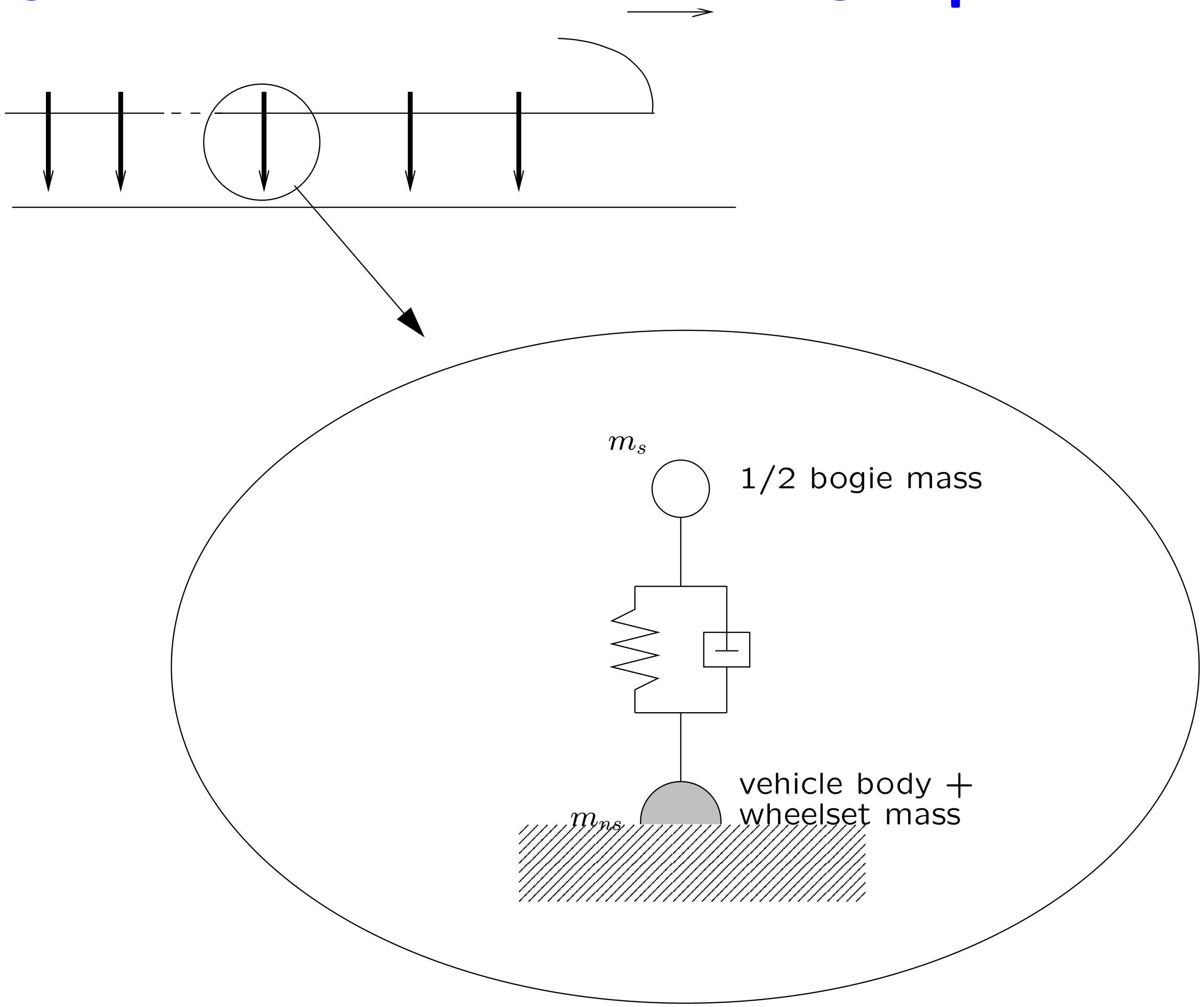
3. Mechanical models.

Travelling loads (TLM)



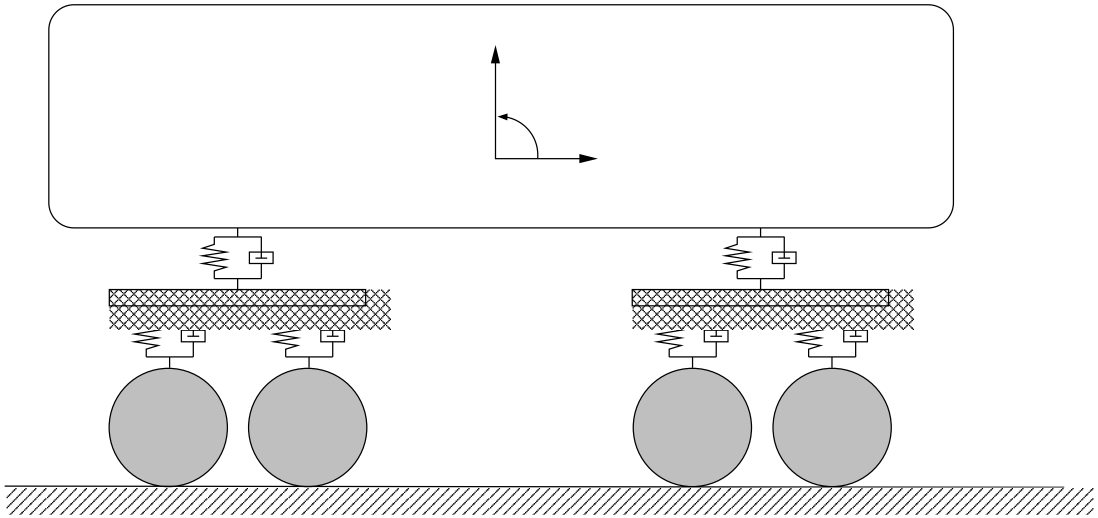
- F_1, $F_2 \ldots F_i$, constant loads.

3. Mechanical models. Simplified interaction model



3. Mechanical models.

Detailed interaction model (DIM)



4. Resonance

- Due to the passage of successive axles with aproximately uniform spacing d$_k$;

- Resonance occurs when the frequency of excitation (or a multiple of it) matches a natural frecuency of the structure;

- resonance occurs when loading and natural oscillation couple:

$$n_0 = \frac{v}{d_k} i$$

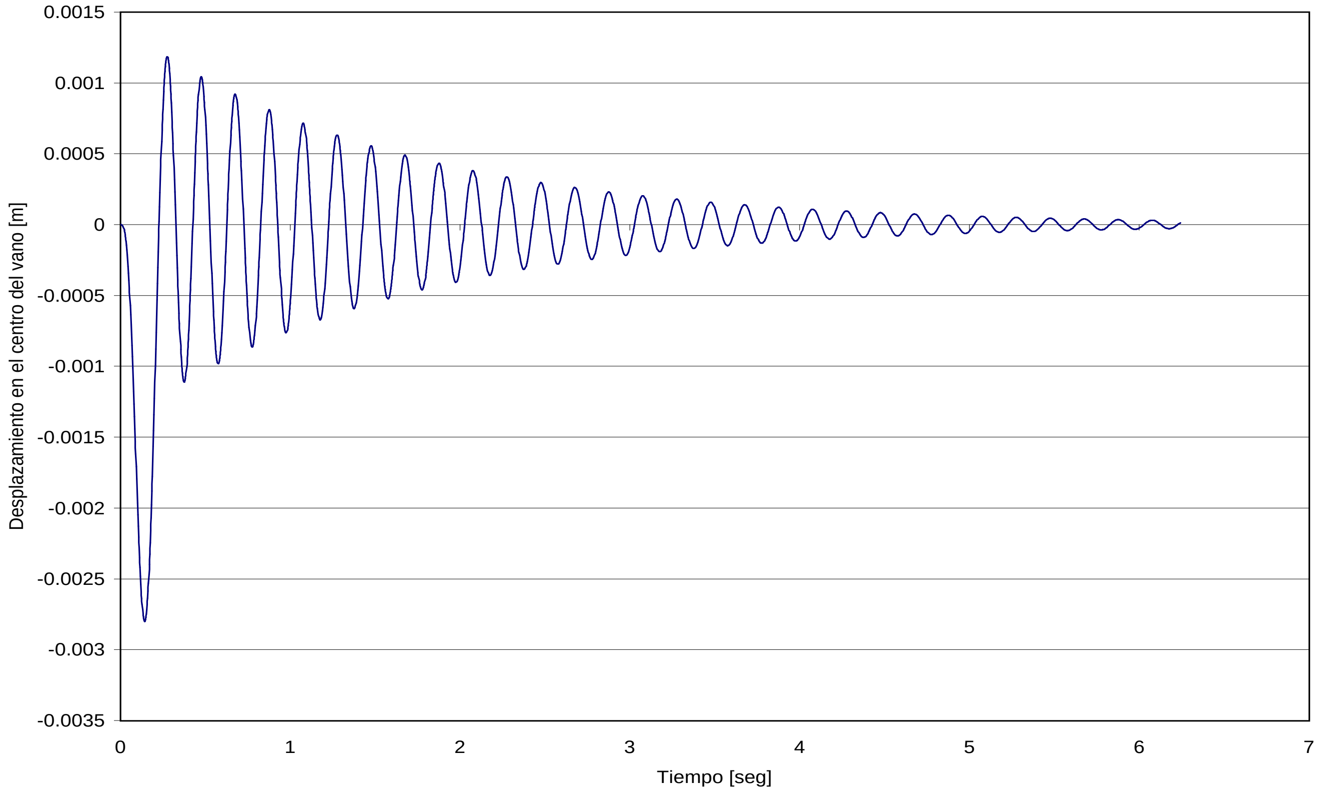
where n_0: natural frequency of the bridge (Hz); v: velocity of travelling loads

4. Resonance.

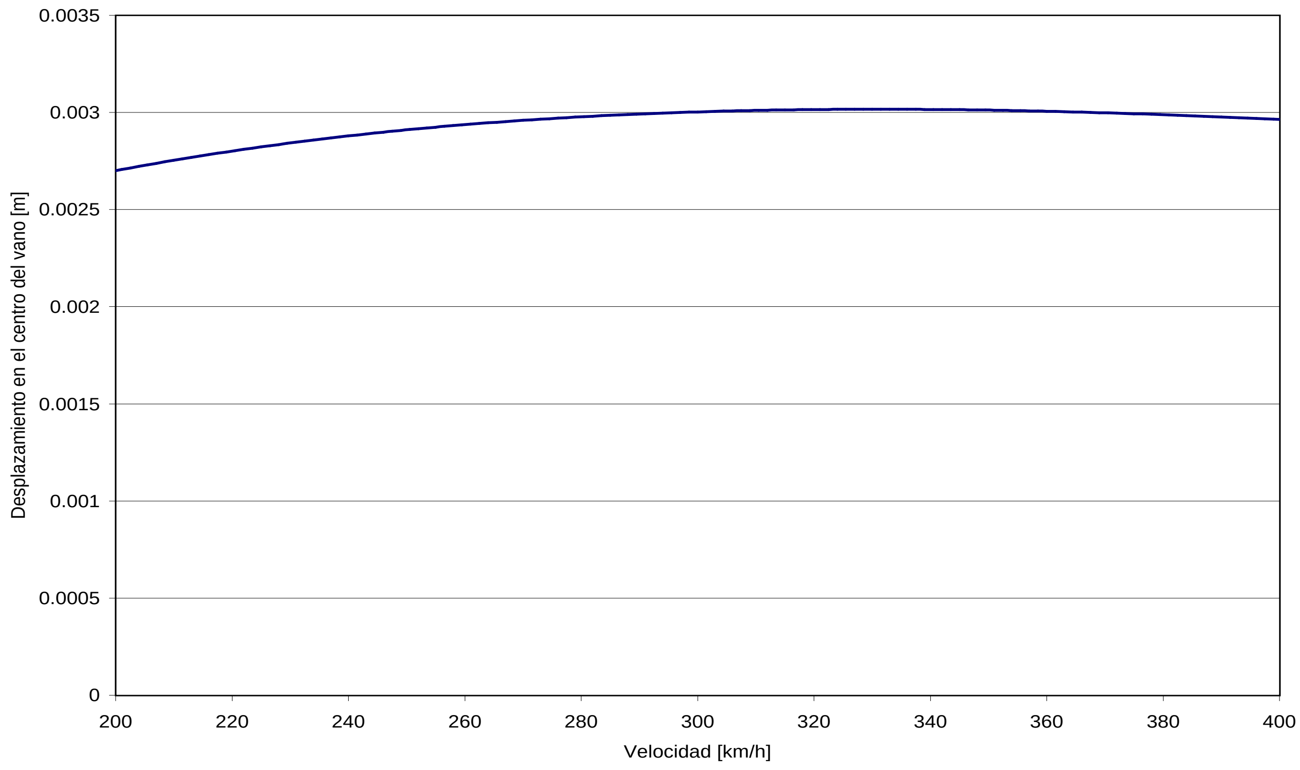
Response of a bridge to an isolated load at speed v

- 15 m span simply supported beam;
- F= 195 kN (ICE2 power car/ axle load);
- Damping ratio $\zeta = 2\%$;
- Speed (200 − 400) km/h

4. Resonance. Response of a bridge to an isolated load at 220 km/h. Midspan deflection in time



4. Resonance. Response of a bridge to an isolated load at speed v. Maximum vertical deflection



4. Resonance.

♠ Response of a bridge to a travelling load: Dynamic factor Φ

- Static deflection :

$$\delta_{\text{sta,lm}} = u(L/2) = \frac{PL^3}{48EI} = 1.78 \text{ mm}$$

- Maximum vertical deflection

$$\delta_{\text{din,real}} = 3.02 \text{ mm}[v \in (200, 400)\text{km/h}]$$

- Dynamic Factor: $\dfrac{\delta_{\text{din,real}}}{\delta_{\text{sta,lm}}} = \mathbf{1.69}$

4. Resonance.

Response of a bridge to a series of loads moving at a uniform speed v

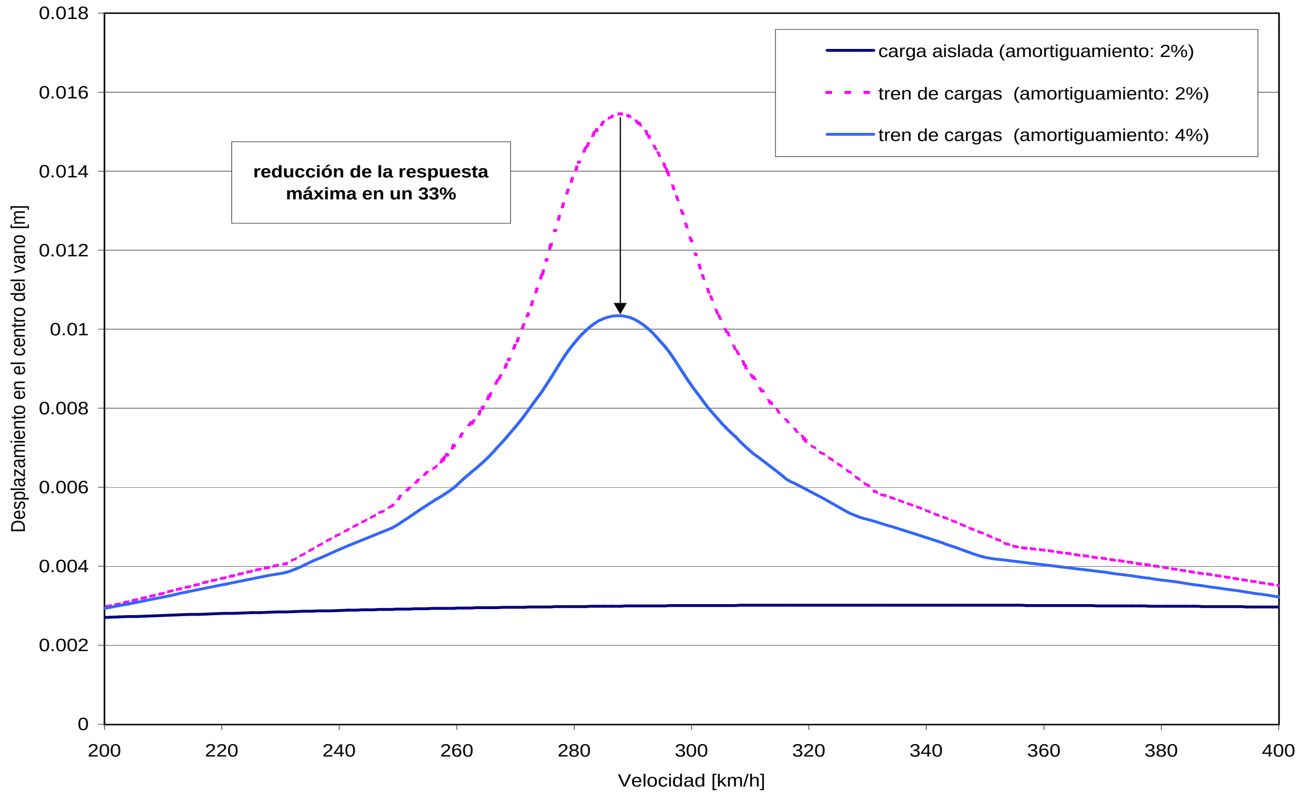
- 15 m span simply supported beam;

- *Fictitious train*: 10 loads of 195 kN (ICE2 power car/ axle load), uniformly spaced (16 m);

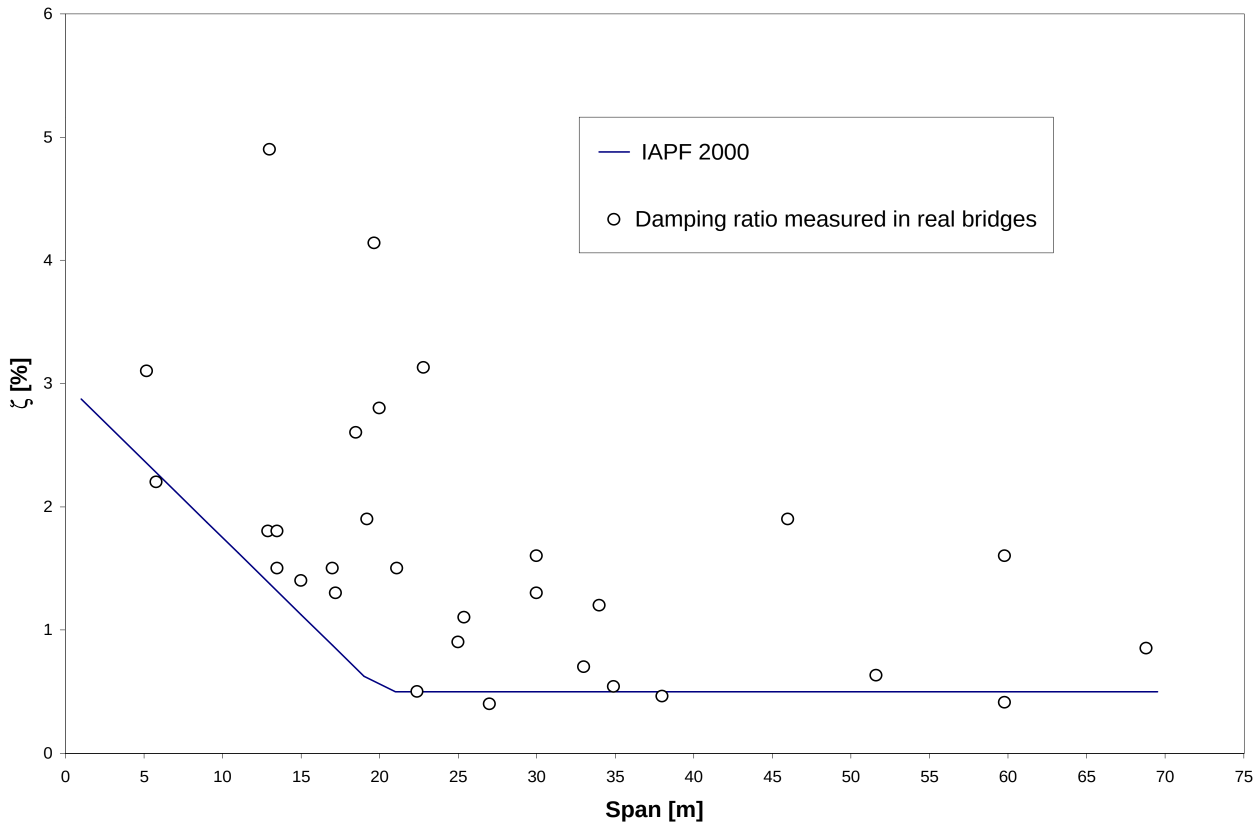
- Damping ratio $\zeta = 2\%$;

- Speed $(200, 400)$ km/h

4. Resonance. Response of a bridge to a fictitious train at speed v. Maximum vertical deflection



4. Resonance. Measured damping in steel bridges



4. Resonance. Response of a bridge to a train: Dynamic factor Φ

- Static deflection :

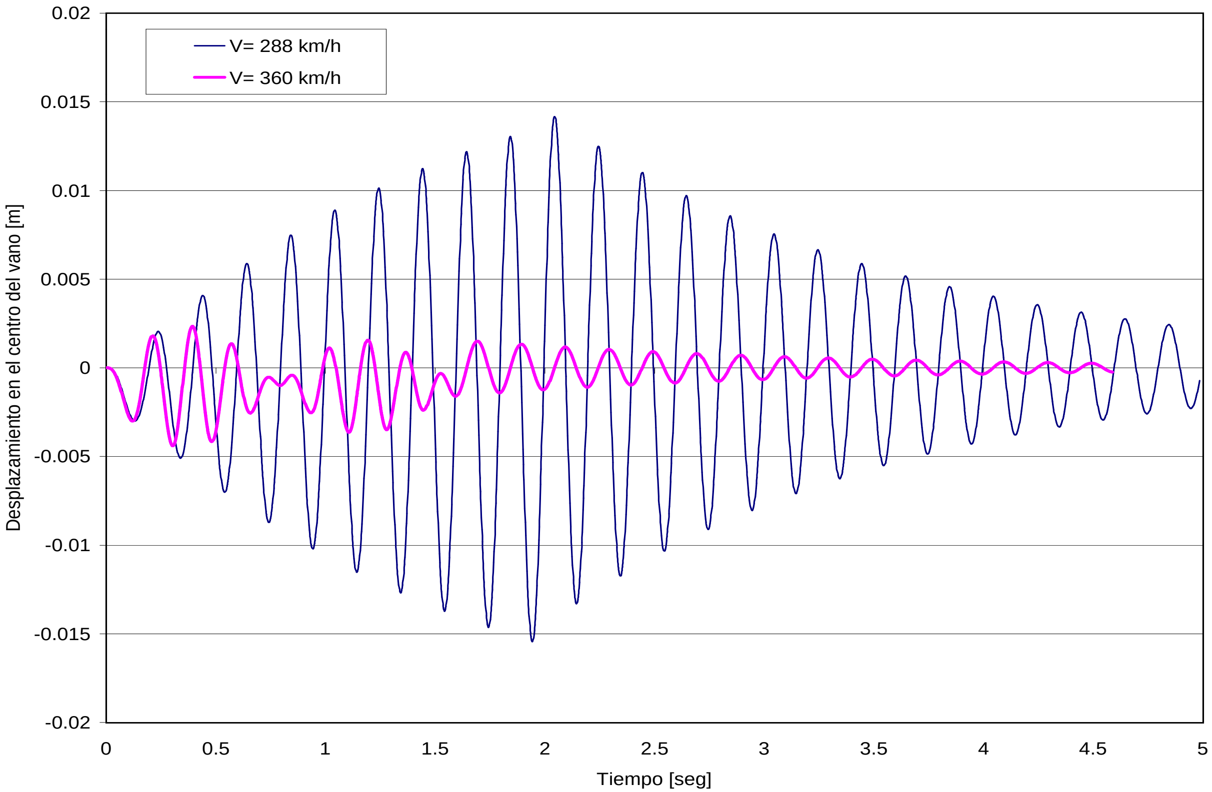
$$\delta_{\text{sta,lm}} = u(L/2) = \frac{PL^3}{48EI} = 1.78 \text{ mm}$$

- Maximum vertical deflection : $\delta_{\text{din,real}} = 14.44$ mm

$$[v \in (200, 400) \text{ km/h}]$$

- Dynamic Factor: $\dfrac{\delta_{\text{din,real}}}{\delta_{\text{sta,lm}}} = \mathbf{8.67}$

4. Resonance. Response of a bridge to a train at 288 km/h and 360 km/h. Deflection vs. time



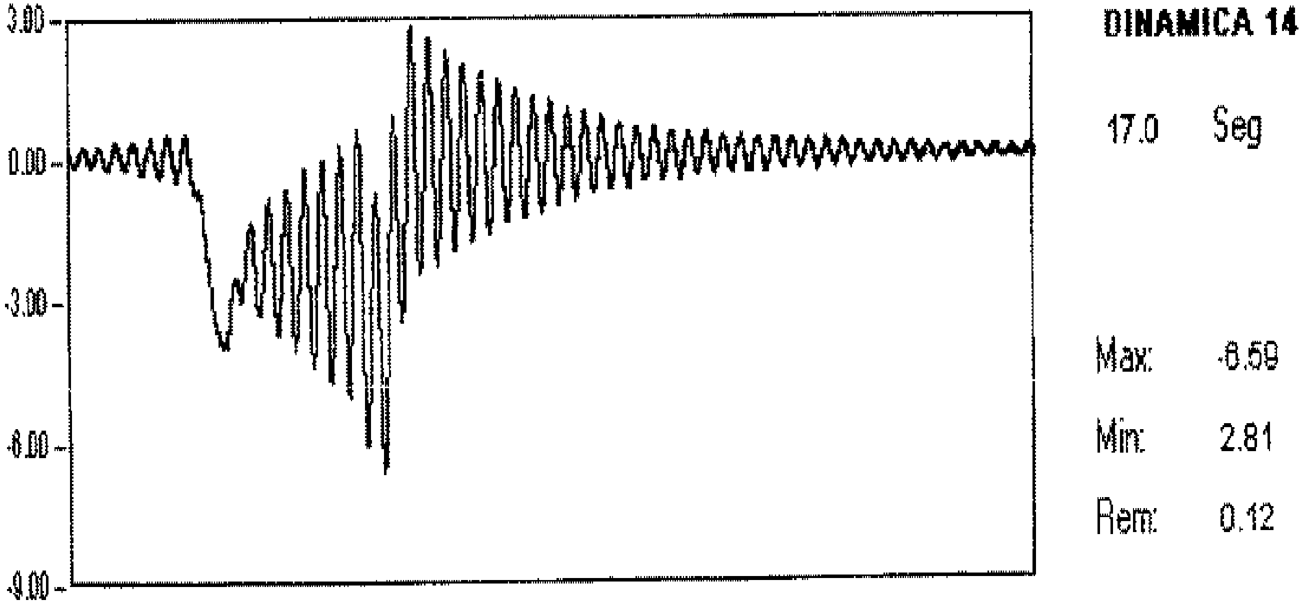
4. Resonance.

Predicted and measured behaviour in real bridges

- Tajo Viaduct;
- AVE train at 216 km/h;
- Madrid-Sevilla high speed railway line;
- Simply supported beam.

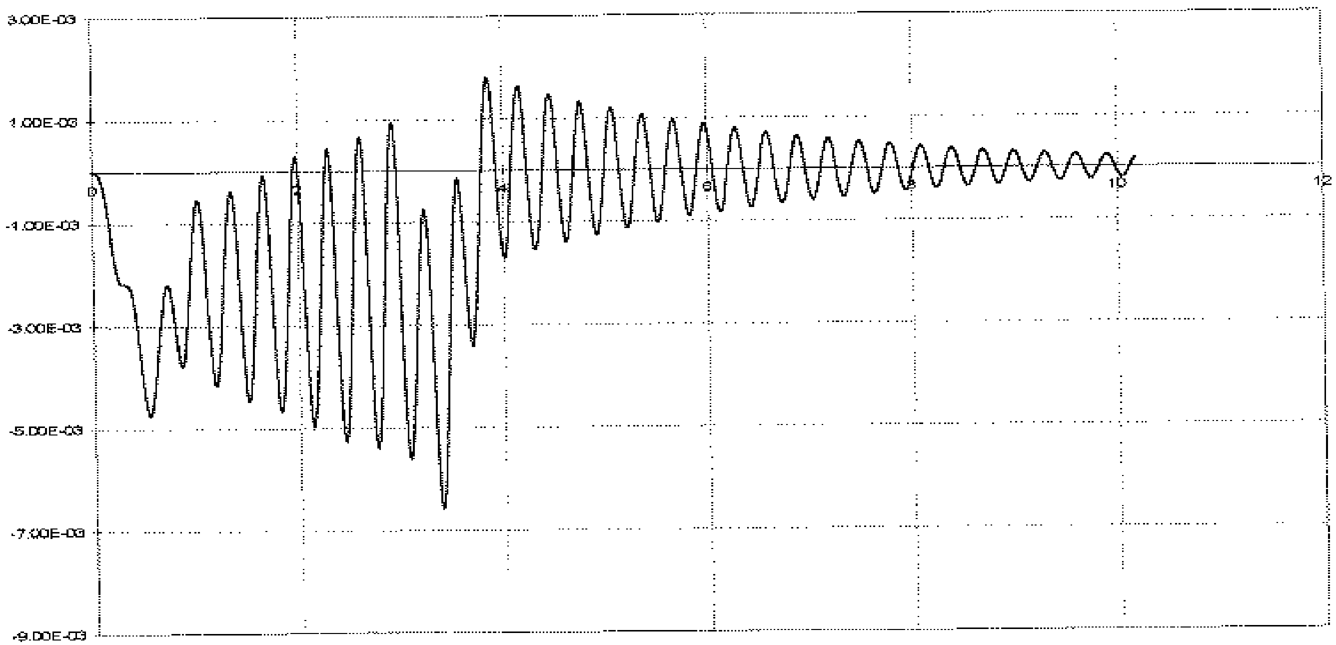
4. Resonance. Tajo Viaduct

Measured



4. Resonance. Tajo Viaduct

Predicted



5. Analysis models

- Dynamic factor + static analysis (velocities up to 220 km/h);
- Travelling loads + dynamic modal analysis;
- Finite element calculations;
- Dynamic analysis with vehicle-bridge interaction models;
- Simplified methods: LIR, DER, etc.

Simplified methods based upon the Train Signature

- AVLS
  Excitation Transform and Response Analysis Methodology and corresponding Train Signature;

- RIL
  Residual influence line;

- IDP
  Proportional train signature

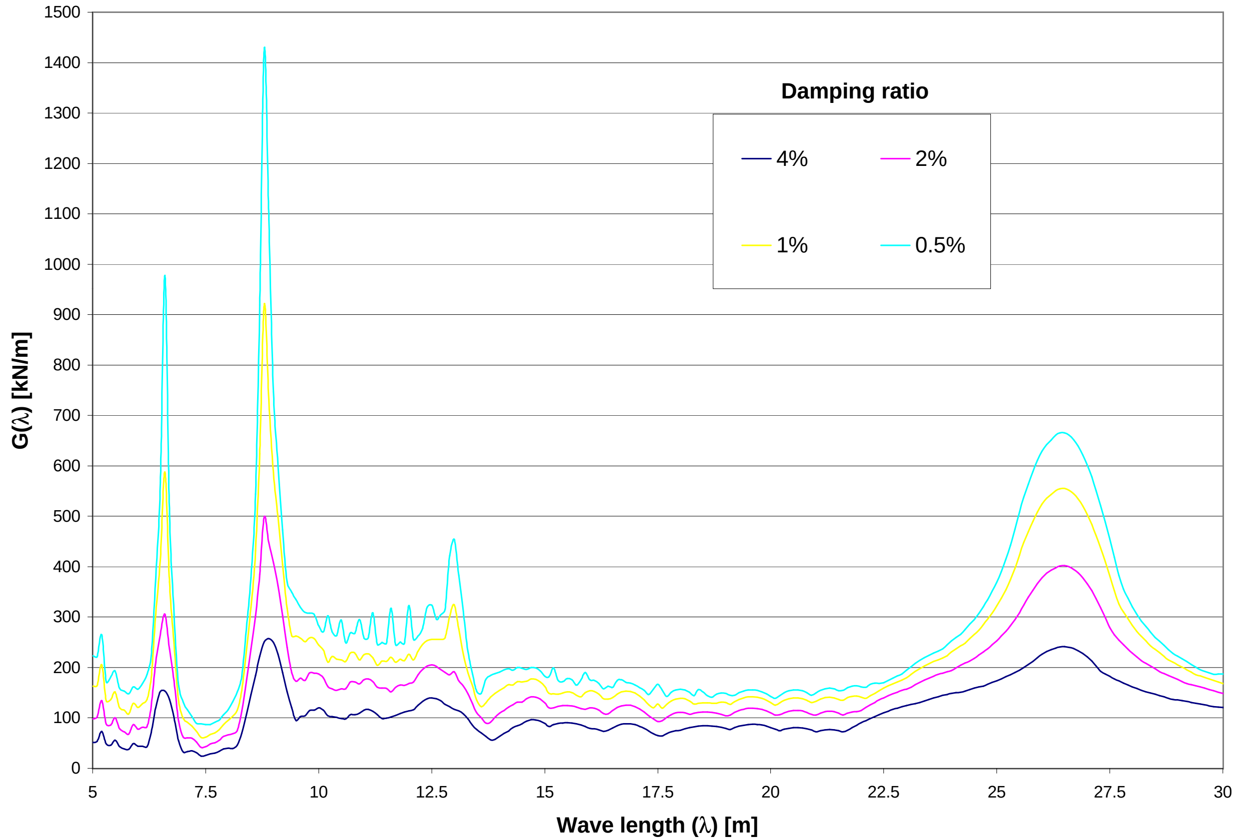
Acceleration calculation

Can be formulated as products of 3 terms:

$$\Gamma = C_t \cdot A(L/\lambda) \cdot G(\lambda)$$

- C_t: Constant term
- $A(L/\lambda)$ Influence line $\rightarrow$ Bridge.
- $G(\lambda)$ Signature $\rightarrow$ Train.
- $\lambda = v/f_0$, Wave length.

Signature of ICE2 train



AVLS method

$$C_t = \frac{4}{m\pi}$$

$$A(L/\lambda) = \left| \frac{\cos(\pi L/\lambda)}{(2L/\lambda)^2 - 1} \right|$$

$$G(\lambda) = \max_{i=0 \ldots N-1} \frac{1}{\zeta X_i} \sqrt{\left[\sum_{k=0}^{i} P_k \cos\left(\frac{2\pi x_k}{\lambda}\right)\right]^2 + \left[\sum_{k=0}^{i} P_k \sin\left(\frac{2\pi x_k}{\lambda}\right)\right]^2} (1 - e^{-2\pi\zeta\frac{X_i}{\lambda}})$$

LIR method

$$C_t = \frac{2}{mL}$$

$$A = \frac{K}{1 - K^2}\sqrt{\mathrm{e}^{-2\zeta\frac{\pi}{K}} + 1 + 2\cos\left(\frac{\pi}{K}\right)\mathrm{e}^{-\zeta\frac{\pi}{K}}}$$

$$G(\lambda) = \max_{x_{ref}=x_1}^{x_{ref}=x_n} \sqrt{\left[\sum_{x_i}^{x_{ref}} P_x \cos\left(2\pi\frac{x_i - x_{ref}}{\lambda}\right)\mathrm{e}^{-2\pi\zeta\frac{x_i - x_{ref}}{\lambda}}\right]^2 + \left[\sum_{x_i}^{x_{ref}} P_x \sin\left(2\pi\frac{x_i - x_{ref}}{\lambda}\right)\mathrm{e}^{-2\pi\zeta\frac{x_i - x_{ref}}{\lambda}}\right]^2}$$

Where $K = \frac{\lambda}{2L}$

Interoperability (I)

- Future: most of the high speed trains will run on international lines in different countries;
- Need to specify minimum conditions in bridge and train design that allow a safety operation.
  - New bridges: induced service loads and accelerations caused by existing trains do not exceed the limits;
  - New trains must be designed so that the induced loads and accelerations of existing bridges does not exceed the limits.
- Train signature envelope (ICE2, VIRGIN, TALGO AV and EUROSTAR) is used for checking the second criterium;

Interoperability (II)

- Other specifications of interoperability:
  - The length of the train should not be higher than 400 m;
  - Static load per wheelset
    $P_0 \leq 17$ t/wheelset if $V > 260$ km/h
  - Classical trains are covered by articulated trains if it is verified that

    $$4 \cdot P' \cos(\pi \cdot \mathrm{d}/L) < 2 \cdot P$$

    where P' is the highest axle load for the classical train and P the highest axle load for the articulated train.

6. Codes and Regulations

- Eurocode EC-1 3rd part, chapter 6;
- Italian code;
- Spanish code IAPF;
- UIC code 776-1 & 776-2; ERRI Comitee D214 tecnichal reports;
- European regulations for interoperability.