PROBABILISTIC ASSESSMENT OF RAILWAY TURNOUTS USING A MULTIBODY SIMULATION SOFTWARE

Symposium Intelliswitch 28-30th August 2017

Master thesis project 23rd of January – 23rd of June 2017

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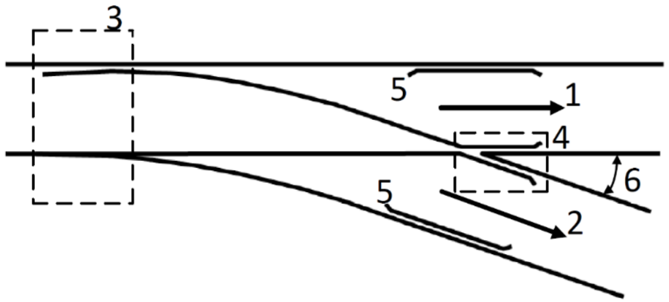
Outline of presentation

1) Motivation
2) Objective
3) General railway dynamics
4) Numerical modelling of railway turnout
5) Probabilistic method
6) Probabilistic assessment of turnout model
7) Concluding and reflecting remarks

Motivation

- Switches & crossings (S&Cs) exposed to accelerated degradation process
- Failure leads to **derailment** of trains
- Around 50 % of condition-based maintenance required for 3500 switches & crossings in Danish railway network
- Unscheduled repair of S&Cs are responsible for a significant portion of temporary speed reductions and associated delays



Objective

- Perform a probabilistic assessment of the accelerations of the train as these are related to degradation when the train travels through a turnout in the diverging track

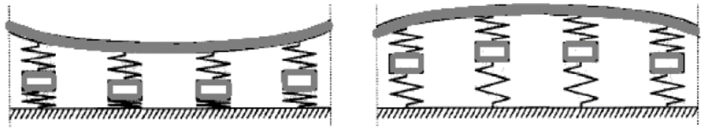
- Probabilistic assessment provides information about:
  1) Level and uncertainty of accelerations
  2) Importance of train and track components

General dynamic properties

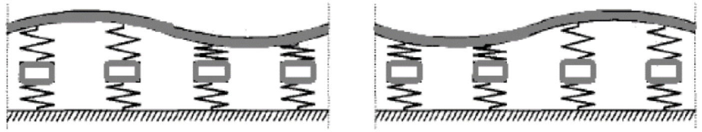
- Sleeper-passing frequency and effect
- Coupled train-track resonance 30-100 Hz
- Three track related resonant frequencies

Track mode shapes related to three main resonance frequencies:

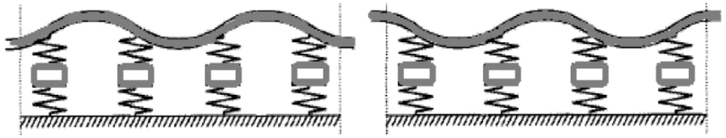
50-300 Hz



200-600 Hz

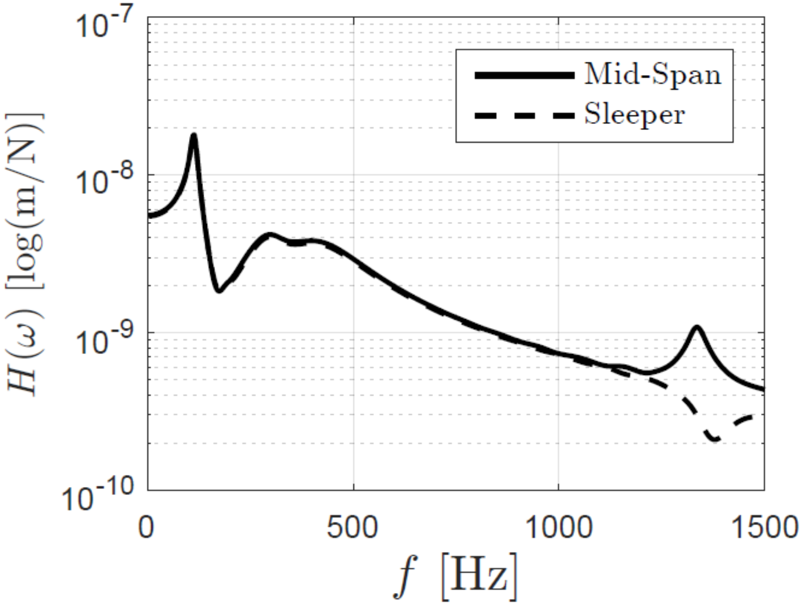


Pinned-pinned frequency



Courtesy of Alejandro de Miguel (2015)

Typical receptance curve:



Numerical modelling

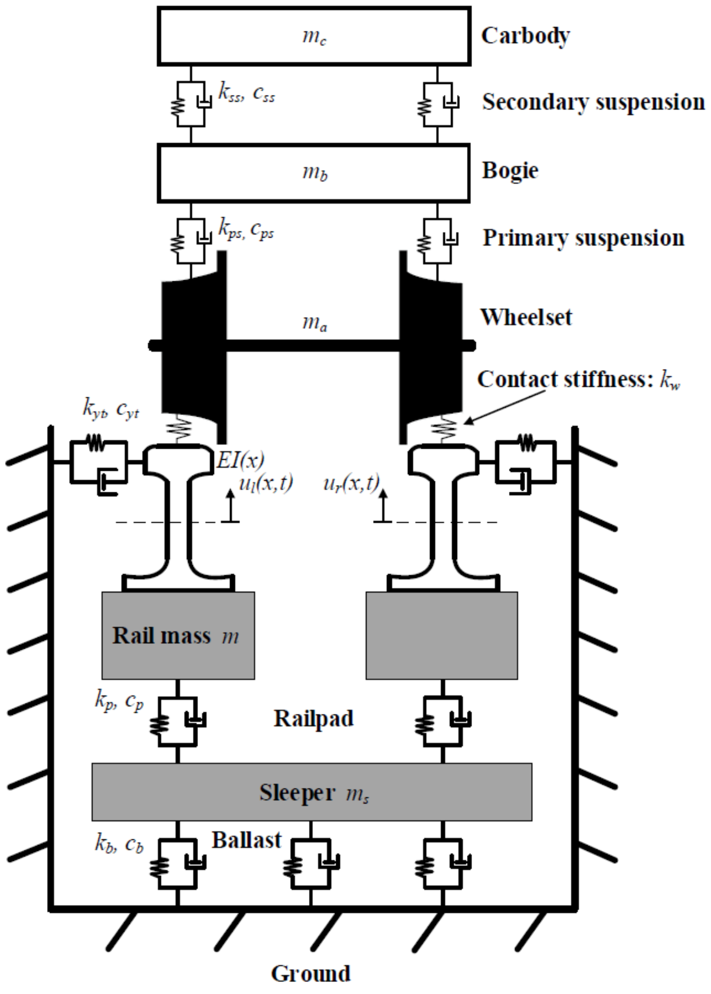
- Multibody simulation software: GENSYS

  Characteristics:

  - Rigid bodies connected by massless flexible elements
  - Detailed rail and wheel profiles -> Accurate contact analysis
  - Low computational time compared to FEM

- Euler-Bernoulli Track (EBT) model
  - A fixed track taking into account the rail bending effect.
  - Realistic model capturing general railway dynamic characteristics.

  Credit: A. de Miguel, I. Santos, I. Hoff & A. Lau



Methodology of probabilistic assessment

- Based on uncertainty and sensitivity analysis that assume the input variables to be stochastic and independent

- Uncertainty analysis includes:
  - Monte Carlo simulation

- Sensitivity analysis includes:
  - Elementary effects method (EEM)

Monte Carlo simulation

- Sample matrix holding *N* samples for *k* input variables:

$$\begin{bmatrix} X_1^{(1)} & X_2^{(1)} & X_3^{(1)} & \cdots & X_k^{(1)} \\ X_1^{(2)} & X_2^{(2)} & X_3^{(2)} & \cdots & X_k^{(2)} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ X_1^{(N-1)} & X_2^{(N-1)} & X_3^{(N-1)} & \cdots & X_k^{(N-1)} \\ X_1^{(N)} & X_2^{(N)} & X_3^{(N)} & \cdots & X_k^{(N)} \end{bmatrix}$$

- Compute model output for each sample to obtain:

$$\mathbf{Y} = \left\{ \begin{matrix} Y^{(1)} \\ Y^{(2)} \\ \vdots \\ Y^{(N-1)} \\ Y^{(N)} \end{matrix} \right\}$$

- The uncertainty is quantified through mean and variance of **Y**
- The uncertainty is visualized by plotting the output distribution in a bar plot

Elementary Effects Method

- Use multiple samples of wide ranges of variations to remove dependency of single sample point
- Idea of EEM owed to Morris who defined the elementary effect of *i*th input as:

$$EE_i = \frac{Y(X_1, X_2, ..., X_{i-1}, X_i + \Delta, ...X_k) - Y(X_1, X_2, ..., X_k)}{\Delta}$$

- Effectiveness of EEM relies on sampling strategy. Using p-levels of input factors, a trajectory is build from:

$$\mathbf{B}^* = \left(\mathbf{J}_{k+1,1}\mathbf{x}^* + \frac{\Delta}{2}\left((2\mathbf{B} - \mathbf{J}_{k+1,k})\,\mathbf{D}^* + \mathbf{J}_{k+1,k}\right)\right)\mathbf{P}^*$$

- Best combination of *r* trajectories determined from largest Euclidean distances between them
- Importance of input variables determined through evaluation of three statistics:

$$\mu_i^* = \frac{1}{r}\sum_{j=1}^{r}|EE_i^j| \qquad \mu_i = \frac{1}{r}\sum_{j=1}^{r}EE_i^j \qquad \sigma_i^2 = \frac{1}{r-1}\sum_{j=1}^{r}\left(EE_i^j - \mu_i\right)^2$$

Probabilistic assessment of turnout model

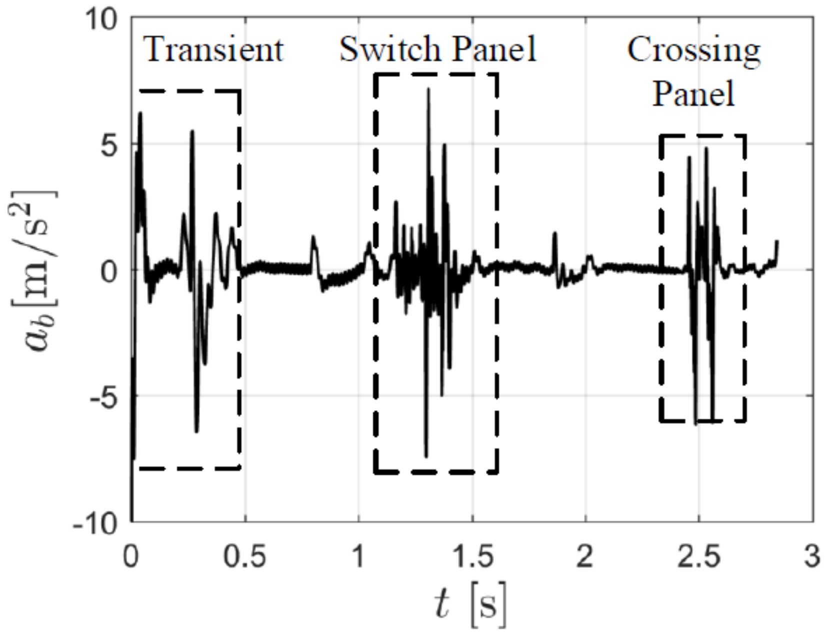
- EBT Turnout model with specifications:

  S&C:
  Type: 60E1-760-1:15r
  Length: 120 m
  30 rail cross sections
  400 rail masses
  200 sleeper masses

  Train:
  Passenger flirt train with single car body
  Bogie base distance: 16.8 m
  Wheelset base distance: 2.5 m
  Wheel profile: S1002

- Reference measure
  - Accelerations of train related to degradation by Lopez Pita(2006)
  - Convenient because these can be measured practically

Vertical accelerations of train:



Used to establish two model outputs: Y_s and Y_c

Probabilistic assessment of turnout model

- Stochastic variables:

Parameter	min/mean	max/std	Distribution	Source
Ballast stiffness k_b	165 MN/m	220 MN/m	Uniform	[9]
Ballast damping c_b	55 kNs/m	82 kNs/m	Uniform	[9]
Sleeper mass m_s	129 kg/m	1.29 kg/m	Normal	[7]
Railpad stiffness k_p	53 MN/m	600 MN/m	Uniform	[15]+ [9]
Railpad damping c_p	30 kNs/m	63 kNs/m	Uniform	[9]
Rail mass m	60 kg/m	0.60 kg/m	Normal	[7]
Bending stiffness EI	6.043×10^6 Nm^2	3.0215×10^4 Nm^2	Normal	[7]

Parameter	min/mean	max/std	Distribution	Source
Bogie mass m_b	2.32 t	3.48 t	Uniform	[15]
Wheelset mass m_a	1.6 t	2 t	Uniform	[15]
Speed v	120 km/h	2 km/h	Normal	[2]
Prim. susp. stiffness k_{ps}	1300 kN/m	3900 kN/m	Uniform	[15]
Prim. susp. damping c_{ps}	6 kNs/m	18 kNs/m	Uniform	[15]
Sec. susp. stiffness k_{ss}	290 kN/m	870 kN/m	Uniform	[15]
Sec. susp. damping c_{ss}	10 kNs/m	30 kNs/m	Uniform	[15]
Contact stiffness k_w	1.61×10^6 kN/m	4.1×10^4 kN/m	Normal	[15]

[2]: Banverket. *Spårgeometrihandboken BVH 586.40.* Banverket, 1996

[7]:P.J. Jensen. *Sporteknik.* Banedanmark, 2 edition, 2016

[9]:X.Lei. *High Speed railway track dynamics. Models, algorithms and application.* Springer, 2015

[15]:J.M. Rocha. Probabilistic safety assessment of a short span high-speed railway bridge. *Elsevier*, 2014

Probabilistic assessment of turnout model

- EEM performed with p=4, M=30, r=4
- Results of EEM:

	Y_s			Y_c				
Variable	μ_i^*	μ_i	σ_i^2	μ_i^*	μ_i	σ_i^2	Rank	Score
k_b	0.4278	0.0023	0.6129	2.0323	2.0323	1.3895	EI	0.0123
c_b	0.6428	-0.6428	0.2323	0.3383	0.2476	0.4548	m	0.0610
m_s	0.0767	0.0645	0.1345	0.1182	-0.1101	0.1112	m_s	0.0974
k_p	3.9176	3.9176	2.7711	2.8122	2.8122	1.4169	k_w	0.2906
c_p	0.5360	-0.5360	0.1220	0.2963	-0.1498	0.4319	c_p	0.4161
m	0.0813	-0.0083	0.1225	0.0406	-0.0306	0.0575	c_b	0.4906
EI	0.0102	0.0102	0.0136	0.0144	-0.0022	0.0218	c_{ss}	0.5086
m_b	3.5622	-3.5622	0.3668	2.4156	-2.4156	1.8547	m_a	0.8427
m_a	0.9438	-0.4790	1.0349	0.7416	-0.7416	0.1744	v	0.8905
v	0.5202	0.3911	0.5709	1.2609	-1.0142	1.6310	k_{ps}	0.9985
k_{ps}	0.8872	0.8872	0.7224	1.1099	1.1099	0.7448	k_{ss}	1.1111
c_{ps}	1.7593	1.7593	0.5971	1.7779	1.7779	0.6503	k_b	1.2300
k_{ss}	1.2354	-0.2783	1.6250	0.9868	0.6549	1.1243	c_{ps}	1.7686
c_{ss}	0.7568	0.2488	1.1765	0.2604	-0.1044	0.2978	m_b	2.9889
k_w	0.4856	0.1194	0.7154	0.0957	-0.0243	0.1474	k_p	3.3649

Non-influential (ranks EI, m, m_s, k_w)

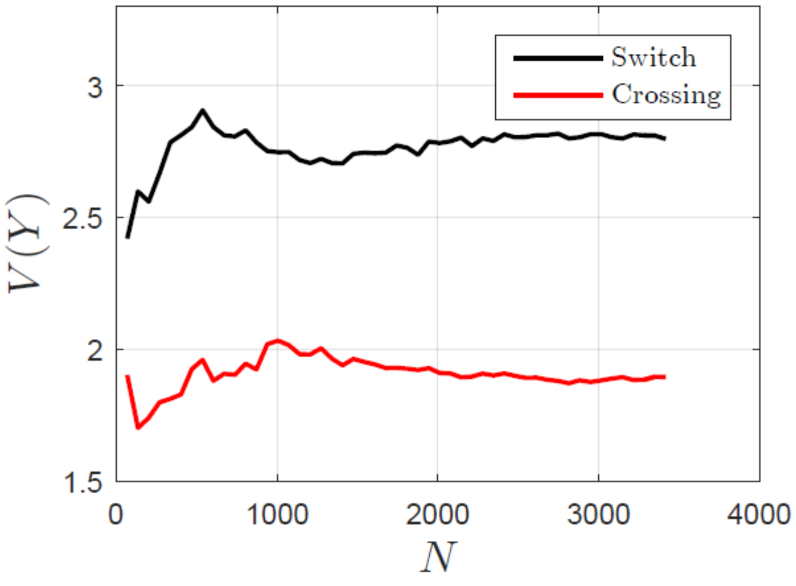
Most important (ranks k_b, c_{ps}, m_b, k_p)

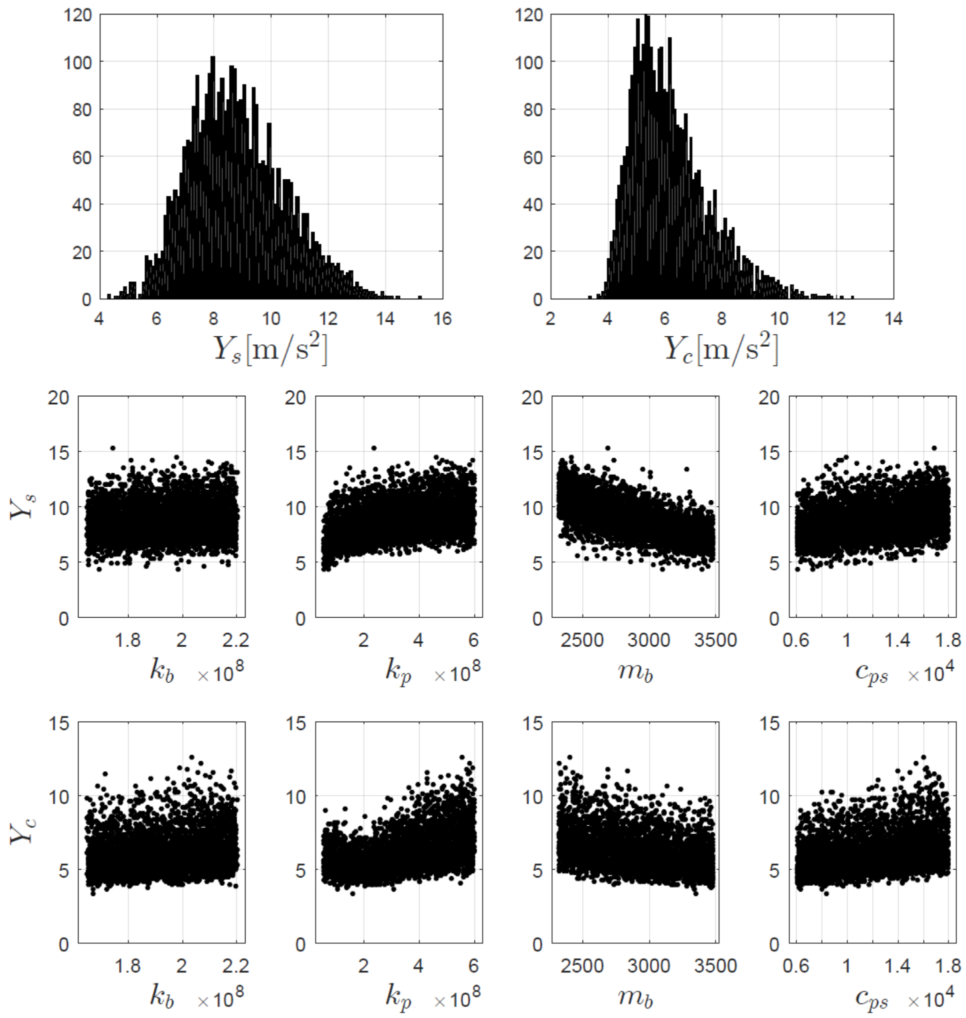
Probabilistic assessment of turnout model

- Monte Carlo simulation with N=3417
  Stabilize around N=2000

Means: $E(Y_s)=8.8\ m/s^2$ and $E(Y_c)=6.2\ m/s^2$

Variances: $V(Y_s)=2.8(m/s^2)^2$ and $V(Y_c)=1.9(m/s^2)^2$





Concluding and reflecting remarks

- Most influential variables: Railpad stiffness, bogie mass, primary suspension damping and ballast stiffness
- Least influential variables: Rail bending stiffness, rail mass, sleeper mass and contact stiffness
- Methodology capabilities: Possible to alter/remove/add input variable distributions and/or change model outputs and perform probabilistic assessment

- Improvement of methodology to increase confidence:
  - Calibrate turnout model against experimental modal analysis