Modelling of braking curves

White, grey and black box approaches

Prof. Dr. Raphael Pfaff

Aachen University of Applied Sciences
pfaff@fh-aachen.de
www.raphaelpfaff.net
@RailProfAC

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Motivation

Henry

Job: ETCS Expert

Employer: Infrastructure manager

Challenges: Ensure safety, maintain or increase capacity

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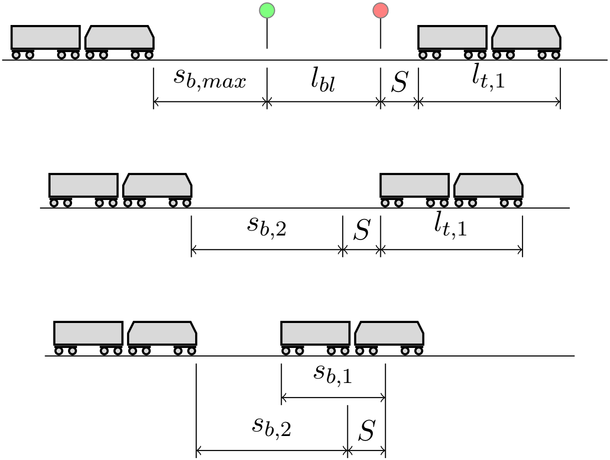
"I need to ensure that signals are practically never overrun while at the same time, the load on my network increases every year."

Efficient operation of trains on limited infrastructure

Appropriate braking curves and the moving block system help to reduce headway.



Section 2

Introduction to braking curves

User: Infrastructure Manager Executive

"With the moving block system, I can improve infrastructure utilisation - I only need to find the braking curves!"

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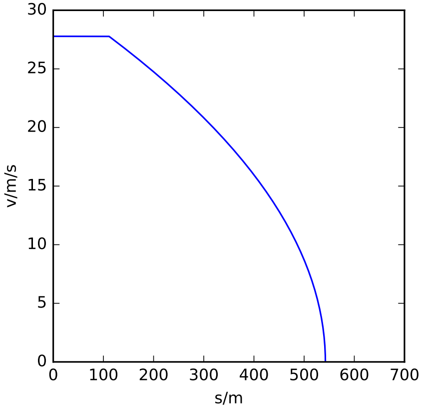
What is a braking curve?

ATP systems rely on braking curves to describe the train's braking capability.

- To supervise train velocity, ATP systems predict the future braking capability of the train



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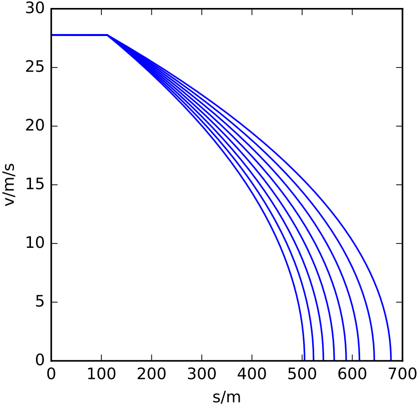

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What is a braking curve?

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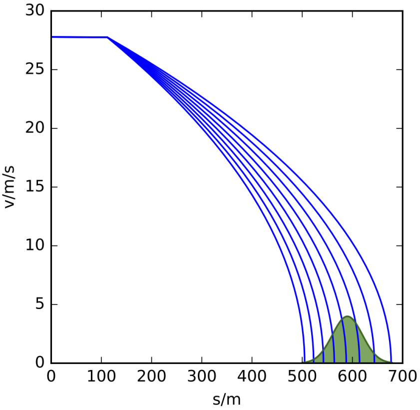
- To supervise train velocity, ATP systems predict the future braking capability of the train
- However, there is not *the* braking capability
- Braking curves exhibit a randomised behaviour



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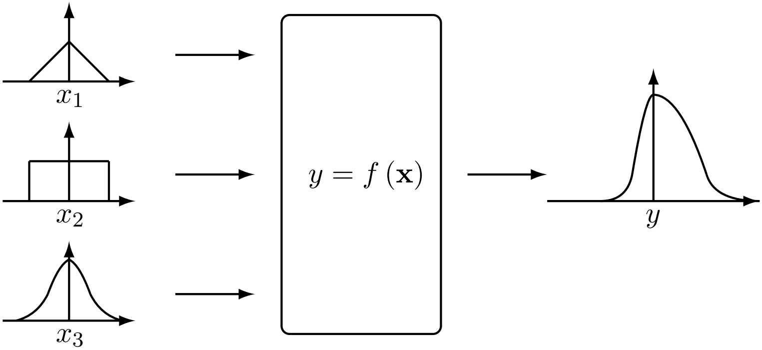
How to obtain a braking curve?

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



Section 3

White box approach

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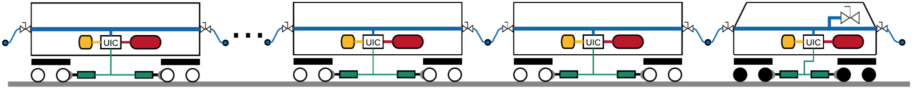
Physical Modelling of the braking system

Which parameters can be identified and which effect do they have on the braking distance?

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



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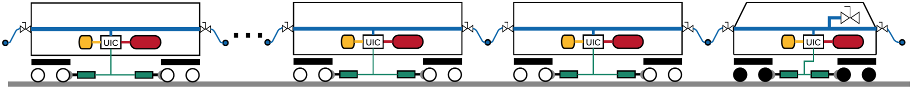

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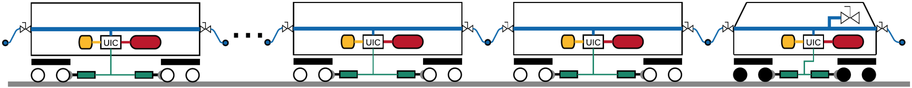

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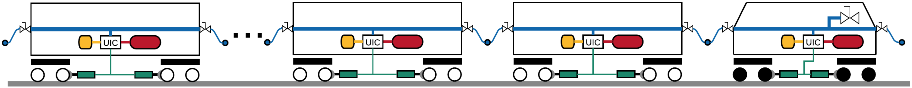

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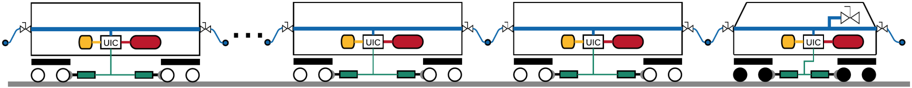
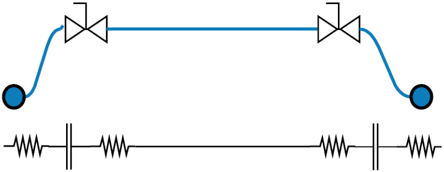


- Also discrete failure events need to be considered

Brake pipe parameters

Brake pipe parameters determine the distribution of the brake command along the train.

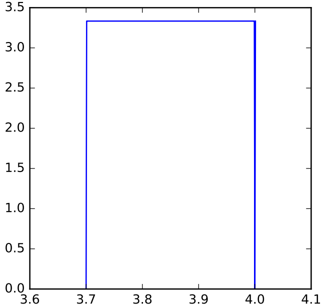
- Propagation velocity:
  - Required: $c \geq 250\,\frac{\mathrm{m}}{\mathrm{s}}$
  - May be considered lower limit
- Flow resistances:
  - Flow resistance in the individual wagons determine filtering behaviour of BP
- Train length:
  - Non-random input parameter
- Wagon position:
  - Distribution of braked mass in train and effective filling time influence overall braking distance



Distributor valve parameters

Distributor valve parameters determine the effectivity of the brake command.

- Filling time t_f:
  - Brake modes P/R: $(4 \pm 1)\,\mathrm{s}$
  - Brake modes G: $(24 \pm 6)\,\mathrm{s}$
  - Uniform distribution (conservative)
- Brake cylinder pressure p_C:
  - Required: $p_C = \left(3.8^{+0.2}_{-0.1}\right)\ \mathrm{bar}$
  - Uniform distribution (conservative)



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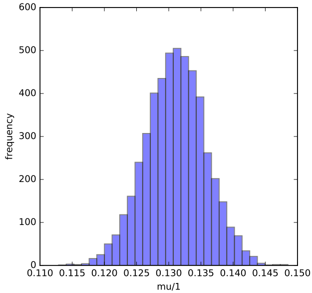
Braking force generation parameters

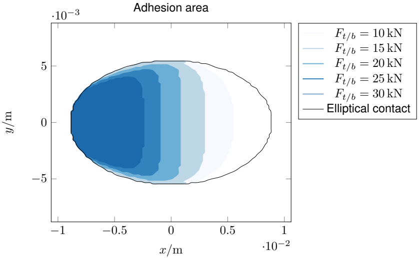
Parameters of the braking force generation subsystem determine the propagation of braking effort between p_C and wheel/disc.

- 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 μ_B
  - Mean friction coefficient depending on v_0
  - Stochastic variation of instantaneous coefficient
  - Normal distribution appropriate



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



User: Infrastructure Manager Executive

"Looks like the simulation model is quite complex? Can we do this online?"

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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: $\varepsilon \in \left[10^{-7} \dots 10^{-9}\right] \Rightarrow N \approx 10^{11}$

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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: γ vs. λ braked trains

- Typical γ-braked trains:
  - Multiple units, other fixed formations
  - Braking curve specification via deceleration values
- Typical λ-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
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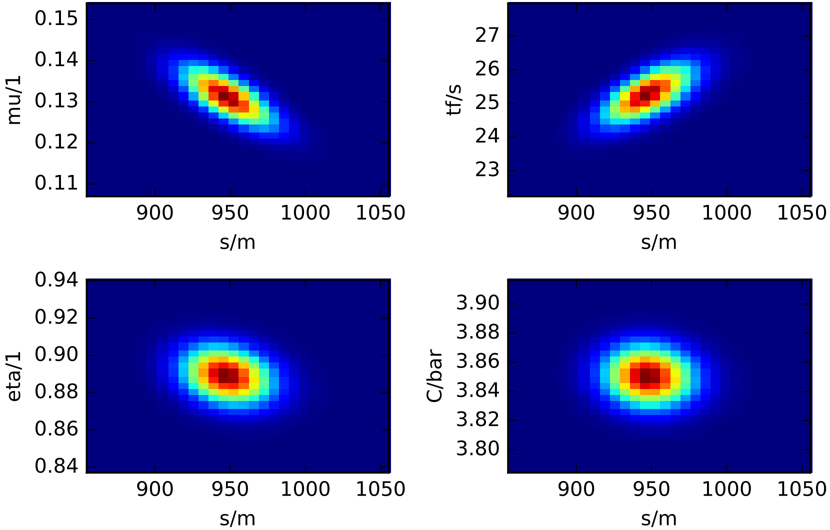
  - It may be of advantage to run certain λ trains as γ trains

Towards a grey box approach

Select dominating parameters



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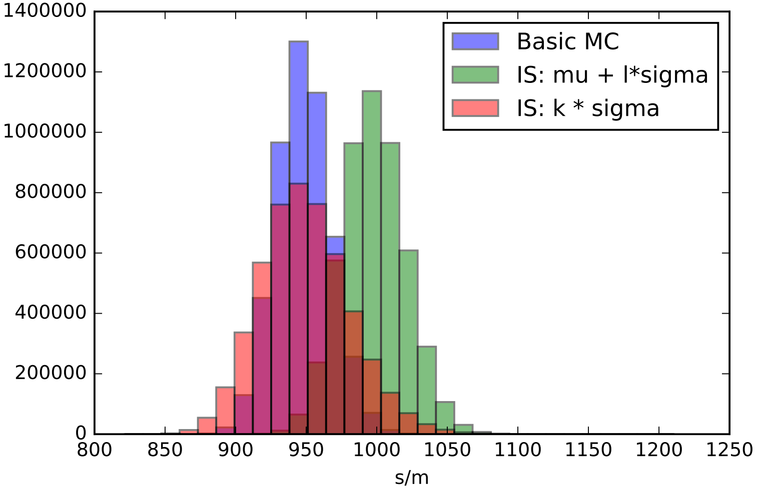
Use importance sampling

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 $L(y) = \frac{f(y)}{\tilde{f}(y)}$

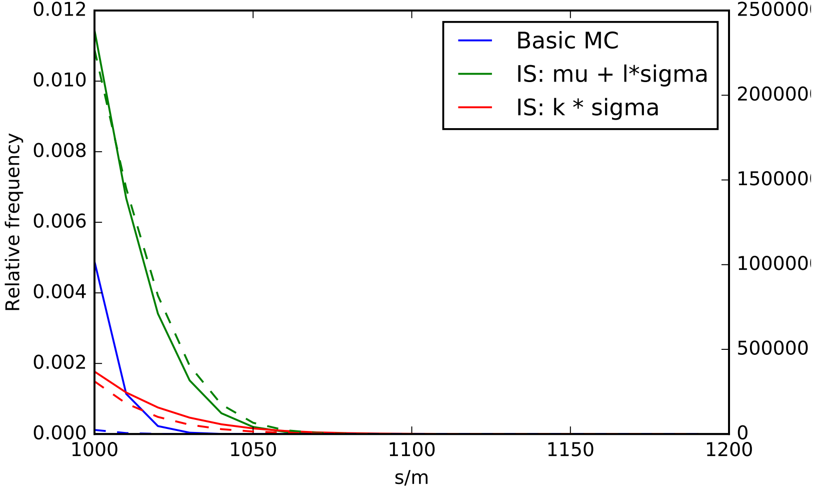
Application of IS to braking curves

Change identified random variables, in the case at hand μ_B



Application of IS to braking curves

Analyse for rare events, here braking distances in excess of 1100 m. $N = 5 \cdot 10^7$



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s	$n_{\mathcal{U}}$	$p_{\mathcal{U}}$	$n_{IS,1}$	$p_{IS,1}$	$n_{IS,2}$	$p_{IS,2}$
1000	24400	$4.89 \cdot 10^{-3}$	$2.27 \cdot 10^{6}$	$1.14 \cdot 10^{-2}$	$3.11 \cdot 10^{5}$	$1.77 \cdot 10^{-3}$
1050	2	$4 \cdot 10^{-7}$	$6.66 \cdot 10^{4}$	$2.02 \cdot 10^{-4}$	$1.48 \cdot 10^{4}$	$1.59 \cdot 10^{-4}$
1100	0	0	115	$2.04 \cdot 10^{-7}$	419	$7.50 \cdot 10^{-6}$
1150	0	0	0	0	15	$3.88 \cdot 10^{-7}$
1160	0	0	0	0	7	$2.05 \cdot 10^{-7}$
1170	0	0	0	0	5	$1.46 \cdot 10^{-7}$
1180	0	0	0	0	4	$1.16 \cdot 10^{-7}$
1190	0	0	0	0	1	$2.90 \cdot 10^{-8}$

Section 5

A black box approach

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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."

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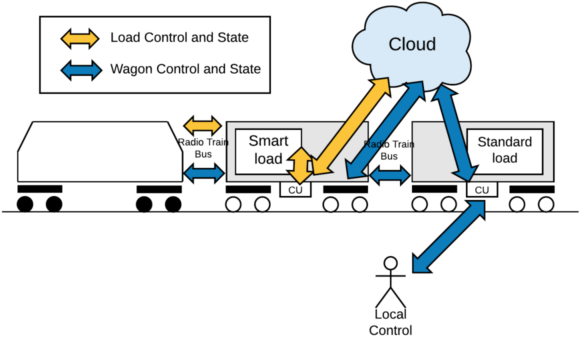
The Wagon 4.0 offers sensing and connectivity as well as cloud representation.

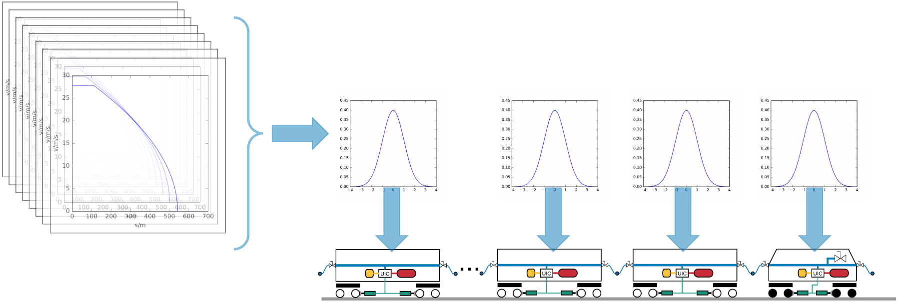
- Sensing: Accelerometers to record deceleration, brake cylinder pressure sensor to measure braking force
- Connectivity: send braking data to cloud



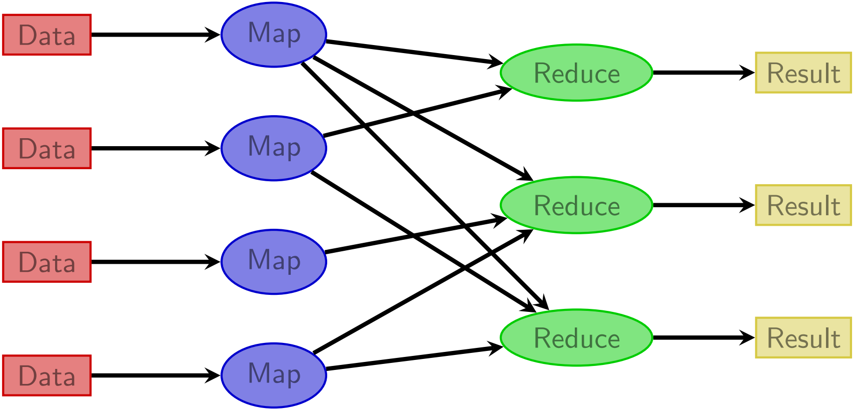
Big data analytics

Big data analytics can be applied to separate train and wagon braking performance

- Record brake deceleration for wagons (in trains) in cloud
- Use big data analytics to derive individual wagon braking performance distribution



MapReduce approach to braking curve estimation



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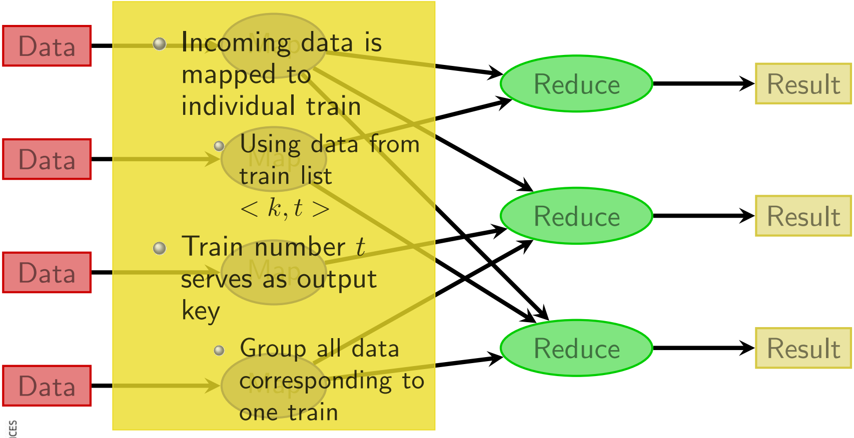
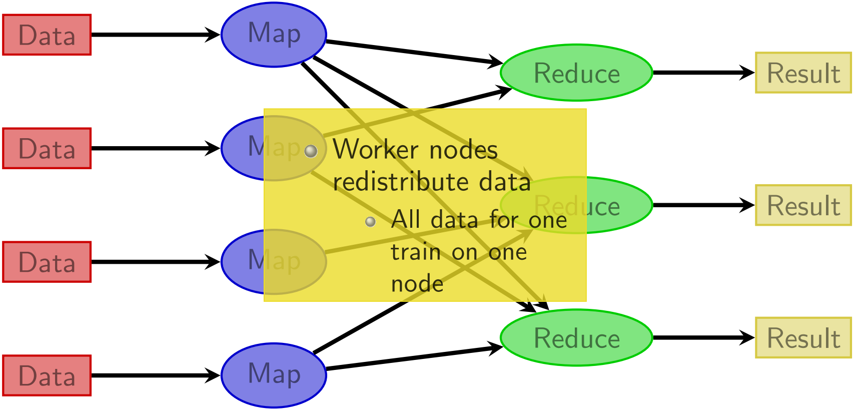


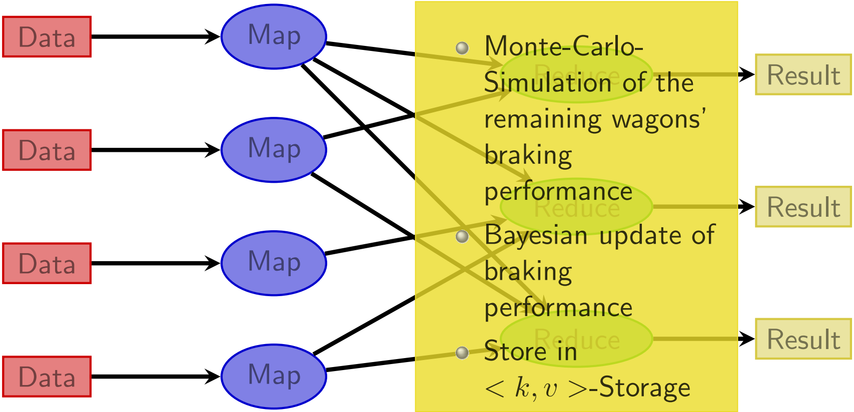
- Incoming data is mapped to individual train
  - Using data from train list $< k, t >$
- Train number t serves as output key
  - Group all data corresponding to one train

MapReduce approach to braking curve estimation



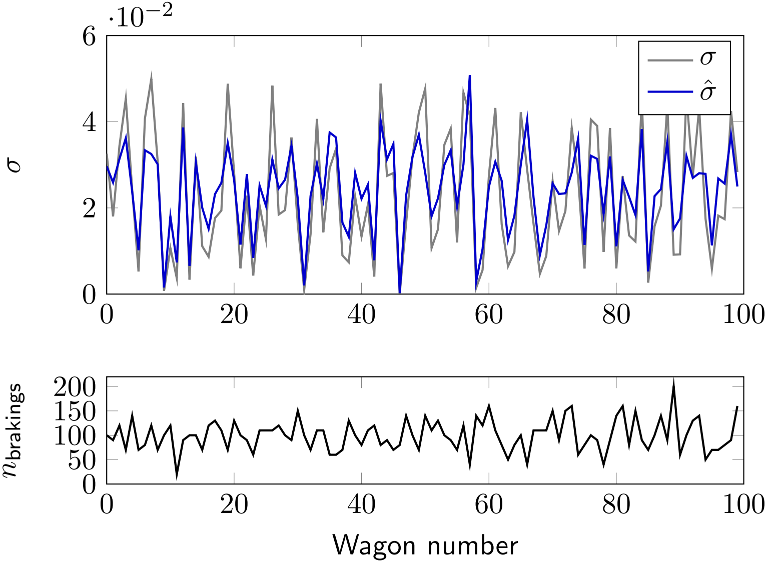
- Worker nodes redistribute data
  - All data for one train on one node

MapReduce approach to braking curve estimation



- Monte-Carlo-Simulation of the remaining wagons' braking performance
- Bayesian update of braking performance
- Store in $< k, v >$-Storage

Simulated results of Big Data analysis



"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 λ-trains."

Thank you!

Full paper available:

Prof. Dr. Raphael Pfaff
Rail vehicle engineering
pfaff@fh-aachen.de
www.raphaelpfaff.net