Reliability assessment of uncertain railway bridges crossed by high-speed trains

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Assessment of bridges for high-speed trains

- Static bridge assessment not sufficient
- Resonance effects
- Exceedance of acceleration limits
  - ✓ Instability of ballast
  - ✓ Train derailment

Resonance of the bridge

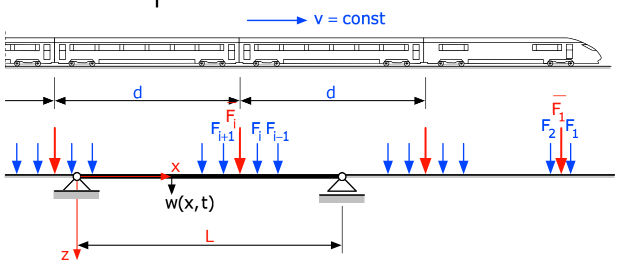
Bridge resonance at critical speeds

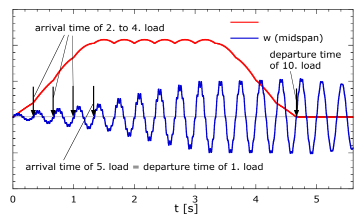
Critical speeds of first order

✓ Rhythmic repetition of moving forces with constant distance d

$$v^{i}_{1,n} = \frac{f_n\, d}{i} \qquad n, i = 1, 2, 3, \ldots$$

f_n ….. n-th natural bridge frequency





Critical speeds of third order

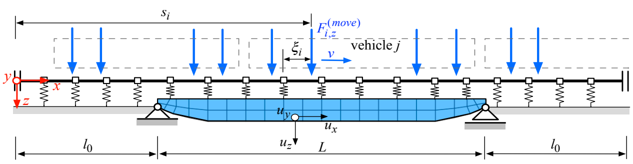
✓ Sway forces of the train induced by track irregularities and wheel hunting moments

Outline

- ✓ Modeling of bridge-train interaction
- ✓ Identification and modeling of uncertainties
- ✓ Limit state based on maximum acceleration response
- ✓ Case study object

Mechanical modeling - substructure technique

Bridge subsystem: 3D finite element model



Equations of motion in nodal coordinates

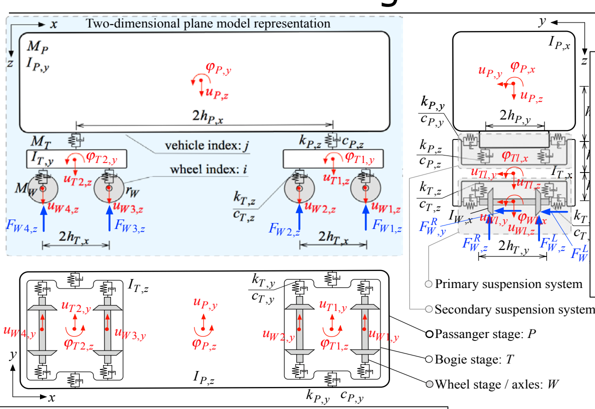
$$\boldsymbol{M}_G \ddot{\boldsymbol{d}}(t) + \boldsymbol{K}_G \boldsymbol{d}(t) = \boldsymbol{f}_G(t) \qquad \boldsymbol{u}(x,y,z,t) = \boldsymbol{N}^e \boldsymbol{d}(t)$$

$$\boldsymbol{f}_G(t) = \sum_i^{N_W} \left(\boldsymbol{N}^{e,L,\mathrm{T}}(\xi_i(t)) \boldsymbol{f}_i^{(move,L)} + \boldsymbol{N}^{e,R,\mathrm{T}}(\xi_i(t)) \boldsymbol{f}_i^{(move,R)} \right) \chi_i(t)$$

Modal decomposition

$$\boldsymbol{d}(t) = \sum_{n=1}^{N \le M} \boldsymbol{\phi}_n q_n(t) = \boldsymbol{\Phi} \boldsymbol{q}(t)$$

Mechanical modeling - substructure technique



- ✓ Train composed of independent vehicles
- ✓ Vehicle composed of rigid bodies, linear springs and dashpots
- ✓ Passenger stage: 5 DOF
- ✓ Bogie stage: 5 DOF
- ✓ Wheel axle: 3 DOF
- ✓ Longitudinal movement neglected

Train subsystem
composed of N_V vehicles

$$\boldsymbol{M}_V \ddot{\boldsymbol{u}}_V(t) + \boldsymbol{C}_V \dot{\boldsymbol{u}}_V(t) + \boldsymbol{K}_V \boldsymbol{u}_V(t) = \boldsymbol{f}_V(t)$$

$$\boldsymbol{M}_V = \mathrm{diag}[\boldsymbol{M}_{V,1}, \ldots, \boldsymbol{M}_{V,j}, \ldots, \boldsymbol{M}_{V,N_V}]$$
$$\boldsymbol{C}_V = \mathrm{diag}[\boldsymbol{C}_{V,1}, \ldots, \boldsymbol{C}_{V,j}, \ldots, \boldsymbol{C}_{V,N_V}]$$
$$\boldsymbol{K}_V = \mathrm{diag}[\boldsymbol{K}_{V,1}, \ldots, \boldsymbol{K}_{V,j}, \ldots, \boldsymbol{K}_{V,N_V}]$$
$$\boldsymbol{u}_V = \{\boldsymbol{u}_{V,1}, \ldots, \boldsymbol{u}_{V,j}, \ldots, \boldsymbol{u}_{V,N_V}\}^{\mathrm{T}}$$

Mechanical modeling - substructure technique

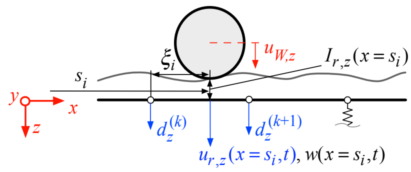
Vertical interaction: Corresponding assumption

- ✓ Displacements of wheels and rails are equal

$$u_{W,z}^{R,L}(s_i(t)) = u_{r,z}^{R,L}(s_i(t)) + I_{r,z}^{R,L}(s_i(t))$$

- ✓ Contact forces are equal

$$F_z^{(move)L,R} - F_{W,z}^{L,R} = 0$$

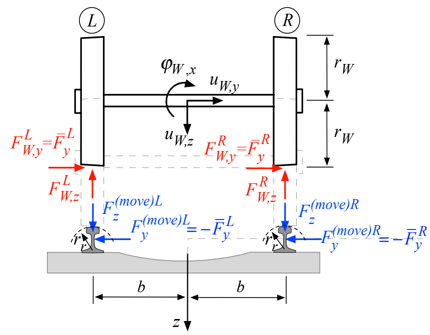


Horizontal interaction: Kalker creep theory

- ✓ No flange contact
- ✓ Cylindrical wheels and rails
- ✓ No moment due to yawing movement
- ✓ Forces in the center of gravity

$$\bar{F}_y^{L,R} = -\bar{f}_{22}\zeta_y^{L,R}$$

$$\zeta_y^{L,R} = \frac{\Delta \dot{u}_{W,y}^{L,R}}{v} = \frac{1}{v}\left(\dot{u}_{W,y} - \dot{u}_{r,y}^{L,R} - \dot{I}_{r,y}^{L,R}\right)$$



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Uncertainties in the model

Load model
- ✓ Operating trains
- ✓ Vehicle parameters
- ✓ Speed
- ✓ Rail irregularities

Structural model
- ✓ Damping
- ✓ Material parameters
- ✓ Construction
- ✓ Ballast (model, stiffness)

Environmental impact
- ✓ Temperature
- ✓ Humidity
- ✓ Sediments
- ✓ Deterioration

Rail irregularities

Three modes of random rail irregularities

- Vertical direction
  - ✓ Vertical settlement of rails and sleepers (z1)
  - ✓ Tilting of rails and sleepers (z2)
- Horizontal direction
  - ✓ Misalignment of rails and sleepers (y)

Profile functions: stochastic superposition of J harmonic functions (Claus & Schiehlen 1998)

$$I_{r,k}(x) = \sqrt{2}\sum_{m=1}^{J} \underline{A_{k,m}} \cos(\Omega_m x + \epsilon_{k,m}), \;\; k = \{y, z1, z2\}$$

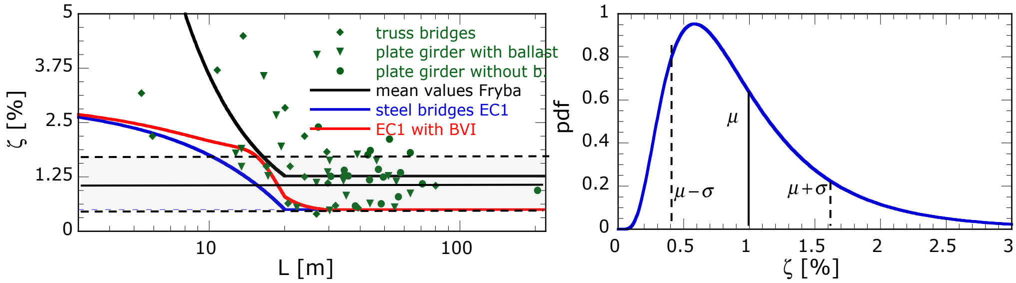
Random variables (uniformly distributed)

Power spectral density functions

$$\underline{A_{k,m}} = \sqrt{\left(\frac{S_k(\Omega_m)}{\pi} + \frac{S_k(0)a}{6\pi}\right)\Delta\Omega} \qquad S_n(\Omega_m) = Q\frac{\Omega_c^2}{(\Omega_r^2 + \Omega_m^2)(\Omega_c^2 + \Omega_m^2)}, \;\; n = \{y, z1\}$$

Uncertain structural damping

- ✓ High influence on maximum response in resonance state
- ✓ Various sources of energy dissipation
- ✓ Modally added viscous damping: $\zeta_n = \zeta$

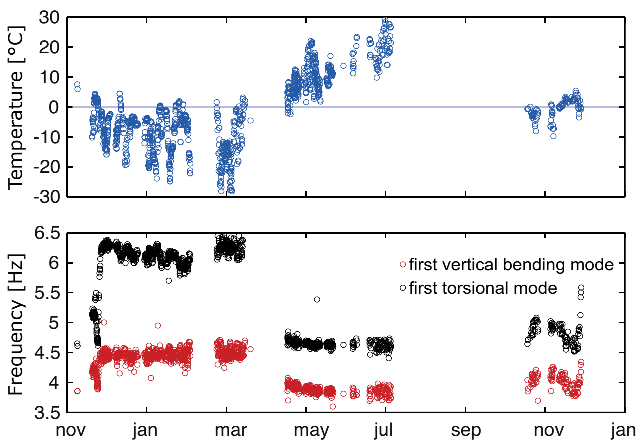


- ✓ Modeling as random truncated log-normally distributed variable

$\mu = 1.00 \quad \sigma = 0.66$

Environmental impact

Environmental temperature and natural frequencies of a ballasted railway bridge (Sweden)

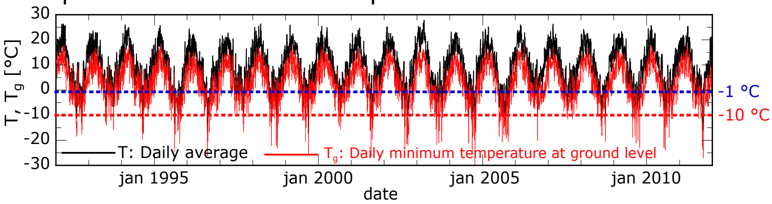


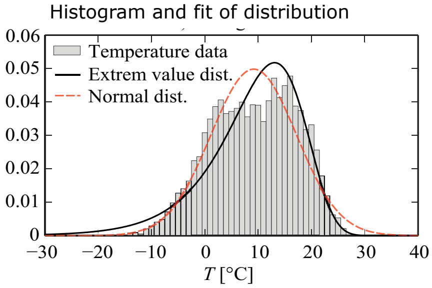
Gonzales et al. (2013)

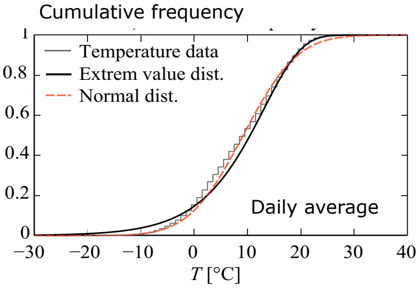
Frequency shift not directly related to surrounding temperature but to the frost depth of ballast and subsoil

Model to capture environmental impact

Temperature data: Munich airport Jan. 1992 – Jan 2012

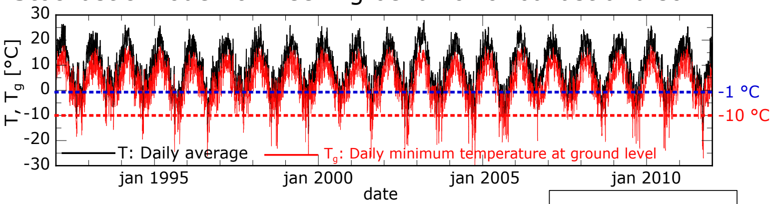






Model to capture environmental impact

Stochastic model for freezing behavior of ballast and soil

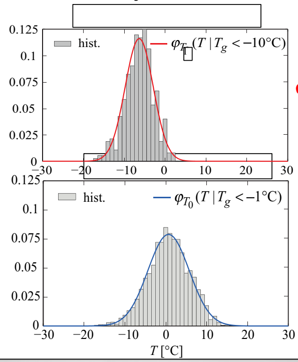


Fully frozen state (variable T_1)

- ✓ Ballast has stiffness of ice
- ✓ Temperature above ground $T_g < -10°C$

Unfrozen state (variable T_0)

- ✓ Unmodified ballast stiffness
- ✓ Temperature above ground $T_g \geq -1°C$



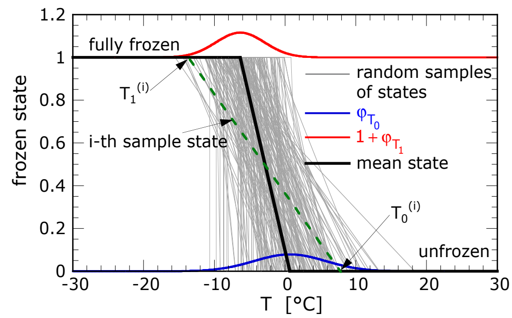
$\varphi_{T_1}(T \mid T_g < -10°C)$

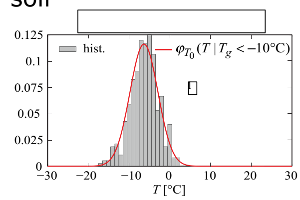
$\varphi_{T_0}(T \mid T_g < -1°C)$

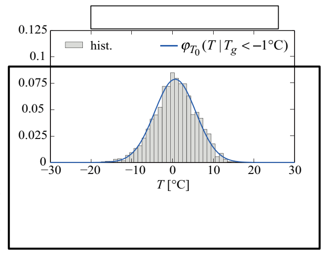
Model to capture environmental impact

Stochastic model for freezing behavior of ballast and soil

based on temperature data from Munich airport Jan. 1992 – Jan 2012







Variable	Distribution	Unit	Mean	CV
Temperature	Extreme value	°C	9.00	1.01
Young's modulus of frozen ballast	Gaussian	GPa	9.45	0.05
Fully frozen state temperature $T_1(T)$	Gaussian	°C	-6.33	0.54
Unfrozen state temperature $T_0(T)$	Gaussian	°C	0.69	7.38

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Failure definition

Assumption: Limit state related to bridge acceleration (ballast instability, derailment)

➡ Limit state function:

$$g(\mathbf{X}) = a_{z,bt/ct}^{(rel)} - \max(\ddot{w}(\mathbf{X}, v < v_0))$$

Ballast instability: $a_{z,bt}^{(code)} = 0.35g$ ➡ include safety factor of 2 ➡ $a_{z,bt}^{(rel)} = 0.7g$

Derailment: $a_{z,ct}^{(code)} = 0.50g$ ➡ $a_{z,ct}^{(rel)} = 1.0g$

Probability of failure

$$p_f = P(\text{failure}) = P(Z < 0) \qquad Z = g(X_1, X_2, \ldots, X_n)$$

Probabilities of failure according to Eurocode 0

- ✓ Serviceability limit state (SLS): $p_f = 10^{-3}$
- ✓ Fatigue limit state (FLS): $p_f = 10^{-4}$
- ✓ Ultimate limit state (ULS): $p_f = 10^{-6}$

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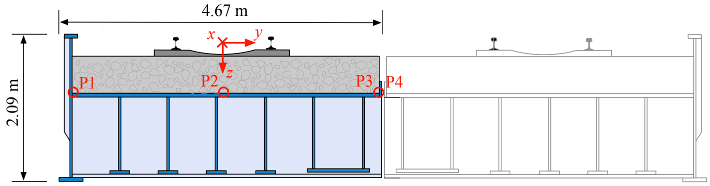
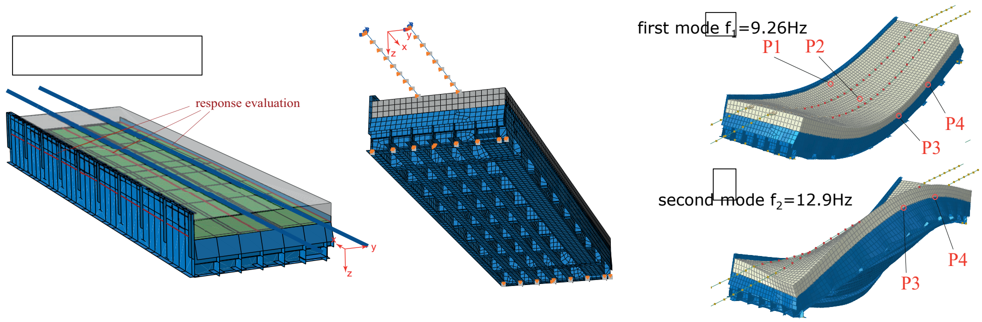
Case study problem

Reliability analysis of a single-span ballasted steel bridge crossed by Railjet train

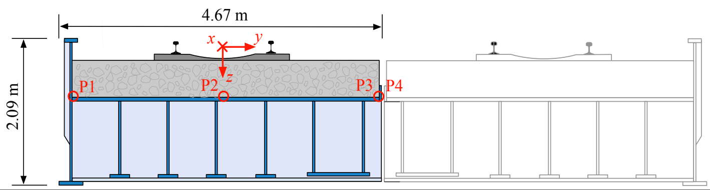
Span 16.8 m





Case study problem

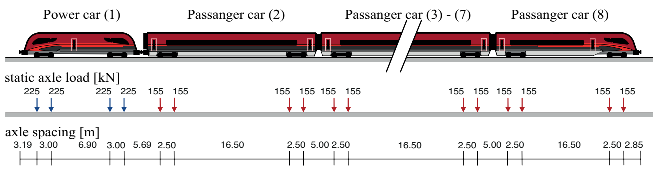
Uncertainties of structural model



Variable	Distribution	Unit	Mean (Gaussian dist.) / Min. (Uniform dist.)	CV (Gaussian dist.) / Max. (Uniform dist.)
Steel Young's modulus	Gaussian	GPa	210	0.03
Steel Poision's ratio	Gaussian	-	0.3	0.03
Steel density	Nominal value	kg/m^3	7850	-
Ballast Young's modulus	Gaussian	GPa	0.177	0.05
Ballast Poision's ratio	Gaussian	-	0.24	0.05
Ballast density	Uniform	kg/m^3	1900	2000
Ballast height	Uniform	m	0.55	0.65
Ballast/soil stiffness factor	Gaussian	-	1.0	0.05
Railpad stiffness	Uniform	MN/m	0.1	0.6
Sleeper mass	Uniform	kg	220	325
Girder dimensions	Gaussian	-	1.0	0.01 - 0.03
Structural damping	Truncated lognormal	%	see Figure 6.2	0.3 stdv.

Case study problem

Excitation uncertainties (train and rail irregularities)

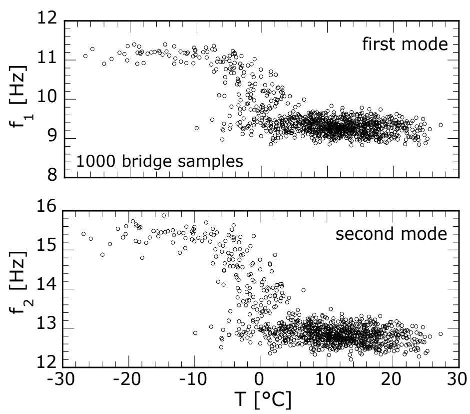


Variable	Distribution	Unit	Mean (Gaussian dist.) / Min. (Uniform dist.)	CV (Gaussian dist.) / Max. (Uniform dist.)
Occupancy factor	Uniform	-	0.0	1.0
Power car passenger stage mass factor	Gaussian	-	1.0	0.01
Power car passenger stage MMoI factor	Gaussian	-	1.0	0.01
Bogie mass factor	Gaussian	-	1.0	0.01
Bogie MMOI factor	Gaussian	-	1.0	0.01
Wheel mass factor	Gaussian	-	1.0	0.01
Wheel MMOI factor	Gaussian	-	1.0	0.01
Primary suspension stiffness factor	Gaussian	-	1.0	0.1
Primary suspension damping factor	Gaussian	-	1.0	0.1
Secondary suspension stiffness factor	Gaussian	-	1.0	0.1
Secondary suspension damping factor	Gaussian	-	1.0	0.1
Irregularity PSD amplitude Q	Uniform	10^{-6} rad m	0.592	1.009
Irregularity frequency content	Discrete uniform	rad/m	0.001	15

Case study problem

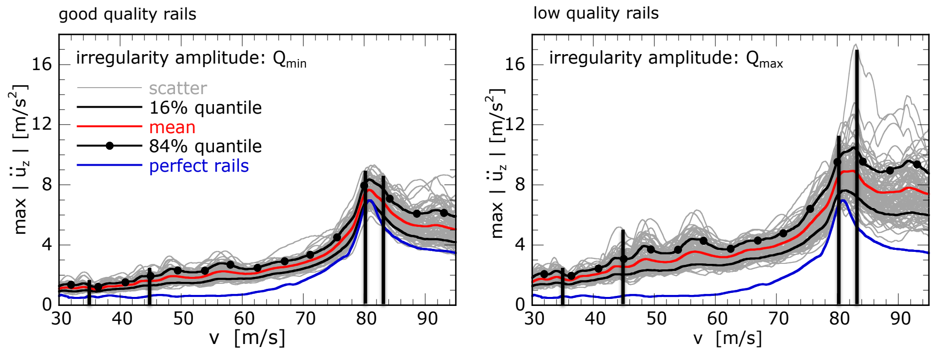
Environmental impact on natural frequencies

Numerical simulation



Case study problem

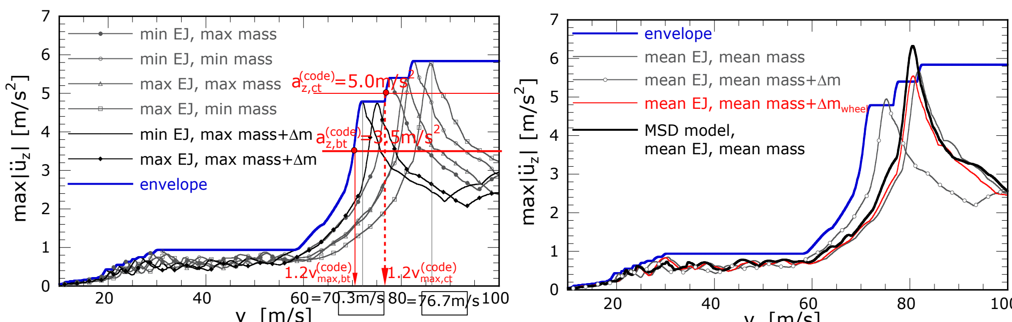
Response scatter due to uncertainties: Rail irregularities



Case study problem

Reliability assessment: Eurocode 1 based approach

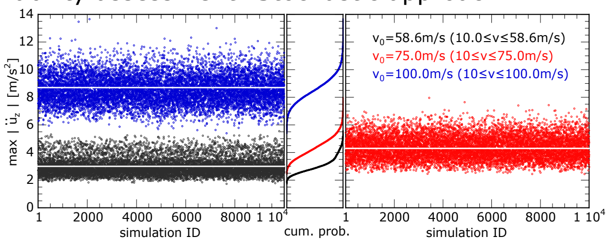
- Single force load model
- Conservative damping
  - ✓ Additional damping admitted for BVI
- Min. & max. bridge mass
- Lower & upper stiffness estimate
- Max. travel speed + 20%
- Acceleration limits with safety factor 2
  - ✓ Instability of ballast $a_z^{(b)} = 0.7g/2 = 0.35g$
  - ✓ Derailment $a_z^{(b)} = 1.0g/2 = 0.50g$

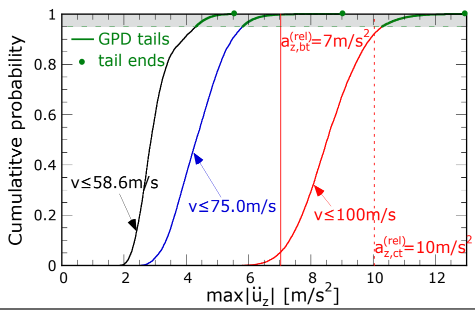


$v_{max,bt}^{(code)} = 58.6m/s$, $v_{max,ct}^{(code)} = 64.1m/s$

Case study problem

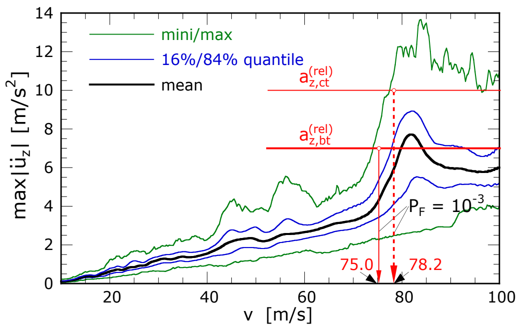
Reliability assessment: Stochastic approach





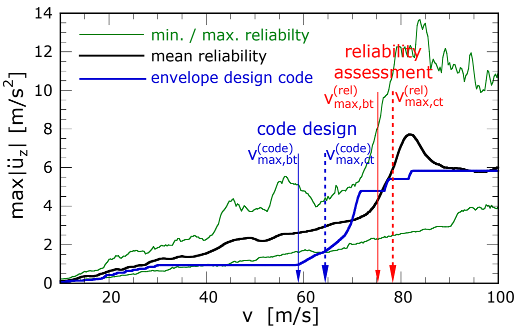
Case study problem

Reliability assessment: Stochastic approach



Case study problem

Reliability assessment: Code based vs. stochastic approach



$v^{(code)}_{max,bt} = 58.6 m/s$ $v^{(rel)}_{max,bt} = 75.0 m/s$

$v^{(code)}_{max,ct} = 64.1 m/s$ $v^{(rel)}_{max,ct} = 78.2 m/s$

Summary

- ✓ Reliability assessment of bridges for high-speed trains with probabilistic approach
- ✓ Limit state based on maximum acceleration response
- ✓ Challenges
  - Sufficiently sophisticated and computational efficient mechanical model
  - Computational efficient simulation methods
  - Identification of random variables and their distributions
- ✓ In the considered example Eurocode based assessment (over-)conservative

Thank you very much
for your attention!