Mathematical Contributions for Braking Systems

Michael Hilden, VM/EMH-DE

Keynote Speaker for Fraunhofer ITWM Alumni, 13.12.2024

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Mathematical Contributions for Braking Systems

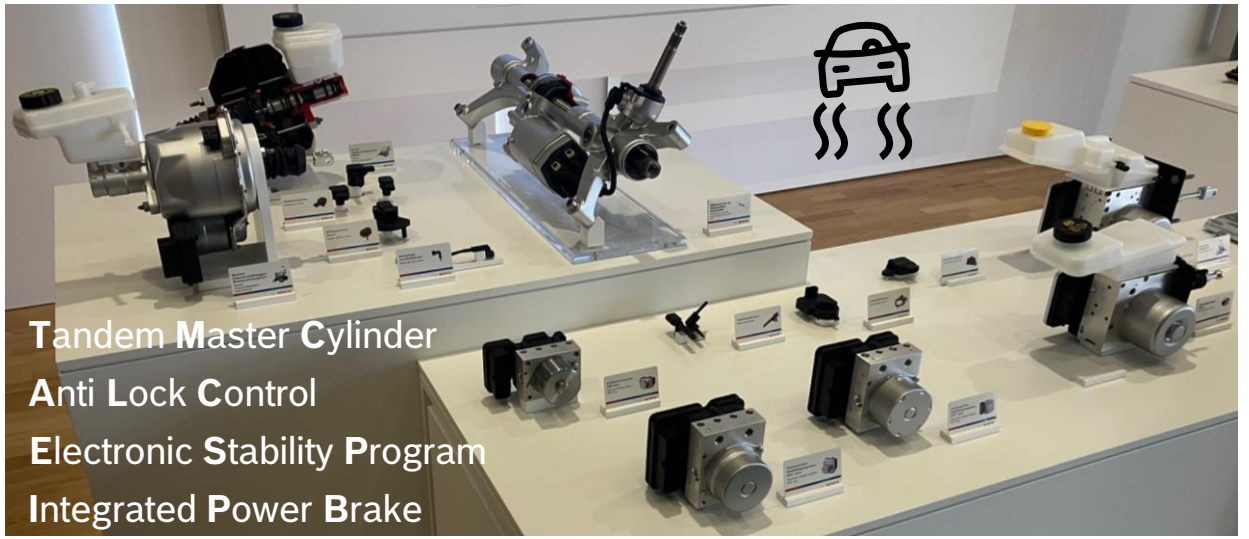
Overview Braking systems @ Bosch Mobility

- Brake systems @ Bosch
- My change: ITWM => Bosch
- Examples for mathematical contributions for braking systems

Who we are
Mobility

In 2023

61%	56.2	237,100
share of Bosch Group sales	billion euros sales revenue	associates (approx.)



Fraunhofer ITWM

Fraunhofer-Institut für Techno- und Wirtschaftsmathematik ITWM

Who we are
Our company values

Programm Alumni-Treffen Dezember 2024

- Begrüßung – Dr.-Ing Joachim Linn, Abteilungsleiter »Mathematik für die digitale Fabrik« im Bereich »Mathematik für die Fahrzeugentwicklung«
- Keynote Speaker – Dr. Michael Hilden (Alumni aus Abteilung »Strömungs- und Materialsimulation«, inzwischen in leitender Funktion bei der Robert Bosch GmbH) »Mathematical Contributions for Braking Systems (Mathematische Beiträge für Bremssysteme)«
- Pitches (Kurzpräsentationen, die jeweils in neun Minuten ein Thema präsentieren)

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Michael Hilden – Chief Expert brake fluid & valves

Development backgrounds

grown up on an island in the Rhine river: Niederwerth

(flood experiences)

BEO

HogC-BF

standardization

WiPaNo Project **TriNoWe**

NO NOise
NOr WEar
= TriNoWe
Tribology in Norms Worldwide

1990 to…	2000 to…	2010 to…	2020 to
Study math (ECMI)	BfG	**Fraunhofer ITWM**	**Robert Bosch GmbH**
			Senior expert
			Chief expert

Fraunhofer ITWM

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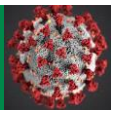
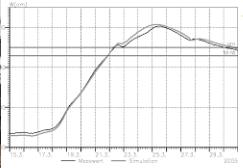
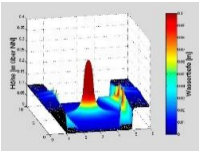
Technik fürs Leben

Lectures for math at university Heilbronn





bfg Bundesanstalt für Gewässerkunde



Joy & fun with competent & reliable product design & fluid “consulting”

“CfD research”

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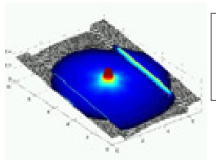
Michael Hilden – Chief Expert brake fluid & valves

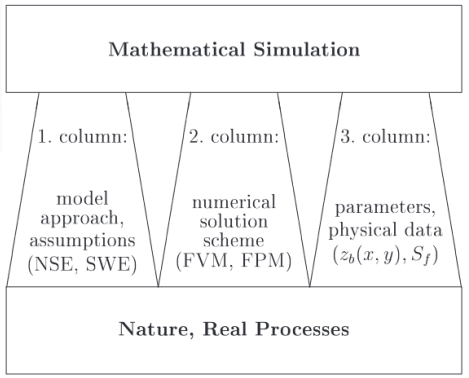
From ITWM to Bosch in 2002

"Latex => Power Point"

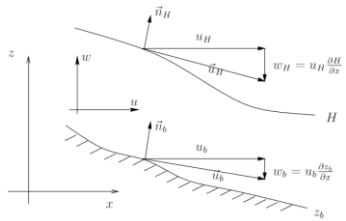
"Matlab => Excel"

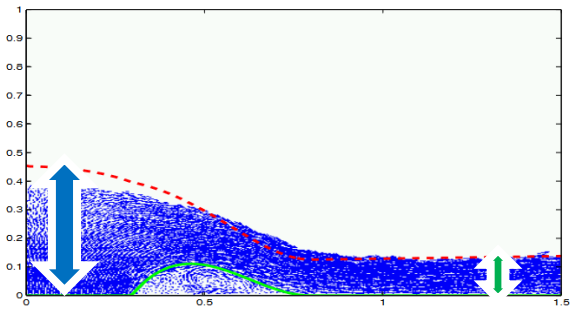
- RisUrSim: RISk for Urban flood SIMulation
- PhD: Extensions of Shallow Water Equations

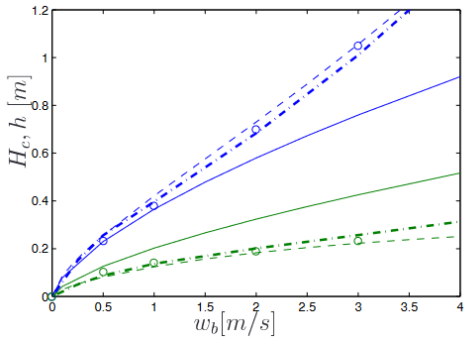




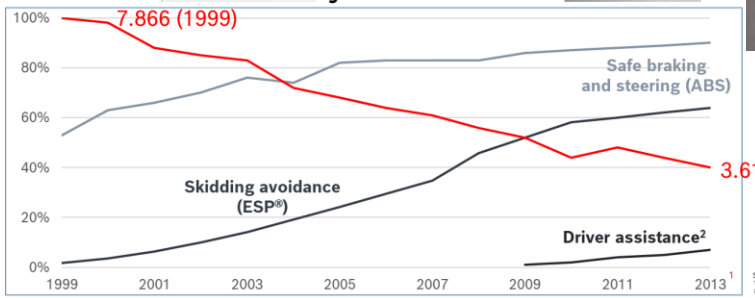
$$\frac{\partial}{\partial t}\begin{pmatrix} h \\ uh \\ vh \end{pmatrix} + \frac{\partial}{\partial x}\begin{pmatrix} uh \\ u^2h+\frac{1}{2}gh^2 \\ uvh \end{pmatrix} + \frac{\partial}{\partial y}\begin{pmatrix} vh \\ uvh \\ v^2h+\frac{1}{2}gh^2 \end{pmatrix} = \begin{pmatrix} q \\ gh(S_{bx}-S_{fx})+S_{p_{cx}} \\ gh(S_{by}-S_{fy})+S_{p_{cy}} \end{pmatrix}.$$





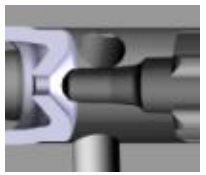


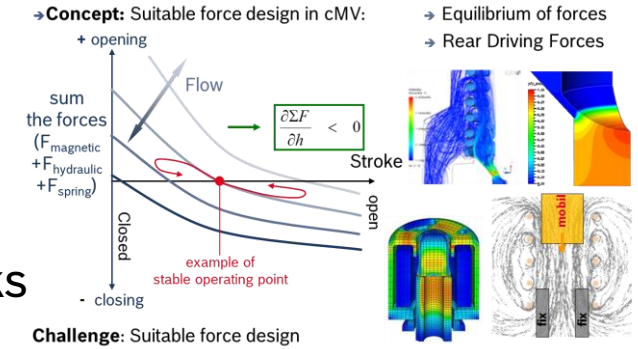
- Hydraulic Braking systems:



Σ > 50.000 life savings

Bosch – we save lifes





- Valve design
- Test bench tasks
- Reliability tasks

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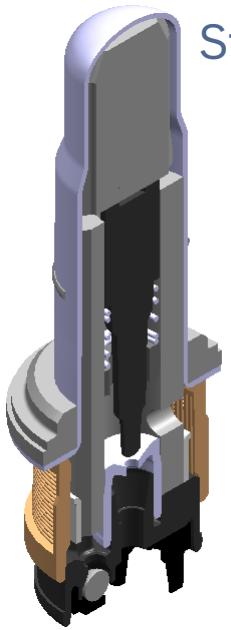
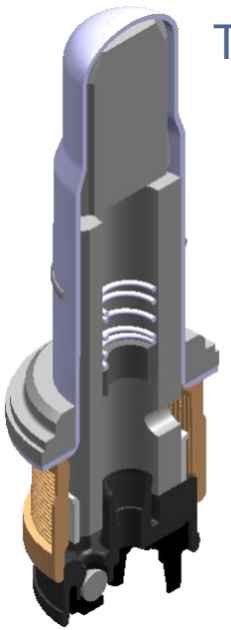
Example valve design development for trucks
Increase flow rates via main seat for high flow

- Improvement of tappet & valve body only (“make parts”).
- Flow improvements +40% + function & reliability advantages, i.p. by appropriately designed hydraulic force layout by CFD.



Standard



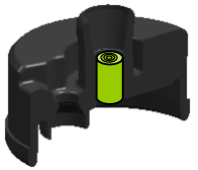
Take over

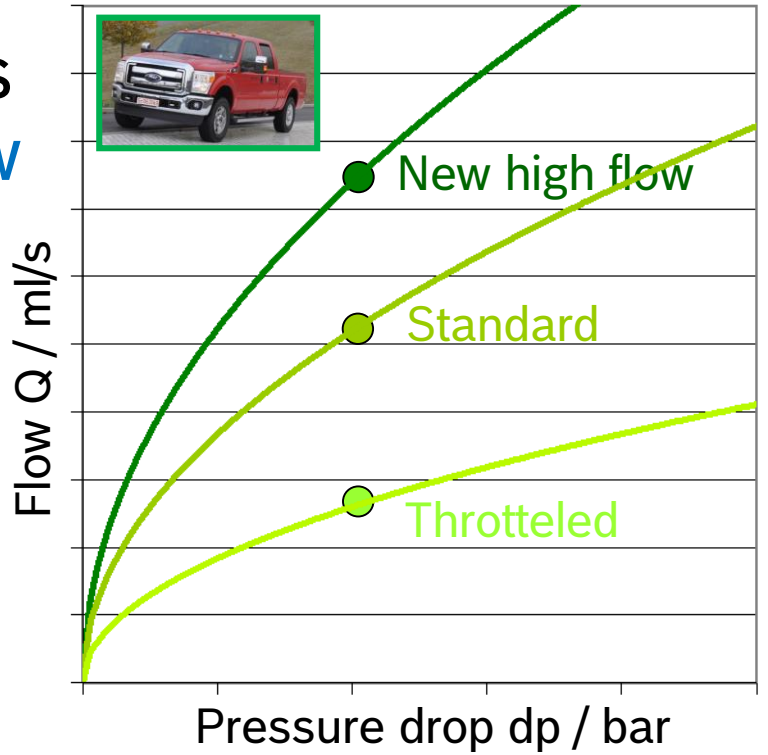
Changes:

tappet

Valve body

Throttel variants by plastic part (KVU)





160 geometries CFD simulated

6 variants with turned steel tappets built & tested

2 variants with PEEK tappet built & tested over T & ok

lower deviation variant chosen

Design improved by mathematics ☺

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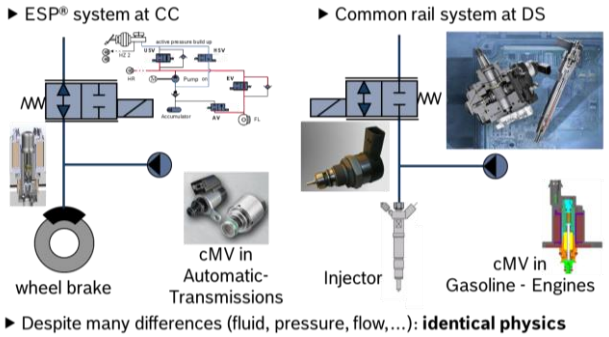
Leading my Business - examples by CE brake fluid & valves

3 examples of leadership by content

- KNW / BEO controllable valves



- Benefits from Bosch internal exchanges among experts
- WG founded 2004

- House of global collaboration brake fluid

- Global actions and harmonization
- Exchange started 2012

- SAE & ISO task force lubrication brake fluid

- Transparent & compliance improvements of standardization by lab tests

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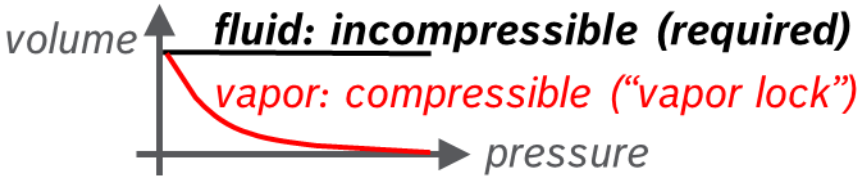
House of global collaboration (HogC-BF)

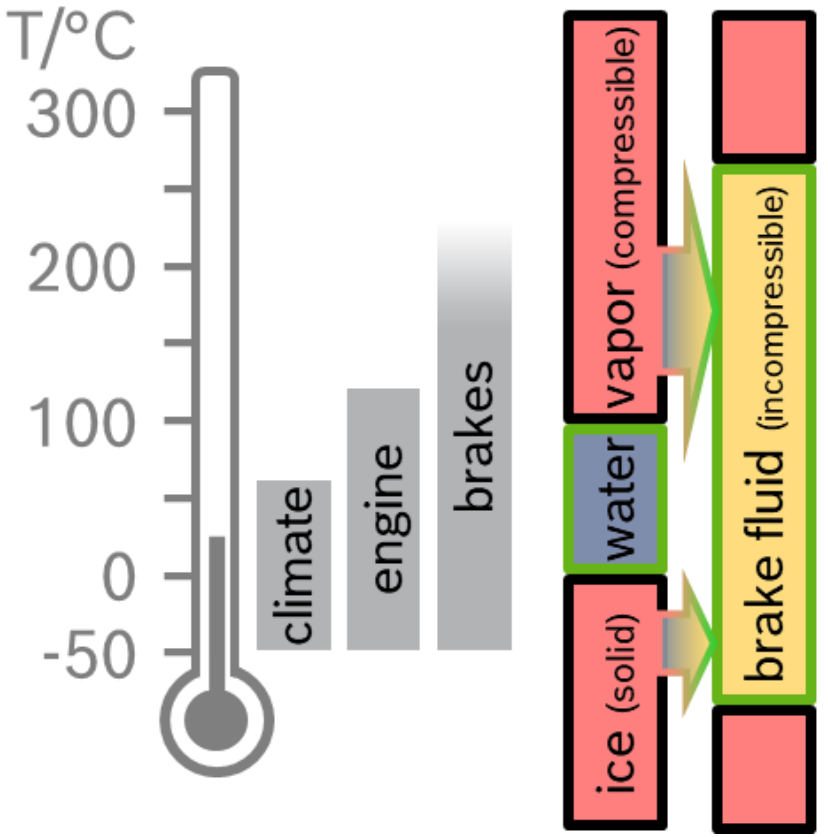
Application for domain brake fluid (BF)

Germany:
VM/EMH-DE
Michael Hilden

Brake fluid

- a key design element
  for braking systems





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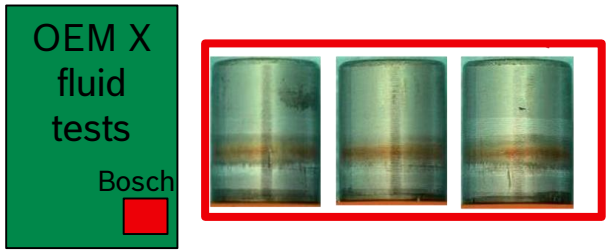
Example brake fluid impact on noise and wear

2012: Challenge…

- Bosch TCD: all DOT 3/4/5.1 fluids ok. OEM X did ask suppliers to release a new brake fluid (“best in class”).



- OEM X “unsatisfied”: all suppliers claim “products ok for all fluids”, but 2 fluids tested => both failed ☹.
- One fluid “canceled” due to noise problems in market.

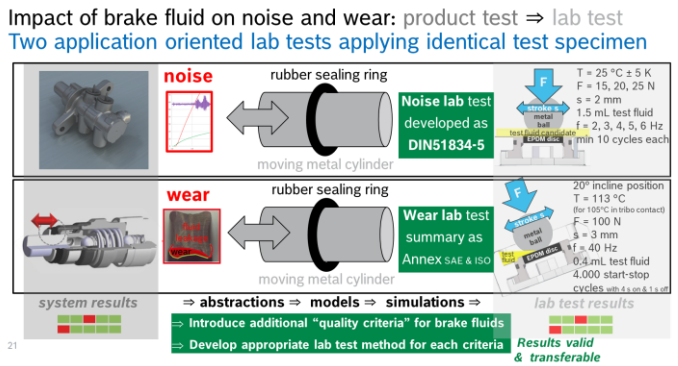
…and actions…

- Transparent collaboration and active deep technical work within DIN, ISO & SAE with pfp TriNoWe

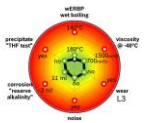
- Bosch did harmonize and enhance TCD: transparent listing of challenges & OEM responsibilities & consulting

…for solution (2024)

- Two new lab test for brake fluids for noise and wear developed and rolled out round robin tests R2TW & R2TW.



- Tests applied in Bosch assessments & to be introduced into brake fluid standards of SAE & ISO



TCD: Technical Customer Document

OEM: Original Equipment Manufacturer

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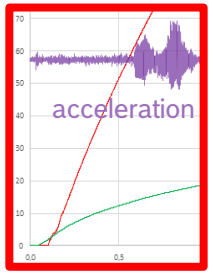
Motivation for development of NOise & WEar standard tests

Future trends emphasis challenges noise and wear for brake fluids

- Brake / clutch

- Few fluids: noise

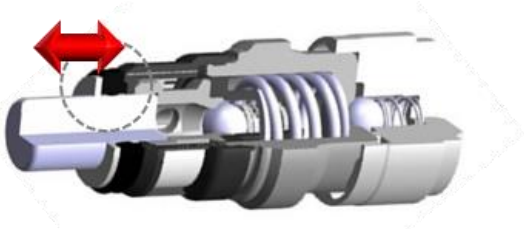
(audible and measurable by acceleration)



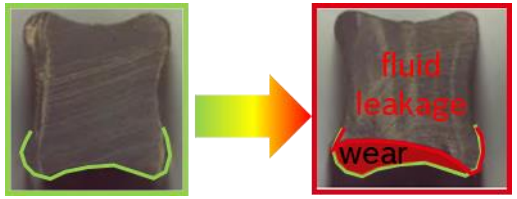
- Future trend:

- Reduction of masking noises in vehicle.
- **Target for fluid:**

- Pump element ESP®



- Few fluids: wear



- Future trend:

- Increasing load for pump sealing ring.
- **Target for fluid:**

- **Introduce additional “quality criteria” for brake fluids**
- **Develop appropriate lab test method for each criteria**

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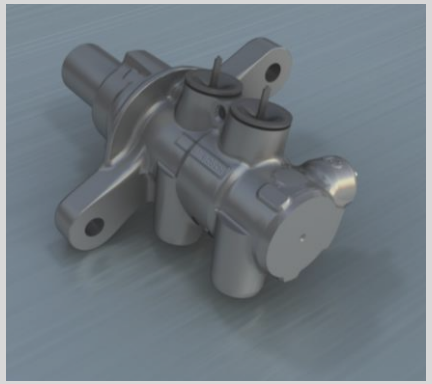
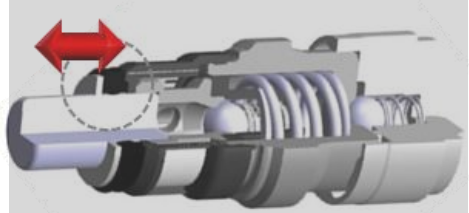
Impact of brake fluid on noise and wear – the pfp TriNoWe

Target: development of lab tests reflecting valid system results





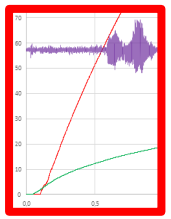
system results

5 test fluids TriNoWe

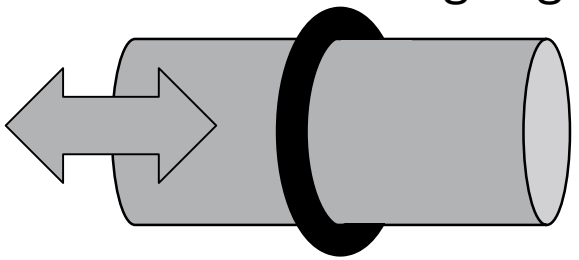
Noise

Wear

noise



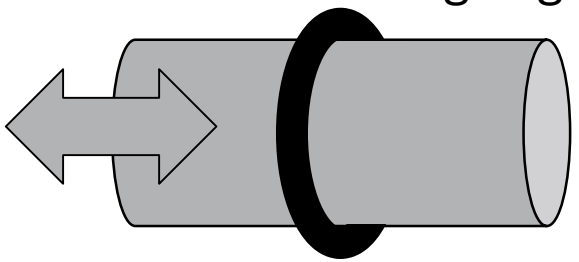
rubber sealing ring



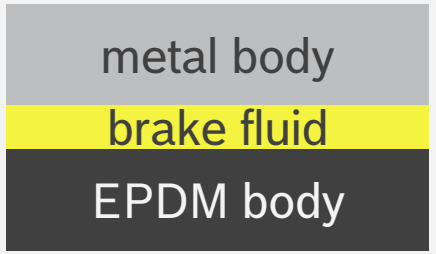
moving metal cylinder

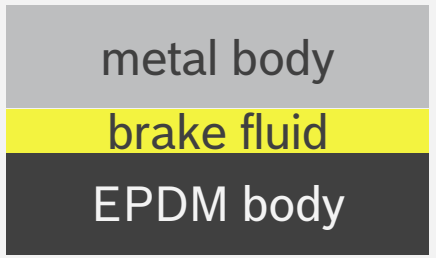
wear

rubber sealing ring



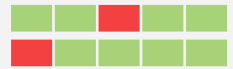
moving metal cylinder





⇒ **abstractions** ⇒ **models** ⇒ **simulations** ⇒

lab test results



SAE & ISO Task Force with pfp TriNoWe (BMWi funded in WiPaNo)

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

Results valid & transferable

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Work & organization model for SAE & ISO Task Force lubrication

Both brake fluid committees of SAE & ISO (SAE: 12.10.2017, ISO: 09.11.2017) and the Task Force itself (TF: 05.10.2017) decided: Agreement, that the TF acts as **SAE & ISO TF** in order to use its deliverables for both.

SAE & ISO TF "delivers" its results to SAE & ISO

Brake fluid committee TEVHBASS1

Scope (18.10.2016)**:**

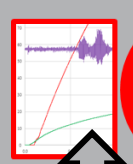
Define lab test to evaluate lubrication capability to measure

a. noise
b. wear

as new **SAE** test method.
(Extend SAE J1703 + J1704)

SAE & ISO Task Force (**TF**)
brake fluid lubrication

lab test noise

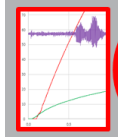


NOISE

WEAR

lab test wear

WiPaNo Project **TriNoWe**



NOISE

NO NOise
NOr **WE**ar
= TriNoWe
Tribology in **No**rms **W**orld**wide**

WEAR

WIPANO

> 1 M€ public funding

Bundesministerium für Wirtschaft und Energie

Brake fluid committee TC22 / SC33 / WG14

Scope (09.11.2017)**:**

Define lab test to evaluate lubrication capability to measure

a. noise
b. wear

as new **ISO** test method.
(Extend ISO 4925)

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SAE & ISO Task Force „brake fluid lubrication“

16 meetings since 2017

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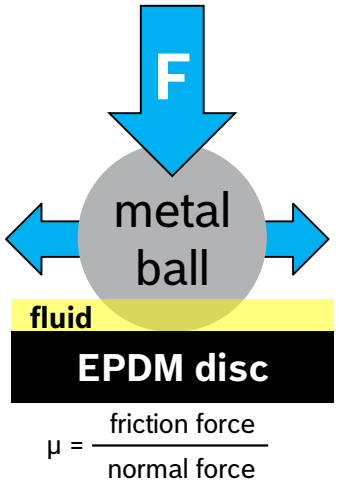
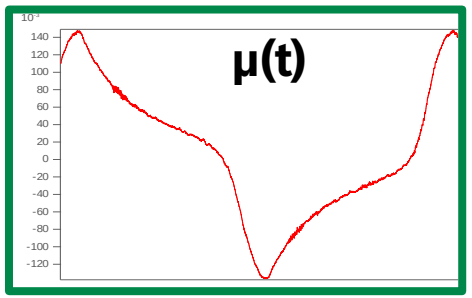
Tribometer test equipment and results (example SRV 4 @Bosch)

Valid differentiation between „not noisy“ and „noisy“ fluids



$$\mu = \frac{\text{friction force}}{\text{normal force}}$$

“not noisy”
brake fluid:
example RF ISO
(ISO 4926 or SAE RM66-07)

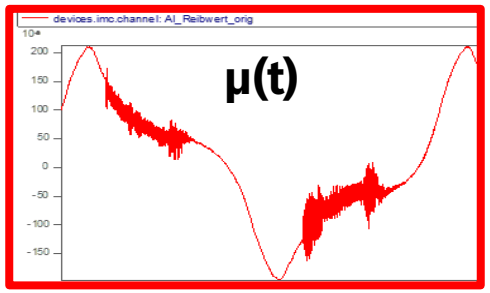


no stick-slip effect

σ = 0,0008 (low: ok)

σ measures μ-oscillations

“noisy”
brake fluid:
example RF 31
(canceled due to noise complaints)



stick-slip effects

σ =0,0245 (high: not ok)

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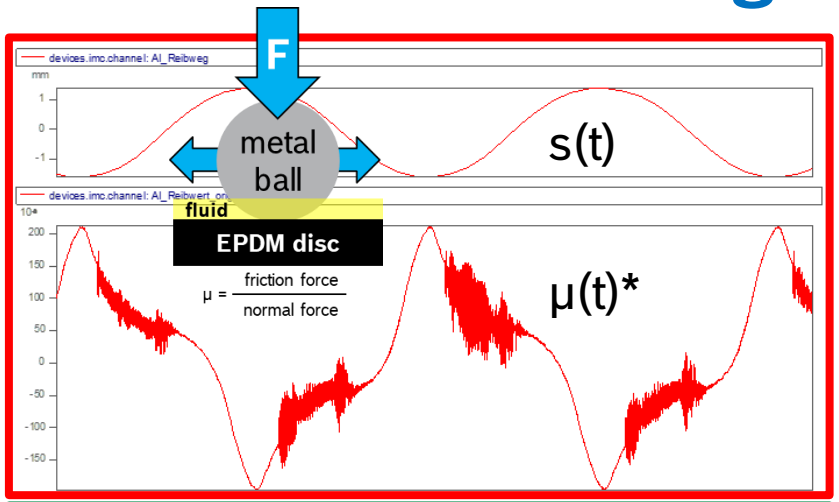
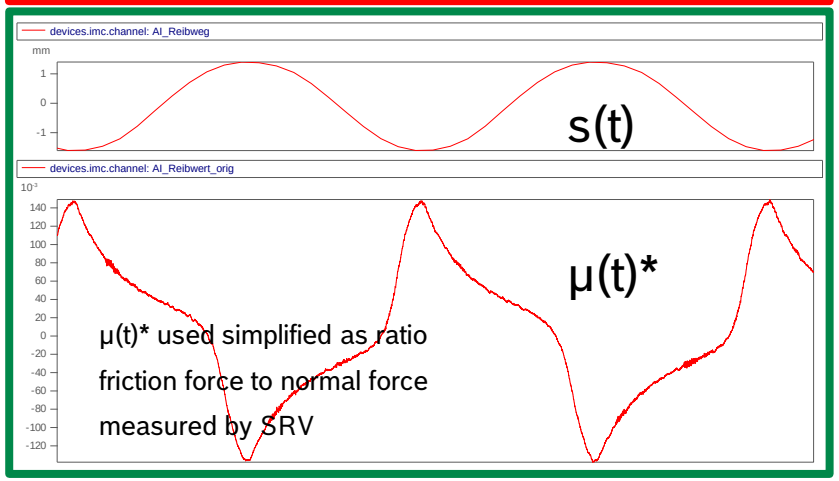
Two assessment values for brake fluids for noise: σ & SFC

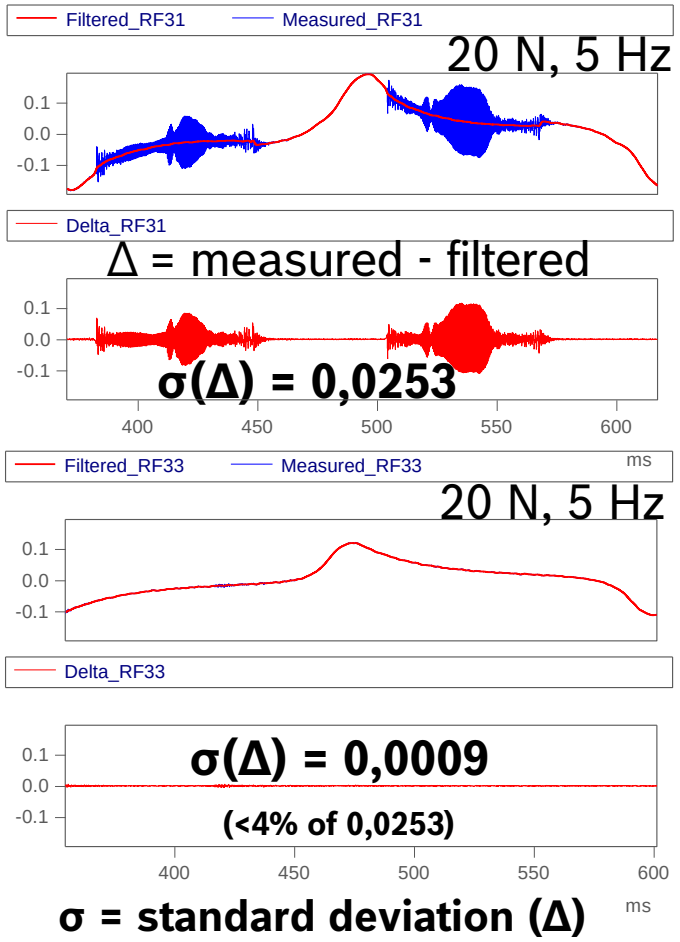
Introduction method: **sigma σ(Δ)**

RF31

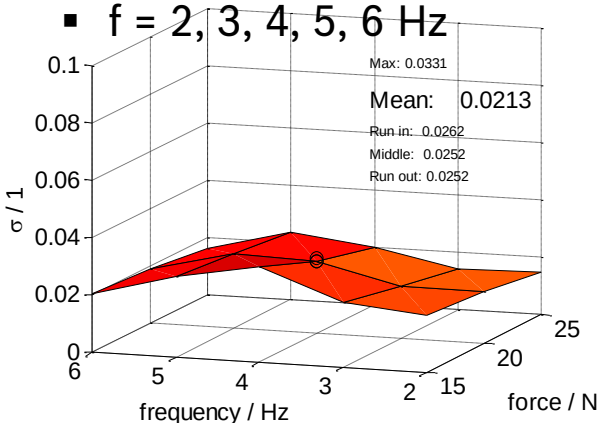


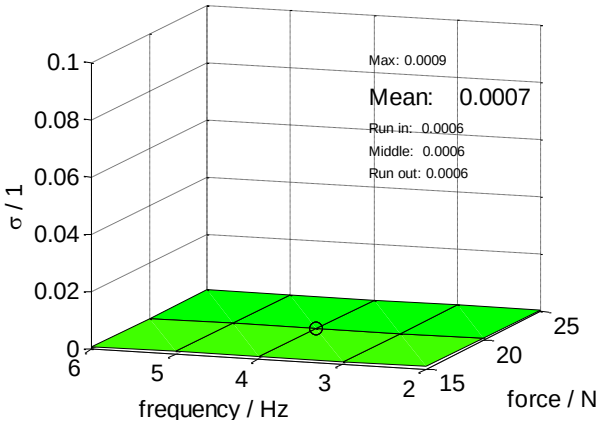
RF ISO





- F = 15, 20, 25 N
- f = 2, 3, 4, 5, 6 Hz





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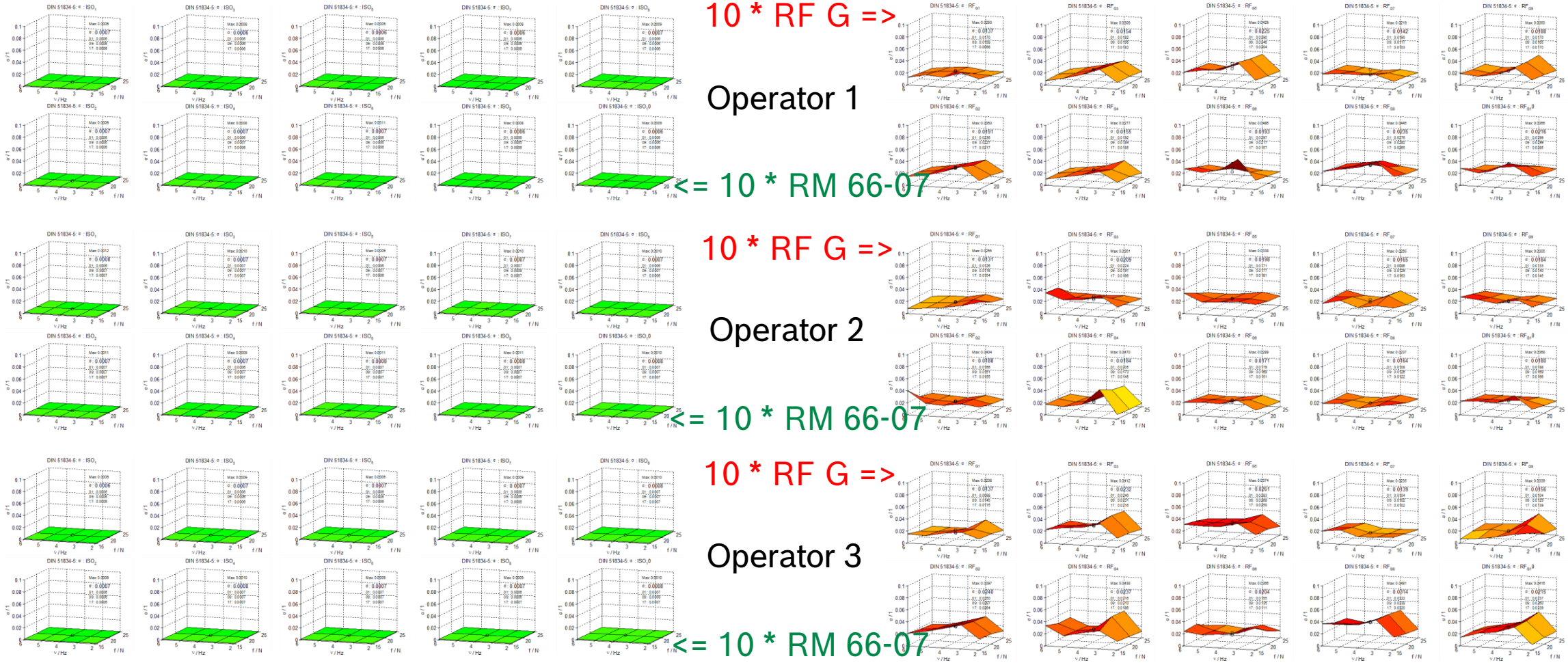
BOSCH

SAE & ISO noise test evaluations of sigma in statistical study

High repeatability and consistency of results for three operators



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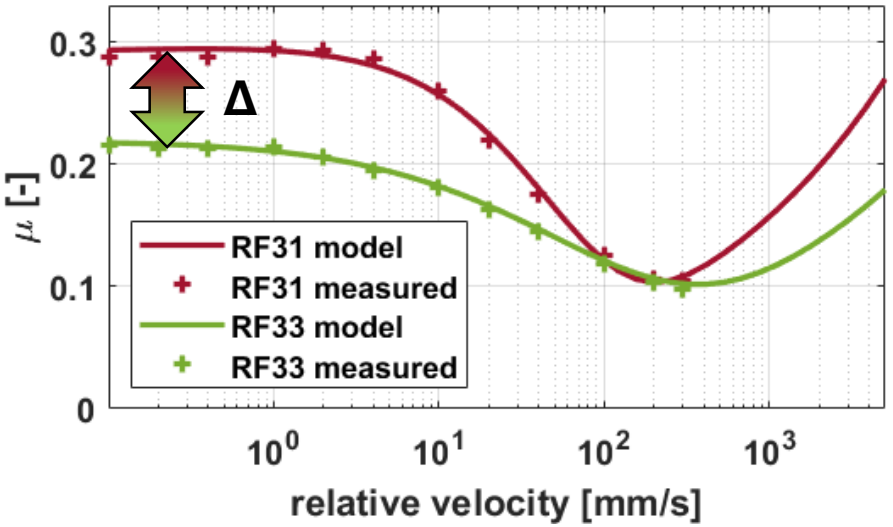
BOSCH

SAE & ISO noise test: consistency of experiments & simulations

Consistency of tests and simulation by measured Stribeck curves

Stationary Stribeck curve for RF31 & RF 33

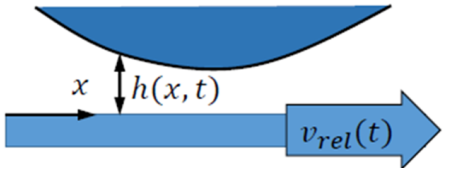
Static Friction Coefficients differ



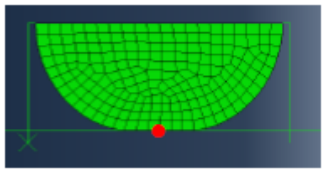
$$\mu(v) = \mu_0 e^{-\left|\frac{v}{v_s}\right|^{\delta}} + (cv)^{\alpha}$$

New dynamic friction approach:

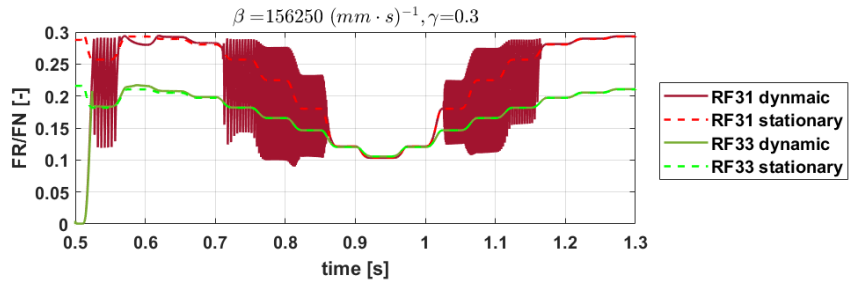
$$\frac{\partial h}{\partial t} = \gamma \cdot v_{rel} - \beta \cdot h^2$$

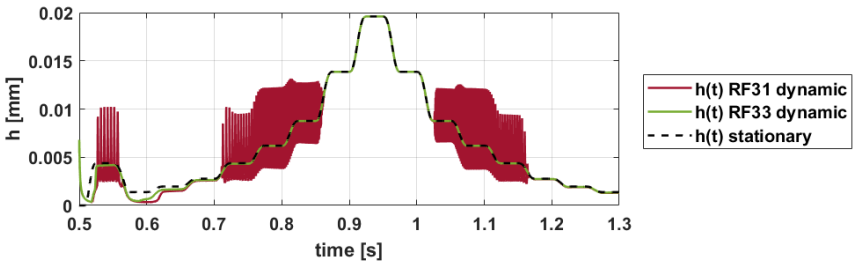


FEM model results for RF 31 / RF 33



rebuilds stick-slip effects for RF 31, but not for RF 33.





Simulation applied to specify noise test criteria (Source: HsH)

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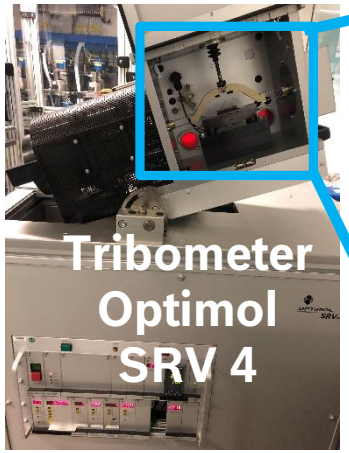
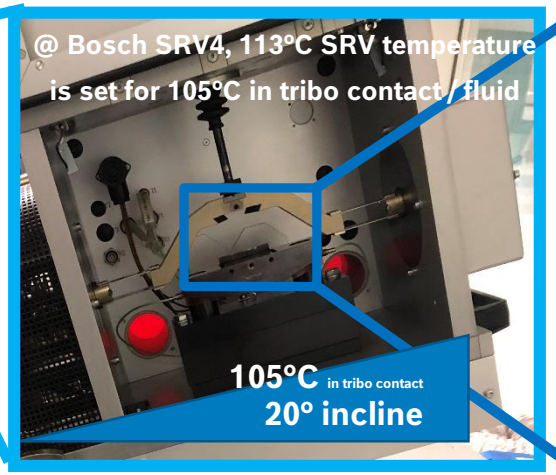
BOSCH

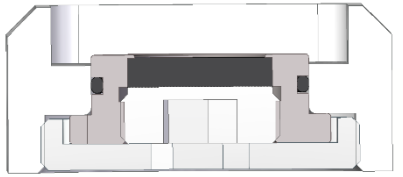
Wear test method according of SAE&ISO TF brake fluid lubrication

Valid differentiation between „no wear“ and „wear“ fluids





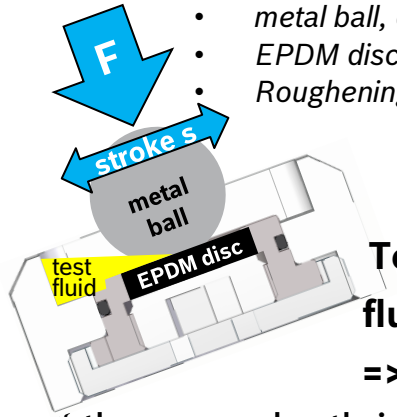
improved test bath with…



…EPDM disc fixation

No wear *in product test*

RM 66-07: no wear (d_{wear} = 0,10 mm)

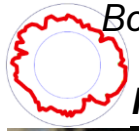


***Test specimen*:**

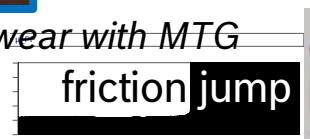
- *metal ball, d=10 mm, G5*
- *EPDM disc, d=10 mm*
- *Roughening EPDM: PDR*

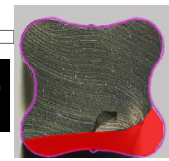
Test bath & fluid amount => fluid level

Bosch product wear with MTG



wear *in product test*





Continental product wear with MTG

MTG: wear (d_{wear} = 0,98 mm)

d_{wear} „measures“ the wear depth in the EPDM test disc after wear test

RM 66-07 = ISO 4926 “reference fluid” (PDR & plastic deformation contained)

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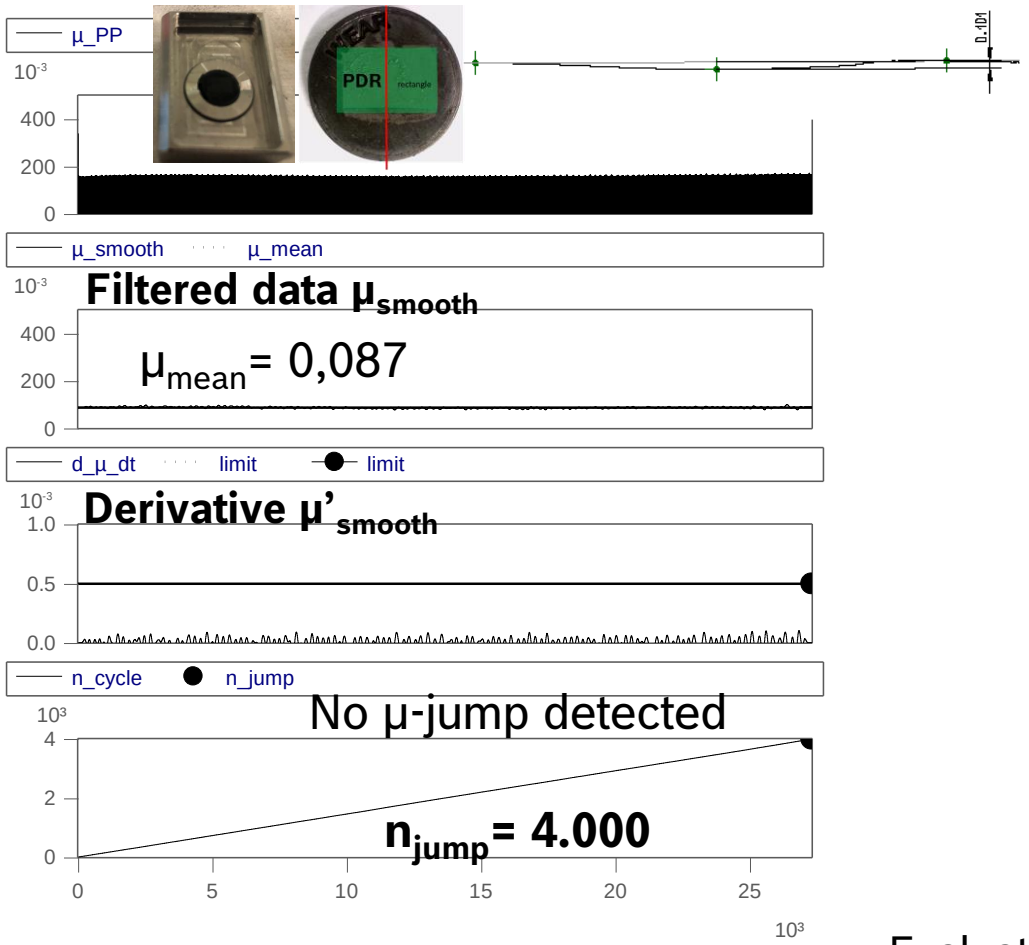
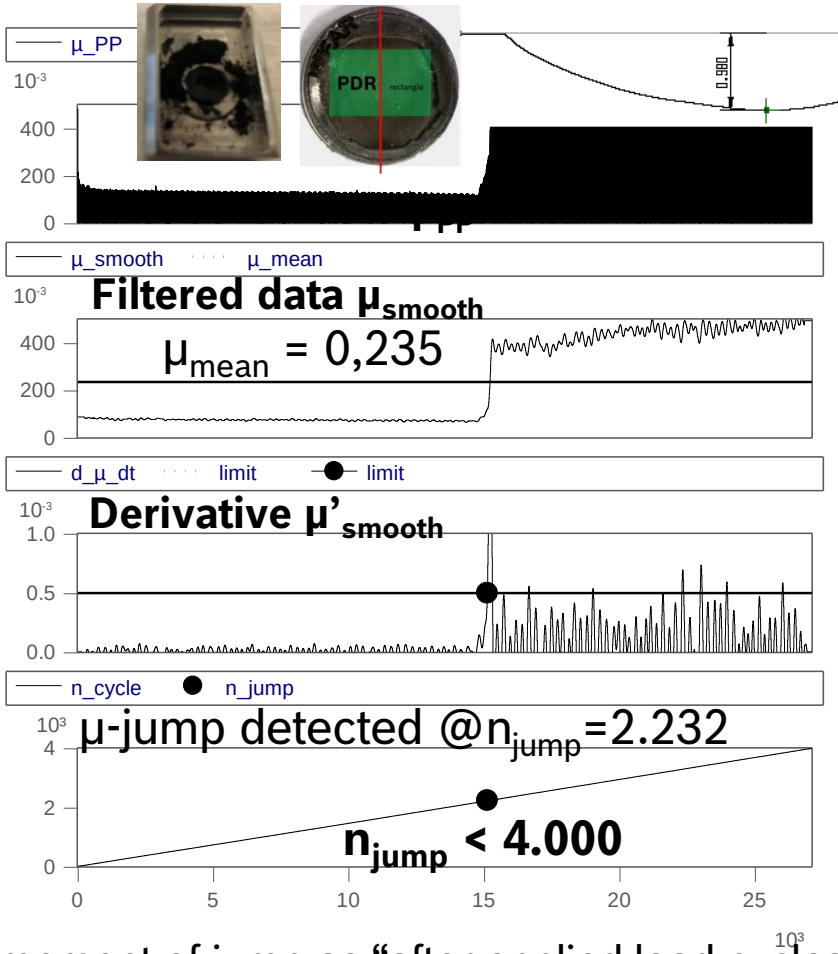
Wear test: evaluations for $\mathbf{d_{wear}}$, μ_{mean} & n_{jump}

RM 66-07 (def. of ref. fluid): no wear (d_{wear} = 0,101 mm)



MTG (raw material): wear (d_{wear} = 0,980 mm)



R2TW-2
Round Robin Test Wear -2
01-08/24

(n_{cycles} only 4.000, only RF3.W&4.W)

R2TW-2:
2 tests / day
2 test days ☺

Evaluate moment of jump as "after applied load cycles n_{jump}"

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BOSCH

Wear evaluations of d_{wear} in statistical study performed by Bosch

High repeatability and consistency of results for three operators

10 * MTG =>

Operator 1

<= 10 * RM 66-07

10 * MTG =>

Operator 2

<= 10 * RM 66-07

10 * MTG =>

Operator 3

<= 10 * RM 66-07

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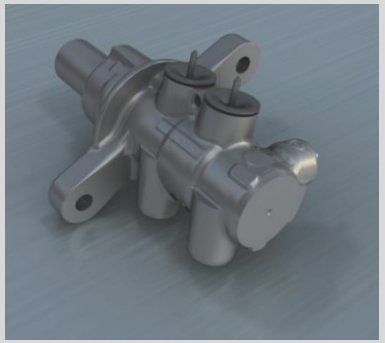
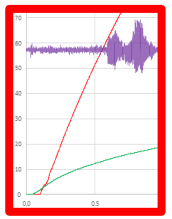
Impact of brake fluid on noise and wear: product test ⇒ lab test

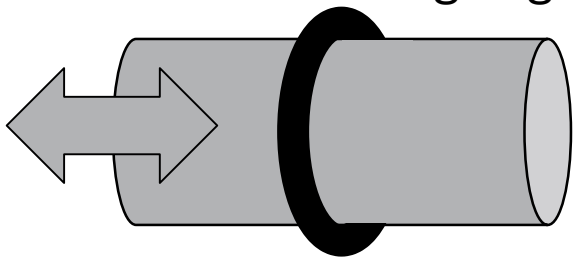
Two application oriented lab tests applying identical test specimen



noise

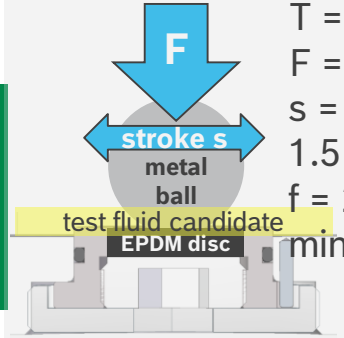


rubber sealing ring

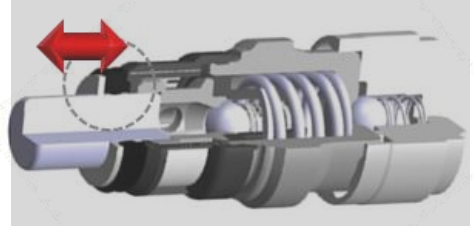


moving metal cylinder

Noise lab test developed as **DIN51834-5**

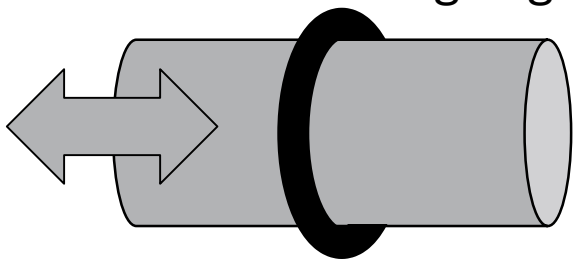


T = 25 °C ± 5 K
F = 15, 20, 25 N
s = 2 mm
1.5 mL test fluid
f = 2, 3, 4, 5, 6 Hz
min 10 cycles each



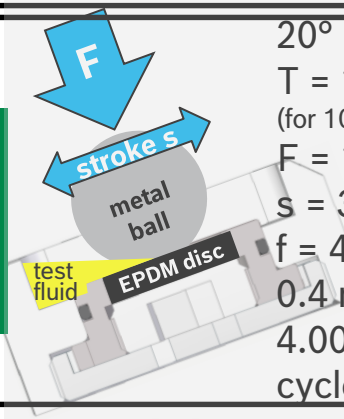
wear

rubber sealing ring



moving metal cylinder

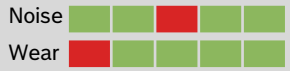
Wear lab test summary as Annex SAE & ISO



20° incline position
T = 113 °C
(for 105°C in tribo contact)
F = 100 N
s = 3 mm
f = 40 Hz
0.4 mL test fluid
4.000 start-stop cycles with 4 s on & 1 s off

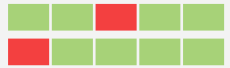
system results

5 test fluids TriNoWe



⇒ **abstractions ⇒ models ⇒ simulations ⇒**

lab test results



⇒ **Introduce additional "quality criteria" for brake fluids**

⇒ **Develop appropriate lab test method for each criteria**

Results valid & transferable

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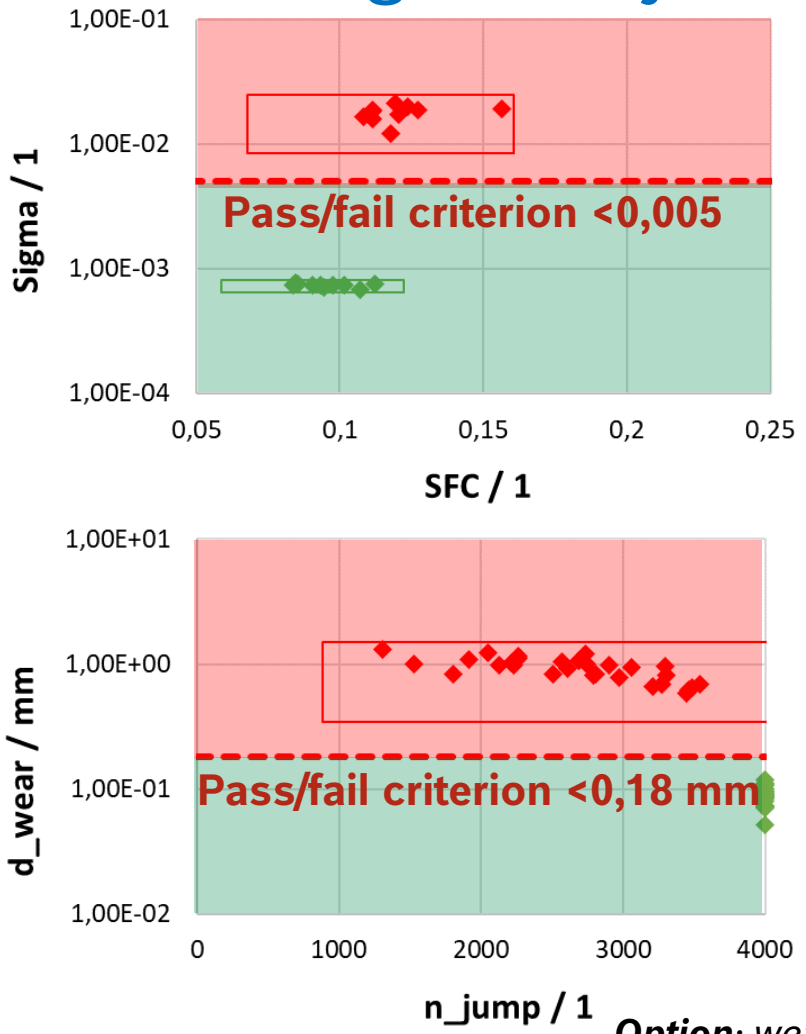
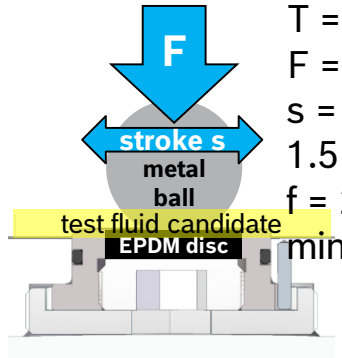
Impact of brake fluid on noise and wear: product test => lab test

Implementation of lab tests reflecting valid system tests results

	Test mimic ok	Draft published	Round robin test	Precision	Standard ok	Standard published	Pass/Fail SAE	Pass/Fail ISO
Noise test DIN 51834-5	Finished	Since 10/2022	08/2021 - 10/2022	Finished	Finished	Finished 02/2024	Finished 03/2024	Decided by committee
Wear test Annex SAE & ISO	Finished	Since 03/2024	02/2024 - 08/2024	Finished	Annex finished	To be published	Decided by committee	Decided by committee

Status 11/2024





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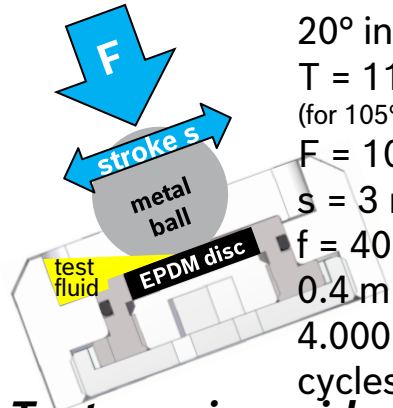
s = 2 mm
1.5 mL test fluid
f = 2, 3, 4, 5, 6 Hz
min 10 cycles each



20° incline position
T = 113 °C ± 5 K
(for 105°C in tribo contact)
F = 100 N
s = 3 mm
f = 40 Hz
0.4 mL test fluid
4.000 start-stop cycles with 4 s on & 1 s off

Test specimen identical:

- *metal ball, d=10 mm, G5*
- *EPDM disc, d=10 mm*
- *Roughening EPDM: PDR*

***Option**: wear test after noise test*

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Michael Hilden – Chief Expert brake fluid & valves

Tasks & passion in 5 sentences

- Joined Bosch ABS & ESP after PhD in computational fluid dynamics at Fraunhofer ITWM in 2002
- > 20 years hydraulic development experience, i.p. for valves and brake fluid tasks
- Deep hydraulic content & solving challenges => motivation & joy & fun ☺
- Success factors: appreciation, good & fair collaboration, deep understanding & design
- Leadership by content: give sense & purpose AND motivate & inspire

Dr.rer.nat. Michael Hilden, Chairman of DIN & ISO brake fluid committees (TC22/SC33/WG14), Coordinator of SAE & ISO TF brake fluid lubrication, Chief Expert brake fluids & valves @ Robert Bosch GmbH

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