OICA inputs for PMP meeting

on 25th of March 2025

Version 24.03.2025

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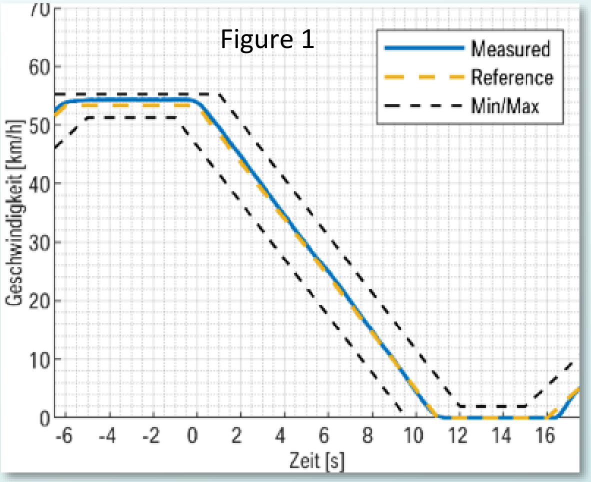
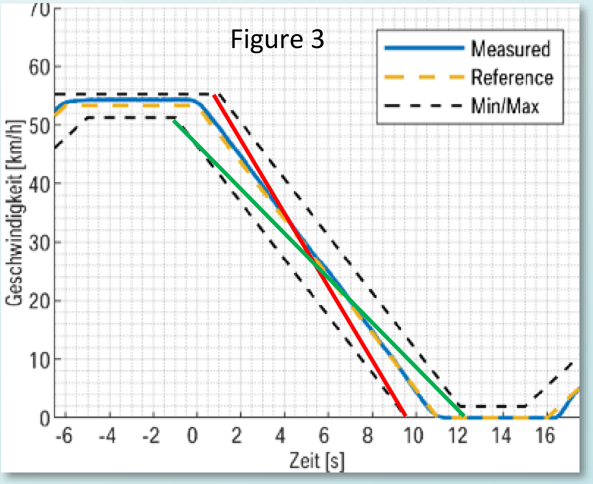
Additional chassis dyno quality criteria

(Item 49)

Brake Emissions Quality Criteria

- EU7 Brake Emissions are measured according to measuring instruction GTR24* by using WLTP Brake Test Cycle.
- WLTP Brake Cycle consists of 303 brake events, representative for an average European driver's braking behaviour[1]
- Every single brake event is represented by one single deceleration rate value = a straight line in speed reduction (---) (see fig 1): e.g. Brake event #060 [2] : 1.345 m/s^2 = 13.8 % g (53.3 km/h to 0 in 11 s)
- Every brake event contributes to one data point in the "fingerprint" distribution of the 303 brake events (figure 2).
- Any deviation from the ideal speed profile (---) results in a derogation of the prescribed WLTP Brake Cycle, even if the driver stays inside the min/max boundaries (---) e.g. 55.3 km/h to 0 in 9 s = 1.707 m/s^2 = 17.4 % g (-) or 51.3 km/h to 0 in 13 s = 1.096 m/s^2 = 11.2 % g (-) (fig. 3).
- Quality Criteria for the driving behaviour during WLTP Brake exist through reference to GTR15 ("smooth", "accurate" and "non-biased" driving), but no braking-behaviour specific and quantifiable criteria exist.
- For a good reproducibility, repeatability and comparability, new Quality Criteria for braking have been developed and shall be supported for a legal certainty & better reproducibility.
- This also leads to a much better comparability of the recuperation behaviour during braking of individual vehicles.





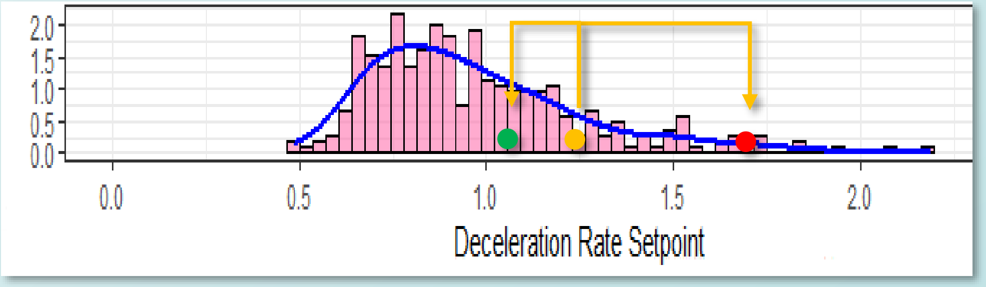


Figure 2: „fingerprint" of deceleration rates of WLTP Brake Cycle

- Any deviation from the ideal speed profile results in different decelerating rates and resulting braking powers and no longer represents the prescribed WLTP Brake Cycle
- **Therefore, new brake-related quality criteria have been developed by OICA for a smooth, accurate & non-biased braking behaviour to insure legal certainty.**

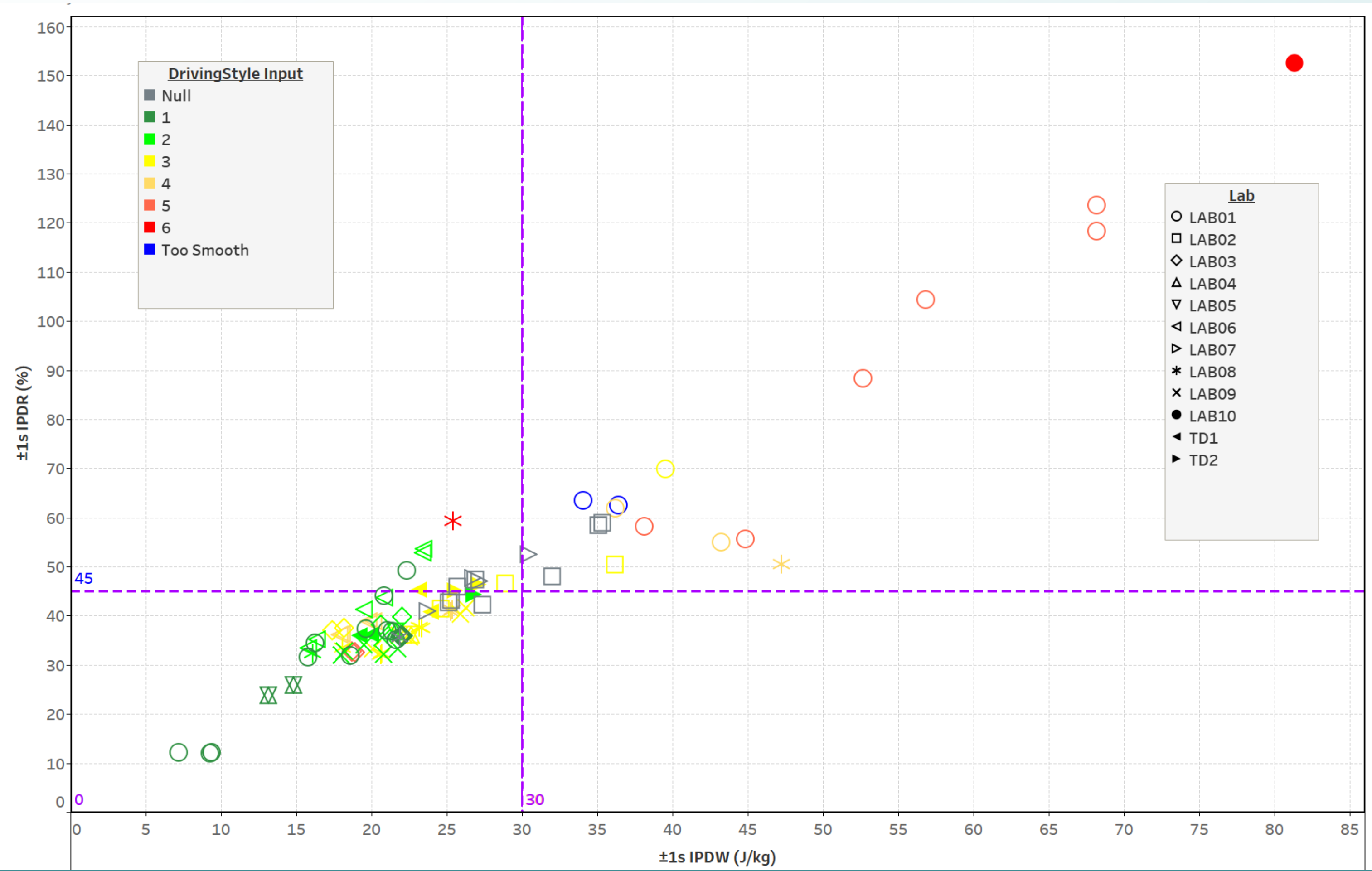
[*] *GTR = Global Technical Regulation* [**] *WLTP = Worldwide*

[1] *A novel real-world braking cycle for studying brake wear particle emissions*, M. Mathissen et al., Wear, 414-415, 219, 2016, https://www.sciencedirect.com/science/article/abs/pii/S004316481830557X

[2] GTR24, Annex B, latest version

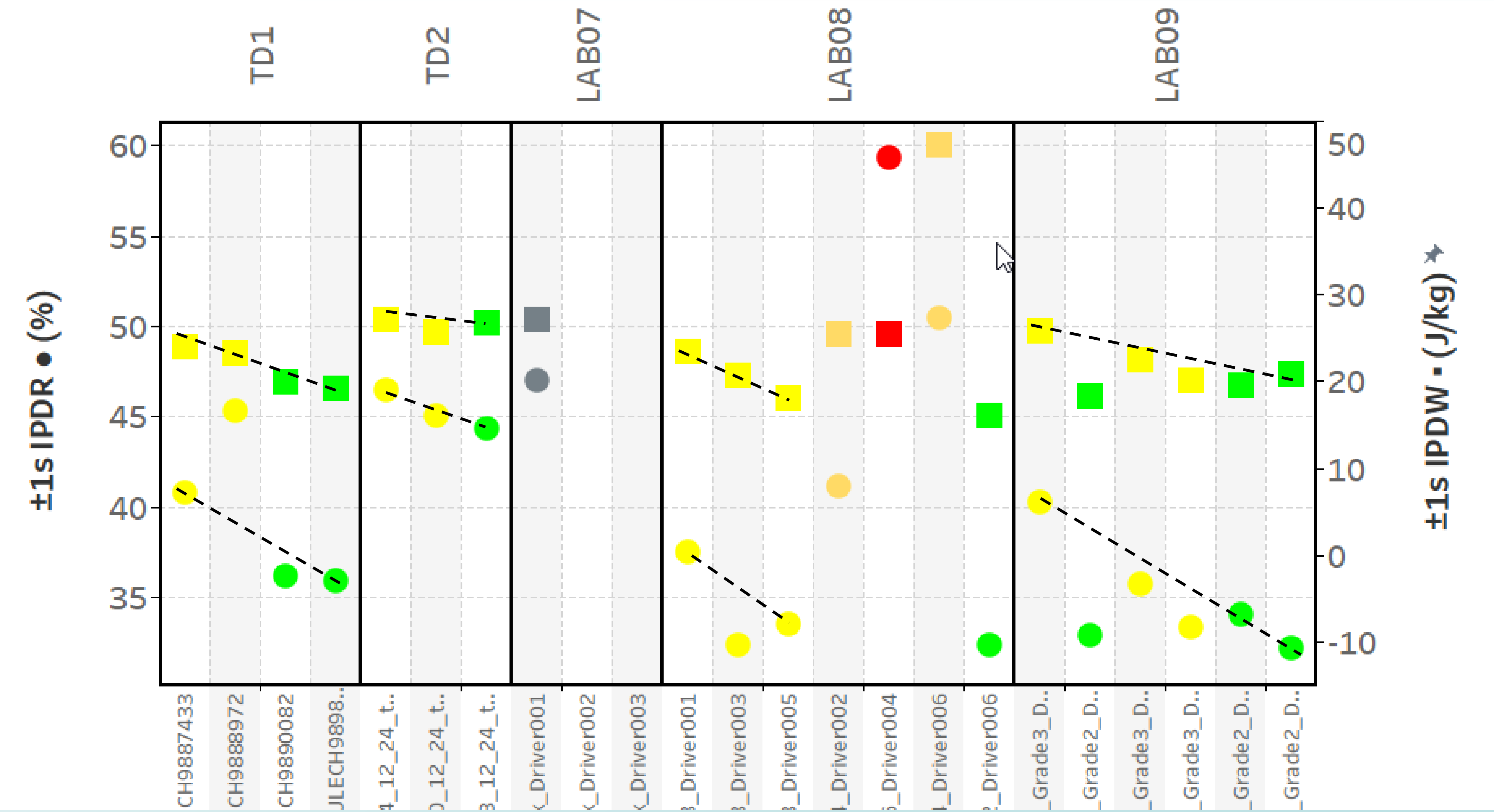
Quality Criteria

Results and Potential Limits of IPDW & IPDR

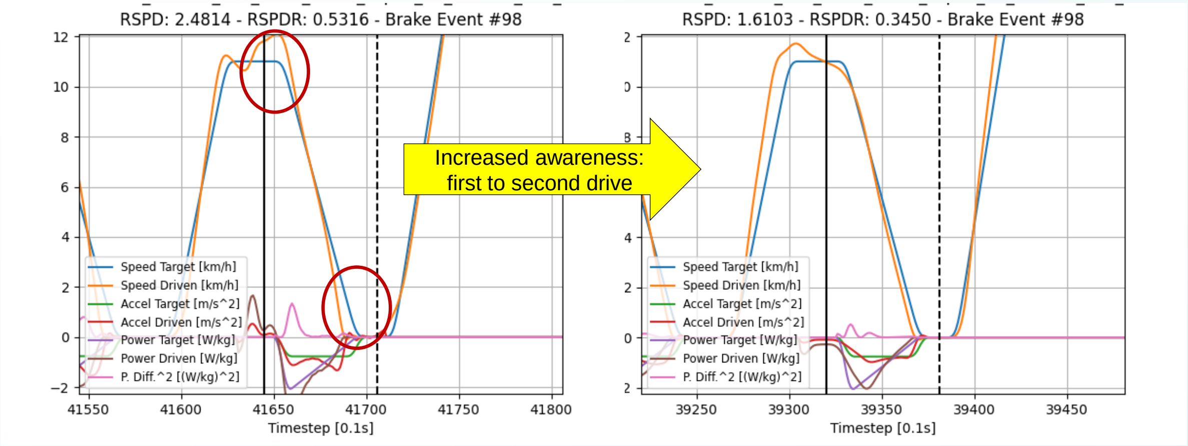


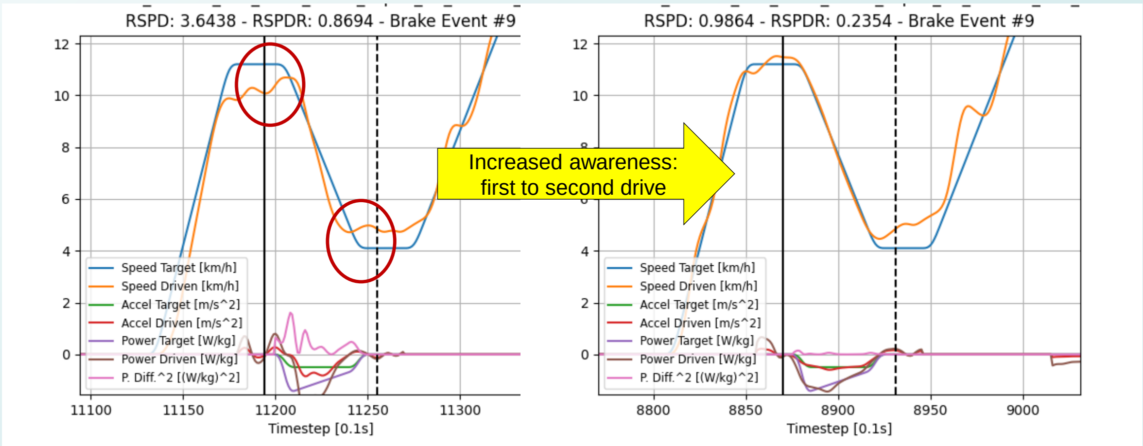
- **12 Labs participated in the OICA Round Robin for Quality Criteria.**
- **IPDW & IPDR successfully detect the different driving/braking quality.**
- **Limit suggestion: IPDR = 45 %, IPDW = 30 J/kg**

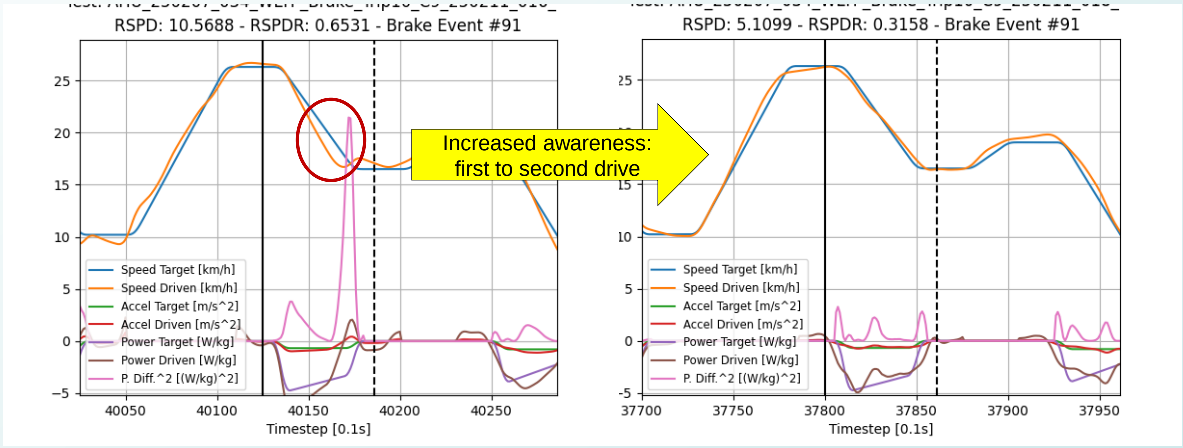
Drivers get used to WLTP-brake cycle quite fast.
Example of learning curves from OICA data collection

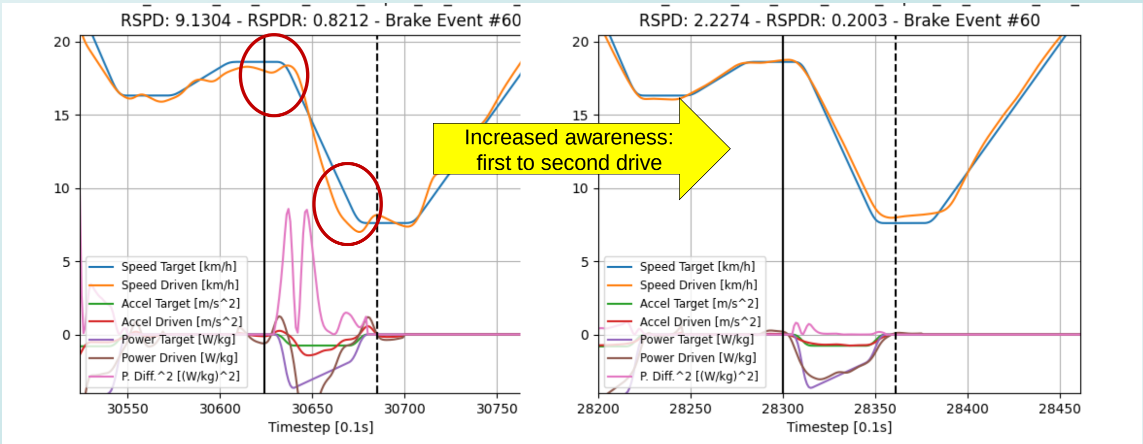


Keeping the concentration over the long cycle is difficult. Quality improves as drivers learn to focus on the brake events rather than acceleration phases.









1. TRIP10

IPDR = 47.5%
IPDW = 46.5 (J/kg)

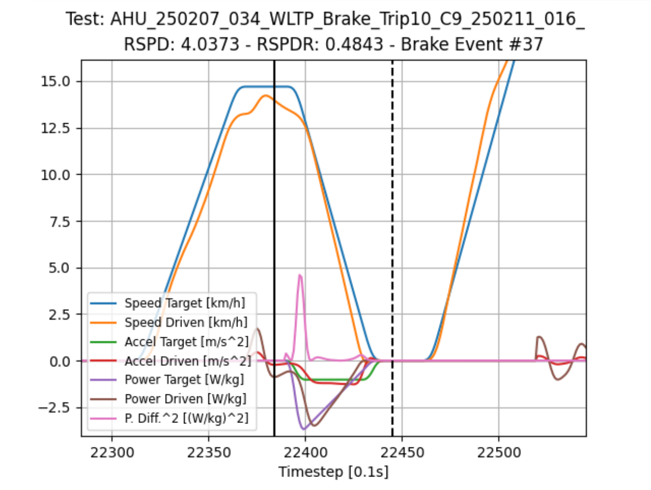
Increased awareness:
first to second drive

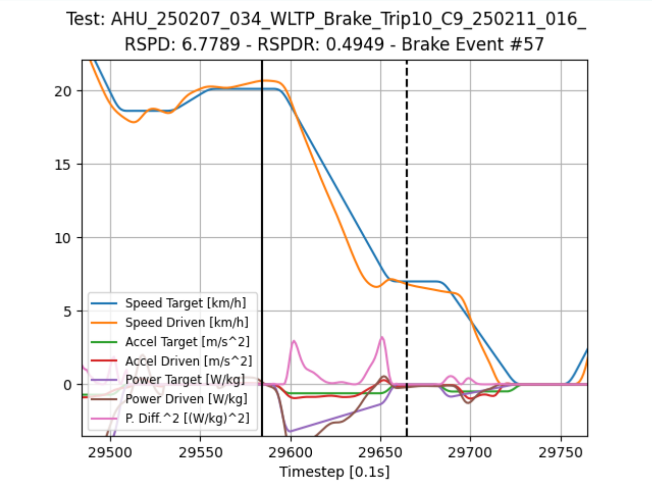
2. TRIP10

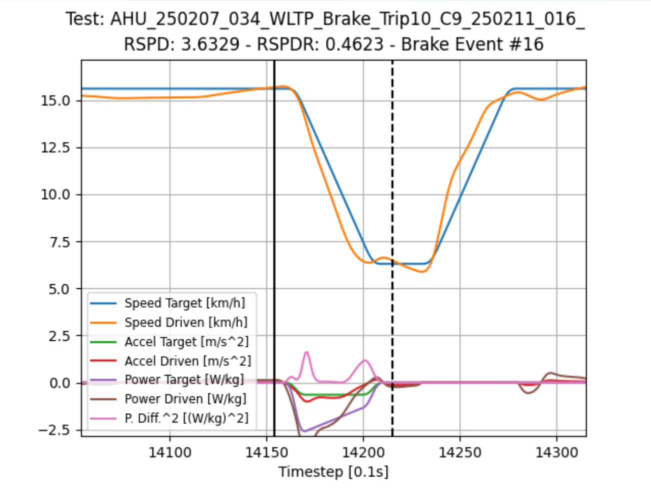
IPDR = 31.4%
IPDW = 14.8

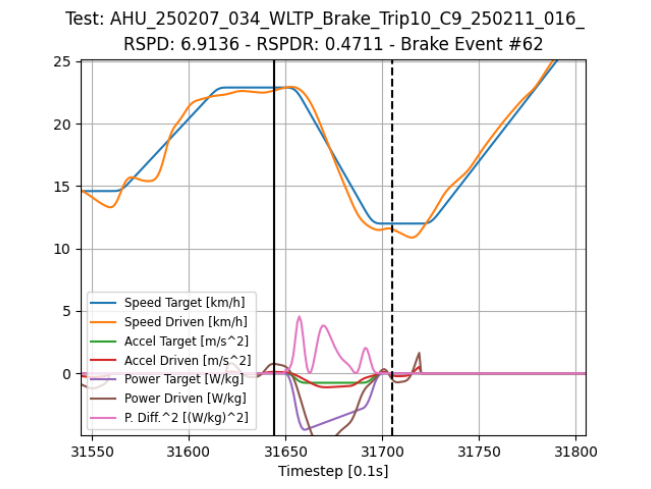
- With the right focus, professional drivers can improve the quality criteria significantly and reach **values below 40% and 30 (J/kg)**
- **No „training“** is needed only **raising awareness**.

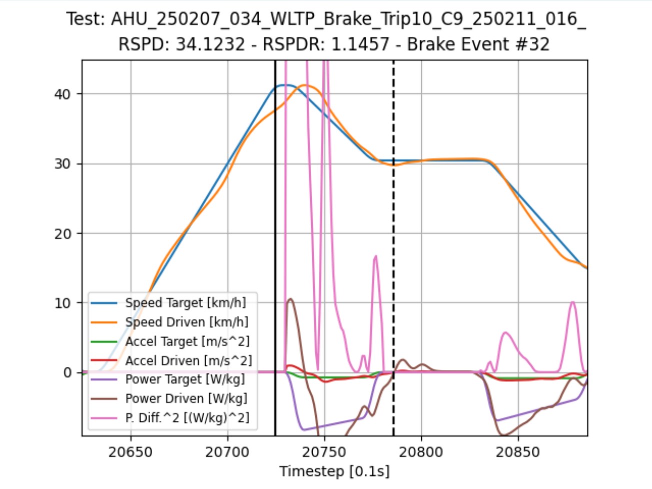
Driven cycles with IPDR Value higher then 45% show bad driving behavior. They are not accurate enough. (Exemplary brake stops of a cycle with 47% RSPDR)

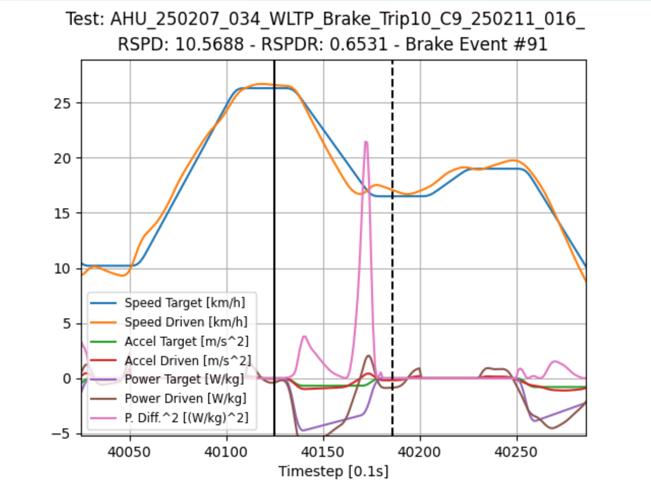












- With the right focus, professional drivers can improve the quality criteria significantly and reach **values below 40% and 30 (J/kg)**
- **No „training“** is needed only **raising awareness**.

Threshold pressure (Item 31)

- **Background**. OICA proposed a statistical approach to derive the threshold pressure from the 250Hz dataset of the corner dyno.
  Testing the methodology with several datasets coming from the ILS-3 resulted in a high variability.
  ILS-3 group proposed to have a default value for disk brakes.

OICA proposal

3.1.19. "*Threshold pressure*" means the minimum hydraulic pressure to overcome the internal friction and seal forces, move the brake calliper's piston or drum wheel cylinder, and onset brake torque output. ~~A fixed value of 100 kPa shall be used for disc brake applications.~~ The OEM may declare a value based on its own accepted methodology. Absent this declaration, a default value of 100 kPa may be used for disc brake applications or 350 kPa for drum brake applications. One or the other shall be used with preference given to the OEM declared value when available. The source of the value shall be declared in the test report.

- **Proposal**. OICA position is that OEMs should be allowed to declare the threshold pressure value when the default value does not reflect the behaviour of the brake system under testing.

- **Next steps.** Further investigations are needed to determine the necessary data filtering/handling of the signals used to compute $P_{threshold}$ (such as pressure and torque) to ensure data quality in order to make OICA procedure a viable option.

Table 5.3

- **Background**. Due to the small amount of data available for fuel-cell vehicles, it was decided not to define fixed c-factor values for NOVC-FCHVs and OVC-FCHVs for the time being.
- **Proposal**. OICA accepted JRC proposal to have 0.9 as temporary fixed c-factor values for fuel-cell vehicles.

OICA proposal

Table 5.3.

Friction braking share coefficients for all vehicle electrification types

Brake type	*Vehicle Electrification Type*	*Friction Braking Share Coefficient (c)*
Full-friction braking	ICE and other vehicle electrification types not covered in the non-friction braking categories in this Table	1.0
Non-friction braking*	NOVC-HEV Cat. 0 **	0.90
	NOVC-HEV Cat. 1	0.72
	NOVC-HEV Cat. 2	0.52
	OVC-HEV	0.34
	PEV	0.17

**Note*: Testing facilities may use vehicle-specific friction braking share coefficients measured and calculated according to Annex C of this UN GTR.

***Note*: NOVC-FCHV and OVC-FCHV vehicle electrification types shall be considered as NOVC-HEV Cat. 0 for the purpose of this table.

Annex C clarifications and adaptations

Annex C has been reviewed and the following modifications are proposed :

- Paragraph 2 (Scope and Application) → Removal of FCEVs from the scope of Annex C due to the absence of a rechargeable battery in the powertrain architecture
- Paragraph 4.1 (Vehicle Selection) → Clarified that some brake functions needs to be deactivated for a safe chassis dyno testing (e.g. AEBS)
- Paragraph 4.5 (Test sequence) → Addition of the GTR15 references for fuel-cell vehicles and corrections of the references for driver-selectable modes
- Paragraph 5.1 (Equivalency of Methods) → Inclusion of fuel-cell vehicles
- Paragraph 6 (Equivalency of Test Cycle) → Clarified that trip 10 shall be executed as stand-alone test cycle starting with fully charged battery
- Corrections in equations C.16, C.19 and C.20

BACK-UP

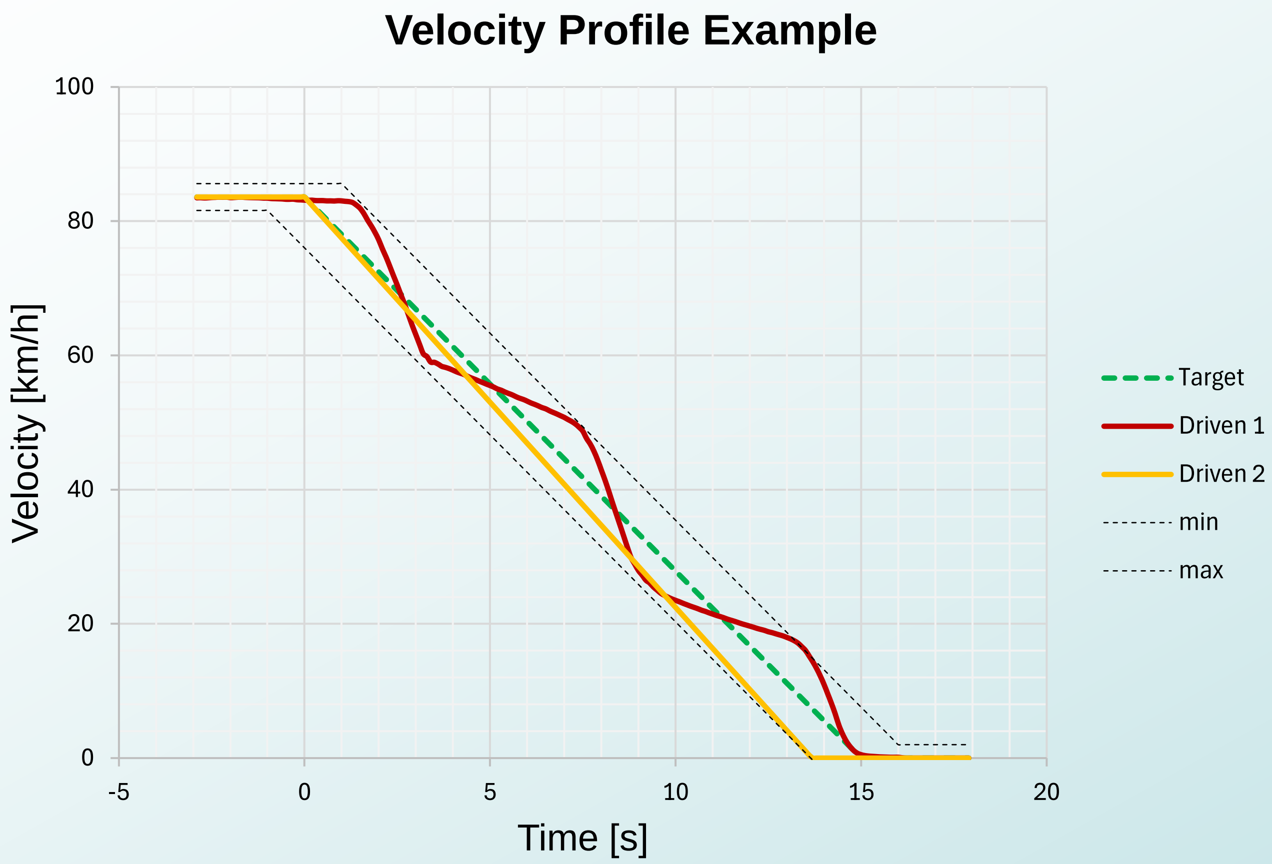
Quality Criteria
Overview

- GTR24 refers to GTR15 for driving quality
- GTR15 defines three quality criteria
  - Allowed velocity deviation – Range of ±2 km/h within ± 1s (same as GTR24)
  - RMSSE – Root Mean Squared Speed Error
  - IWR – Inertial Work Rating

- All criteria were developed for driving/acceleration
- GTR24 deals with braking/deceleration

- **Existing criteria are not sufficient to detect poor driving/braking style during the WLTP Brake Cycle.**
- **Thus two new criteria are suggested to ensure an accurate and smooth braking.**

Quality Criteria
Insufficient RMSSE-Criterion



RMSSE-Criterion from GTR15:

- Root Mean Squared Speed Error
- Average difference of velocity

Example Result:

$$\mathbf{RMSSE_1} = 3.62\ \frac{\mathbf{km}}{\mathbf{h}}$$

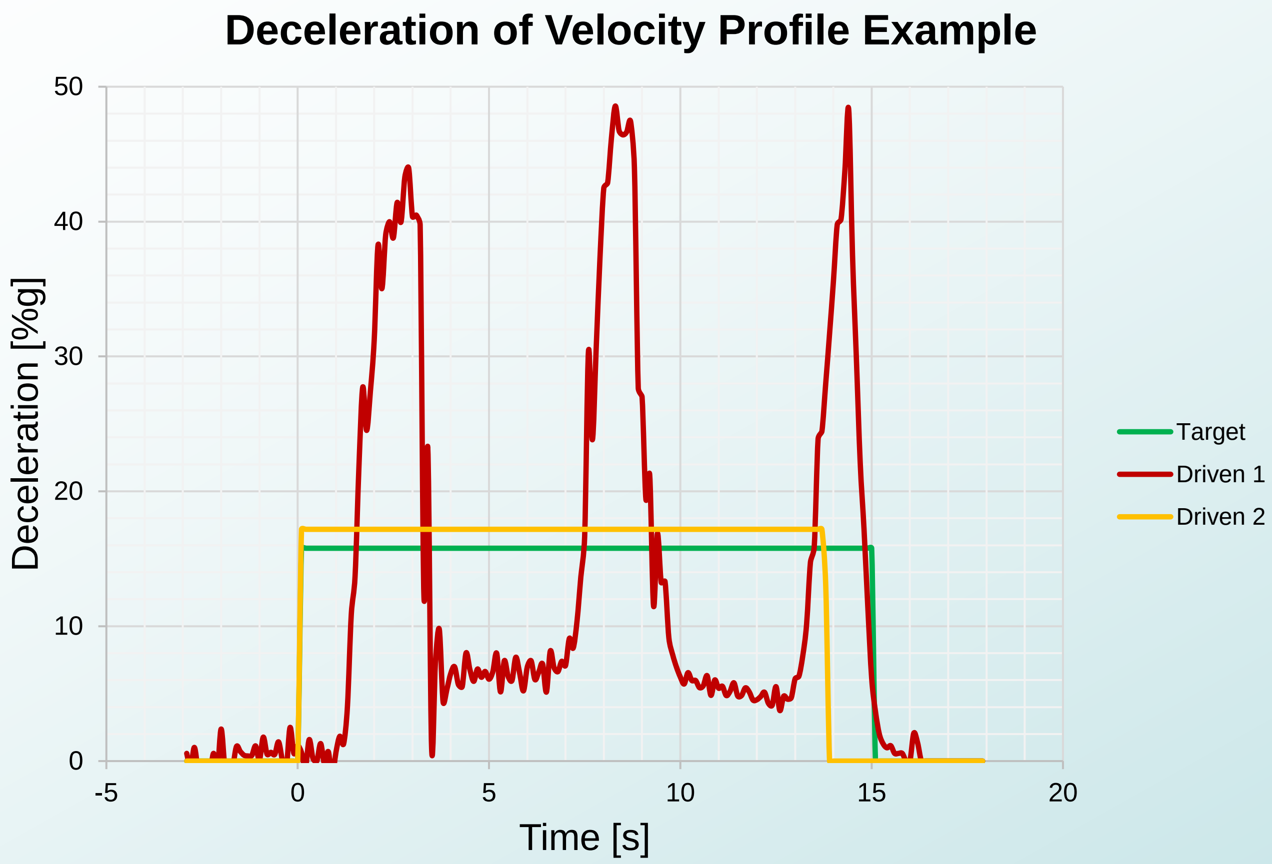
$$\mathbf{RMSSE_2} = 3.62\ \frac{\mathbf{km}}{\mathbf{h}}$$

- Same result for absolutely different driving characteristic

Reason: The average deviation of a small constant deviation is similar to a large oscillating deviation.

➢ **Same RMSSE results for absolutely different driving styles**

Quality Criteria
Insufficient RMSSE-Criterion



Maximum Deceleration

- Different velocity profiles yield very different deceleration profiles

Example Result:

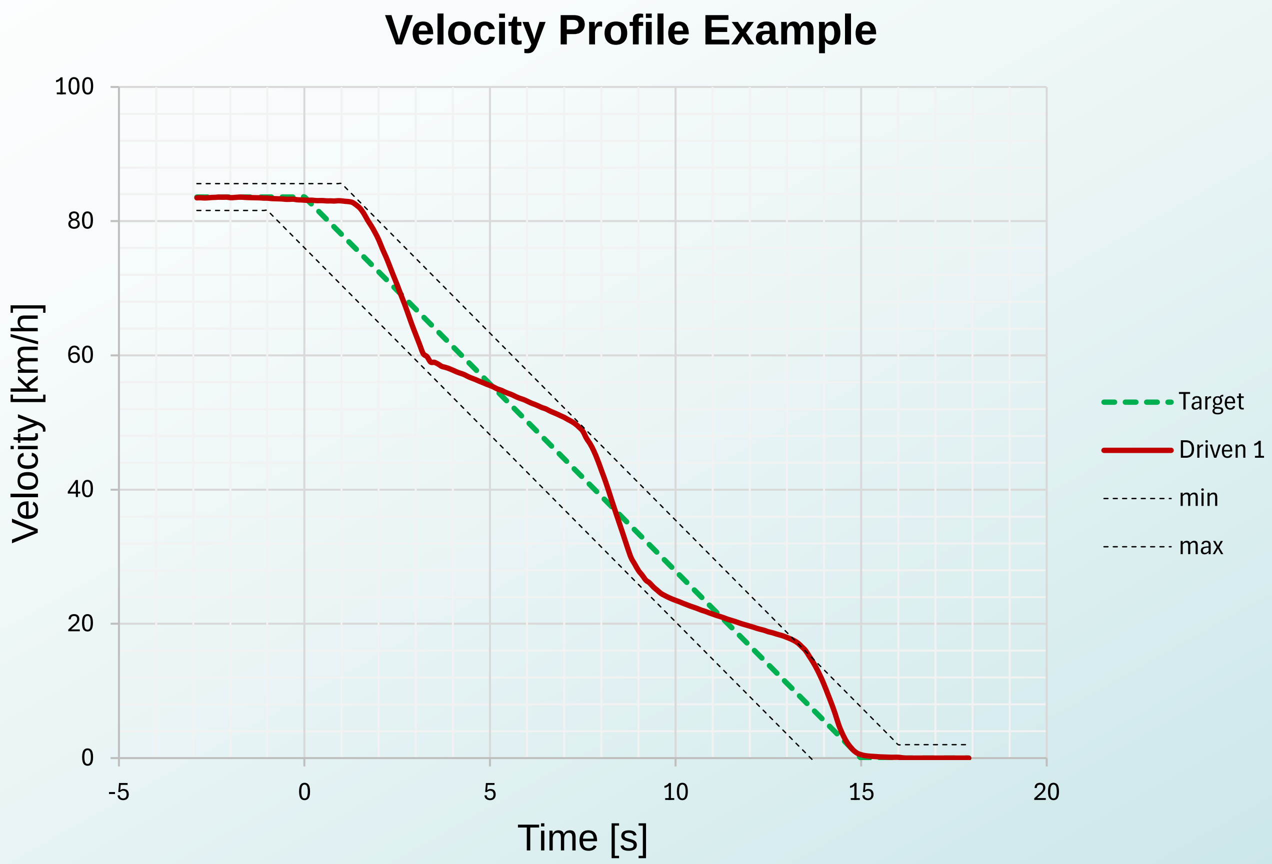
$a_T \approx 16\ \%g$

$a_1 \approx 50\ \%g$

$a_2 \approx 18\ \%g$

- ➢ **Same RMSSE result but 2-3x higher deceleration and thus 2-3x higher braking force/torque**
- ➢ **RMSSE not sufficient**

Quality Criteria
Insufficient IWR-Criterion



IWR-Criterion from GTR15:

- Inertial Work Rating
- Relative difference of actual and target inertial work
  (Defined in GTR15 for acceleration → adapted to deceleration for GTR24)

Example Result:

$$\mathbf{IWR_1 = 0.005\,\%}$$

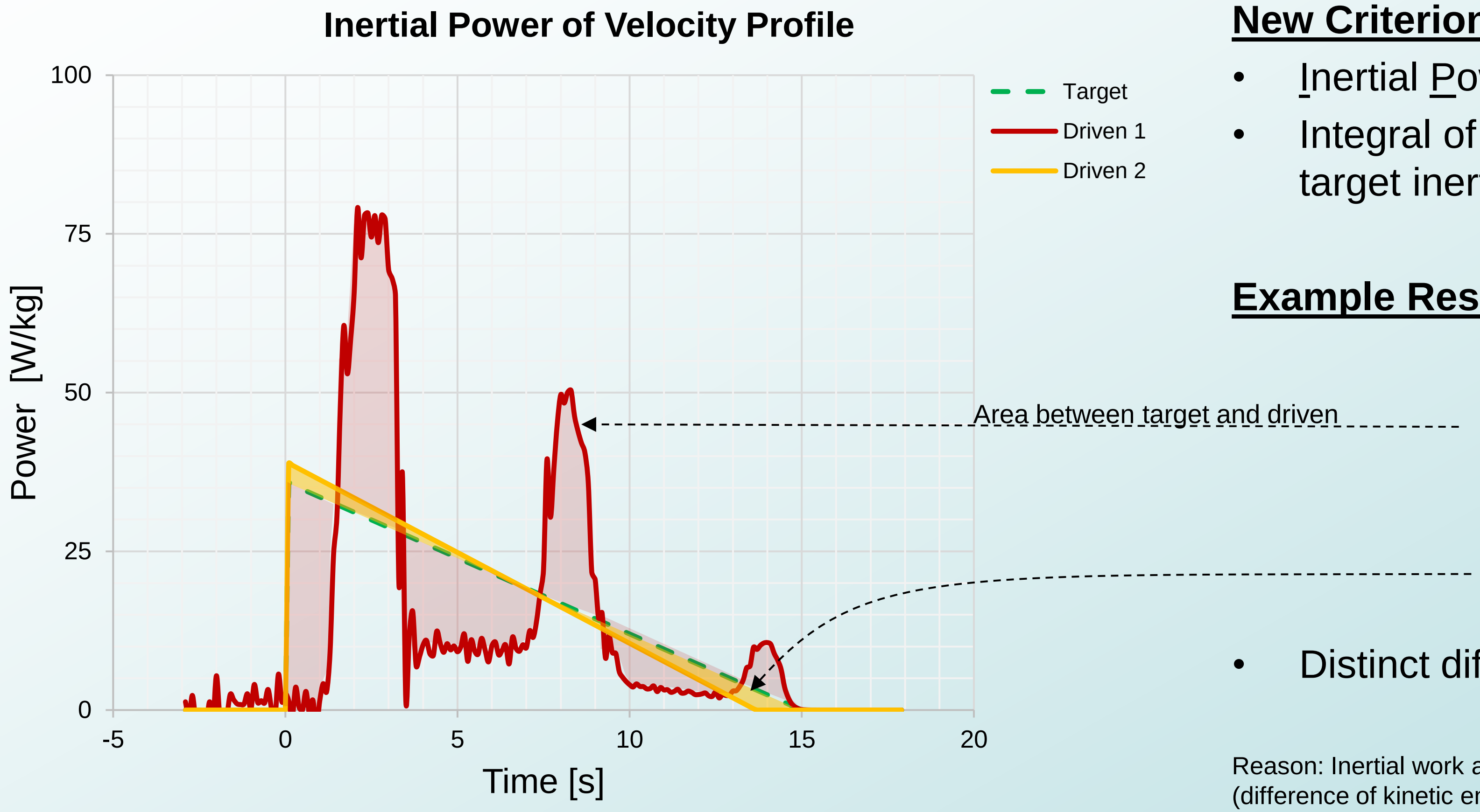
- IWR does not detect a deviation
- Allowed (GRT15): $-2.0\% < \mathrm{IWR} < 4\,\%$

Reason: Inertial work actually depends only on the start and end velocity (difference of kinetic energy).

➢ **IWR does not detect deviation as long as start and end velocity are matching the target.**

Quality Criteria

New Criterion – Inertial Power Difference Work



New Criterion - IPDW:

- Inertial Power Difference Work
- Integral of difference between actual and target inertial power

Example Result:

$$\mathbf{IPDW_1} = 311.4\ \frac{\mathbf{J}}{\mathbf{kg}}$$

$$\mathbf{IPDW_2} = 28.4\ \frac{\mathbf{J}}{\mathbf{kg}}$$

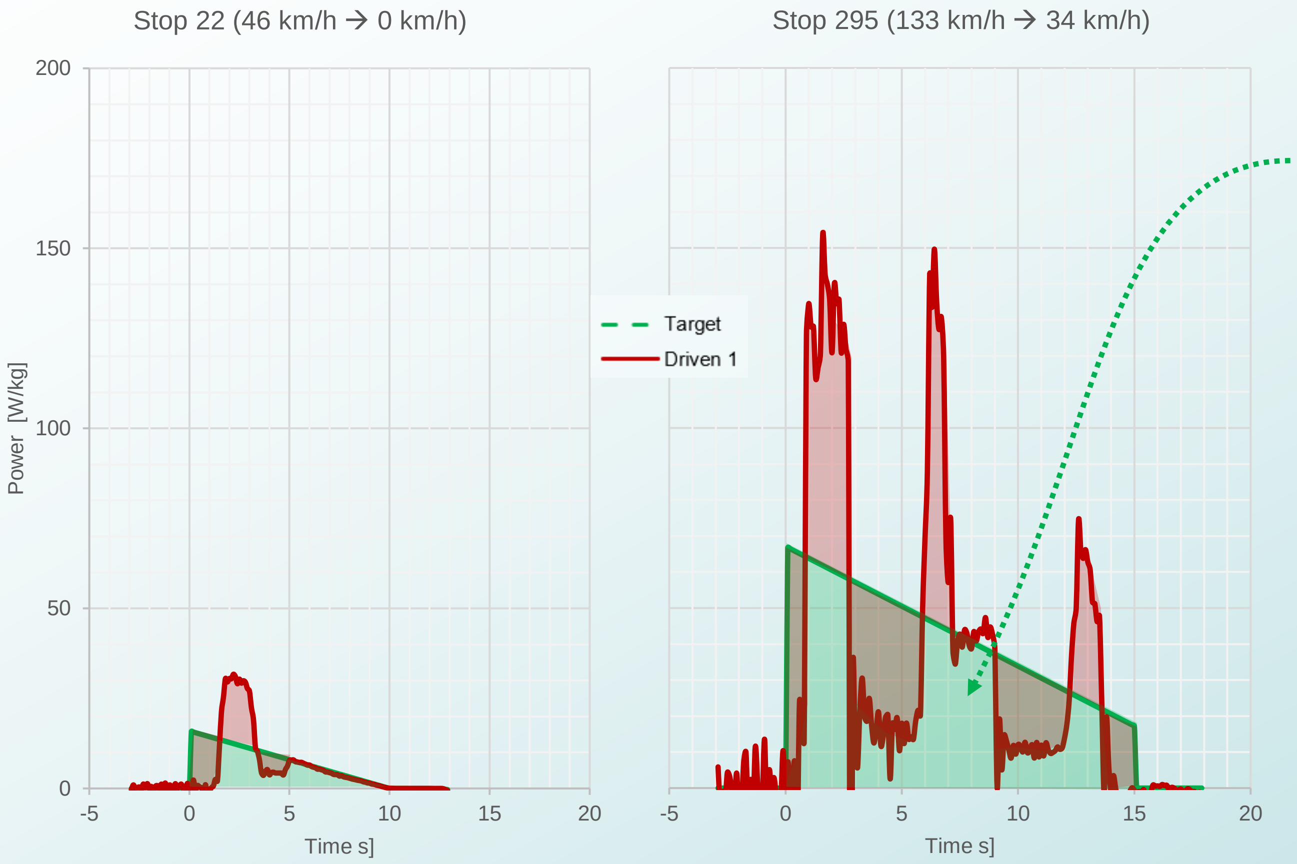
- Distinct difference between both profiles

Reason: Inertial work actually depends only on the start and end velocity (difference of kinetic energy).

➢ **IPDW separates the different driving styles by a factor of ~10x.**

Quality Criteria

New Criterion – Inertial Power Difference Rating



New Criterion - IPDW:

- Inertial Power Difference Rating
- Relative to **target work**
- Accounts for different absolute energy levels of brake stops (e.g. 46 km/h vs. 133 km/h)

Example Result:

$$\mathbf{IPDR_{22}} = \frac{\mathbf{111.2}}{\mathbf{79.9}} = \mathbf{139.2\ \%}$$

$$\mathbf{IPDR_{295}} = \frac{\mathbf{661.6}}{\mathbf{374.3}} = \mathbf{176.7\ \%}$$

Absolute values factor x6

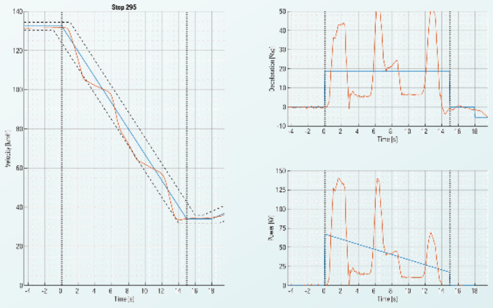
Relative values similar

➢ **IPDR detects poor driving style independent of the velocity/energy level of each stop.**

Chassis Dyno Quality Criteria
Relevant Values of New Criteria

Approach

- Survey with manual/visual labeling of 50 brake stops by experts as valid/invalid
- Computation of new criteria (RSPDR) for each stop
- Only relative power difference is investigated, since absolute value is strongly influence by stop energy



1 – Perfect
2 – Ok
3 – Borderline Ok
4 – Borderline not OK
5 – Not Ok
6 – Biased

Valid
Invalid

Result

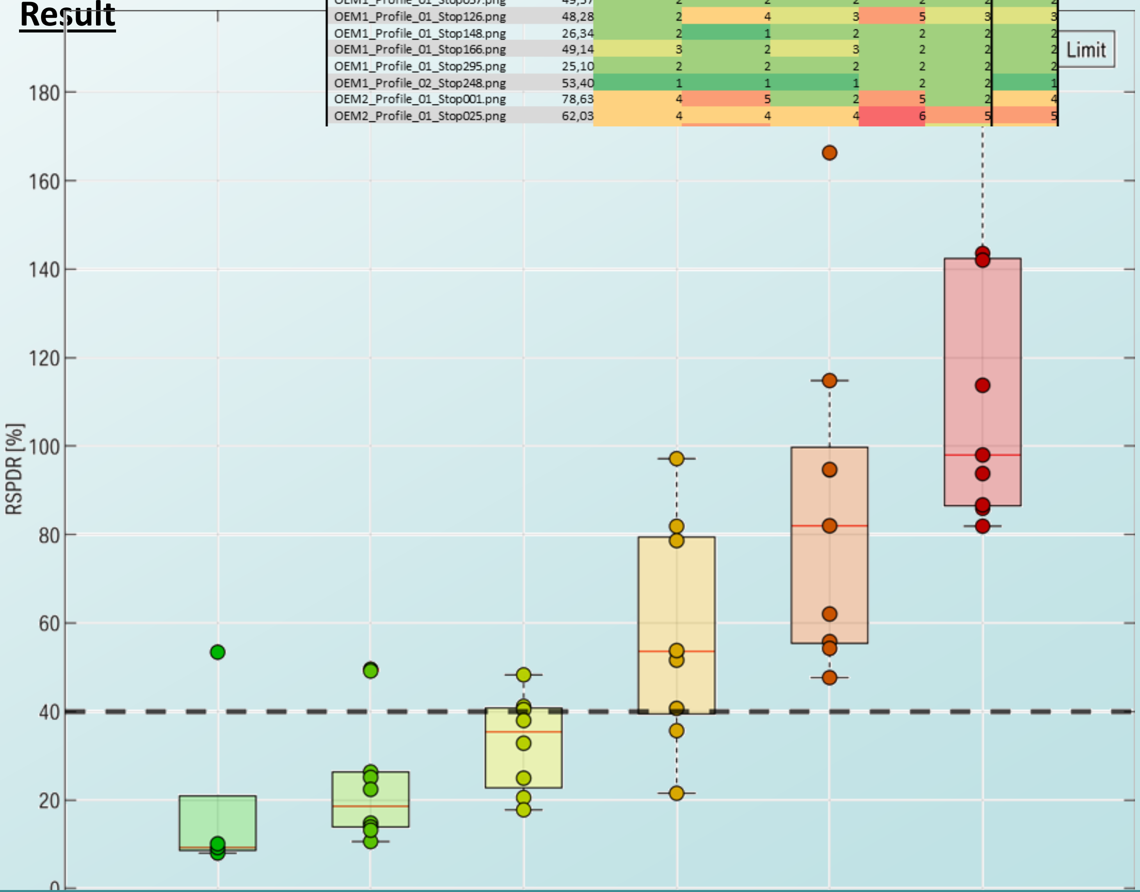


Image	RSPDR [%]	OEM1	OEM2	OEM3	OEM4	OEM5	Mean
OEM1_Profile_01_Stop048.png	53,59	3	3	4	4	4	4
OEM1_Profile_01_Stop057.png	49,57	2	2	2	2	2	2
OEM1_Profile_01_Stop126.png	48,28	2	4	3	5	3	3
OEM1_Profile_01_Stop148.png	26,34	2	1	2	2	2	2
OEM1_Profile_01_Stop166.png	49,14	3	2	3	2	2	2
OEM1_Profile_01_Stop295.png	25,10	2	2	2	2	2	2
OEM1_Profile_02_Stop248.png	53,40	1	1	1	2	2	1
OEM2_Profile_01_Stop001.png	78,63	4	5	2	5	2	4
OEM2_Profile_01_Stop025.png	62,03	4	4	4	6	5	5

- RSPDR correlates good with average manual evaluation
- Allowed values for RSPDR might be in the range of 40%

Quality Criteria
Background Information

v_ist1 [km/h]	v_ist2 [km/h]	v_soll [km/h]	v_min [km/h]	v_max [km/h]	a_ist1 [%g]	a_ist2 [%g]	a_soll [%g]
83,48	83,60	83,60	81,60	85,60	-0,57	0,00	0,00
83,50	83,60	83,60	81,60	85,60	0,51	0,00	0,00
83,46	83,60	83,60	81,60	85,60	-1,01	0,00	0,00
83,49	83,60	83,60	81,60	85,60	0,73	0,00	0,00
83,53	83,60	83,60	81,60	85,60	1,28	0,00	0,00
83,56	83,60	83,60	81,60	85,60	0,63	0,00	0,00
83,59	83,60	83,60	81,60	85,60	1,00	0,00	0,00
83,57	83,60	83,60	81,60	85,60	-0,57	0,00	0,00
83,59	83,60	83,60	81,60	85,60	0,65	0,00	0,00
83,51	83,60	83,60	81,60	85,60	-2,38	0,00	0,00
83,53	83,60	83,60	81,60	85,60	0,57	0,00	0,00
83,57	83,60	83,60	81,60	85,60	1,14	0,00	0,00
83,59	83,60	83,60	81,60	85,60	0,46	0,00	0,00
83,55	83,60	83,60	81,60	85,60	-1,08	0,00	0,00
83,52	83,60	83,60	81,60	85,60	-0,71	0,00	0,00
83,51	83,60	83,60	81,60	85,60	-0,43	0,00	0,00
83,49	83,60	83,60	81,60	85,60	-0,38	0,00	0,00
83,48	83,60	83,60	81,60	85,60	-0,41	0,00	0,00
83,44	83,60	83,60	81,60	85,60	-1,13	0,00	0,00
83,44	83,60	83,60	81,60	85,60	-0,08	0,00	0,00
83,37	83,60	83,60	81,04	85,60	-1,78	0,00	0,00
83,36	83,60	83,60	80,49	85,60	-0,51	0,00	0,00
83,33	83,60	83,60	79,93	85,60	-0,65	0,00	0,00
83,32	83,60	83,60	79,37	85,60	-0,49	0,00	0,00

M [kg]	2500
RESULTS	
RMSSE 1 [km/h]	3,618
RMSSE 2 [km/h]	3,623
IWR 1 [%]	0,005
IWR 2 [%]	-0,823
IW_ist1 [J]	-669628
IW_ist2 [J]	-664084
IW_soll [J]	-669596

- Computations done according to SAE J2951 as referenced in GTR15
- Excel with example data and computations can be shared on request: brake-emissions@bmwgroup.com

Deep Dive Threshold Pressure

Background & Computation Method in Detail

Threshold pressure calculation method
Recap GTR24 Annex C

Calculation of Friction Work in GTR Annex C:

- Friction work is calculated using torque
- Torque is calculated using pressure signal

$$\tau_{brake,b}(t) = C_{p,b} \cdot p_{brake,b}(t)$$

- Torque is only developed above a specific threshold, see GTR24 definition:

"Threshold pressure" means the minimum hydraulic pressure to overcome the internal friction and seal forces, move the brake calliper's piston or drum wheel cylinder, and onset brake torque output.

Up to now, no method for the calculation of the threshold pressure was suggested.
Method should be specified

A deep dive to the methodology of threshold pressure determination is given in the backup

Threshold pressure calculation method Key Question

How to find the threshold pressure?

Below p_{thr} the torque does not change:

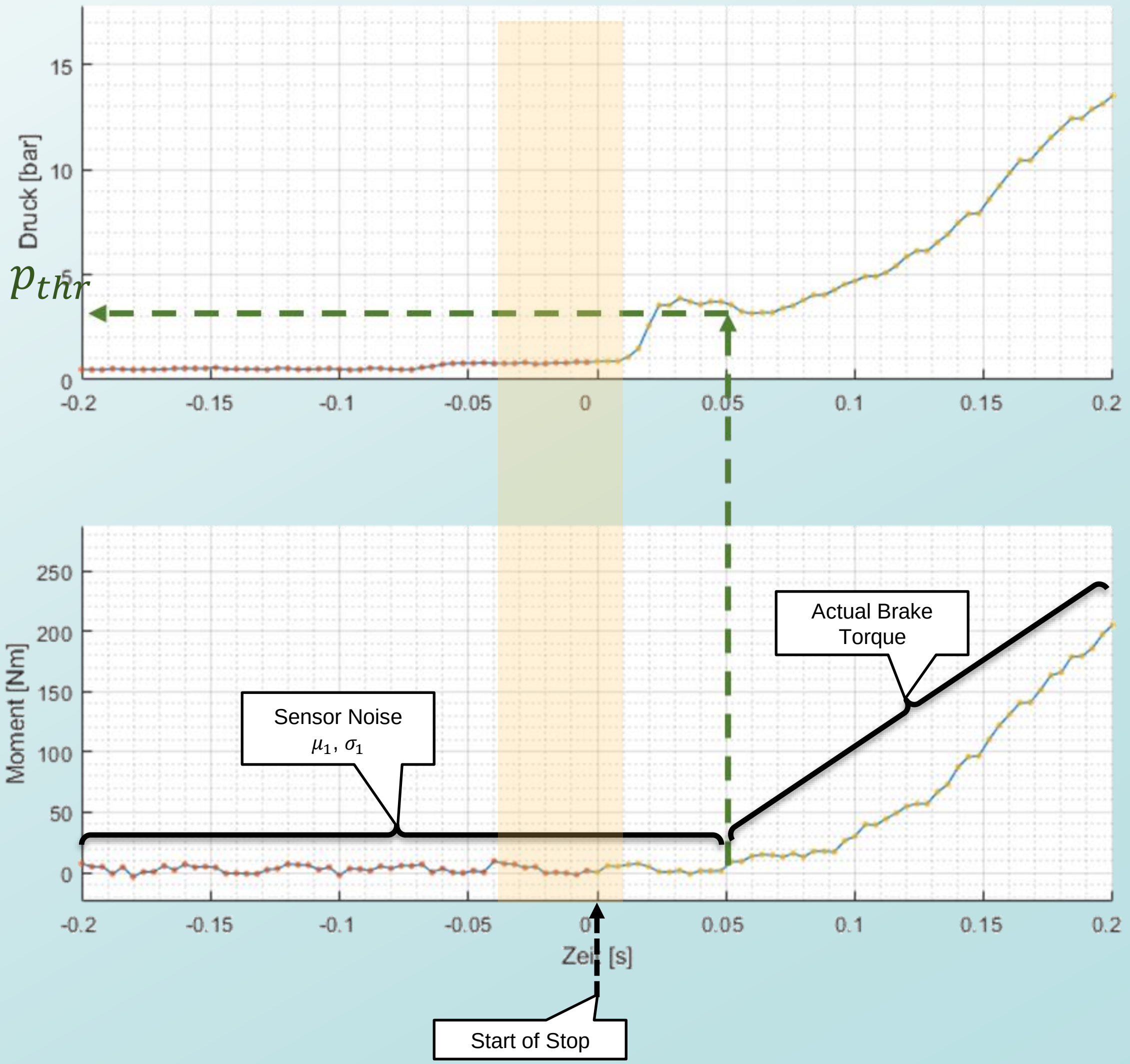
- Still sensor noise and residual torque
- Same properties as before the brake stop (mean, variance …)

Above p_{thr} the torque does change:

- sensor noise and residual torque are less relevant
- Torque value actually increases

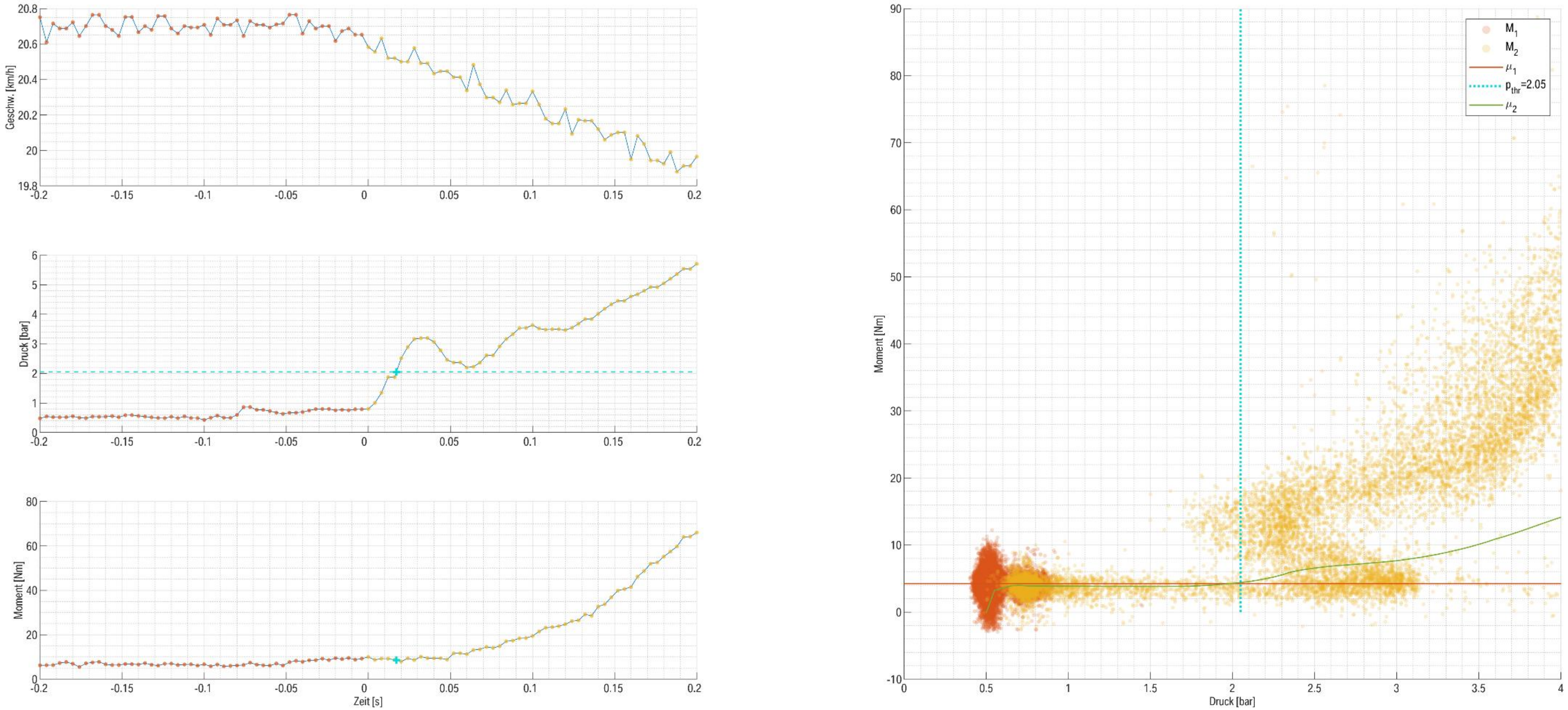
Idea:

- Characterize torque noise floor
- Check above which p_{thr} the properties of torque signal are not longer comparable to the noise floor (statistical T-test)
- **250 Hz** Sampling needed for accurate analysis of steep slopes



Working and tested Matlab script is available!
Code was **successfully tested** by different OICA members and labs applying it to different brake corners in EU & US-Market: disc & drum brakes, NAO &

Threshold pressure calculation method
Example Result 1



DEEP DIVE THRESHOLD PRESSURE
OVERVIEW

<u>Content</u>

1. Why do we need the threshold pressure?
2. Where is the threshold pressure used in the Annex C?
3. Why is its exact value crucial?
4. What is the difference between the well-known piston-movement-pressure and the threshold pressure?
5. How can we compute the threshold pressure? (Bonus: … and directly obtain the residual drag torque)
6. What results have been obtained?

DEEP DIVE THRESHOLD PRESSURE

1. Why do we need the threshold pressure?

Computation of Friction Work:

- The friction work is computed as integral of the friction power.
- The friction power is the product of torque τ and rotational velocity $\omega = v/r_{dyn}$:

$$P = \tau \cdot \frac{v}{r_{dyn}}$$

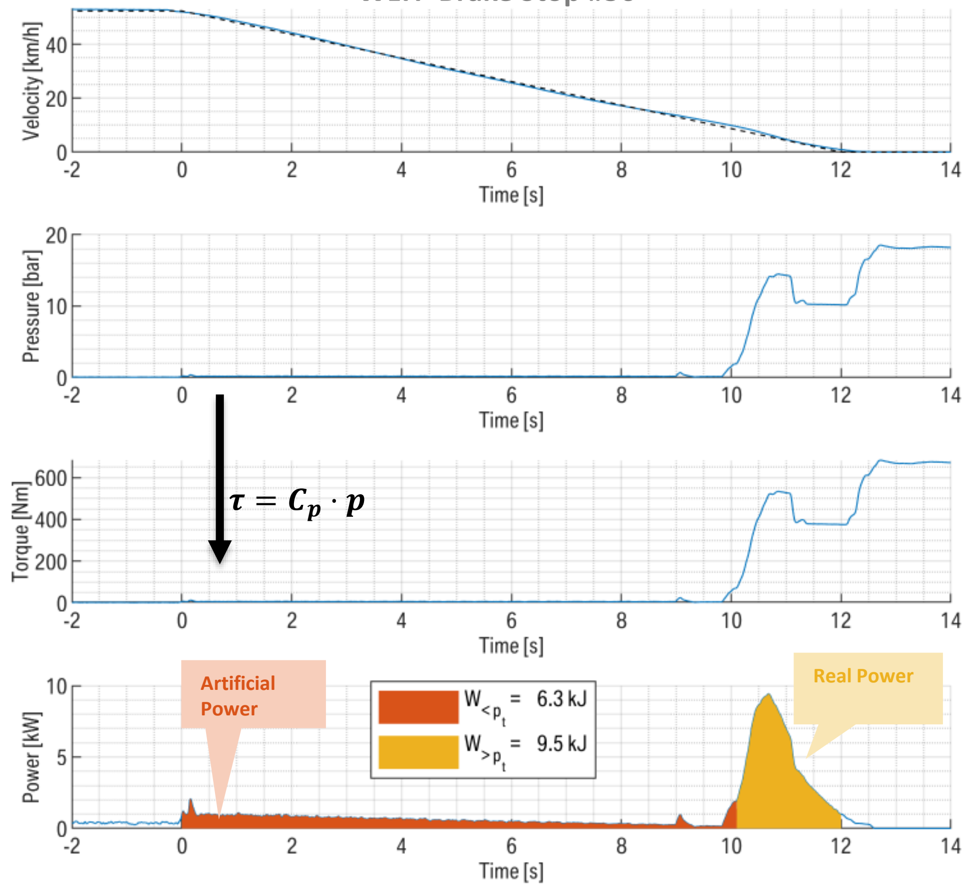
- Since the torque is difficult to measure, we compute it from the brake pressure p using the C_p constant:

$$\tau = C_p \cdot p$$

Problem:

- Torque is only acting above a specific threshold pressure
- If this threshold is not considered, an "artificial" torque is computed
- This would lead to very large amount of "artificial" friction work – especially for BEVs!

ILS2 Example – BMW 19" front Brake
WLTP Brake Stop #56



➢ Without the threshold pressure, the "artificially" computed friction work might be in the <u>same range</u> as the actual friction work.

DEEP DIVE THRESHOLD PRESSURE

2. Where is the threshold pressure used in the GTR24?

Eq.

Content

Computation of Torque

- In the section “3.2.2 Methods to Determine the Friction Brake Torque” under “3.2.2.2 Pressure Based Method”
- Measured brake pressure is only considered to be relevant and cause brake torque above this threshold pressure limit (“p_meas > p_threshold”)
- This torque is then used to compute the C-Factor

$$\tau_{brake,b}(t) = C_{p,b} \cdot p_{brake,b}(t) \qquad \text{(Eq. C9)}$$

$$p_{brake,b}(t) = \begin{cases} p_{meas,b}(t) & \text{for} \quad p_{meas,b}(t) > p_{threshold,b} \\ 0 & \text{otherwise} \end{cases} \qquad \text{(Eq. C10)}$$

Computation of C_p

- In the section “3.3.3 Calculation of C_p”
- The measured torque and pressure is only considered when the pressure is above the threshold
- C_p is also used for computation of the C-Factor

$$C_{p,b} = \frac{\int_{t_{start}}^{t_{end}} \tau_{brake,b} \cdot \omega_b(t)\, dt}{\int_{t_{start}}^{t_{end}} \cdot p_{brake,b}(t) \cdot \omega_b(t)\, dt} \qquad \text{(Eq. C12)}$$

Additionally, to avoid the usage of invalid signals the following applies for the correct calculation of the brake pressure and brake torque:

$$\tau_{brake,b}(t) = \begin{cases} \tau_{meas,b} & \text{for} \quad p_{meas,b}(t) > p_{threshold,b} \text{ and } \tau_{meas,b} > 0 \\ 0 & \text{otherwise} \end{cases} \qquad \text{(Eq. C13)}$$

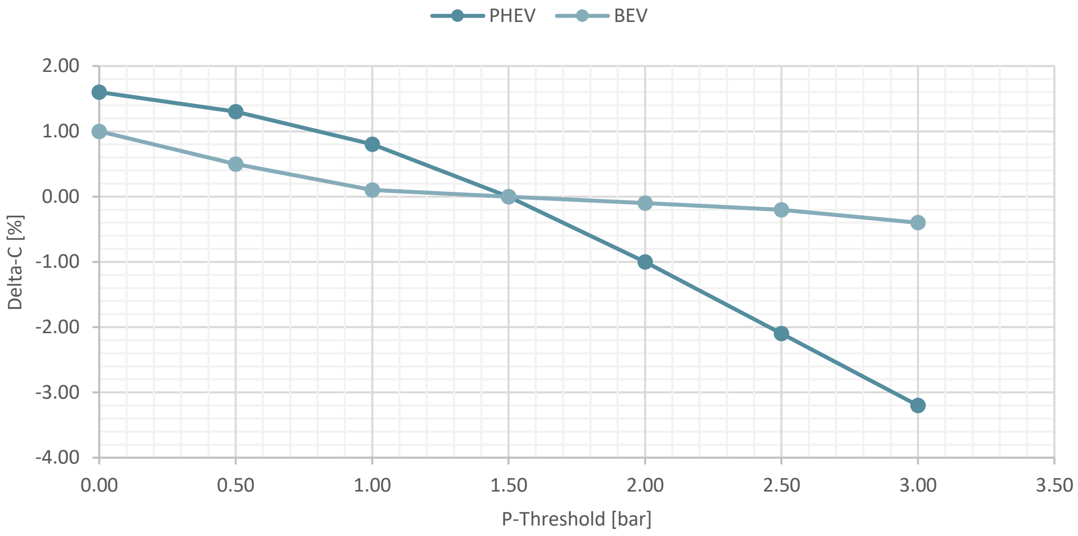
$$p_{brake,b}(t) = \begin{cases} p_{meas,b} & \text{for} \quad p_{meas,b}(t) > p_{threshold,b} \text{ and } \tau_{meas,b} > 0 \\ 0 & \text{otherwise} \end{cases} \qquad \text{(Eq. C14)}$$

➢ The threshold pressure is used in two different formulas in Annex C which both have direct impact on the C-Factor.

DEEP DIVE THRESHOLD PRESSURE
3. Why is its exact value crucial?

Influence on C-Factor

- Since the threshold pressure is used to calculate the C-Factor it has a direct impact.
- The computation of the C-Factor for the same dyno vehicle test but different threshold pressures, leads to non-neglectable deviations
- Different brake systems might have threshold pressures from 0.5 bar up to 5.0 bar or more (especially light vehicles with drum brakes)



p_{thr} [bar]	ΔC – PHEV [%]*	ΔC - BEV [%]*
0.0	+1.6	+1.0
0.5	+1.3	+0.5
1.0	+0.8	+0.1
1.5	**0.0**	**0.0**
2.0	-1.0	-0.1
2.5	-2.1	-0.2
3.0	-3.2	-0.4

*absolute percentage points

➢ Different threshold pressures have a non-neglectable influence on the C-Factor.

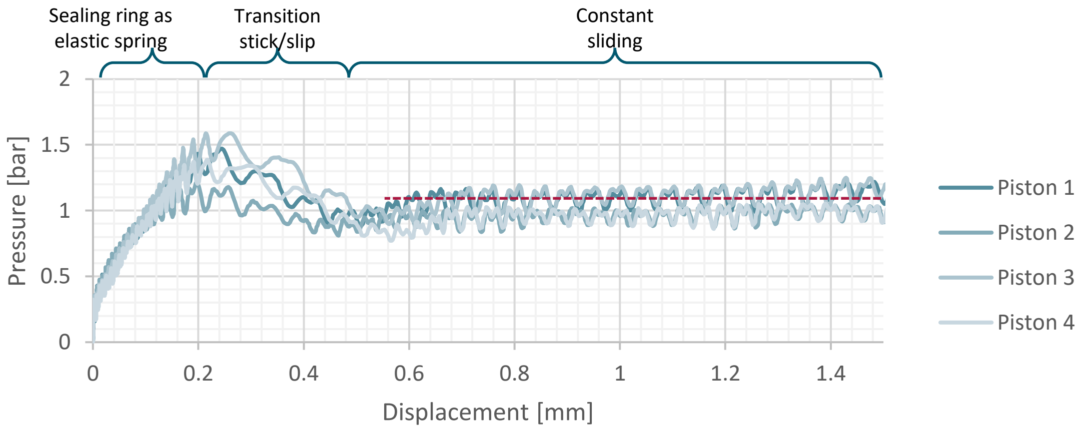
DEEP DIVE THRESHOLD PRESSURE

4. Difference to piston-movement-pressure?

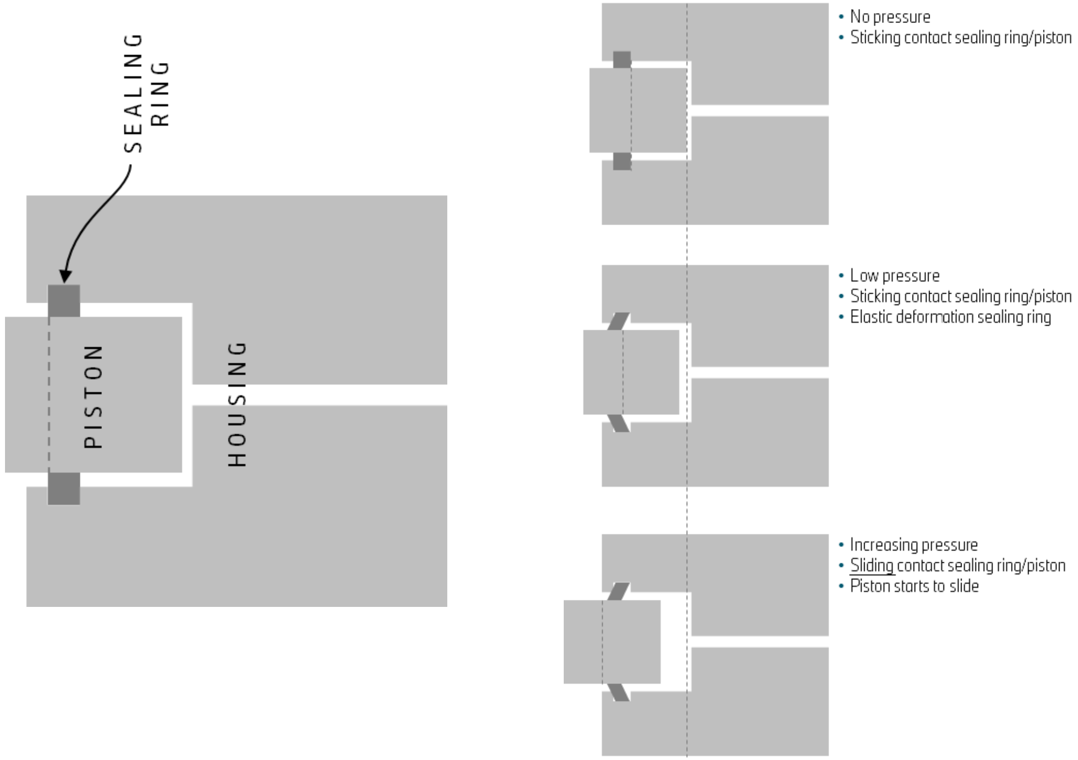
Piston Movement Test

- Test for characterization of sealing ring
- Only brake caliper is used and movement of piston is measured over increasing/decreasing pressure
- At low pressures the sealing ring acts as spring
- With increasing pressure the piston starts to slide out of the housing

ILS2 Example – BMW 19" front Brake



Test Setup & Simplified Model



➢ The standard "piston-movement-pressure" only considers the piston sealing ring

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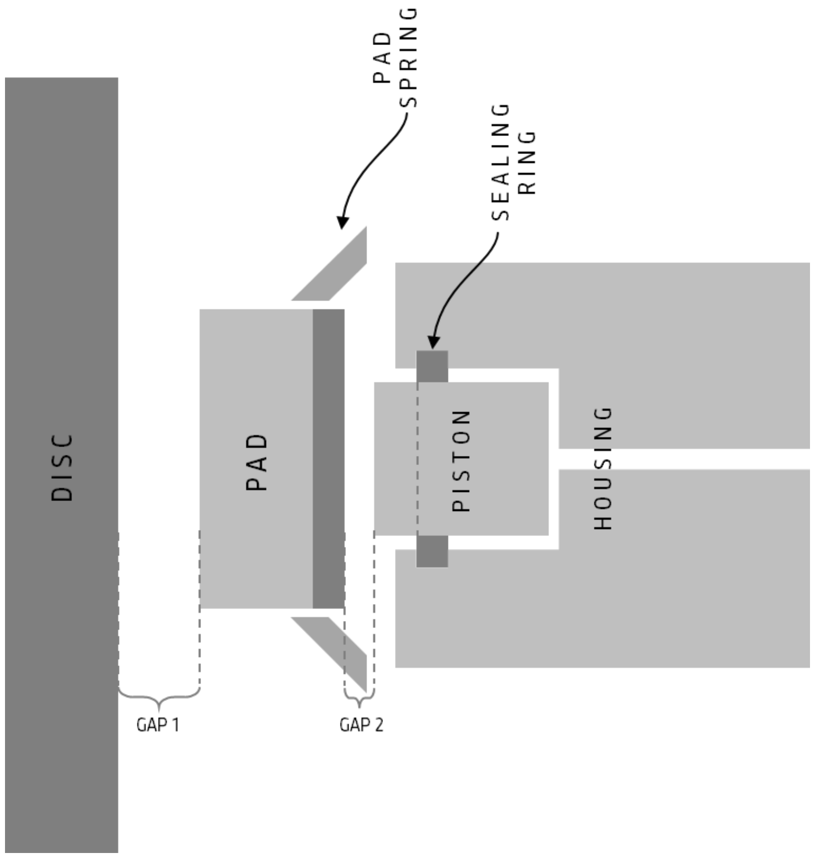
DEEP DIVE THRESHOLD PRESSURE
4. Difference to piston-movement-pressure?

Content

Threshold Pressure

- Measured on component bench with full brake corner
- Describes property of the whole brake corner
- At low pressures the sealing ring acts as spring
- Pad springs and contact friction act as additional counter force
- With increasing pressure the piston starts to slide
- After closing the gaps all parts are in contact and torque occurs



Threshold pressure Is defined in GTR24 in chapter 3.1.19. as

3.1.19. "*Threshold pressure*" means the minimum hydraulic pressure to overcome the internal friction and seal forces, move the brake calliper's piston or drum wheel cylinder, and onset brake torque output.

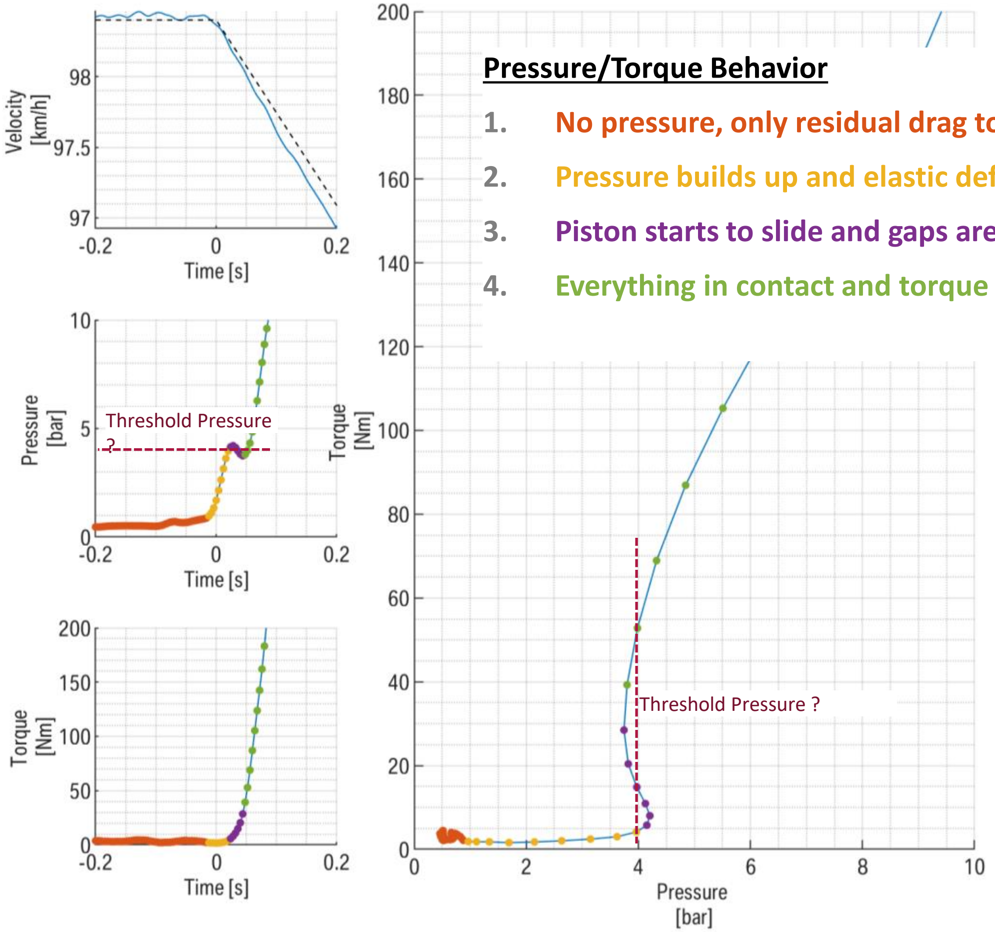
➢ The standard "piston-movement-pressure" does not represent the meaning of a threshold pressure, especially as defined in GTR24.

DEEP DIVE THRESHOLD PRESSURE

4. Difference to piston-movement-pressure?

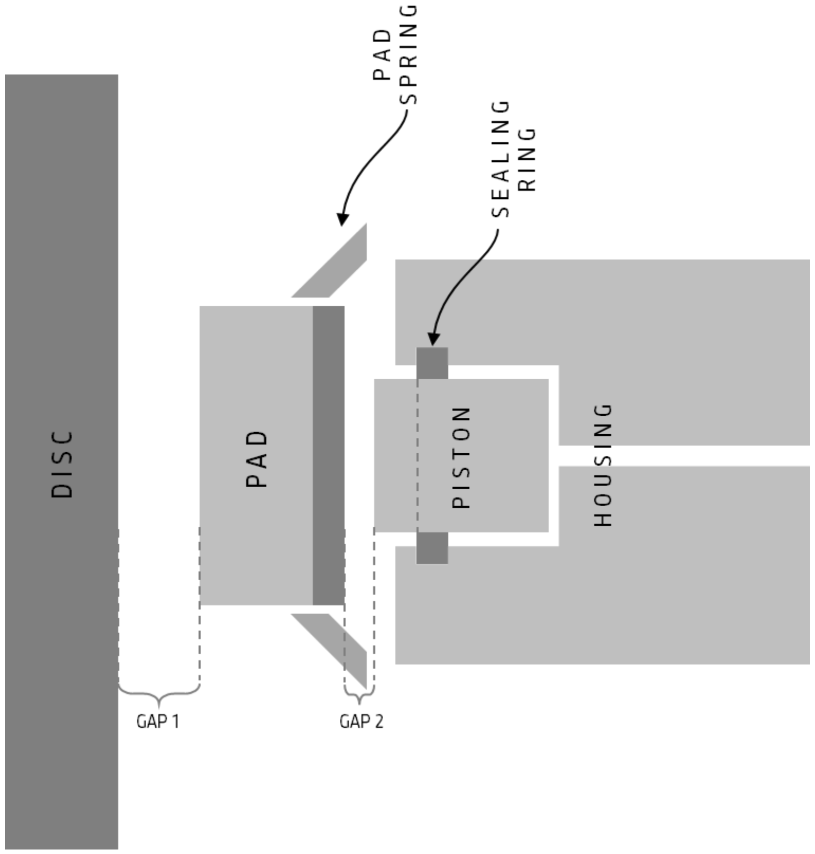
Content

ILS2 Example – BMW 19” front Brake



Pressure/Torque Behavior

1. No pressure, only residual drag torque
2. Pressure builds up and elastic deformation
3. Piston starts to slide and gaps are closed
4. Everything in contact and torque increases



➢ The threshold pressure describes a <u>different physical behavior</u> as the piston movement pressure.

DEEP DIVE THRESHOLD PRESSURE
5. How can the threshold pressure be computed?

Measurement on Component Test Bench

- The component test bench measures the torque and pressure precisely and with a high sampling rate
- These signals can be used to compute the threshold pressure

Approach – Properties of Torque Signal

- Below p_{thr}: the torque signals is the residual drag torque τ_{res} with some measurement noise

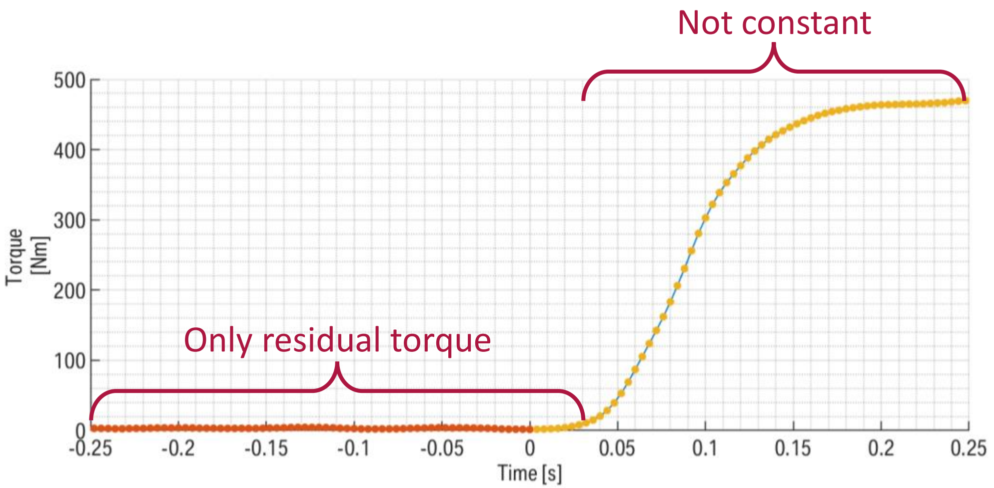
$$\tau_{below} = \mathcal{N}(\tau_{res}, \sigma_{noise})$$

(Normally distributed white noise with mean τ_{res} and standard deviation σ_{noise})

- Above p_{thr}: the torque signal actually increases and the mean is not longer the residual torque

$$\tau_{above} \neq \mathcal{N}(\tau_{res}, \sigma_{noise})$$

(Mean of τ_{above} is much bigger than τ_{res})



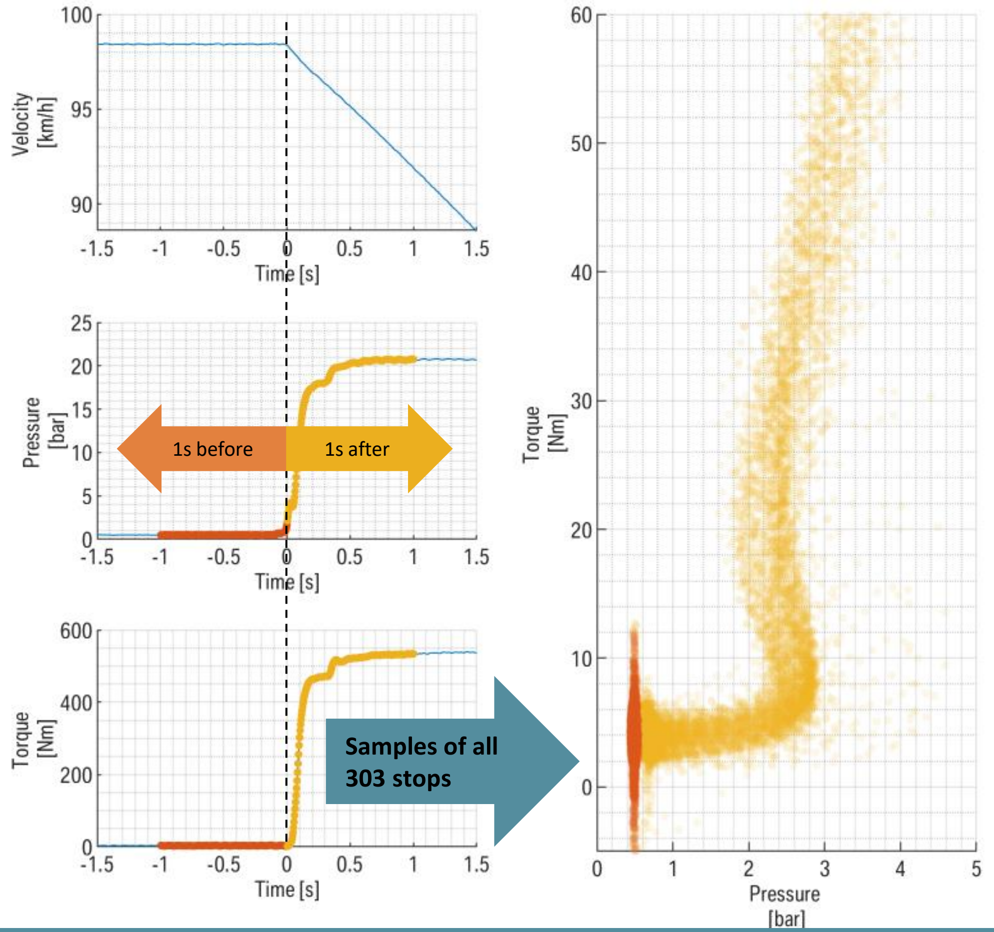
➢ How can we get the pressure where the torque signal changes from noisy but constant residual torque to a different behavior?

DEEP DIVE THRESHOLD PRESSURE

5. How can the threshold pressure be computed?

Statistical Approach

- Instead of analyzing the time domain only torque and pressure is considered
- Two groups of measurement samples are selected
  1. Torque-Pressure samples 1 second before start of all 303 stops (Set T_1)
  2. Torque-Pressure samples 1 second after start of all 303 stops (Set T_2)
- 250 Hz sampling is needed to capture behavior
- All 303 stops are considered at once
  (1s x 250 Hz x 303 Stops = 75 750 Samples per Group)



➢ Two data sets are created from the signals: the set for the residual torque (1s before) and the set for increasing torque (1s after).

DEEP DIVE THRESHOLD PRESSURE

5. How can the threshold pressure be computed?

Content

Comparing Mean Values

1. Computation of mean of the set 1s before

$$\mathrm{mean}(\mathrm{T}_1) = \tau_{res}$$

2. Selection of subset of T_2 where the pressure is less than an initial threshold

$$\mathrm{T}_2(p_{thr})$$

3. Computation of mean of subset

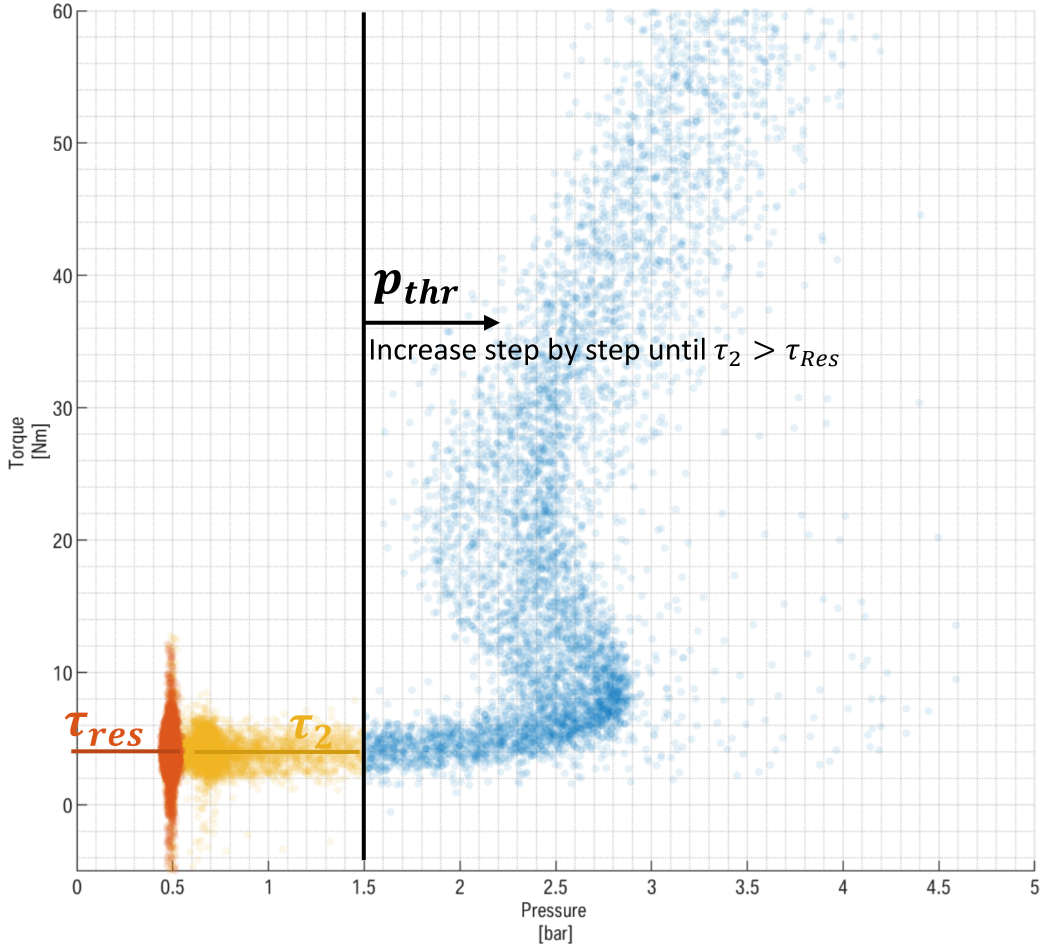
$$\tau_2 = \mathrm{mean}(\mathrm{T}_2(p_{thr}))$$

4. Check if the average torque is still similar to the residual torque

$$\tau_2 \leq \tau_{res}$$

→If yes the threshold is to low and can be increased and the check start again

→If not the threshold pressure was found



- By increasing the threshold pressure step by step and checking whether the torque is still similar to the residual torque, the actual threshold pressure can be found.

DEEP DIVE THRESHOLD PRESSURE

5. How can the threshold pressure be computed?

Comparing Mean Values

1. Computation of mean of the set 1s before

$$\text{mean}(\mathrm{T}_1) = \tau_{res}$$

2. Selection of subset of T_2 where the pressure is less than an initial threshold

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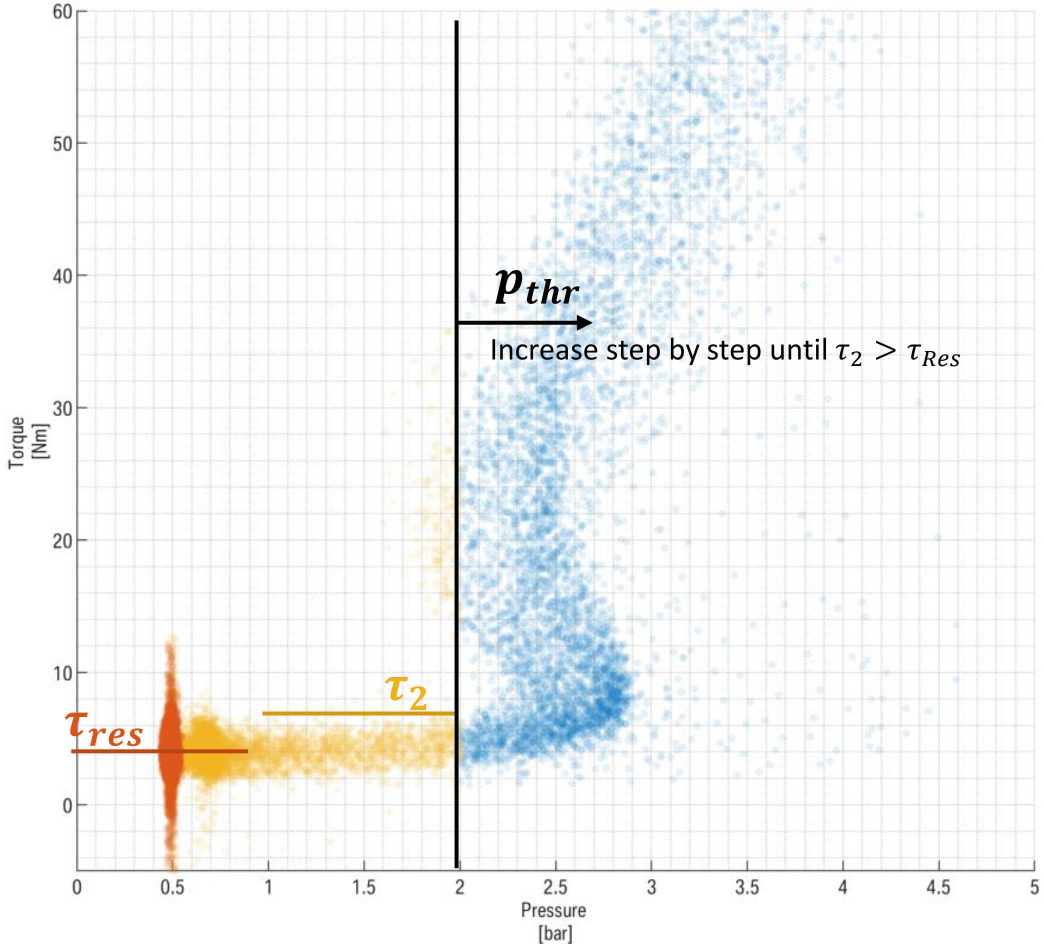


➢ By increasing the threshold pressure step by step and checking whether the torque is still similar to the residual torque, the actual threshold pressure can be found.

DEEP DIVE THRESHOLD PRESSURE
5. How can the threshold pressure be computed?

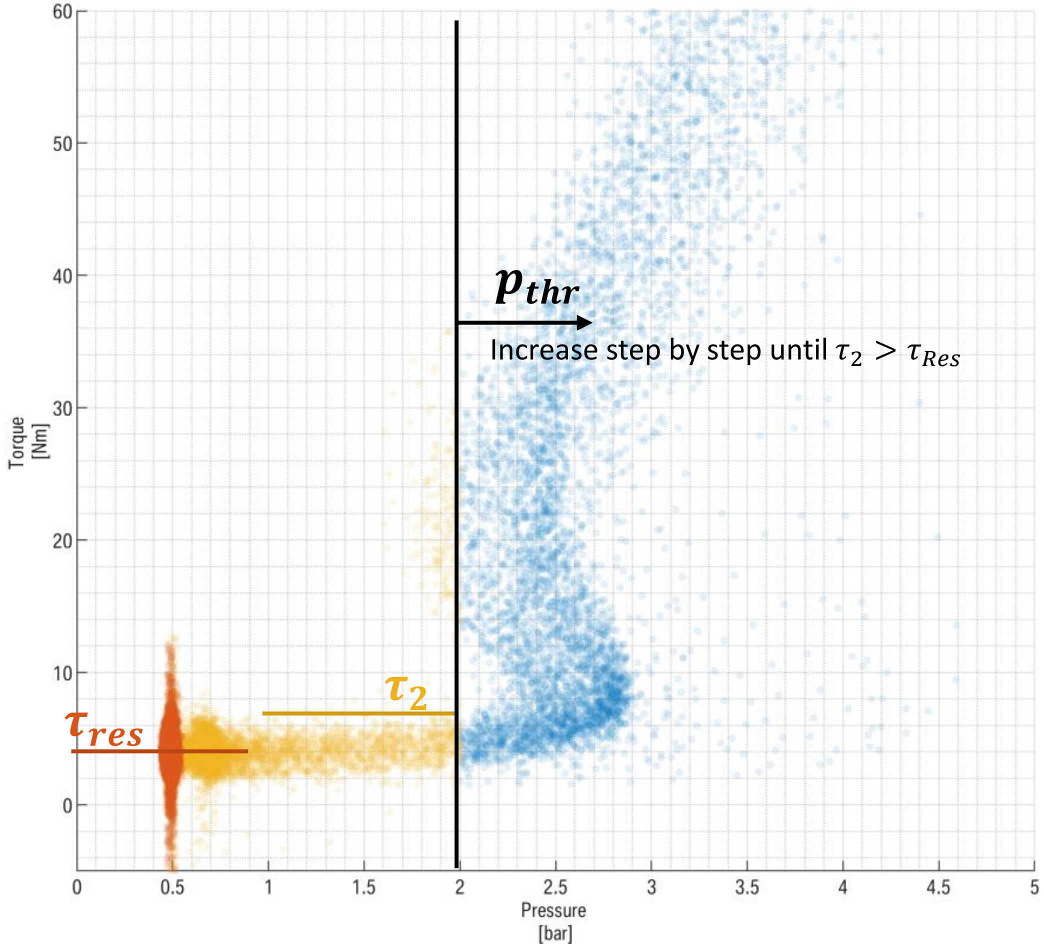
Content

Performing Statistical Test instead of Comparing Mean

- Even though the comparison of mean values serves as good explanation, the comparison of both sets is better represented using a statistical test.
- The "T-Test" tests whether a data sample has the same mean as a given one

$H_0\colon \tau_2 \leq \tau_{\mathrm{res}}$	Mean of set T_2 is smaller than the given average (residual torque)
$H_1\colon \tau_2 > \tau_{\mathrm{res}}$	Mean of set T_2 is larger than the given average (residual torque)

- Even Excel has build-in formula available for T-Test



➢ Using the T-Test also the number of samples and uncertainties are included. This is the methodological correct approach.

5. How can the threshold pressure be computed?

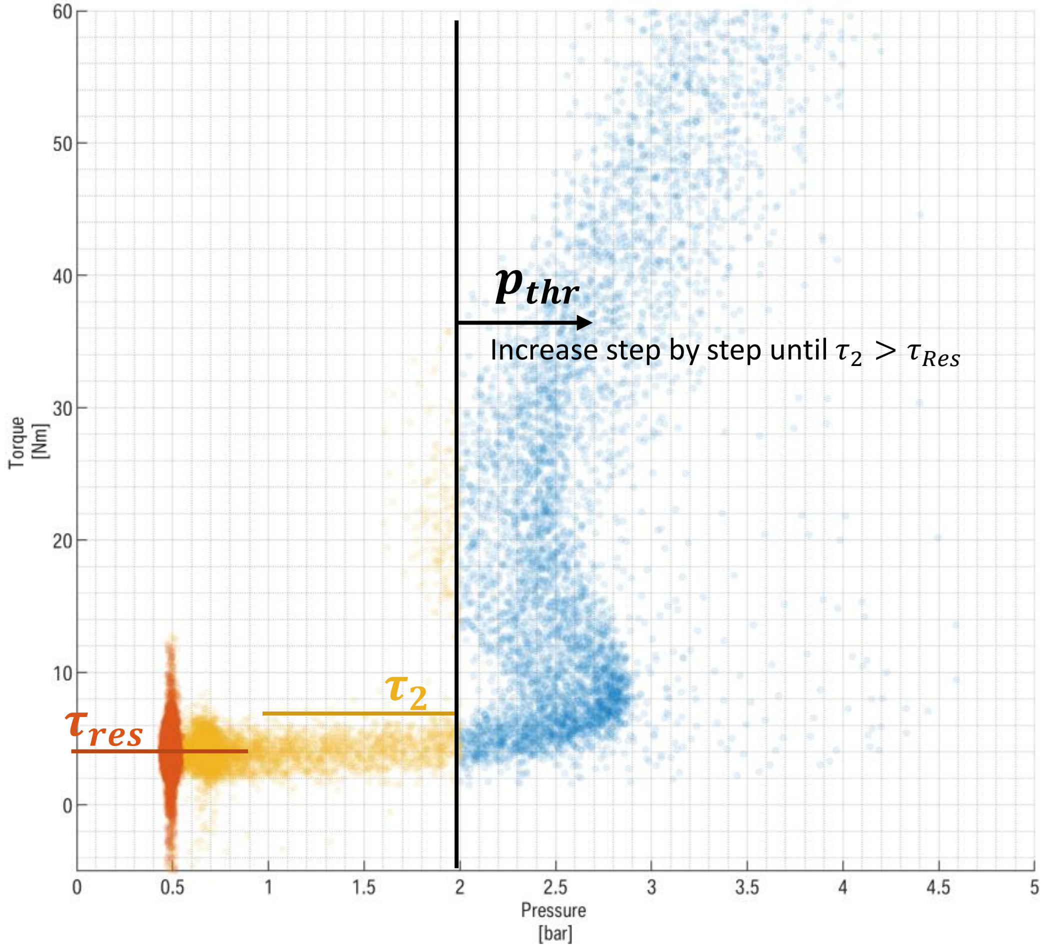
Content

Algorithm for find p_{thr}

1. Compute mean torque of Set T_1 → τ_{res}
2. Set initial $p_{thr} = 0$
3. Increase $p_{thr} = p_{thr} + \Delta p$
4. Select all data points of T_2 which are below p_{thr} → $\mathrm{T}_2(p_{thr})$
5. Perform right-sided T-Test for mean of $\mathrm{T}_2(p_{thr}) = \tau_2$:

   $H_0: \tau_2 \leq \mu_{res}$

   $H_1: \tau_2 > \mu_{res}$
6. If H_0 continue with Step 3, else you have found p_{thr}



➢ The iterative T-Test approach allows a robust estimation of the threshold pressure.

DEEP DIVE THRESHOLD PRESSURE

5. How can the threshold pressure be computed?

Content

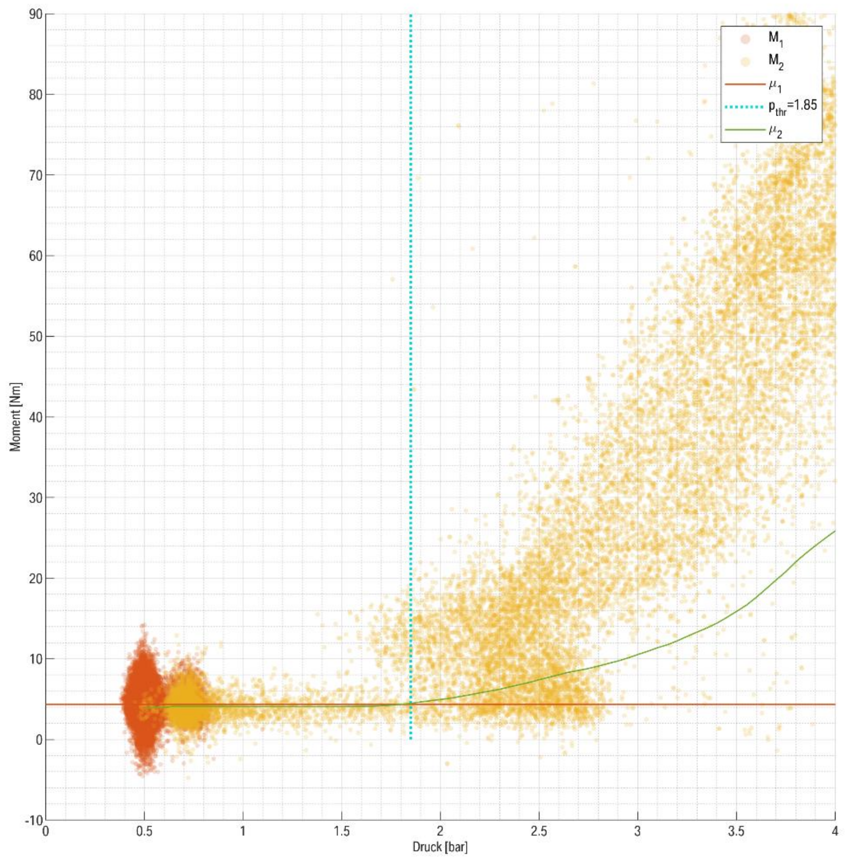
Algorithm: p_{thr} computation

$\tau_1 = \{\tau_i \mid (t_{n,start} - 1s) \leq t_i < (t_{n,start}) \;\; for\ all\ n = 1, \ldots 303\}$	select all torque sample 1s before all stops
$\bar{\tau}_1 = \frac{1}{K}\sum_{k=1}^{K} \tau_{1,k}$	compute the mean of the torque before all stops
for $p_{thr} = \{0.00, 0.01, \ldots, 10.00\}$	increase p_{thr} from 0.0 bar by 0.01 bar steps
$\tau_2(p_{thr}) = \left\{\tau_i \middle\vert \begin{matrix} t_{n,start} \leq t_i < (t_{n,start} + 1) \;\; for\ all\ n = 1, \ldots 303 \\ p_i < p_{thr} \end{matrix}\right\}$	select all torque samples 1s after start of all stops which are below
$\bar{\tau}_2 = \frac{1}{L}\sum_{l=1}^{L} \tau_{2,l}$	compute mean of torque
$\sigma_2 = \sqrt{\frac{\sum_{l=1}^{L}(\tau_{2,l} - \bar{\tau}_2)^2}{L-1}}$	compute standard deviation
$t_{test} = \sqrt{L}\frac{\bar{\tau}_2 - \bar{\tau}_1}{\sigma_2}$	compute test statistik
if $t_{test} > t(1-\alpha, L-1)$ **and** $L > 100$	check if test statistic is below value of students t-Distribution and if number of sampes is large enough
break for loop	if criteria are fullfilled stop loop: p_{thr} was found
end if	
end for	

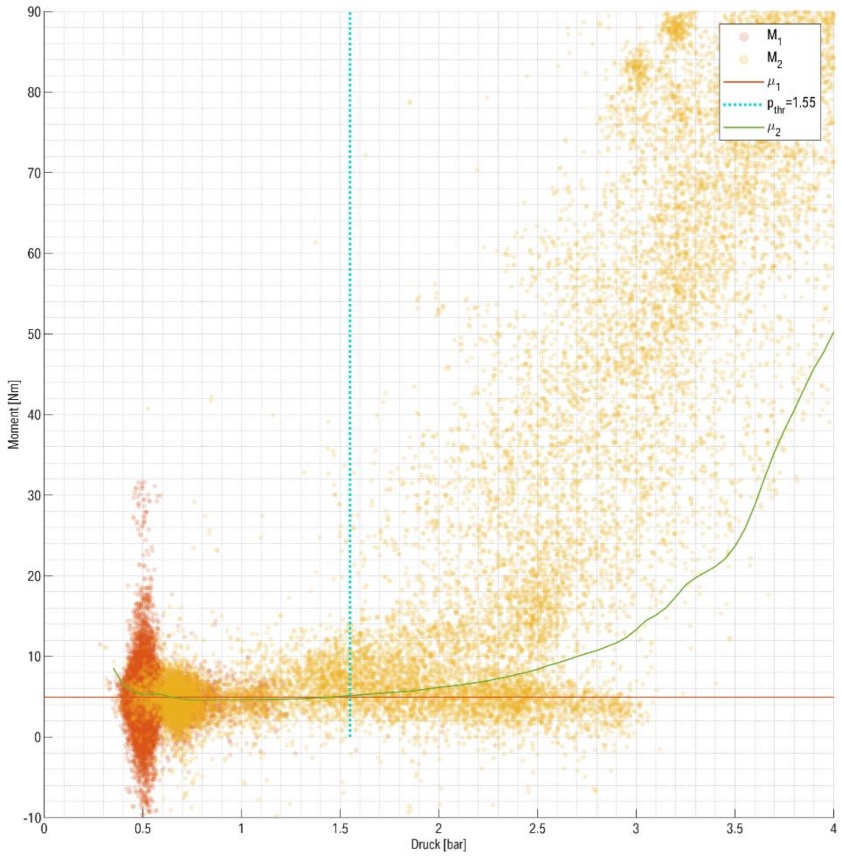
Hint: $t(1-\alpha, L-1)$ is the t-distribution for significance α and degrees of freedom $L-1$

DEEP DIVE THRESHOLD PRESSURE
6. What results have been obtained?

ILS2 - Brake System I



ILS2 - Brake System II



DEEP DIVE THRESHOLD PRESSURE
6. What results have been obtained?

Content

ILS2 - Brake System IV