London calling (probably)
Parameters and stochastic behaviour of braking force generation and transmission

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Henry
Job: ETCS Expert
Employer: Infrastructure manager
Challenges: Ensure safety, maintain or increase capacity
“I need to ensure that signals are practically never overrun while at the same time, the load on my network increases every year.”
ETCS provides the answer
“With the moving block system, I can improve infrastructure utilisation - I only need to find the braking curves!”

Raphael Pfaff (Aachen UAS)

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What is a braking curve?

CCS systems rely on braking curves to describe the train’s braking capability.

- To supervise train velocity, CCS systems predict the future braking capability of the train.
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- To supervise train velocity, CCS systems predict the future braking capability of the train.
- However, there is not the braking capability.
- Braking curves exhibit a randomised behaviour.
How to obtain a braking curve?

To obtain a braking curve, the stochastic behaviour of the system needs to be analysed, typically by help of a Monte Carlo Simulation.

\[ y = f(x) \]
White Box Modelling of the braking system
Which parameters can be identified and which effect do they have on the braking distance?

- Brake pipe: propagation velocity, flow resistances, train length

Also discrete failure events need to be considered.
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- Distributor valve: Filling time, brake cylinder pressure
- Braking force generation: efficiency, brake radius (for disc brakes), pad/block friction coefficient
- Wheel/rail contact: rail surface, contaminants, slip, ...
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- **Markov Chains**
  - Discrete state changes, e.g. defects
Brake pipe parameters
Brake pipe parameters determine the distribution of the brake command along the train.

- **Propagation velocity:**
  - Required: \( c \geq 250 \, \text{m/s} \)
  - May be considered lower limit

- **Flow resistances:**
  - Flow resistance in the individual wagons determine filtering behaviour of BP

- **Train length:**
  - Non-random input parameter

- **Wagon position:**
  - Distribution of braked mass in train and effective filling time influence overall braking distance
Distributor valve parameters

Distributor valve parameters determine the effectiveness of the brake command.

- **Filling time** $t_f$:
  - Brake modes P/R: $(4 \pm 1) \text{ s}$
  - Brake modes P/R: $(24 \pm 6) \text{ s}$
  - Uniform distribution (conservative)

- **Brake cylinder pressure** $p_C$:
  - Required: $p_C = (3.8^{+0.2}_{-0.1}) \text{ bar}$
  - Uniform distribution (conservative)
Braking force generation parameters

Parameters of the braking force generation subsystem determine the propagation of braking effort between $p_C$ and wheel/disc.

- **Efficiency**
  - Typical dynamic efficiency:
    \[ \eta \in [0.75, 95] \]
  - Depending on maintenance state
  - Assumed uniform distribution

- **Brake radius**
  - Systematic variation with pad wear, not relevant for block brakes

- **Pad/block friction coefficient $\mu_B$**
  - Mean friction coefficient depending on $v_0$
  - Stochastic variation of instantaneous coefficient
  - Normal distribution appropriate

![Histogram of $\mu_B$ distribution](image)
Wheel-rail surface parameters

- Rail surface:
  - According to Hertzian theory
  - Non-Hertzian contacts due to hunting

- Contaminants:
  - Empirical estimation due to network
  - Mostly dry braking curves simulated

- Slip:
  - Curving motion, hunting impose 3D-slip on contact patch
  - Adhesion “budget” gets used

![Diagram of adhesion area with elliptical contact and force levels](image)
“Looks like the simulation model is quite complex? Can we do this online?”
Approaches to obtain braking distance distributions

- **Error-propagation:**
  - Conservative: assumes normal distribution for all parameters
  - Complex: requires explicit function formulation and partial differentiation

- **(Standard) Monte-Carlo-Simulation:**
  - Efficient (in terms of confidence): returns shortest (also asymmetric) confidence interval
  - Inefficient (in terms of computational effort):
    - For rare event $\varepsilon \ll 1$, $N \approx \frac{100}{\varepsilon}$ trials required
    - Typical according to CSM: $\varepsilon \in [10^{-7} \ldots 10^{-9}] \Rightarrow N \approx 10^{11}$

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- ERA proposes to precalculate braking curves for limited number of train formations
  - Freight trains to be handled using braked weight and correction factor
“OK, basic Monte-Carlo is too complex to be calculated for each freight train. I fear a correction factor may be too conservative for well maintained wagon fleets. Are there any means to overcome this?”
ETCS: $\gamma$ vs. $\lambda$ braked trains

- **Typical $\gamma$-braked trains:**
  - Multiple units, other fixed formations
  - Braking curve specification via deceleration values

- **Typical $\lambda$-braked trains:**
  - Any in-service configurable trains, especially freight trains
  - Braking curve using correction factors ($K_{dry,rst}$, $K_{wet,rst}$) to calculate based on brake weight
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  - The distribution of braking distances for freight trains of the same braked weight may be large:
    - Empty/loaded selection vs. automatic load detection
    - Maintenance state
    - Tread vs. disc brake
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    - Empty/loaded selection vs. automatic load detection
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  - It may be of advantage to run certain $\lambda$ trains as $\gamma$ trains
Proposed solution (part 1): use importance sampling

Importance sampling (IS) increases the probability of “desired” outcomes in Monte-Carlo-Simulations.

- Typical IS approaches:
  - Stratification: select only relevant strata of the sampling range
  - Scaling: Scale random variable
  - Translation: Move random variable to more relevant part of sampling space
  - Change of random variable: Replace random variable by one more likely to produce outcomes in the relevant range
  - Adaptive approaches

- Effect: higher number of samples in region of interest

- Correction factor: Likelihood ratio \( L(y) = \frac{f(y)}{\tilde{f}(y)} \)
Application of IS to braking curves

Step 1: Select relevant variables for IS.

![Graphs of braking curves variables](image)
Application of IS to braking curves

Step 2: Change identified random variables, in the case at hand $\mu_B$
Application of IS to braking curves

Step 3: Analyse for rare events, here braking distances in excess of 1100 m. \( N = 5 \cdot 10^7 \)
Application of IS to braking curves

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“Well, this reduces the required Monte Carlo iterations by far, however handling braking curves for each wagon during brake assessment doesn’t appear feasible.”
Solution (part 2): Connect the wagon subsystem

The Wagon 4.0 offers sensing and connectivity as well as cloud representation.

- Sensing: Accelerometers to record deceleration, brake cylinder pressure sensor to measure braking force
- Connectivity: send braking data to cloud
Record brake deceleration for wagons (in trains) in cloud

Use big data analytics to derive individual wagon braking performance distribution
“Great, the approach to use Importance Sampling, IoT-technologies and Big Data analytics to gain the braking curves of each individually composed train improves our performance compared to running \( \lambda \)-trains.”
Thank you!

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