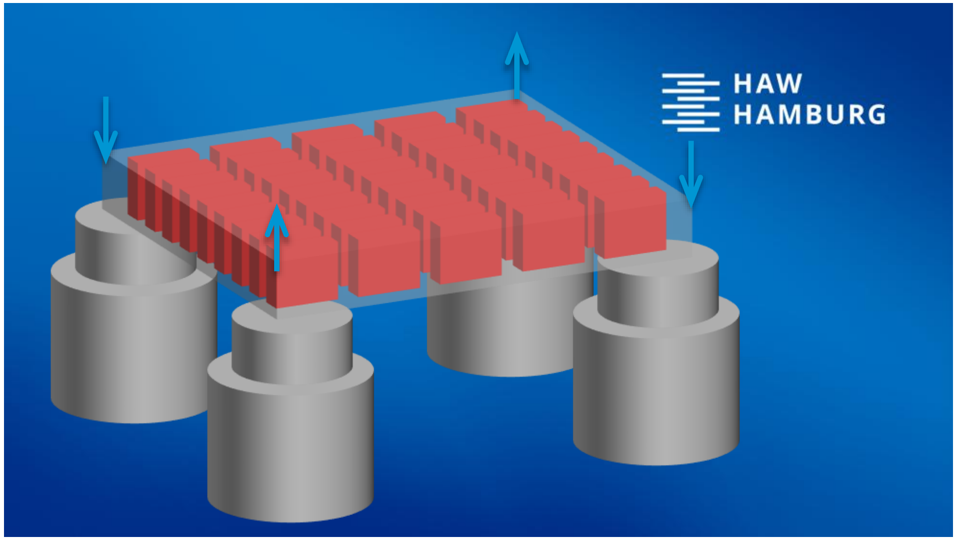
Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

AUSWERTUNG VON PSDS MIT DEM NORMAL TOLERANCE LIMIT

für Beschleunigungsdaten an Battery Packs von verschiedenen Battery Electric Vehicles



Prof. Dr.-Ing. Benedikt Plaumann,
M.Sc. Eugen Hein
Faculty Aviation and Automotive Systems

HAW HAMBURG

ROADMAP "TOWARDS REALISTIC BEV BATTERY TESTING"

Faculty Aviation and Automotive Systems
Prof. Dr.-Ing. Benedikt Plaumann

BEV BATTERY PACK STRUCTURAL DYNAMICS

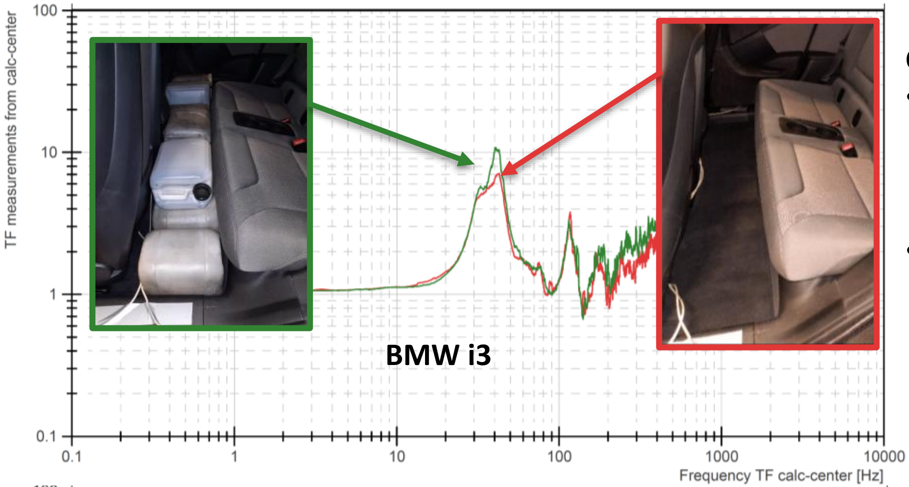
Goals and boundaries

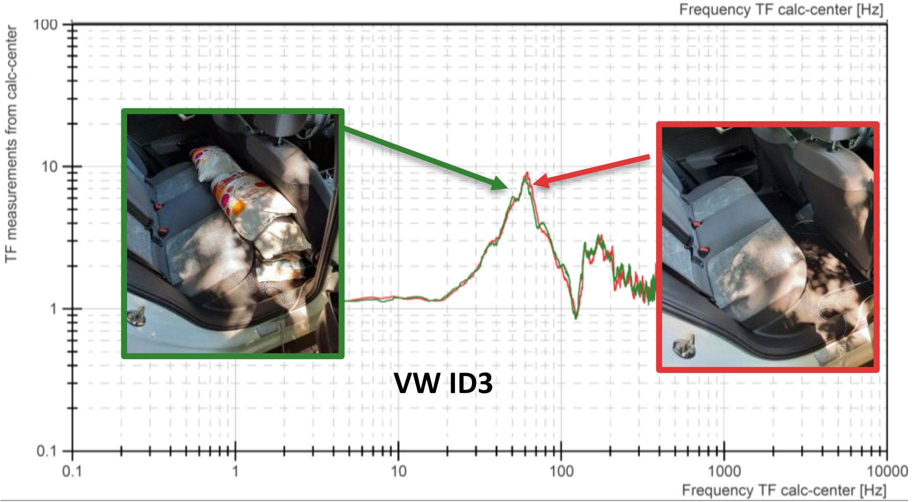
- Derive suitable test method for replication of realistic of dynamic (vertical loads) on Battery Pack
- Applicable to almost all standard BEV Cars
- Best „replication“: Field Data Replication / Time History Replication / Amplitude History
- Generalization: not „the one car“, not „the one measurement“, >500 measurements
- Needed: Statistical solid generalization
- Typical: Gaussian broadband random test method, if needed with higher Kurtosis or extra shocks
- Test time as short as possible: not need to test low test levels that don‘t cause any damage
- Large battery packs interact with “rest of vehicle”, heavy battery is not an “add-on component”

RESULTS FROM PRIOR ANALYSIS

comparison small&stiff vs. large&flexible

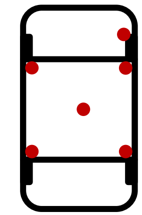
Innotesting 2022

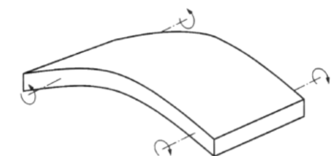




Compact BEV floor segment

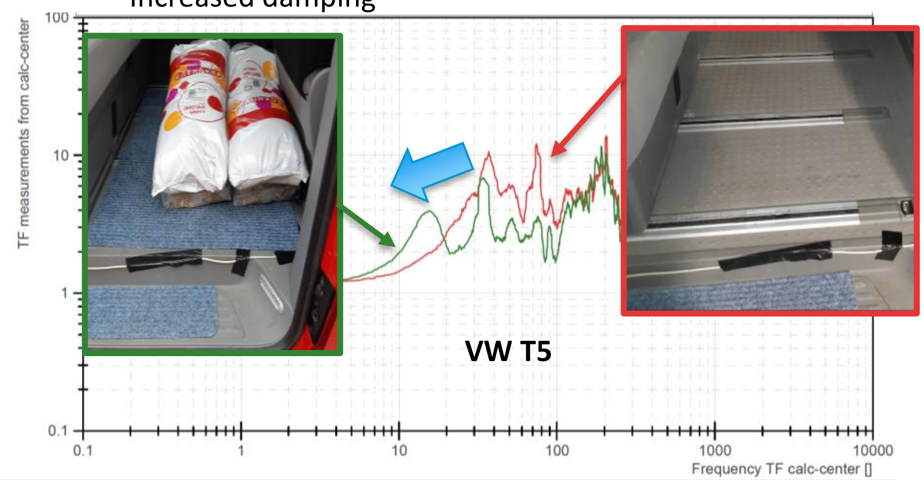
- No visible impact of additional mass loading on bending modes due to high stiffness of frame with large battery mass
- Presumable highly decoupled battery pack from vehicle structure





Large ICE floor segment (high coupling)

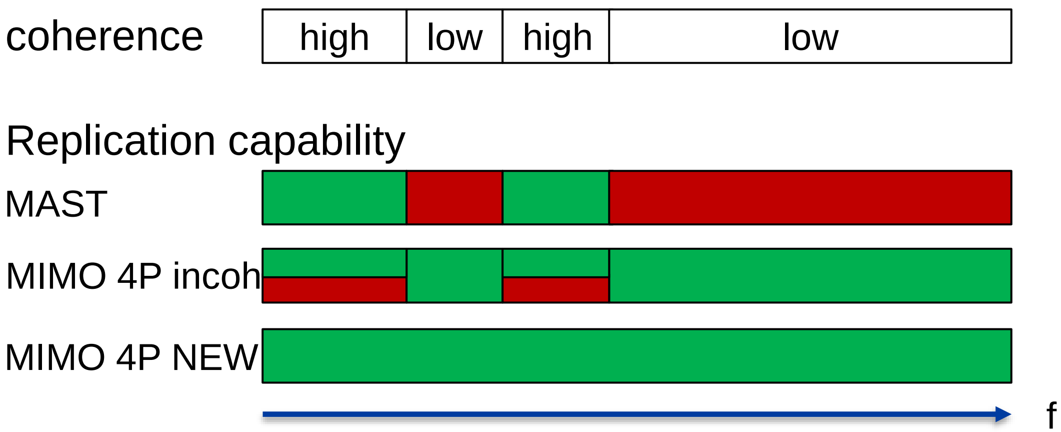
- Significant impact of mass loading on two bending modes
- Increased damping



Future: BEV – Battery Pack Interaction

RESULTS FROM PRIOR ANALYSIS

Simplified results coherence – 4 Poster needed



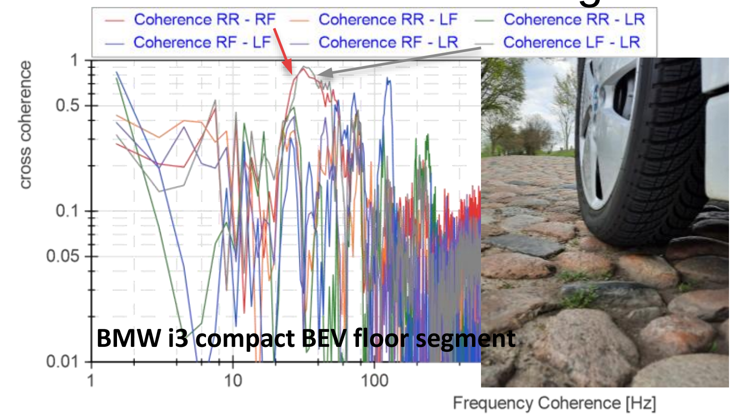
coherent excitation: potentially overtest bending, undertest torsion

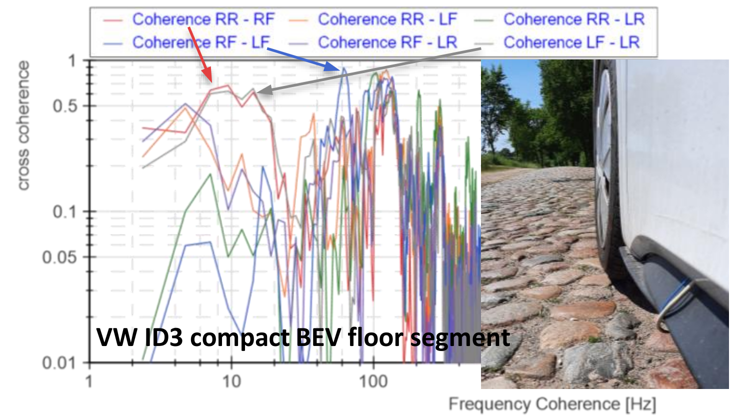
uncoherent excitation: potentially undertest bending, overtest torsion

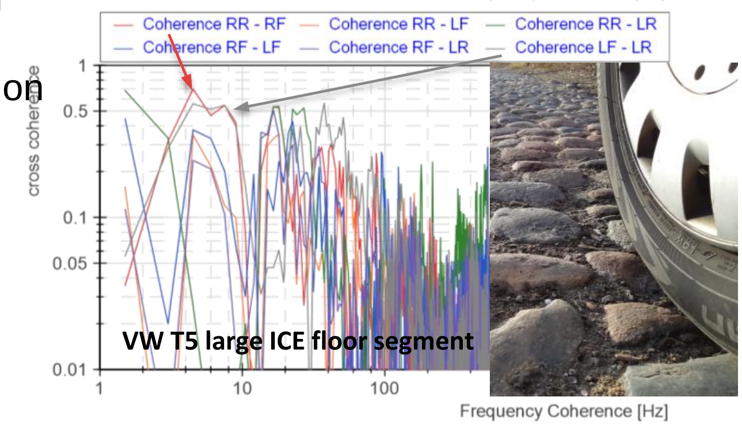
reality: mixed coherent / uncoherent

MAST: stiff fixture = coherent
MIMO 4 Poster can be coherent and uncoherent, controller!

$$coherence = \frac{|S_{XY}|^2}{{S_{XX}}^2 \cdot {S_{YY}}^2}$$

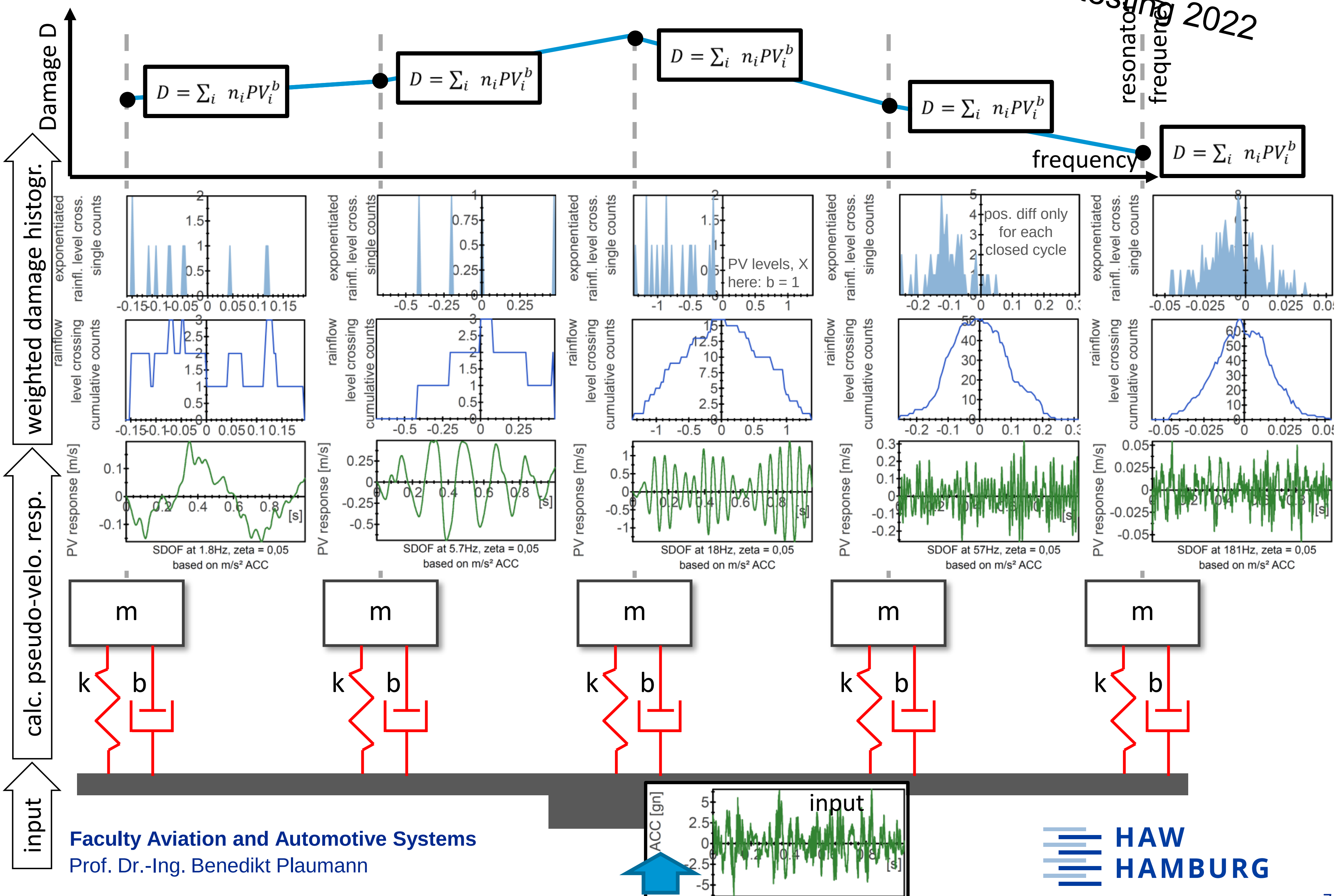






RESULTS FROM PRIOR ANALYSIS

Innotesting 2022



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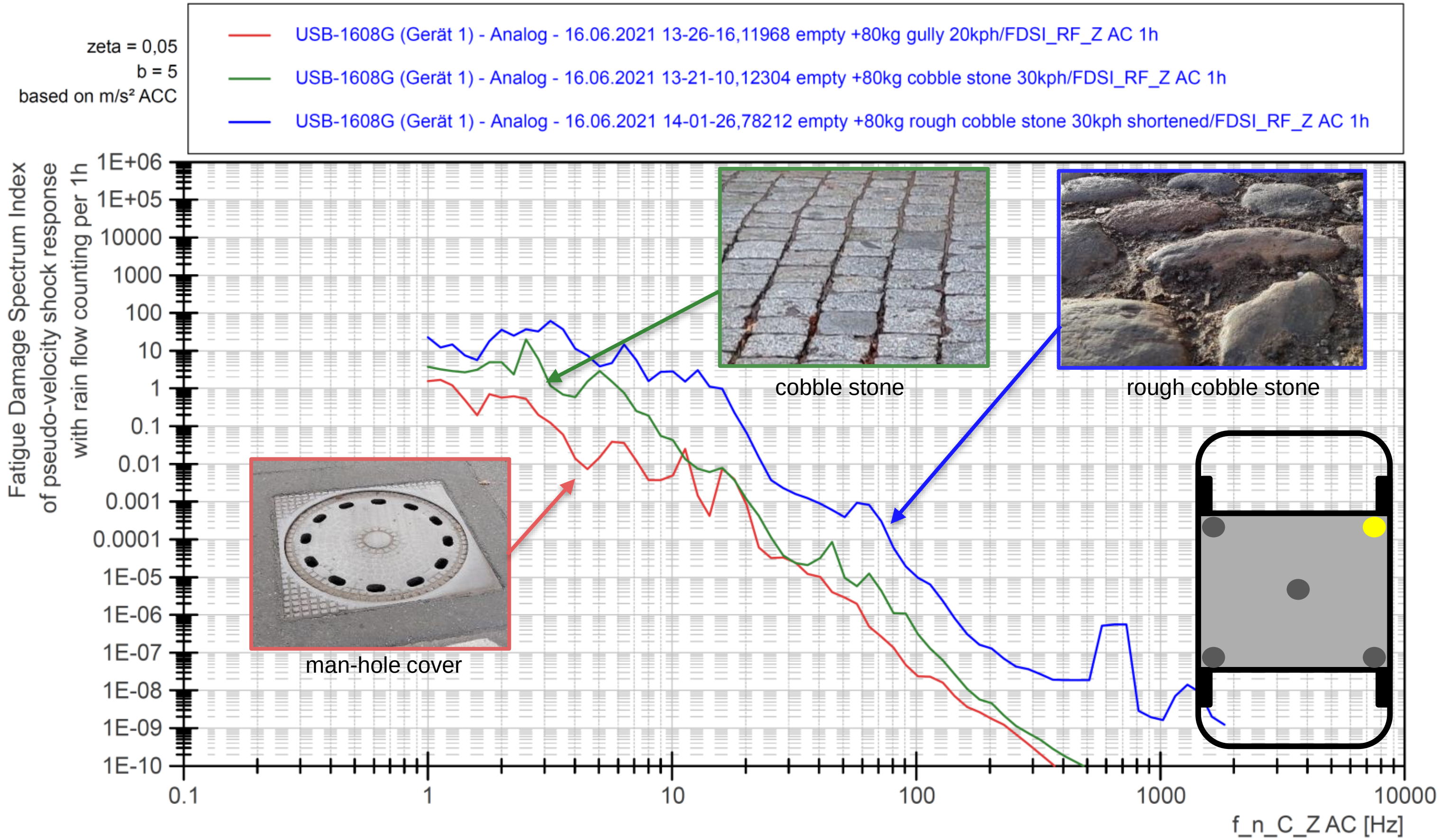
RESULTS FROM PRIOR ANALYSIS

Innotesting 2022

VW ID3 Fatigue Damage Spectrum

- FDS of the right front (RF) corner of the battery pack with
- Wöhler-curve exponent of 5 and 5% damping



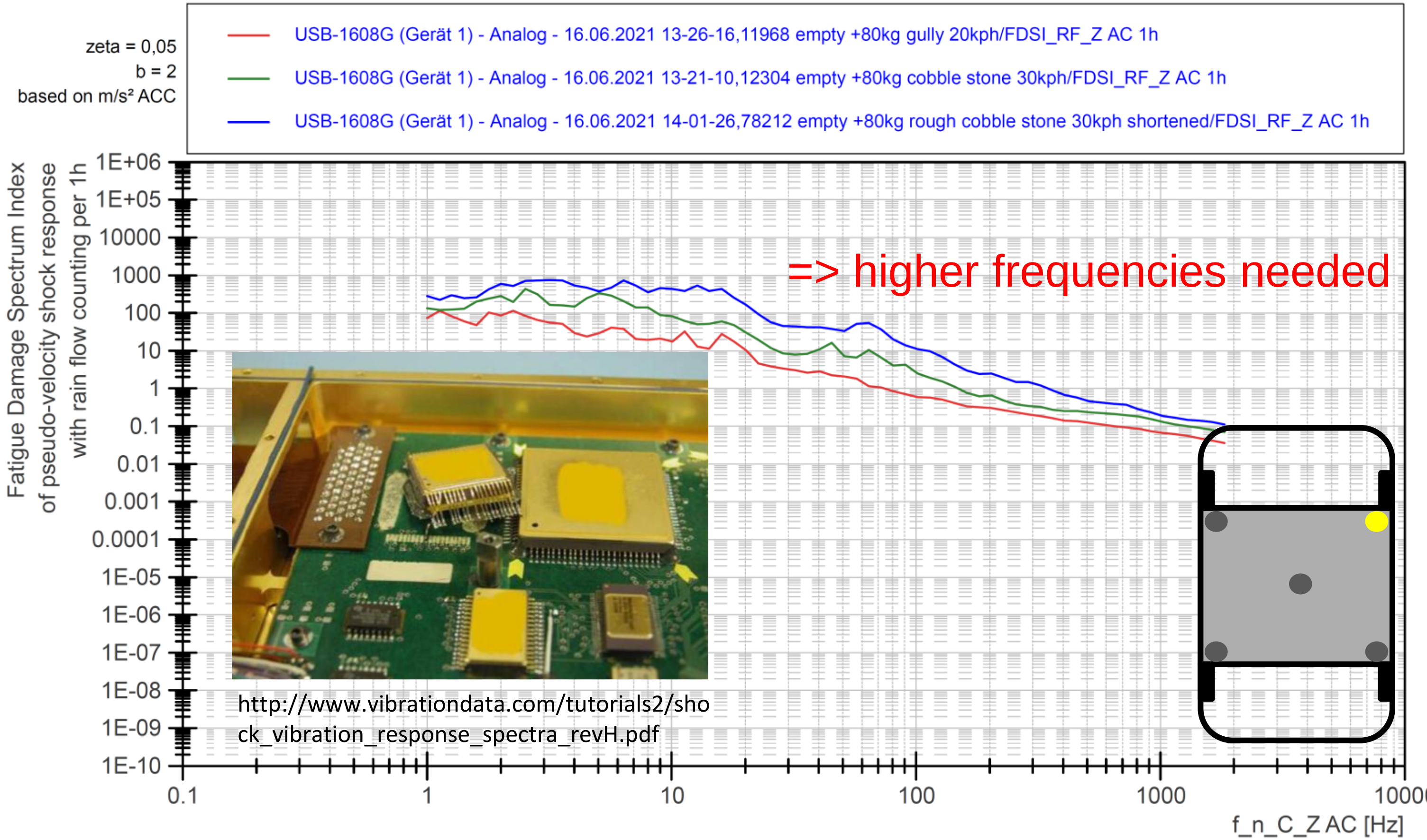
- Fatigue damage calculated to 1h of exposure is highest from rough cobble stone track

RESULTS FROM PRIOR ANALYSIS

Innotesting 2025

VW ID3 Fatigue Damage Spectrum

- FDS of the right front (RF) corner of the battery pack with
- Wöhler-curve exponent of 2 and 5% damping



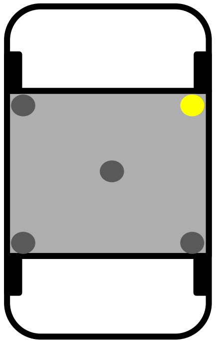
- Solder with (low cycle fatigue) suffers more from high frequency input
- For SDOF RMS < 1 (as for ground acceleration in [m/s]): higher frequencies rotated upwards

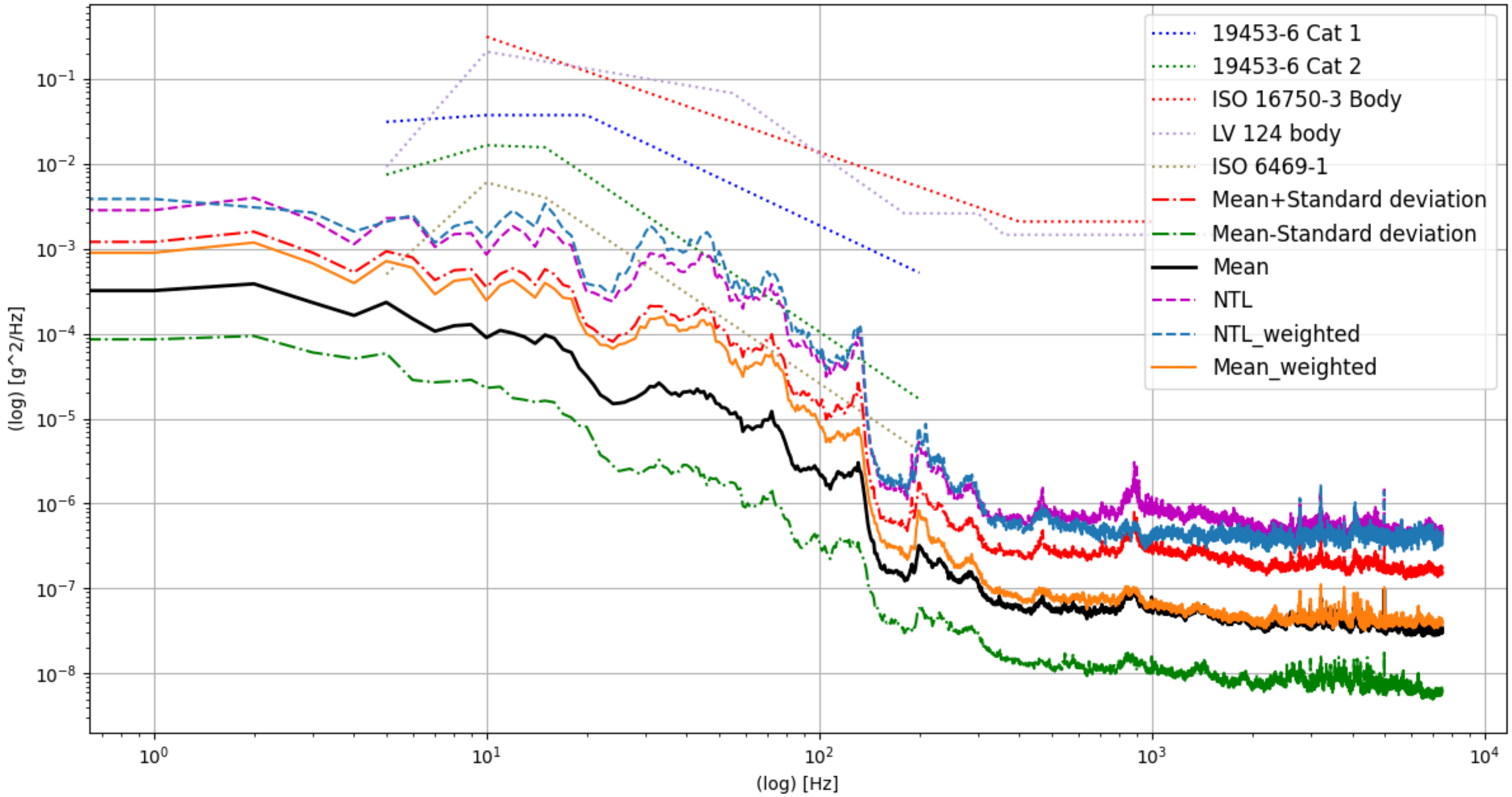
RESULTS FROM PRIOR ANALYSIS

preliminary results VW ID3, BMW i3 load profile for bad road

- 80% good road
- 20% bad road (10% cobble stone, 10% rough cobble stone)
- good road < infinite life

Innotesting 2022



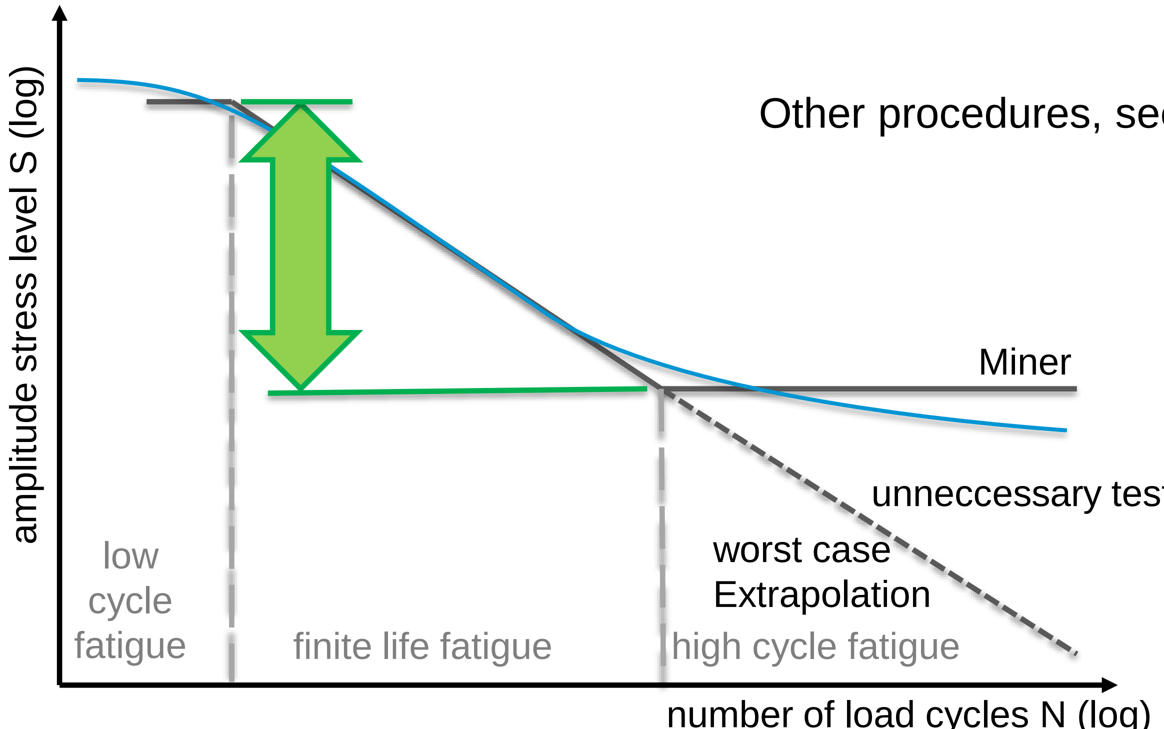


RESULTS FROM PRIOR ANALYSIS

Test Time Reduction based on measurement selection

- 80% good road
- 20% bad road (10% cobble stone, 10% rough cobble stone)
- good road < infinite life
- Any measurement file with SRS lower than factor 4 than maximum SRS measurement will be neglected

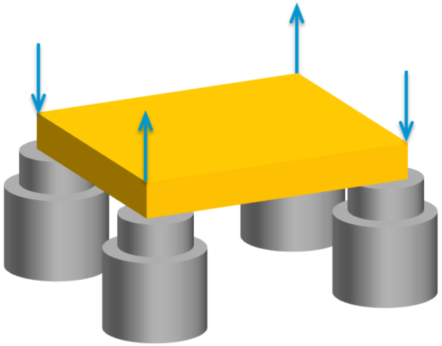
- 80% good road => can safely be neglected



BEV STRUCTURAL DYNAMICS

Measurements so far

- Ongoing measurement campaigns with various types of vehicles and battery pack designs
- Analysis for design impacts
- Development of test method
- Specification of test



Opel Corsa E

road surface events
rough cobble stone 30kph
cobble stone 30kph
manhole cover 30kph
city drive tarmac HH 50kph
country roads tarmac-100kph
motorway tarmac-120kph
motorway concrete-120kph

BEV STRUCTURAL DYNAMICS

Statistical

Tesla Model 3 performance (sporty suspension)

Rough Cobble Stone (main NTL driver)

TRACK19_2_Tesla_3_rough_cobble_stone_30kph_285kg_edited

Channel	Minimum gn	Maximum gn	ArithmeticMean gn	SquareMean gn	StandardDeviation gn	Skewness 1	Kurtosis 1
C_Z AC	-5.09	5.83	-9.89E-18	0.171	0.171	0.0748	20.95
RF_Z AC	-4.22	3.81	1.25E-17	0.234	0.234	-0.0610	4.90
RR_Z AC	-9.71	5.42	-2.73E-17	0.328	0.328	-0.0783	6.17
LR_Z AC	-3.86	3.41	1.96E-17	0.352	0.352	0.0175	3.08
LF_Z AC	-12.04	6.74	7.57E-18	0.237	0.237	-0.227	17.82
Ax_RF_Z AC	-8.78	7.25	-6.94E-17	1.86	1.86	-0.0755	3.24
Be_RF_X AC	-1.57	1.57	2.62E-17	0.111	0.111	0.0234	3.70
Be_RF_Z AC	-2.25	3.34	-3.64E-18	0.262	0.262	9.87E-04	3.03
RM_Z AC	-2.68	2.37	1.01E-17	0.305	0.305	-0.0413	3.00
LM_Z AC	-14.87	2.21	-1.24E-17	0.324	0.324	-0.173	11.54
FrontM_Z AC	-3.68E-03	3.41E-03	-8.56E-19	7.18E-04	7.18E-04	7.09E-03	3.00
RearM_Z AC	-3.31E-03	4.27E-03	1.36E-18	7.63E-04	7.63E-04	0.0456	3.02
AX_LR_Z AC	-15.04	17.65	-3.52E-18	2.55	2.55	-0.126	3.51
BE_LR_Z AC	-8.23	7.85	-8.49E-18	0.379	0.379	0.0785	7.35
Be_RF_Y AC	-2.83	2.83	-5.87E-18	0.180	0.180	-0.0171	3.60

BEV STRUCTURAL DYNAMICS

Statistical

Tesla Model 3 performance (sporty suspension)

Rough Cobble Stone (main NTL driver)

TRACK19_2_Tesla_3_rough_cobble_stone_30kph_285kg_edited

Channel	Minimum gn	Maximum gn	ArithmeticMean gn	SquareMean gn	StandardDeviation gn	Skewness 1	Kurtosis 1
C_Z AC	-5.09	5.83	-9.89E-18	0.171	0.171	0.0748	20.95
RF_Z AC	-4.22	3.81	1.25E-17	0.234	0.234	-0.0610	4.90
RR_Z AC	-9.71	5.42	-2.73E-17	0.328	0.328	-0.0783	6.17

- Center: very high Kurtosis, correct?
- Right Front: slightly higher Kurtosis than 3, very low Skewness, correct?
- Right Rear: higher Kurtosis than 3, very low Skewness, correct?

- Log10 bell curve?

$$Kurtosis = \frac{E(X-\mu)^4}{\sigma^4}, here\ \frac{1}{n}\sum_{i=1}^{n}\left(\frac{x_i - 0}{RMS}\right)^4$$

BEV STRUCTURAL DYNAMICS

Statistical

Tesla Model 3 performance (sporty suspension)
Rough Cobble Stone (main NTL driver)

Log10 bell curve?

- Shapiro-Wilk-Test

p ist die Wahrscheinlichkeit, dass ein Datensatz, der wirklich normalverteilt ist, mindestens so stark von einer perfekten Normalverteilung abweicht wie dein beobachteter Datensatz
Je kleiner p, desto unwahrscheinlicher, dass die Daten normalverteilt sind
$p > 0{,}05$ (typischer Schwellenwert) → keine ausreichenden Belege gegen Normalverteilung→ Daten normalverteilt
$p \leq 0{,}05$ → die Daten weichen statistisch signifikant von einer Normalverteilung ab
→ Nullhypothese ablehnen

BEV STRUCTURAL DYNAMICS

Statistical

Tesla Model 3 performance (sporty suspension)
Rough Cobble Stone (main NTL driver)

Log10 bell curve?
Shapiro-Wilk Test

Channel: C_Z
Shapiro raw a : p = 1.2599e-27
Shapiro log10(|a|) : p = 8.5223e-50

Channel : RF_Z
Shapiro raw a : p = 8.7086e-27
Shapiro log10(|a|) : p = 3.0573e-53

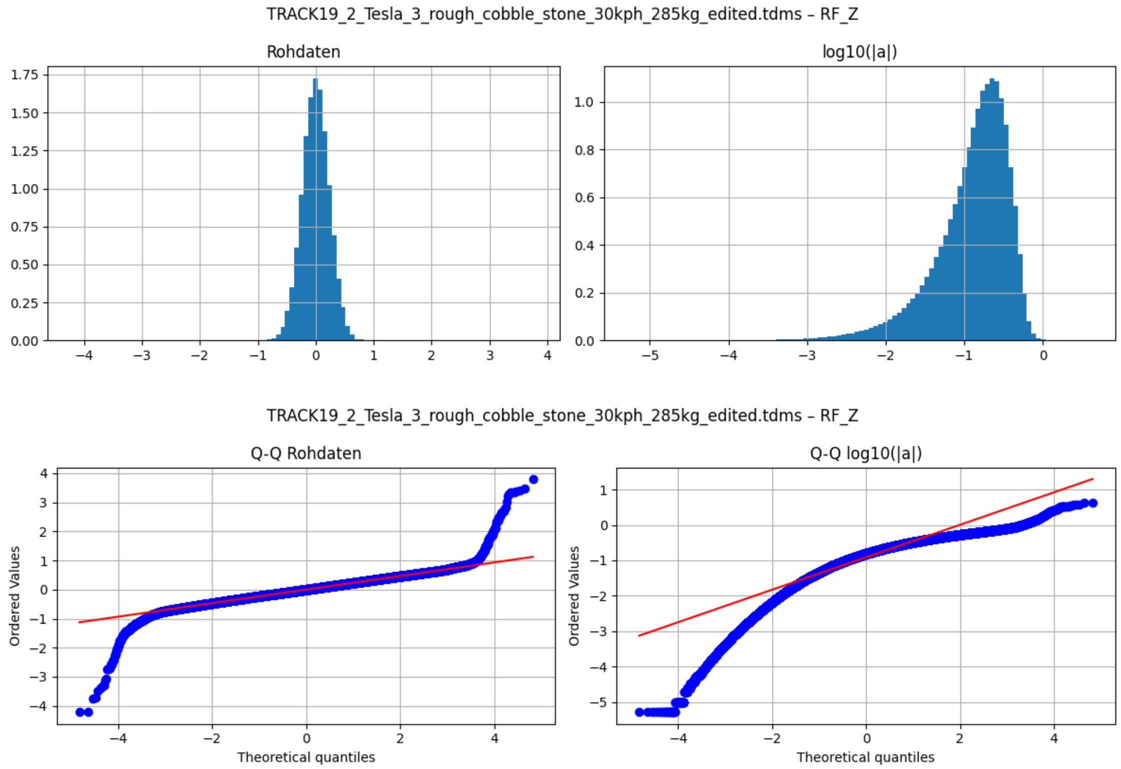
Channel : RR_Z
Shapiro raw a : p = 8.6611e-19
Shapiro log10(|a|) : p = 1.3686e-55

- Both are very low, not clear

BEV STRUCTURAL DYNAMICS

Statistical

- Right Front
- Log10 bell curve?
- Histogram and Quantile – Quantile plot
- Mapping data set to be tested against ideal Kurtosis 3 data set
- Data set to be tested either raw data or log10 of raw data



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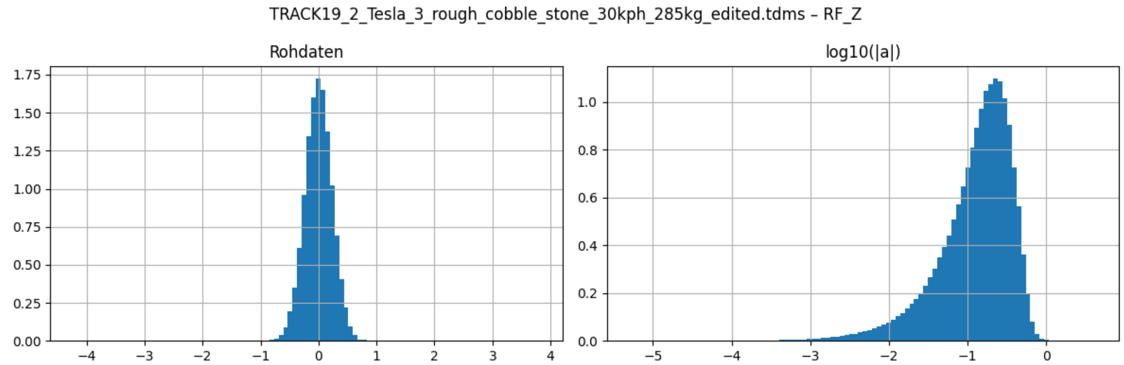
BEV STRUCTURAL DYNAMICS

Statistical

- Right Front
- Histogram

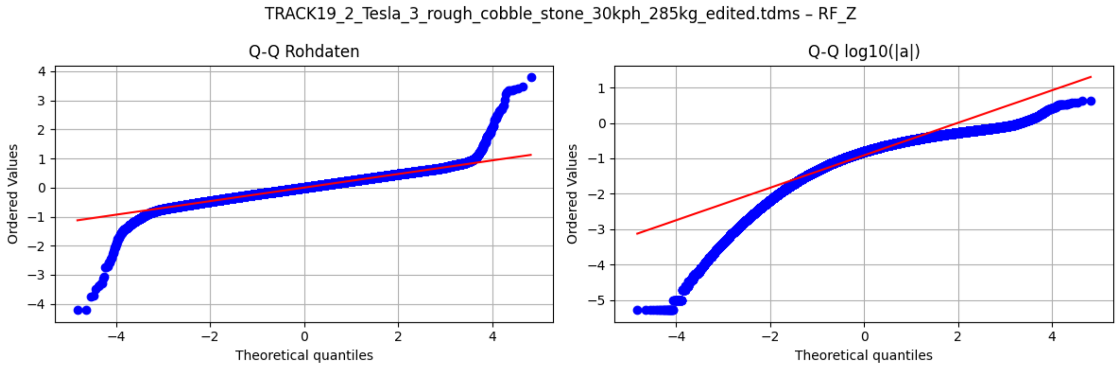


- Both no gaussian / bell curve
- Log10 could be more gaussian if not for possible Skewness influence

BEV STRUCTURAL DYNAMICS

Statistical

- Right Front
- Log10 bell curve?
- Quantile – Quantile plot

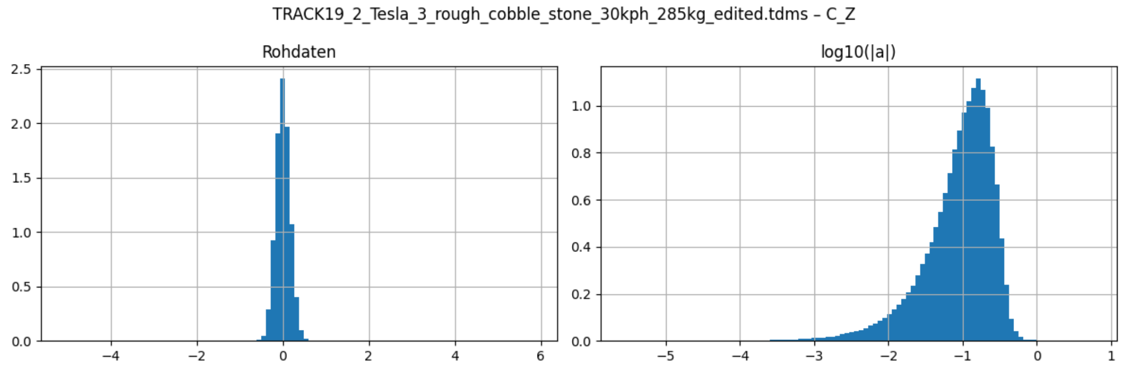


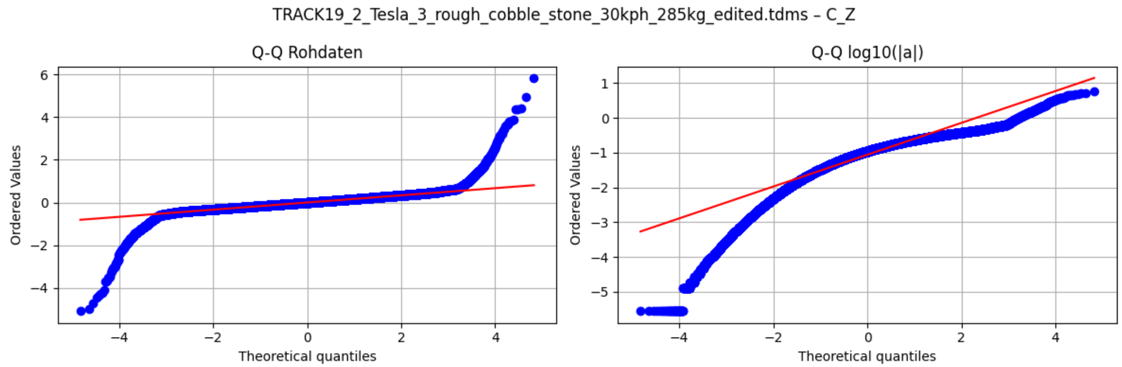
- Straight line: gaussian / bell curve
  - True for many values around the center (around 0) for non-log10
  - Over all values including the tails: better in log10 (at least for positive tail)
- Clearly a lot of extreme values outside normal distribution => high Kurtosis!
- Offset from 0,0: mean not exactly 0? Or unsymmetric even though not clearly detected by Skewness
- Probably unsymmetric extremes

BEV STRUCTURAL DYNAMICS

Statistical

- Center (with heavy mass of battery pack)
- Histogram and Quantile – Quantile plot



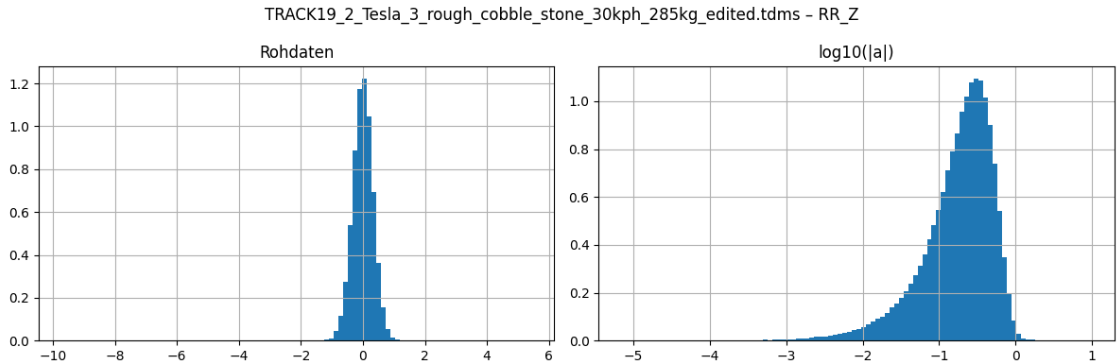


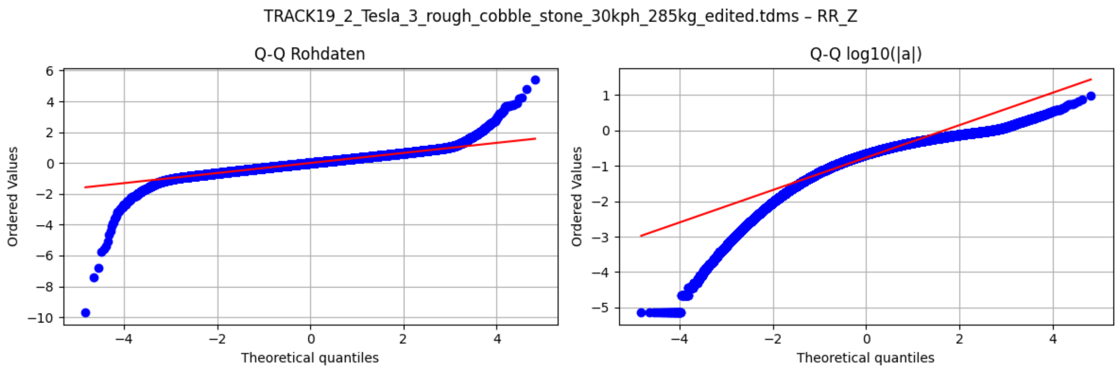
- Extreme Kurtosis: Rattling? (Other measurements have less, but still high Kurtosis)
- Log10 corners at least the positive tail better
- Probably unsymmetric extremes from non-linear contact

BEV STRUCTURAL DYNAMICS

Statistical

- Right Rear
- Histogram and Quantile – Quantile plot





- high Kurtosis: Rattling?
- Log10 corners at least the positive tail better
- Probably unsymmetric extremes from non-linear contact

BEV STRUCTURAL DYNAMICS

Statistical

Assumptions from statistical analysis

- Rattling causes non-linear extremes
- Log10 corners at least the positive tail better
- Probably unsymmetric extremes (non-linear contact)
- Heavy unsymmetric tails:
  Shapiro-Wilk not helpful, Skewness and Kurtosis to be used with caution
- D'Agostino, Anderson: not gaussian for raw as well as log10

Consequences

- Extremes are important for failure analysis
- Log10 gaussian bell curve distribution used for analysis for lack of alternatives
- Normal Tolerance Limit is using log10 gaussian bell curve distribution

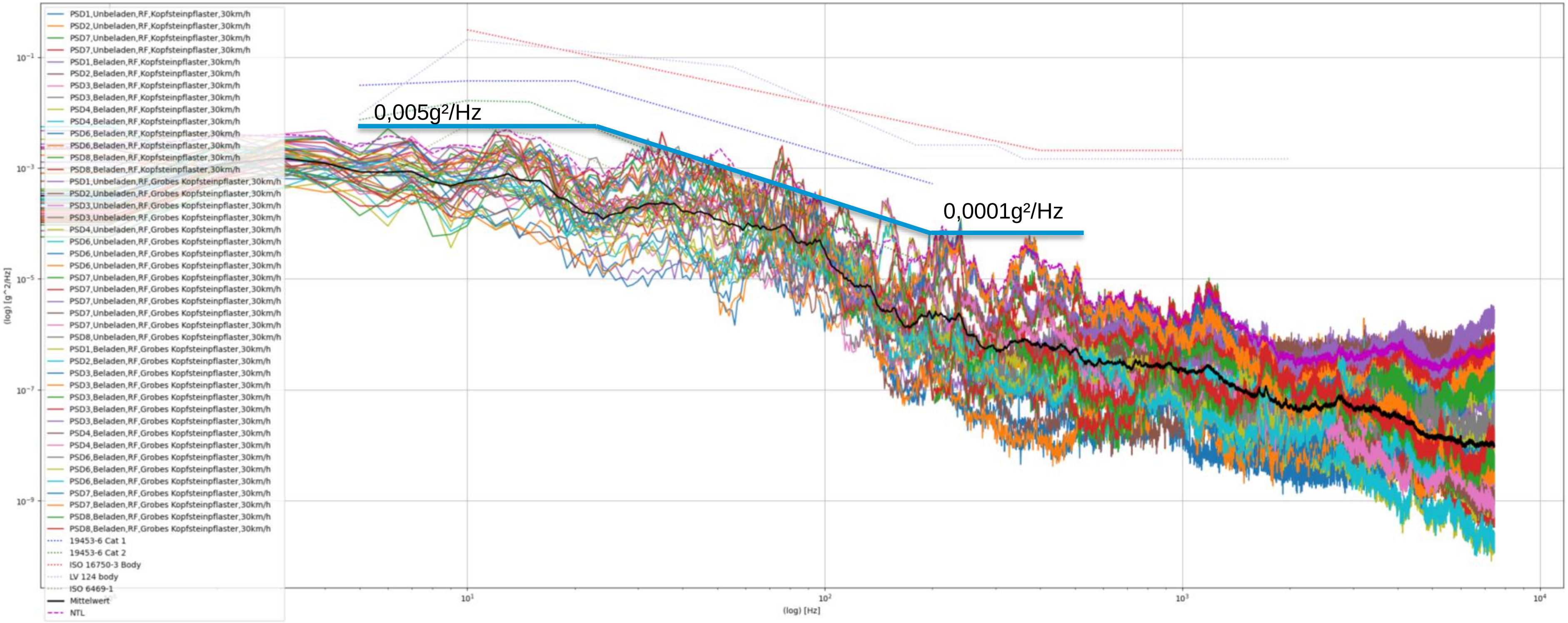
Statistical

- IEC 60721-2-9: Normal Tolerance Limit is using log10 gaussian bell curve distribution
- 95 % of the measurements considered for analysis are under this limit
- 50 % probability / confidence 50 %, that a new measurement will also be under this limit (statistically neutral, no extra safety factor to the 95%)

BEV STRUCTURAL DYNAMICS

NTL 95/50

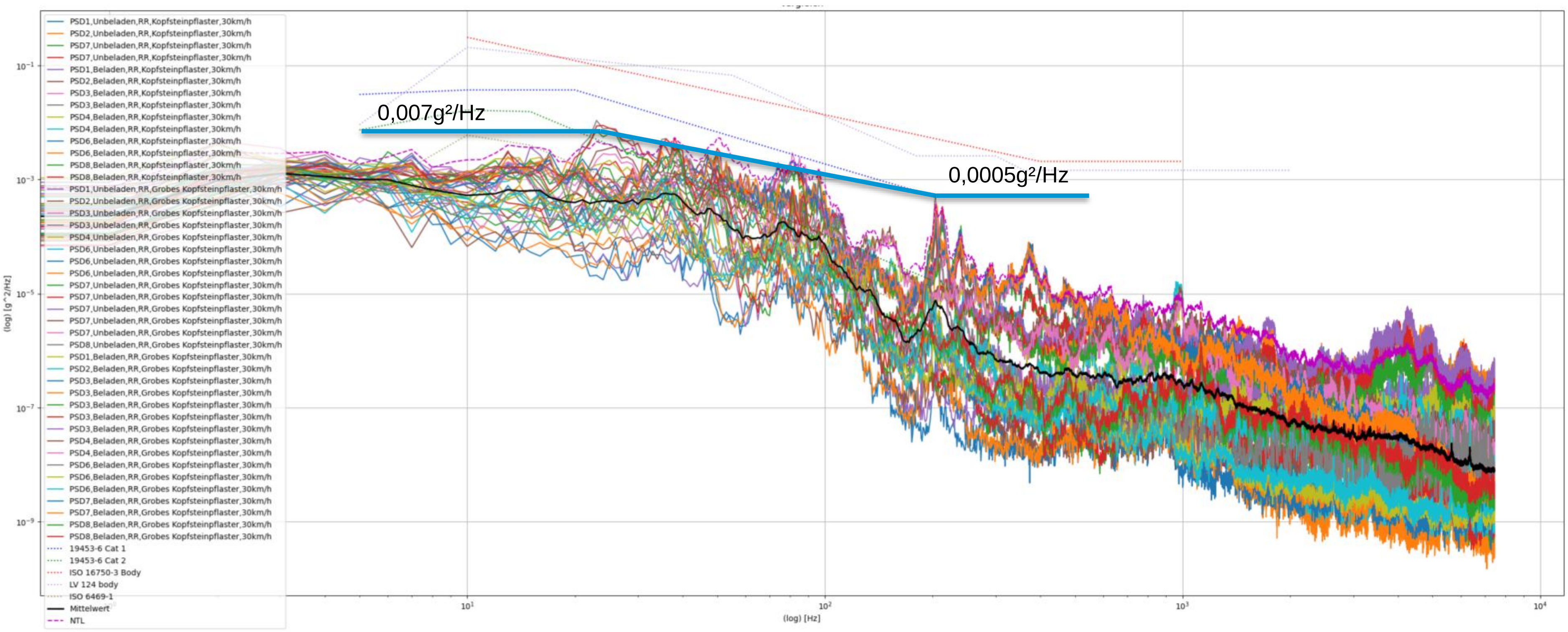
- All passenger cars, not A-Car small commercial
- Only rough surfaces (cobble stone and rough cobble, ca. 1:1), loaded and empty
- Right Front



BEV STRUCTURAL DYNAMICS

NTL 95/50

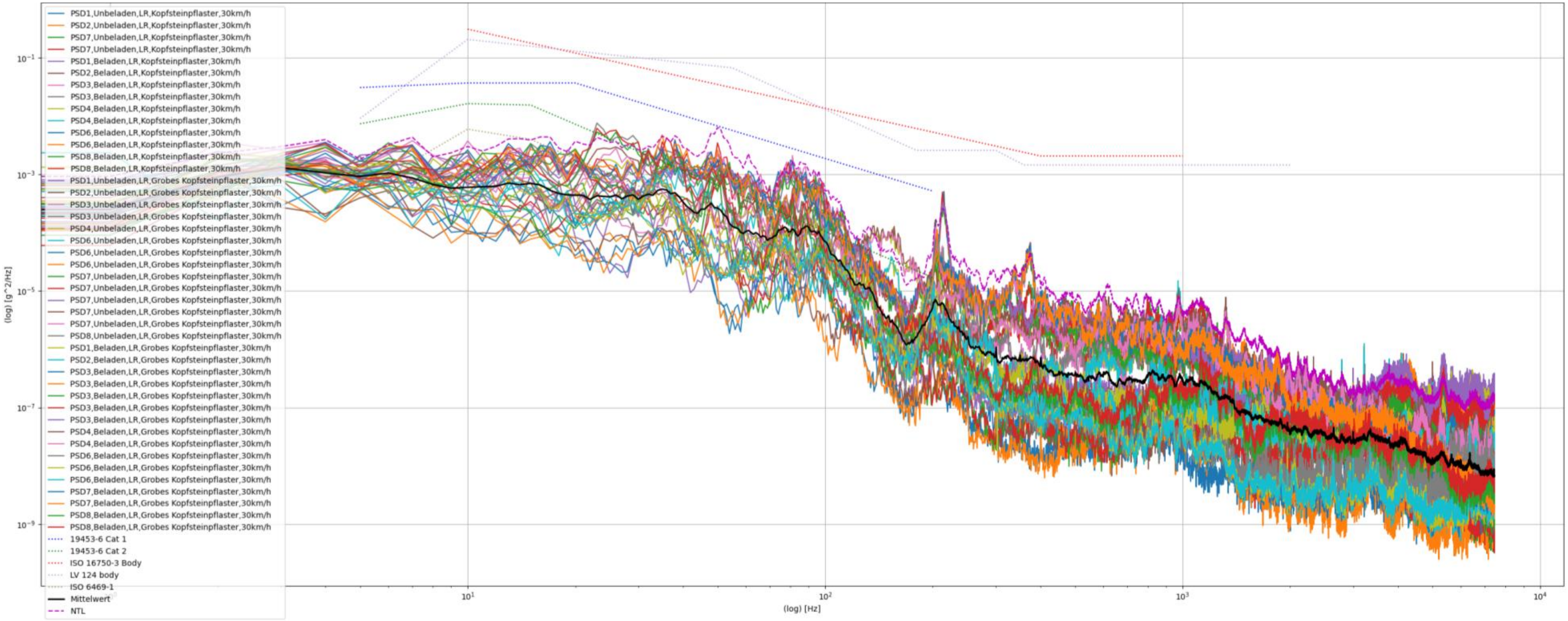
- All passenger cars, not A-Car small commercial
- Only rough surfaces (cobble stone and rough cobble, ca. 1:1), loaded and empty
- Right Rear



BEV STRUCTURAL DYNAMICS

NTL 95/50

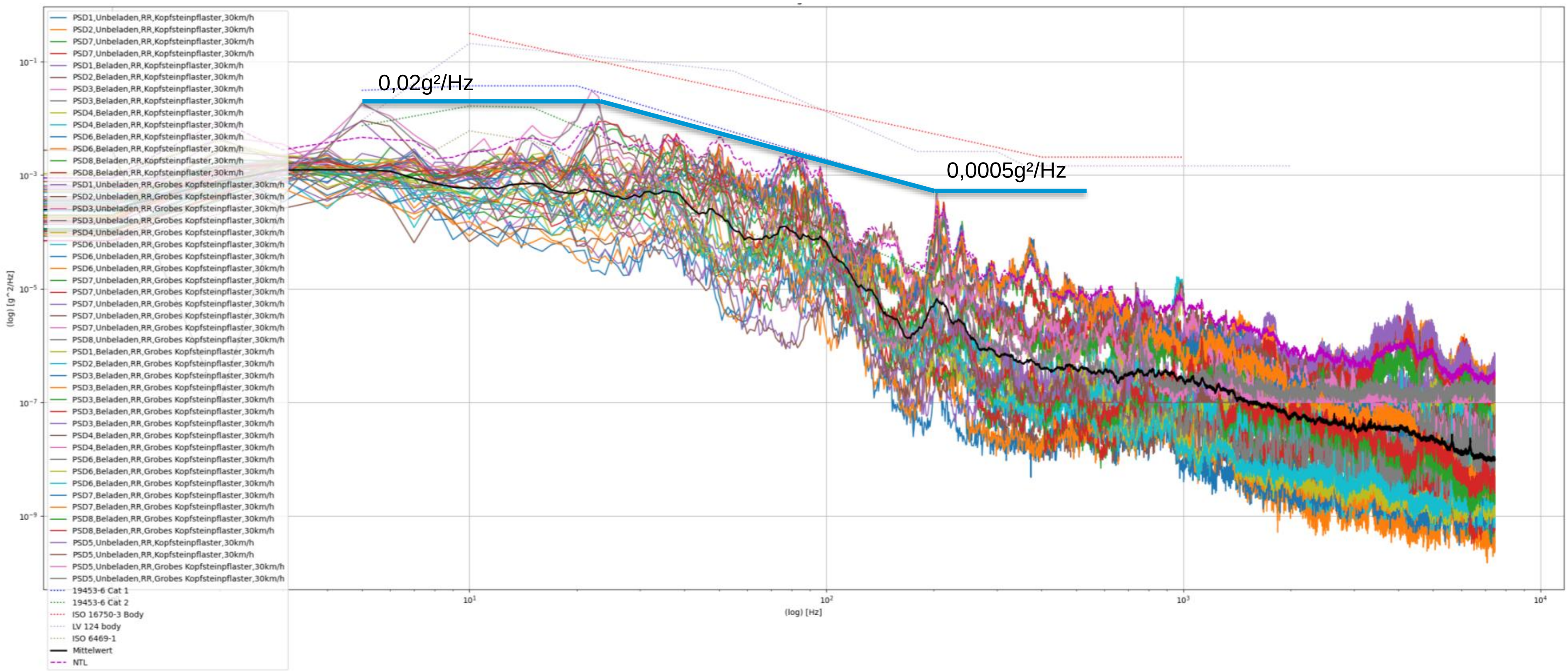
- All passenger cars, not A-Car small commercial
- Only rough surfaces (cobble stone and rough cobble, ca. 1:1), loaded and empty
- Left Rear



BEV STRUCTURAL DYNAMICS

NTL 95/50

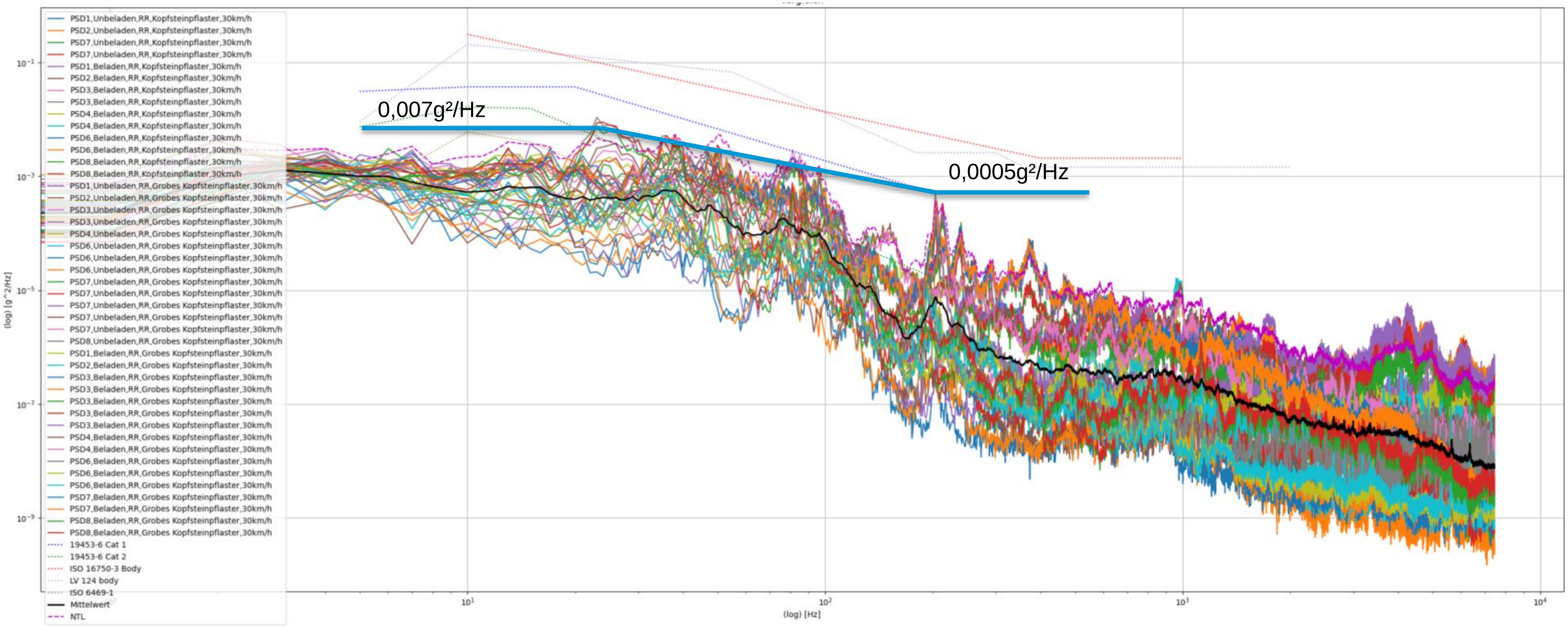
- All vehicles measured, including A-Car small commercial
- Only rough surfaces (cobble stone and rough cobble, ca. 1:1), loaded and empty
- Right Rear
- A-Car is statistical outlier



BEV STRUCTURAL DYNAMICS

NTL 95/50

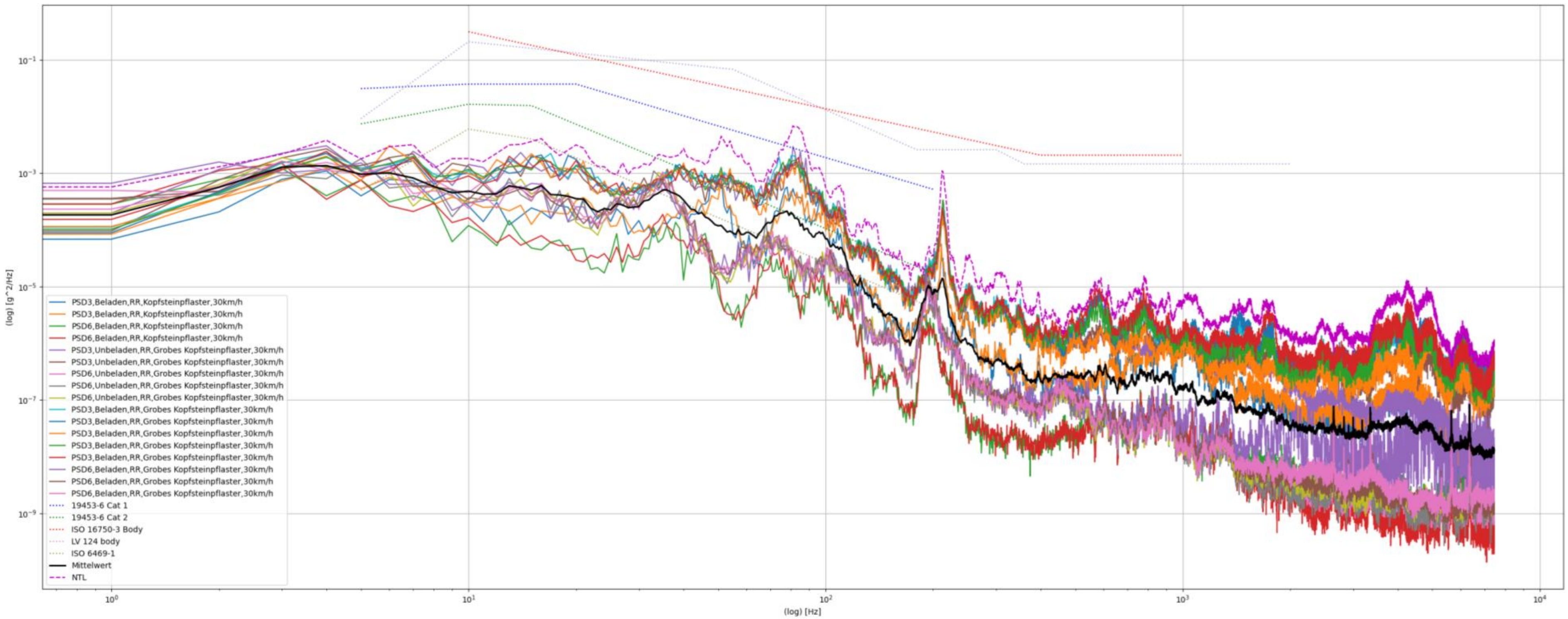
- All passenger cars, not A-Car small commercial
- Only rough surfaces (cobble stone and rough cobble, ca. 1:1), loaded and empty
- Right Rear
- (reference)



BEV STRUCTURAL DYNAMICS

NTL 95/50 – outlook to future with higher coupling

- Tesla Model 3 Performance & ID.Buzz (higher coupling to vehicle)
- Only rough surfaces (cobble stone and rough cobble, ca. 1:1), loaded and empty
- Right Rear
- Higher resonance peaks up to 500Hz (but also less statistical data)



BEV STRUCTURAL DYNAMICS

NTL 95/50

Results:

- Right Rear higher than Right Front
- right side higher than left side
- A-Car small commercial (worst case) increases overall slightly and in certain bands significantly
- incoherent for higher frequencies >200Hz
- coherent and incoherent depending on conditions <200Hz

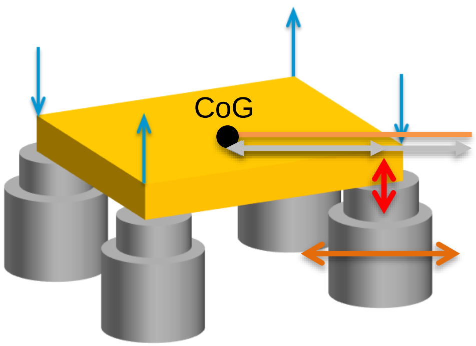
- 95/50 NTL somewhere between Cat 1 und Cat 2 in ISO 19453-6
- Log10 not really capturing extreme heavy tails from non-linear one-sided rattling

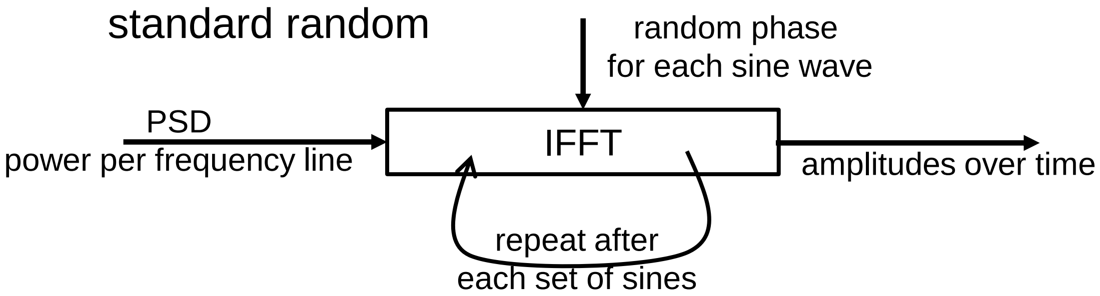
BEV STRUCTURAL DYNAMICS

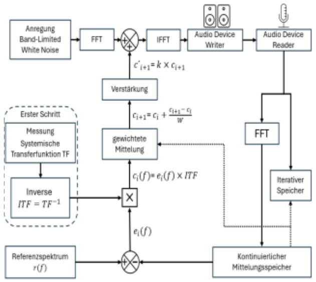
Ideas and outlook:

- Stiffness influence of vehicle is partly considered by moving the shakers more closely to the center (stiffer vehicle, less lever) or outwards (more yield of the battery due to more yield of vehicle, long lever)

- Stiffness of vehicle transferred to control system?







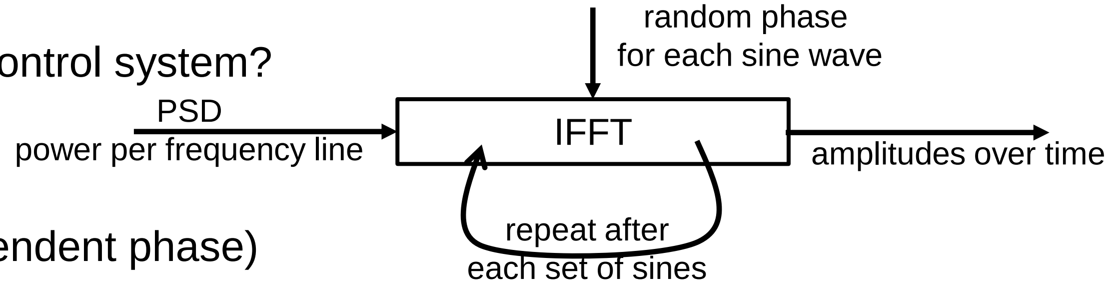
Martin Knorr:

BEV STRUCTURAL DYNAMICS

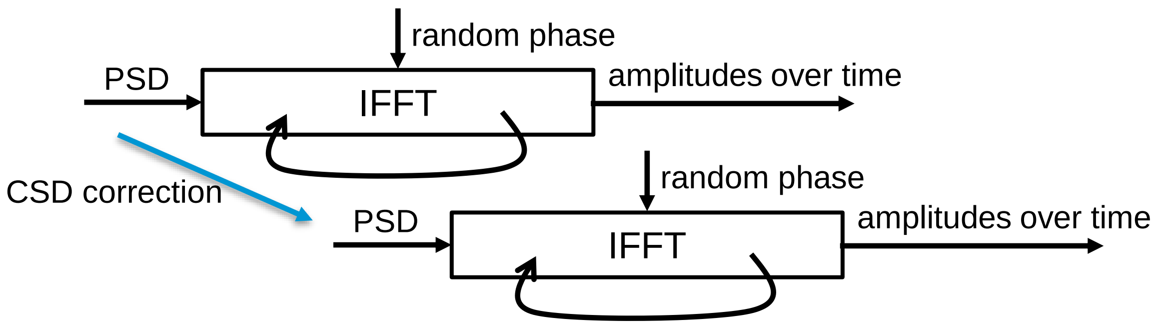
Ideas and outlook:

Stiffness of vehicle transferred to control system?

standard random

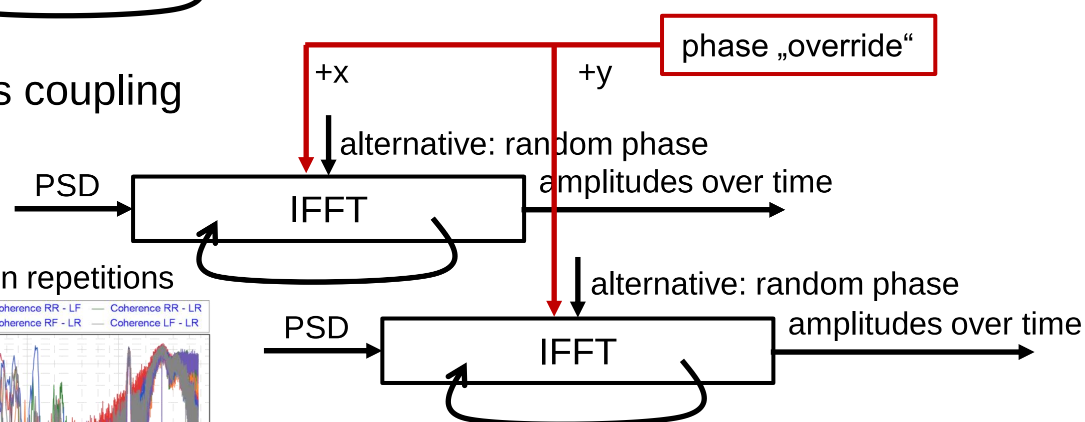


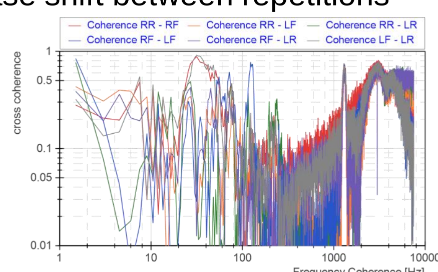
MIMO 2P standard random (independent phase)



MIMO 2P NEW with gradual stiffness coupling

- by frequency range
- coupling on/off for gradual coupling
- same phase vs. constant phase shift between repetitions





Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

Vielen Dank für die Aufmerksamkeit!

Faculty Aviation and Automotive Systems
Prof. Dr.-Ing. Benedikt Plaumann

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