THE EFFECT OF CONTAMINATION ON FRICTION MODIFICATION IN THE WHEEL-RAIL CONTACT

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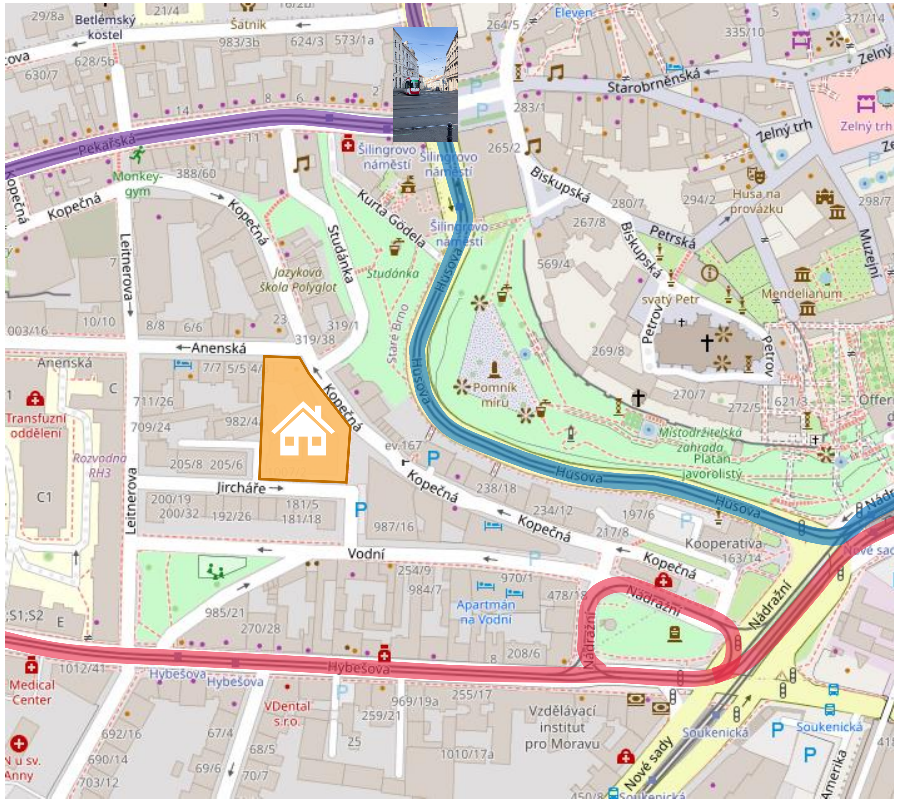
Co-supervisor: Doc. Ing. Radovan Galas, PhD

Brno, 2026

BRNO UNIVERSITY OF TECHNOLOGY

MOTIVATION

Line 6

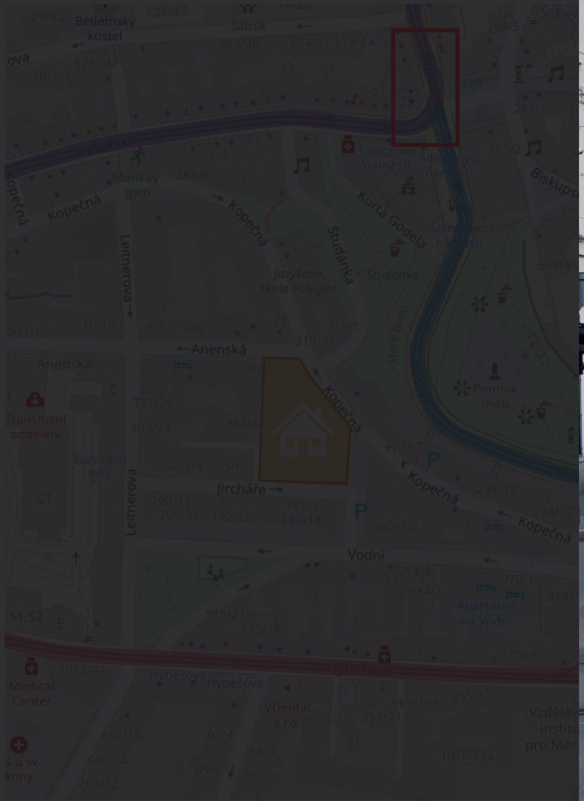


Line 12

Line 1

Trams operate daily from 5:00 AM to 11:00 PM.

Line 6



Line 1

Trams operate daily fro
to 11:00 PM

MOTIVATION

More than **22.6 million** EU residents are exposed to noise emissions from rail transport.

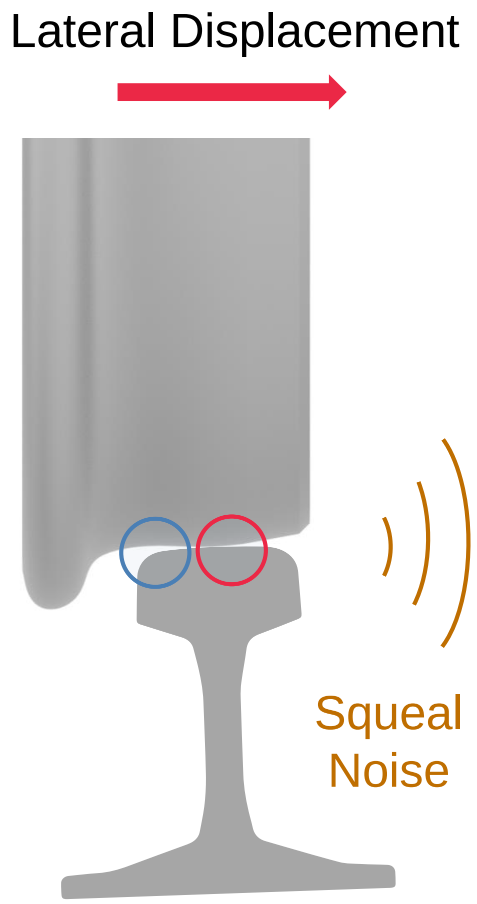
Up to **6.5 million** people living near transport corridors suffer from sleep disturbances.

Long-term exposure leads to **12,000** premature deaths and **48,000** cases of ischemic heart disease annually.

World Health Organization

European Environment Agency

MOTIVATION



Wheel Flange Contact

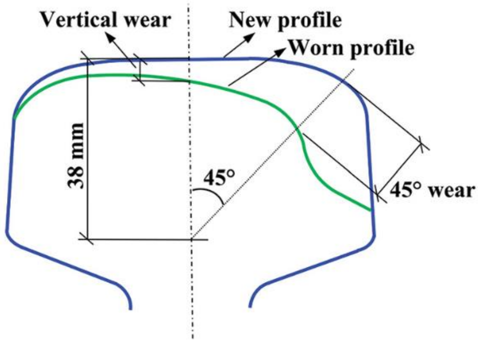
- High pressure: 0.6–2.6 GPa
- High slip: < 8 %
- Target friction: f (μ) < 0.1
- Flange lubrication

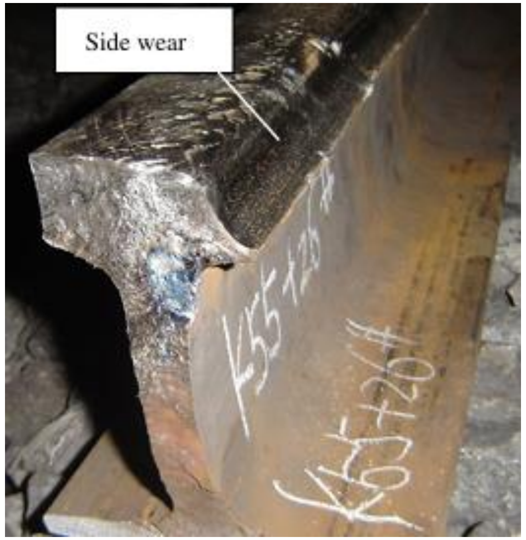
Top-of-Rail Contact

- Pressure: 0.5–1.5 GPa
- Slip: < 3 %
- Target friction: f (μ) ~ 0.2–0.4
- Top-of-rail friction modification

MOTIVATION

1) The American Association of Railroads; 2) Jin et al. (2009); upper left: Vernaillen et al. (2023); lower left: Jin et al. (2009); middle right: Tsunashima et al. (2012); uppper right: Huang et al. (2018); lower right: Igwemezie Jude (2014)



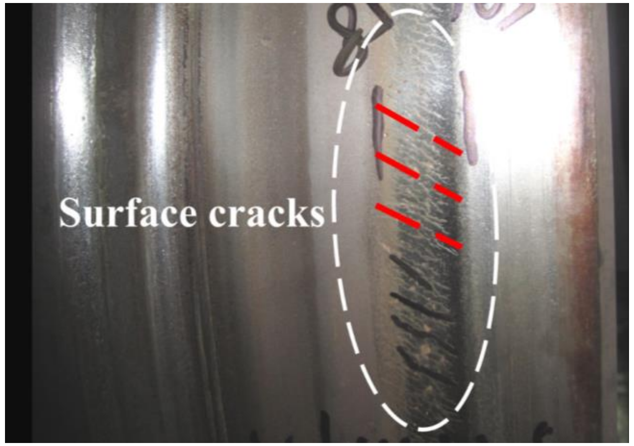


Wear Due to High Slip

Annual Cost of Wear:

$ **2B** (USA)[1]
1.2B (China)[2]

Corrugation



Rolling Contact Fatigue

MOTIVATION

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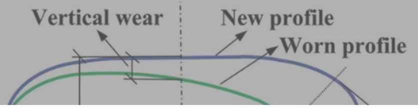


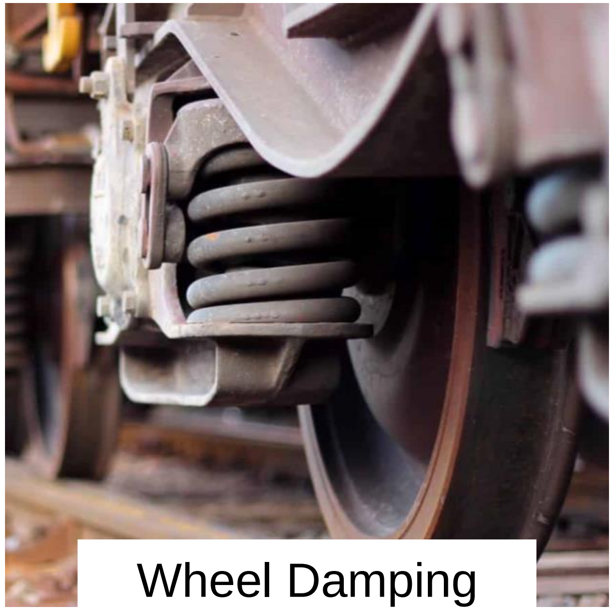
Annual Cost of Wear:


its-acoustique.fr

Sound Barriers


lbfoster.com

TOR Friction Modification


thechopal.com

Wheel Damping

Wear Due to High Slip

Corrugation

Rolling Contact Fatigue

STATE OF THE ART

STATE OF THE ART

lbfoster.com

„Solid sticks“ are used to address problems with noise and corrugation on the Vancouver SkyTrain.

Early 1990s | 2000s | 2016 | 2017 | 2018 | 2021

STATE OF THE ART

Off-board Application

On-board Application

Liquid-based Friction Modifiers

STATE OF THE ART

Categorisation of Products for TOR Friction Modification

Contents lists available at ScienceDirect
Wear
journal homepage: www.elsevier.com/locate/wear

Material concepts for top of rail friction management – Classification, characterisation and application

Richard Stock[a,*], Louisa Stanlake[a], Chris Hardwick[b], Marcia Yu[a], Donald Eadie[a], Roger Lewis[c]
[a] L.B. Foster Rail Technologies, Burnaby, Canada
[b] L.B. Foster Rail Technologies, Sheffield, United Kingdom
[c] Department of Mechanical Engineering, The University of Sheffield, Sheffield, United Kingdom

Liquid Forms of Top-of-Rail Products:

1) Friction Modifiers (Water-based)
2) TOR Lubricants (Oil/Grease-based)
3) TOR Hybrids (Both Water and Oil)

Early 1990s | 2000s | 2016 | 2017 | 2018 | 2021

STATE OF THE ART

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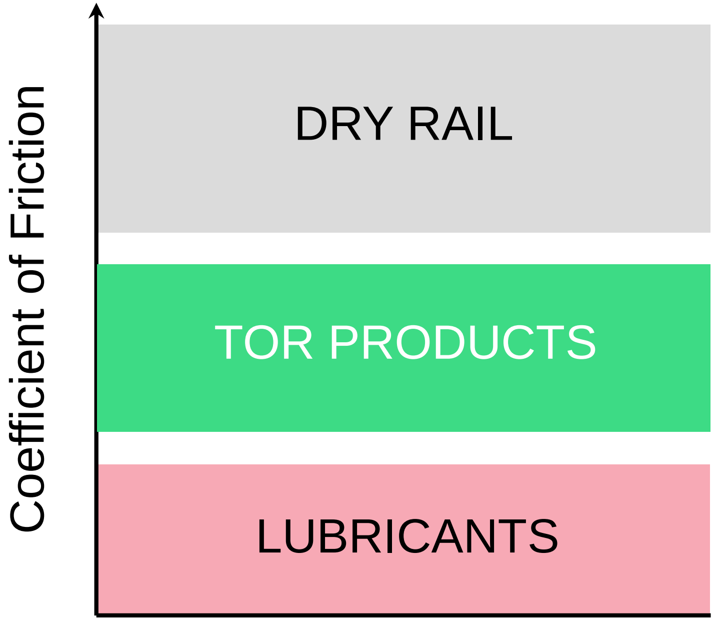
Friction Levels



Dry Friction ($f > 0.5$)
(high wear and noise, but no problems with traction/braking)

Intermediate Friction ($f \sim 0.2$–0.4)
(wear and noise reduced without low adhesion problems)

Low Adhesion ($f < 0.15$)
(low wear and noise, problems with traction and braking)

Early 1990s | 2000s | 2016 | 2017 | 2018 | 2021

STATE OF THE ART

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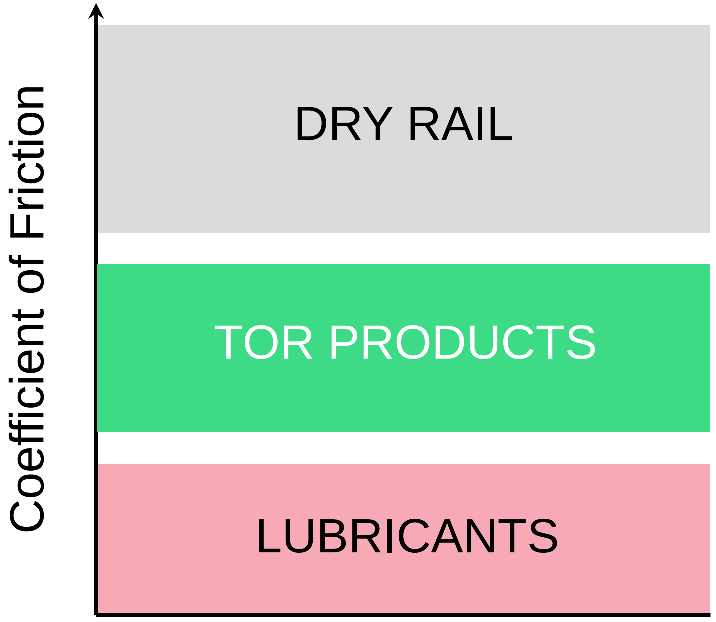
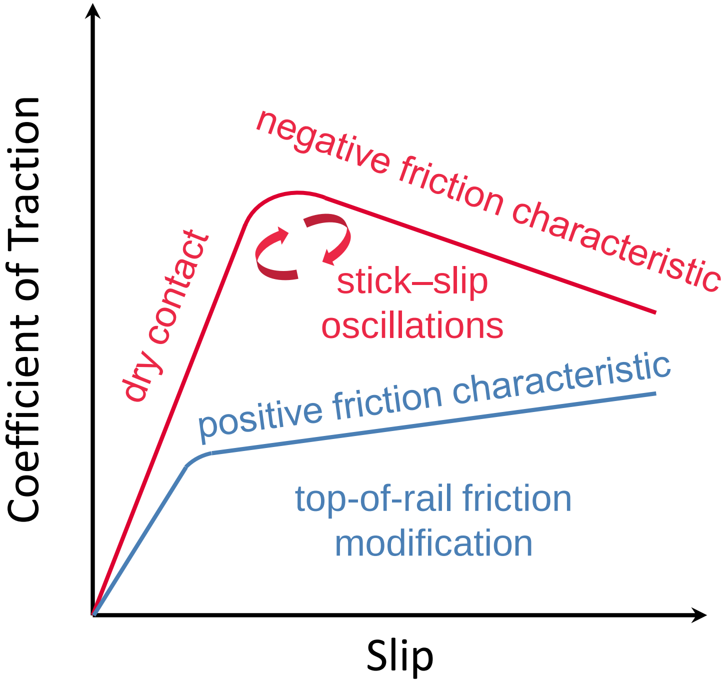


Creep Curves



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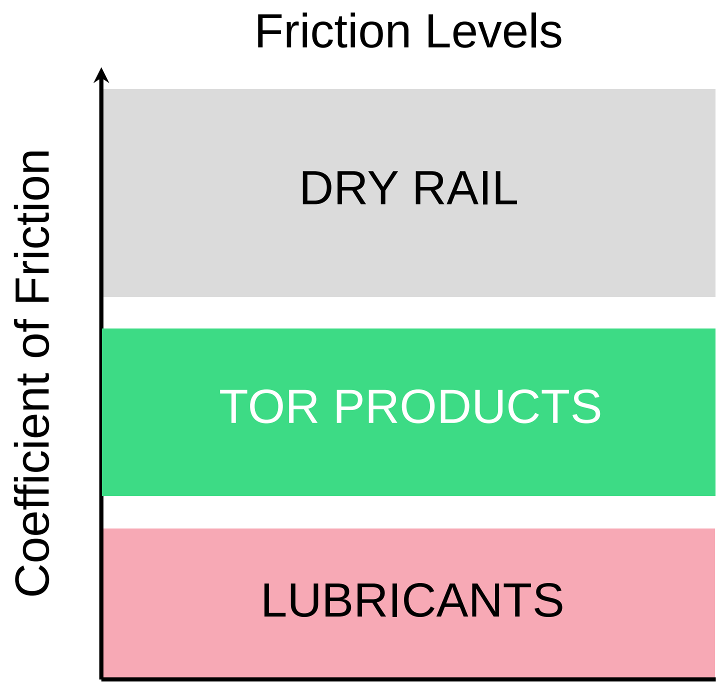
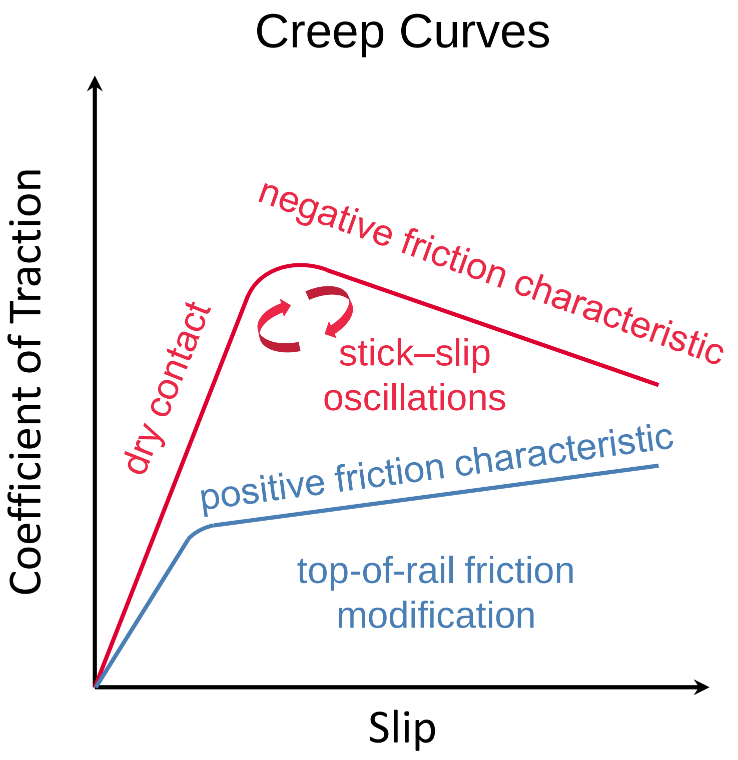
The Main Function of TOR Products





Early 1990s | 2000s | 2016 | 2017 | 2018 | 2021

STATE OF THE ART

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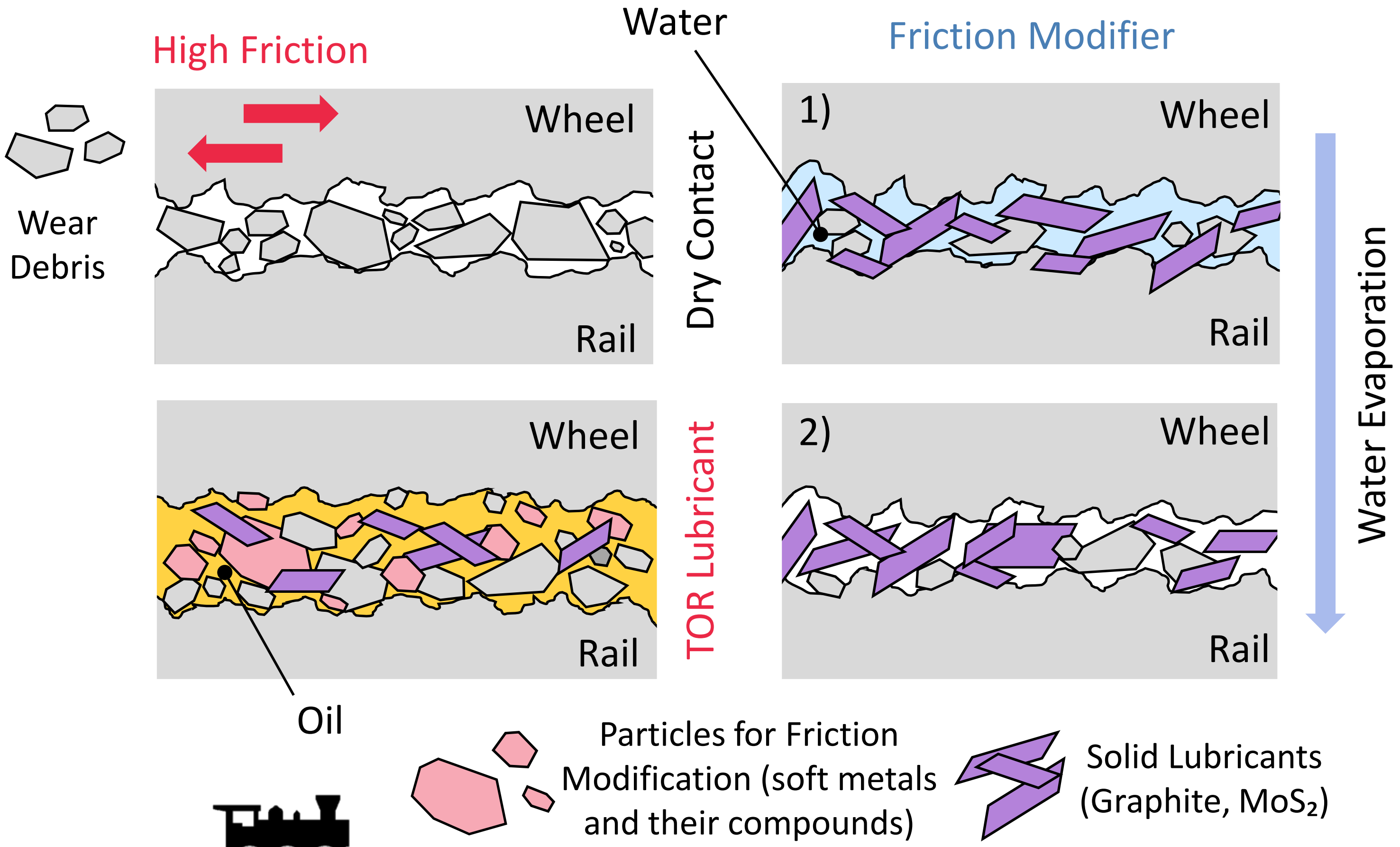
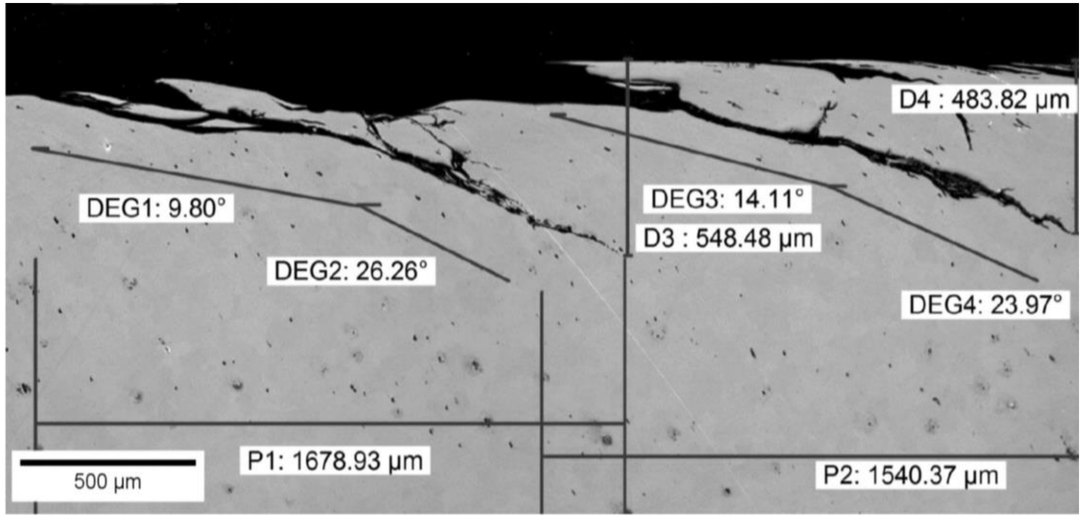


Early 1990s | 2000s | 2016 | 2017 | 2018 | 2021

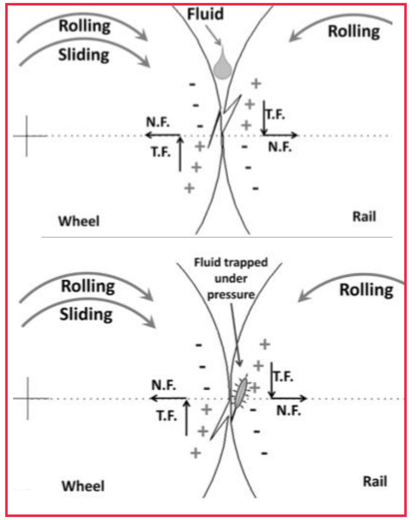
STATE OF THE ART

Possible drawbacks of TOR products

State of the Surface after the use of the TOR Lubricant



Liquid-assisted Crack Propagation



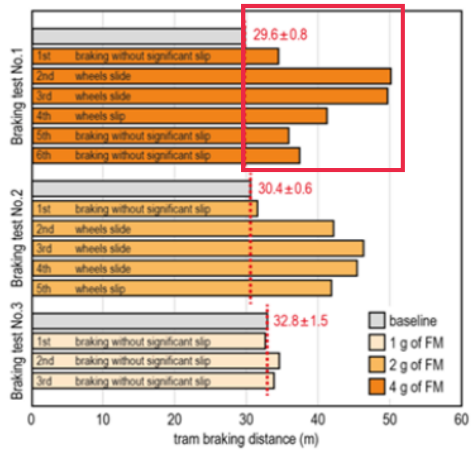
left: Hardwick et al. (2017); right: Maya-Johnson et al. (2017)

Early 1990s | 2000s | 2016 | 2017 | 2018 | 2021

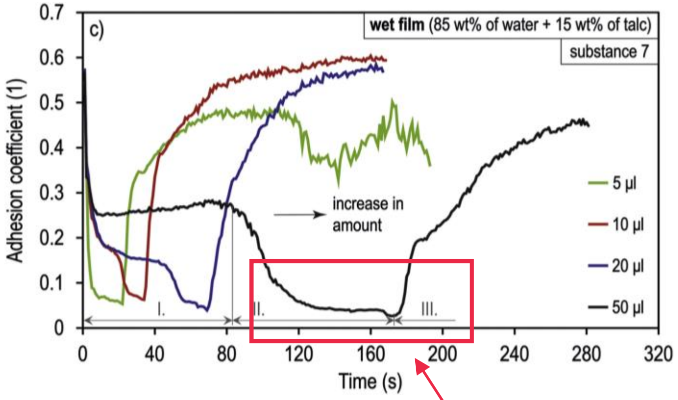
STATE OF THE ART

Braking distance extended for up to 20 meters

Oil-based TOR Lubricants



Water-based Friction Modifiers



left and middle: Galas et al. (2017); right: Galas et al. (2018)

Possible drawbacks of TOR products

Low Adhesion

Early 1990s | 2000s | 2016 | 2017 | 2018 | 2021

STATE OF THE ART

„Start of my PhD Journey“

Early 1990s | 2000s | 2016 | 2017 | 2018 | 2021

STATE OF THE ART

PROS

1. **Wear Mitigation**
Film formation reduces metal-to-metal contact.

2. **Noise Reduction**
A positive creep curve prevents stick-slip oscillations.

3. **Reduction in Airborne Particles**
Less wear debris, and residual lubricant captures airborne particles.

CONS

1. **Wheel Slips**
Traction problems during acceleration.

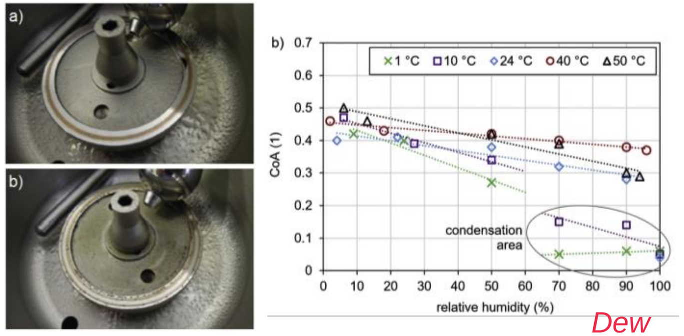
2. **Station Overruns**
Low adhesion conditions increase the stopping distance.

3. **Adverse Effects on RCF**
Residual lubricant can promote crack propagation.

Early 1990s — 2000s — 2016 — 2017 — 2018 — 2021

STATE OF THE ART

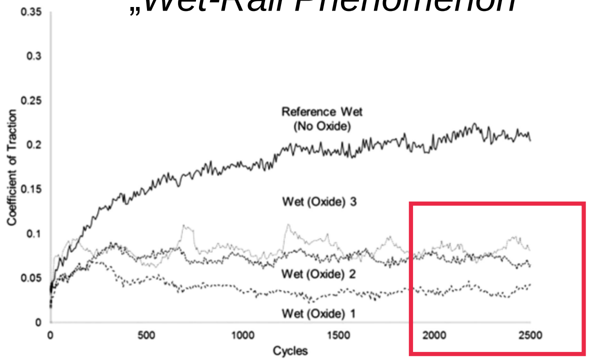
The effect of Humidity and Dew



Galas et al. (2020)

Dew Conditions

The effect of Dew and Iron Oxides
„*Wet-Rail Phenomenon*“

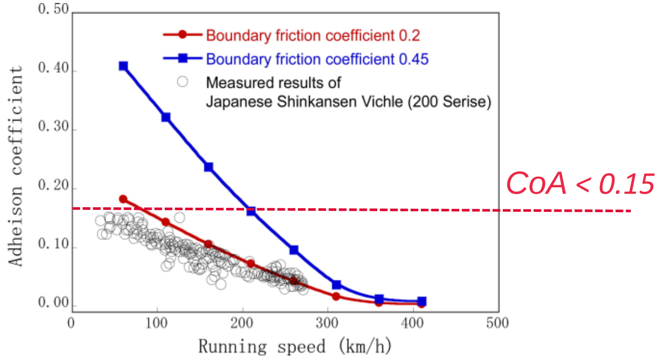


Hardwick et al. (2014)

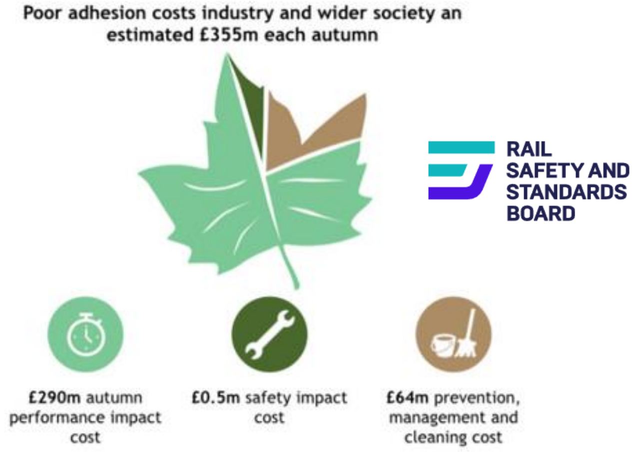
Low Adhesion

TOR Contact Is an Open Interface

The effect of Water (Precipitation)

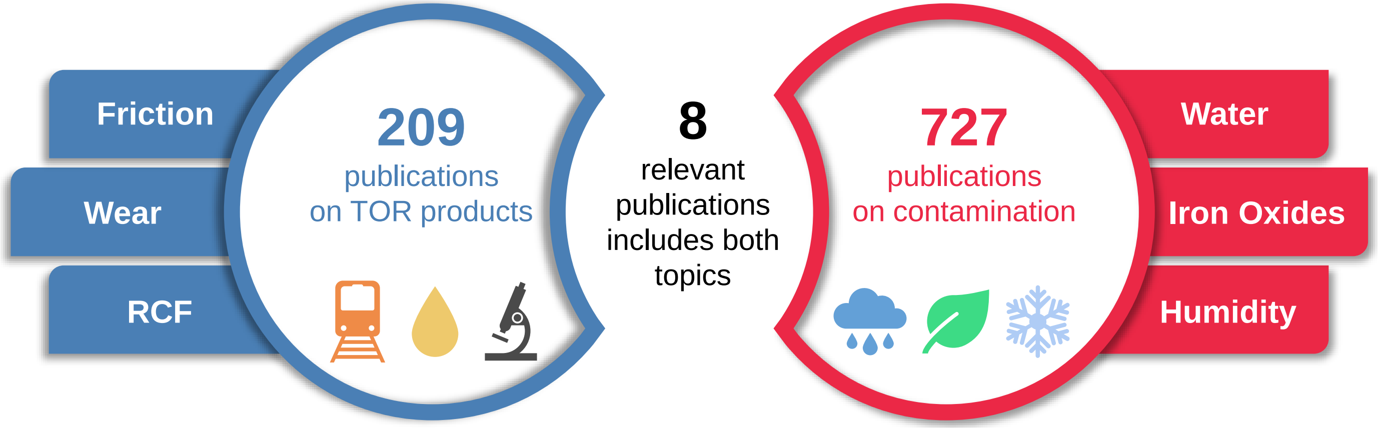


Chen et al. (2011)

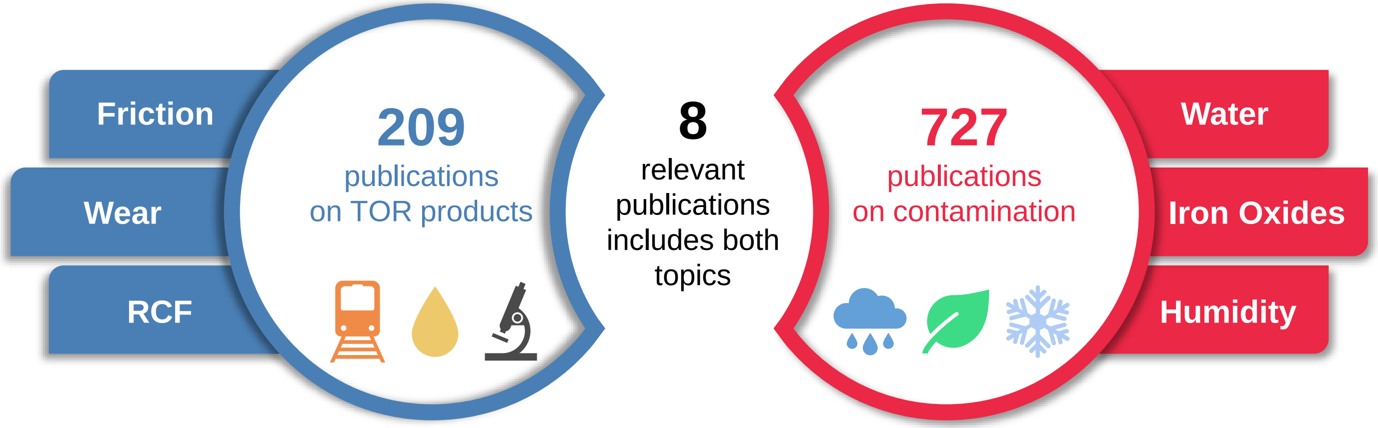


Humidity Dew Precipitation Iron Oxides Leaves

RESEARCH GAP



RESEARCH GAP



Lewis et al. (2012)

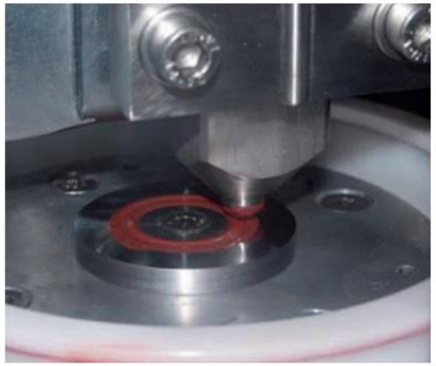
DOI: 10.1177/0954409712452239

- Conditions: humidity, temperature and iron oxides
- TOR product: water-based friction modifier
- Setup: pin-on-disc tribometer, climate chamber

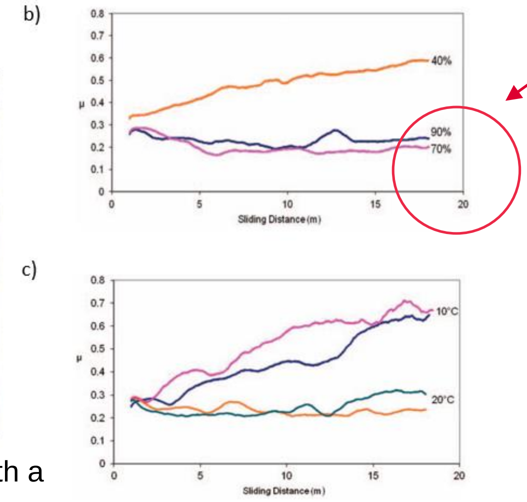
Main Findings:

1) In a humid environment, evaporation of the base medium is slowed down and retentivity increases
2) Iron oxides disrupt the FM film and increase friction

a)



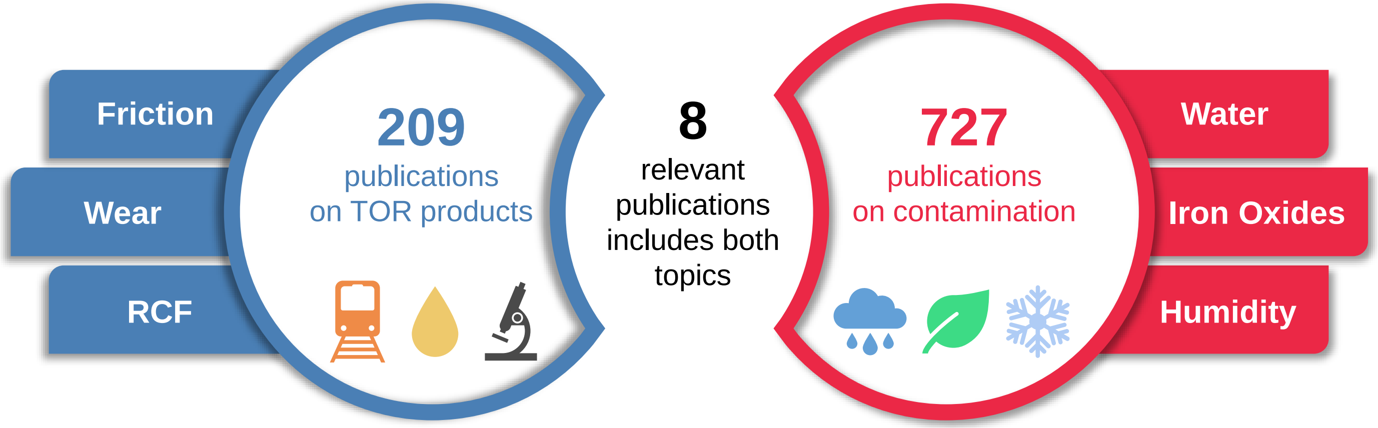
The pin-on-disc tribometer with a climate chamber.



Retentivity is Prolonged with an Increase in RH

Warmer Air Contains more Water Vapours

RESEARCH GAP



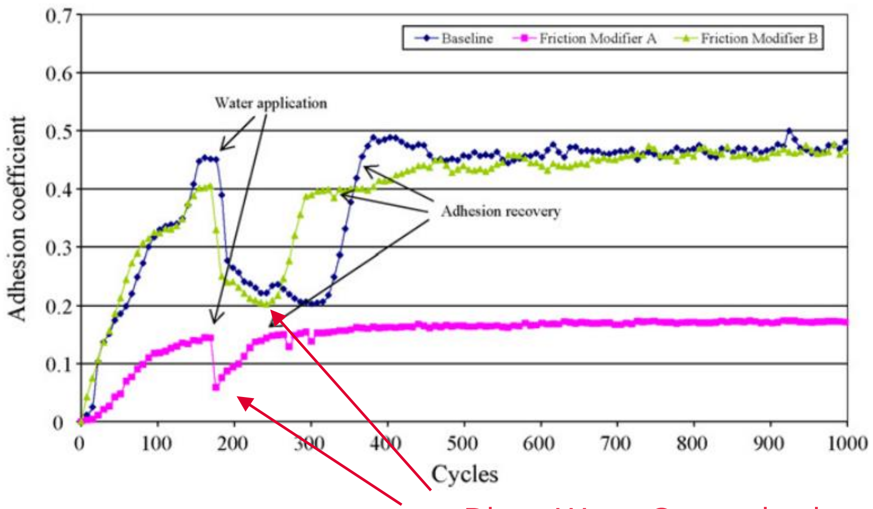
Arias-Cuevas et al. (2010)

DOI: 10.1016/j.wear.2009.09.015

- Conditions: direct water application
- TOR product: two commercial water-based FMs
- Setup: a twin-disc machine

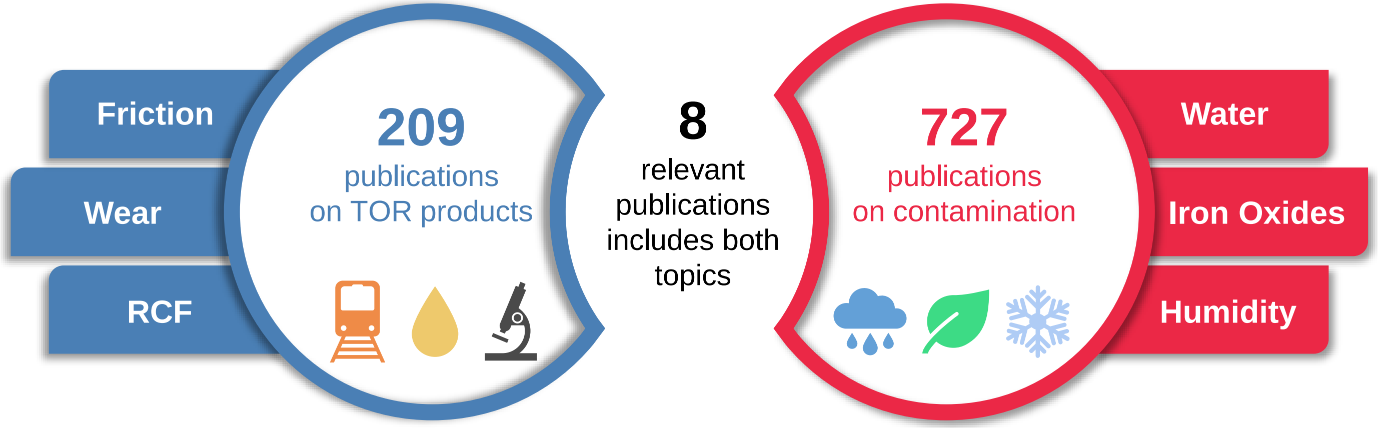
Main Findings:

1) Direct water application caused a drop of CoA below 0.1
2) However, the tested products contained particles for traction enhancement, which is not typical for FMs



Direct Water Contamination
Caused a Drop of CoA

RESEARCH GAP



Seo et al. (2018)

DOI: 10.1080/10402004.2016.1271487

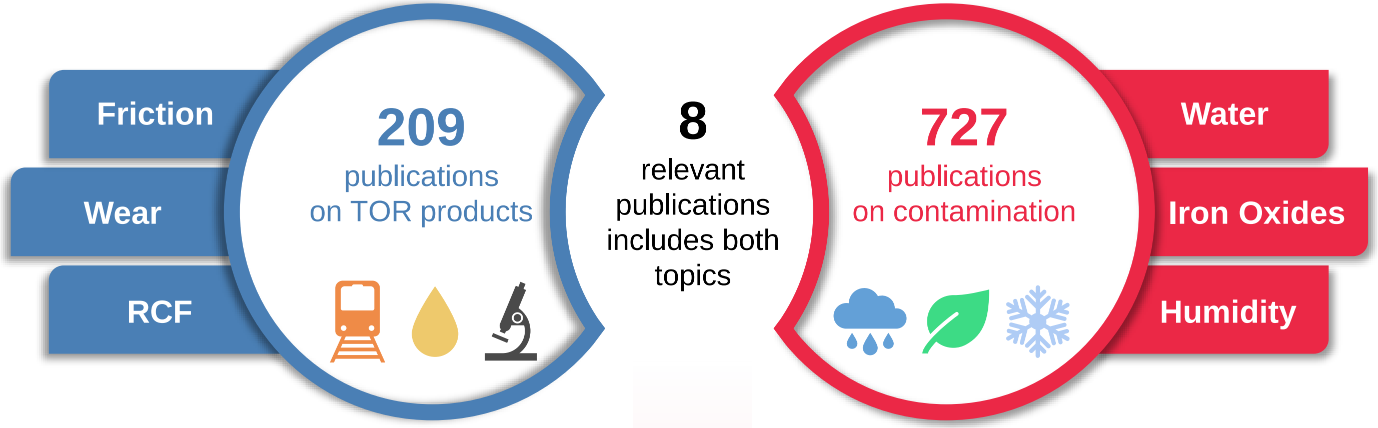
- RCF Test
- TOR product: TOR hybrid (both water and oil)
- Setup: a twin-disc machine

Main Findings:

TOR hybrid caused severe RCF as a result of the combination of high tangential forces and liquid-assisted crack propagation.

Rail Disc Surface after 200 000 cycles, Severe Spalling

RESEARCH GAP



Wang et al. (2011): Water, Oil

Arias-Cuevas et al. (2019): Water, Traction Enhancer

Oldknow et al. (2013): Water, FM

Lu et al. (2005): Iron Oxides, FM, Grease

Olofsson et al (2004): Humidity, Oil

Li et al. (2009): Water, Leaves, Traction Enhancer

Chenet al. (2014): Water, FM, Oil

Lewis et al. 2013: Humidity, Iron Oxides, FM

Research Gap: While FMs were tested in some publications, none of them has examined TOR lubricants. The effect of contamination on the performance of TOR products is largely unknown.

SCIENTIFIC QUESTIONS

CONDITIONS	TOR PRODUCT	BEHAVIOUR
Water Humidity/Dew Iron Oxides	Friction Modifier TOR Lubricant	Adhesion Wear Rolling Contact Fatigue

SCIENTIFIC QUESTIONS

CONDITIONS	TOR PRODUCT	BEHAVIOUR
Water	**Friction Modifier**	**Adhesion**
Humidity/Dew	**TOR Lubricant**	Wear
Iron Oxides		Rolling Contact Fatigue

Q1: How does water contamination influence the ability of TOR products to modify friction?

SCIENTIFIC QUESTIONS

CONDITIONS	TOR PRODUCT	BEHAVIOUR
Water	Friction Modifier	**Adhesion**
Humidity/Dew	**TOR Lubricant**	Wear
Iron Oxides		Rolling Contact Fatigue

Q1: How does water contamination influence the ability of TOR products to modify friction?

Q2: How does the performance of TOR lubricants change with increasing ambient humidity and under dew conditions?

SCIENTIFIC QUESTIONS

CONDITIONS	TOR PRODUCT	BEHAVIOUR
Water	**Friction Modifier**	Adhesion
Humidity/Dew	**TOR Lubricant**	**Wear**
Iron Oxides		**Rolling Contact Fatigue**

Q1: How does water contamination influence the ability of TOR products to modify friction?

Q2: How does the performance of TOR lubricants change with increasing ambient humidity and under dew conditions?

Q3: How do TOR products affect wear and rolling contact fatigue in the presence of oxide layers under wet conditions?

SCIENTIFIC QUESTIONS

Q1: How does water contamination influence the ability of TOR products to modify friction?

Q2: How does the performance of TOR lubricants change with increasing ambient humidity and under dew conditions?

Q3: How do TOR products affect wear and rolling contact fatigue in the presence of oxide layers under wet conditions?

AIM OF THE THESIS

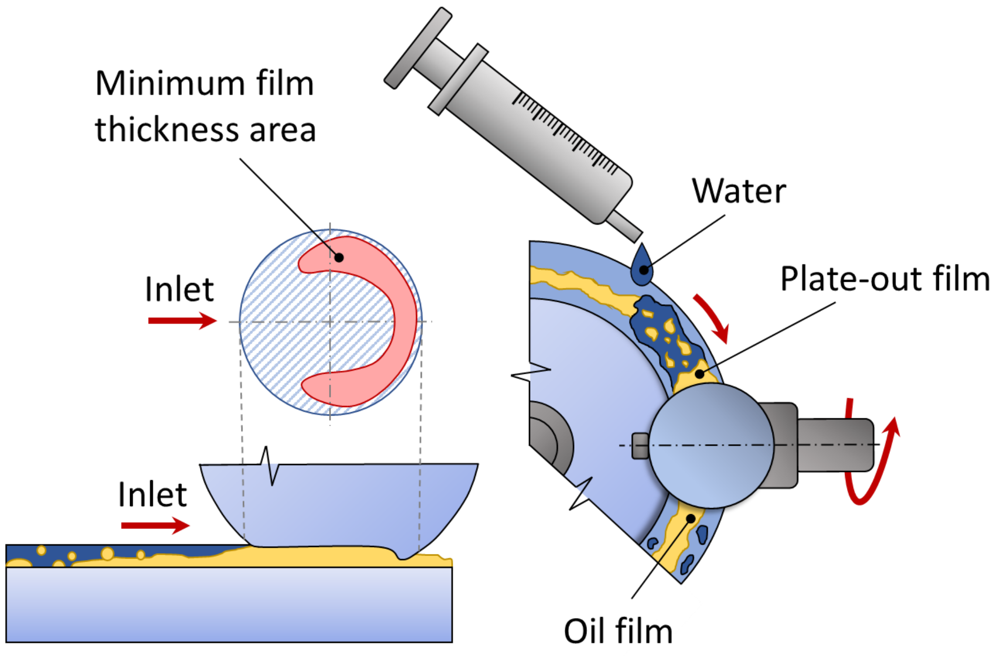
The thesis aims to explore the effect of environmental contamination on the performance of TOR products, with scope and conditions defined by the three scientific questions above.

THE EFFECT OF WATER CONTAMINATION

THE EFFECT OF WATER CONTAMINATION

QUESTION AND HYPOTHESIS

Q1: How does water contamination influence the ability of TOR products to modify friction?



Better separation of surfaces and higher contact replenishment.

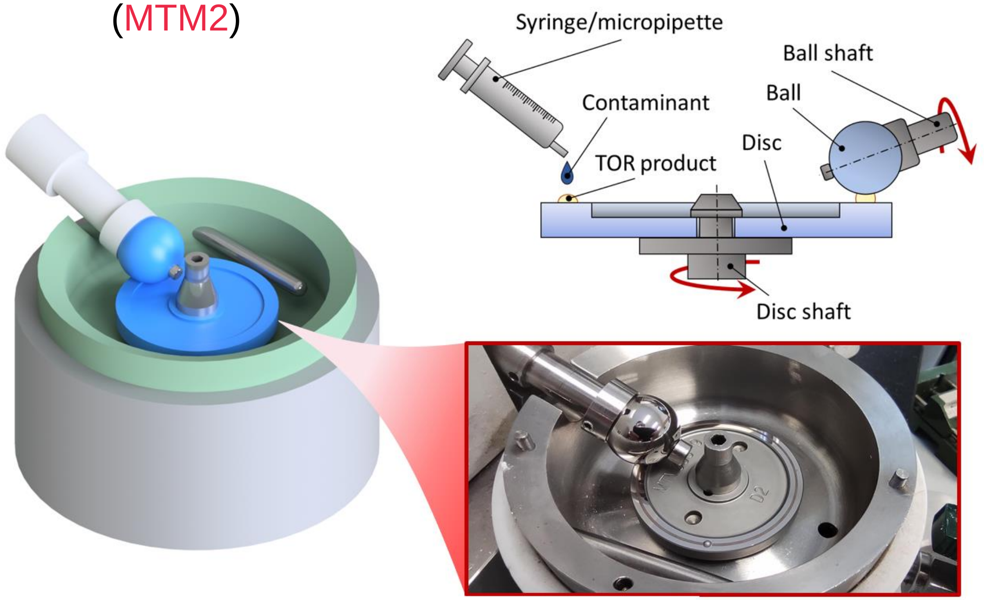
H1.1: TOR lubricants are expected to cause over-lubrication because the presence of water disrupts the balance between the liquid and solid phases, shifting it in favour of a stronger lubricating effect. (…)

H1.2: For FMs, the effect of water is expected to depend on the amount of water. Small amounts of water may enhance lubrication by slowing evaporation of the base medium. In contrast, larger quantities are likely to disrupt film formation and result in higher and less stable friction.

THE EFFECT OF WATER CONTAMINATION

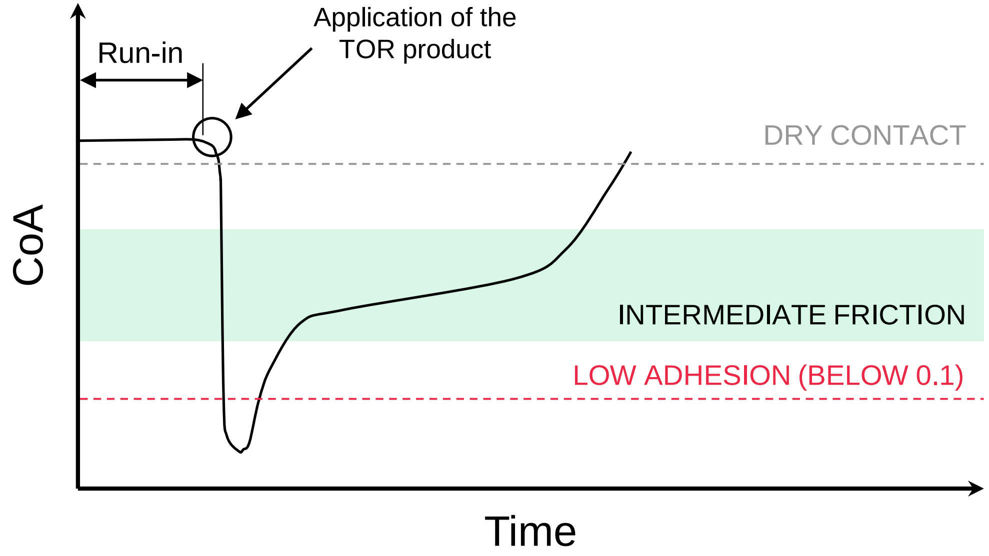
MATERIALS AND METHODS

Mini-Traction Machine
(MTM2)



AISI 52100   0.8 GPa   1 m/s   SRR 2%   1x FM   2x TOR Lubricant

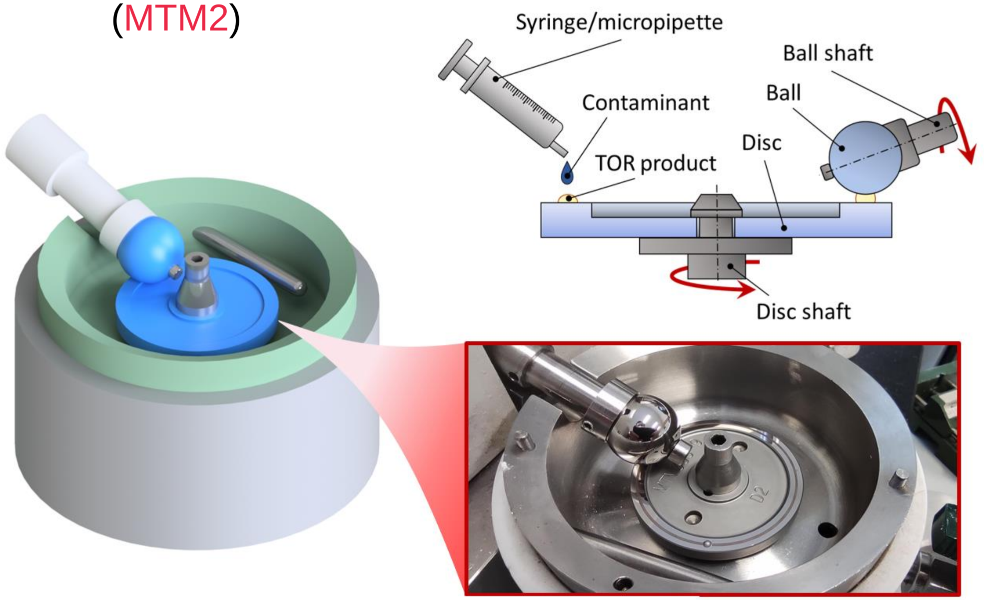
A typical adhesion curve for the TOR product



THE EFFECT OF WATER CONTAMINATION

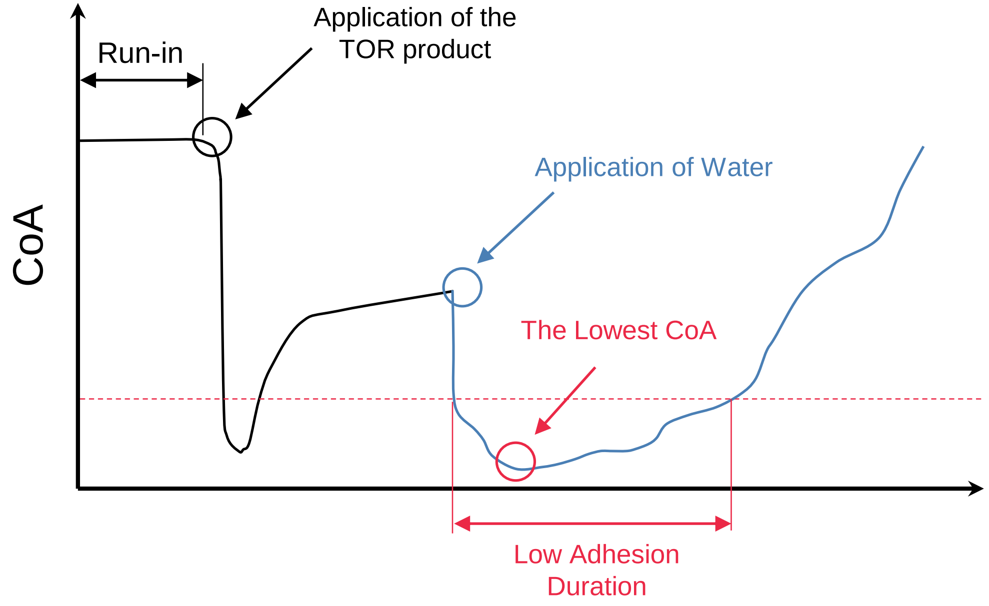
MATERIALS AND METHODS

Mini-Traction Machine (MTM2)



AISI 52100 0.8 GPa 1 m/s SRR 2% 1x FM 2x TOR Lubricant

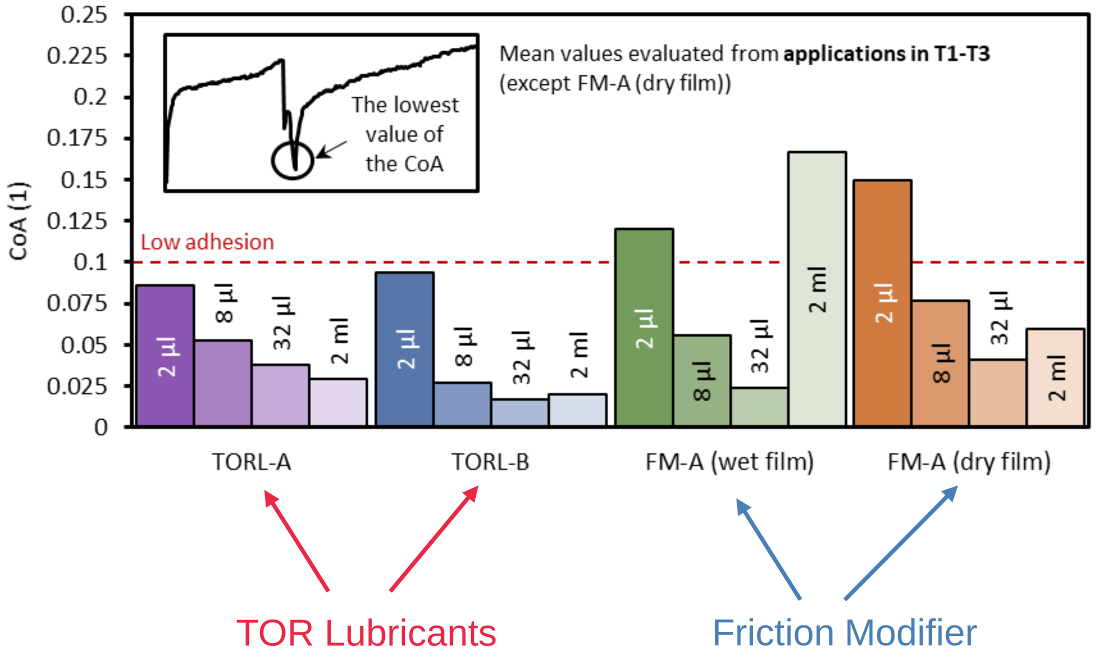
Water was applied at three distinct time points: during the initial lubricant drop, in the intermediate friction zone, and under starved lubrication conditions.



AIM: To investigate low adhesion caused by water contamination.

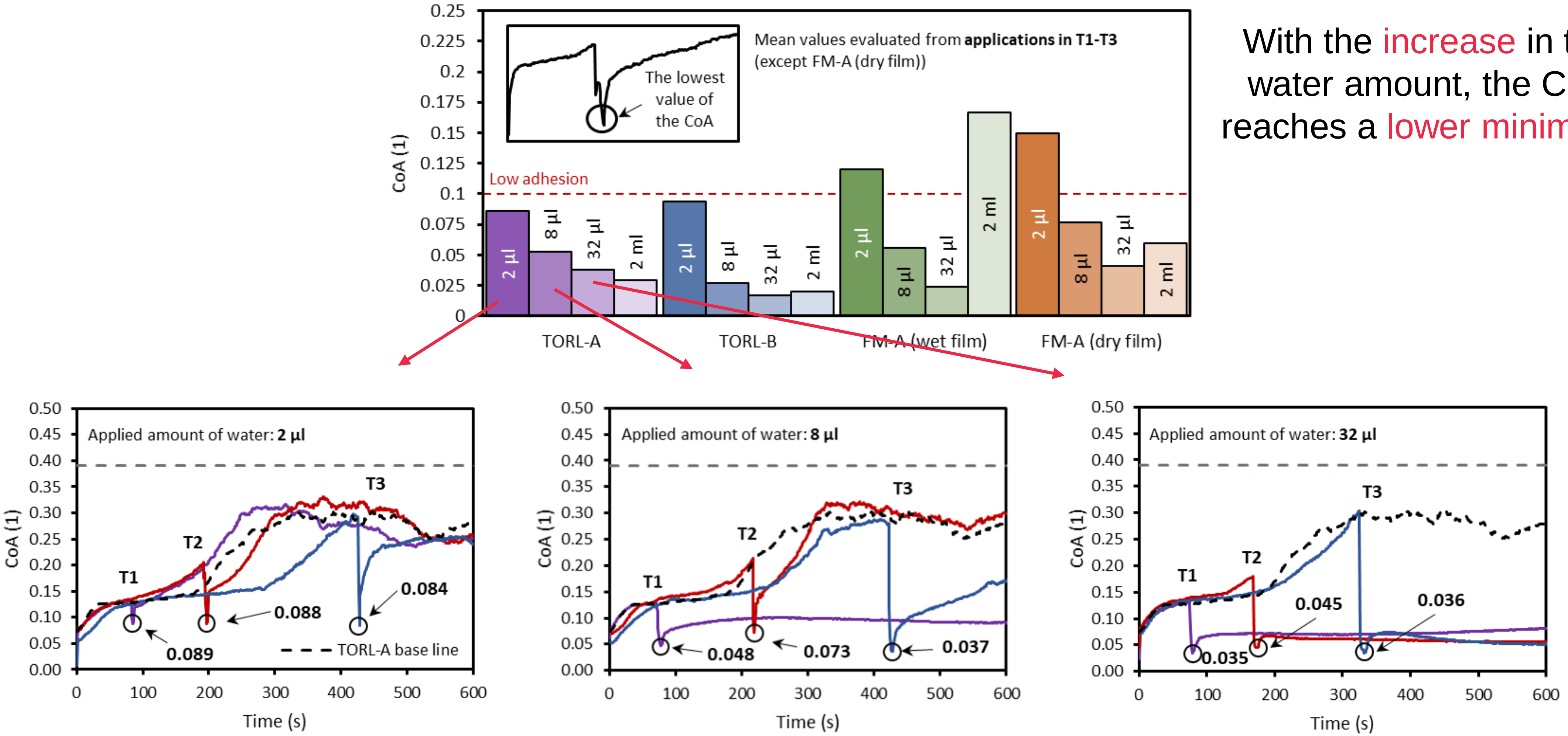
THE EFFECT OF WATER CONTAMINATION

RESULTS



THE EFFECT OF WATER CONTAMINATION

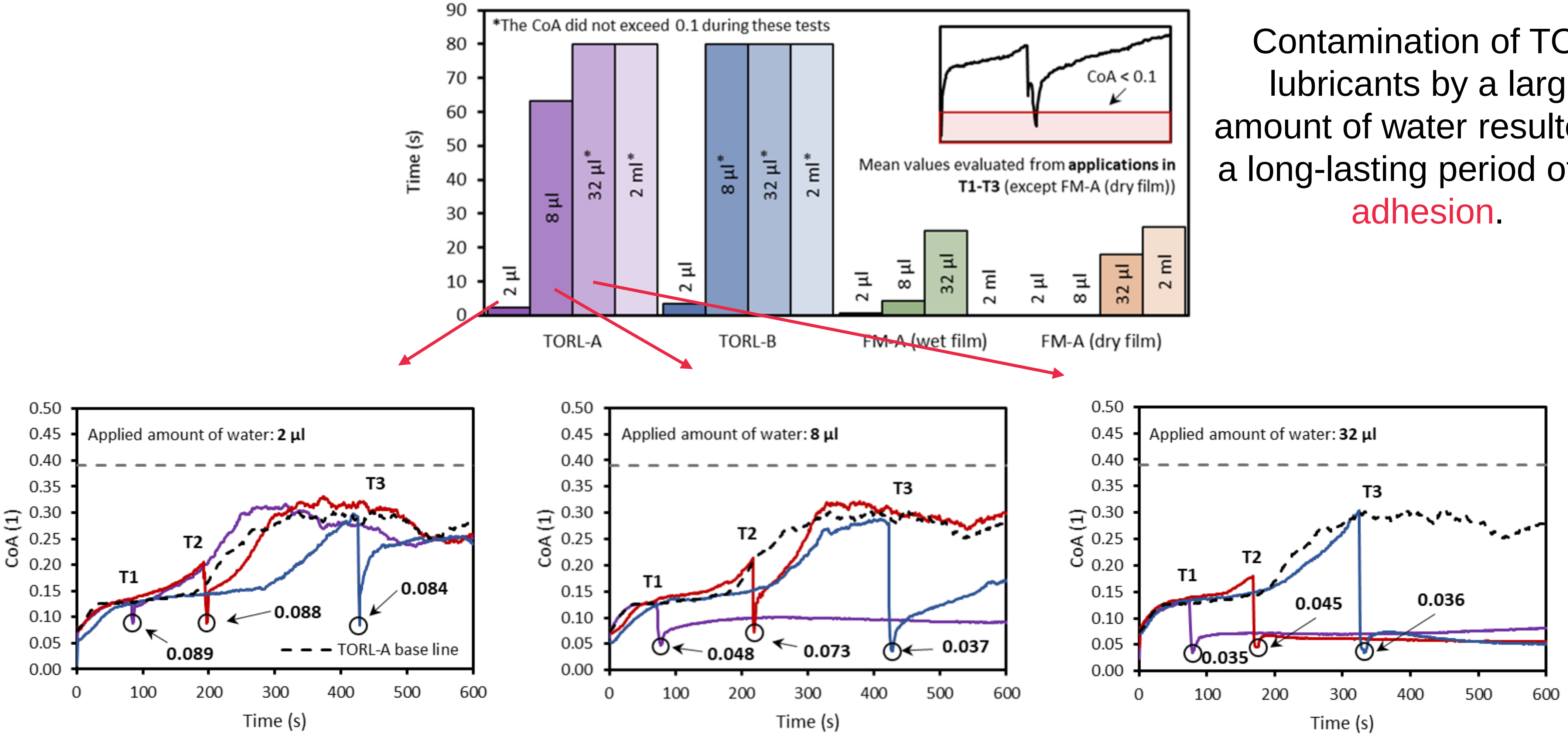
RESULTS



With the increase in the water amount, the CoA reaches a lower minimum.

THE EFFECT OF WATER CONTAMINATION

RESULTS

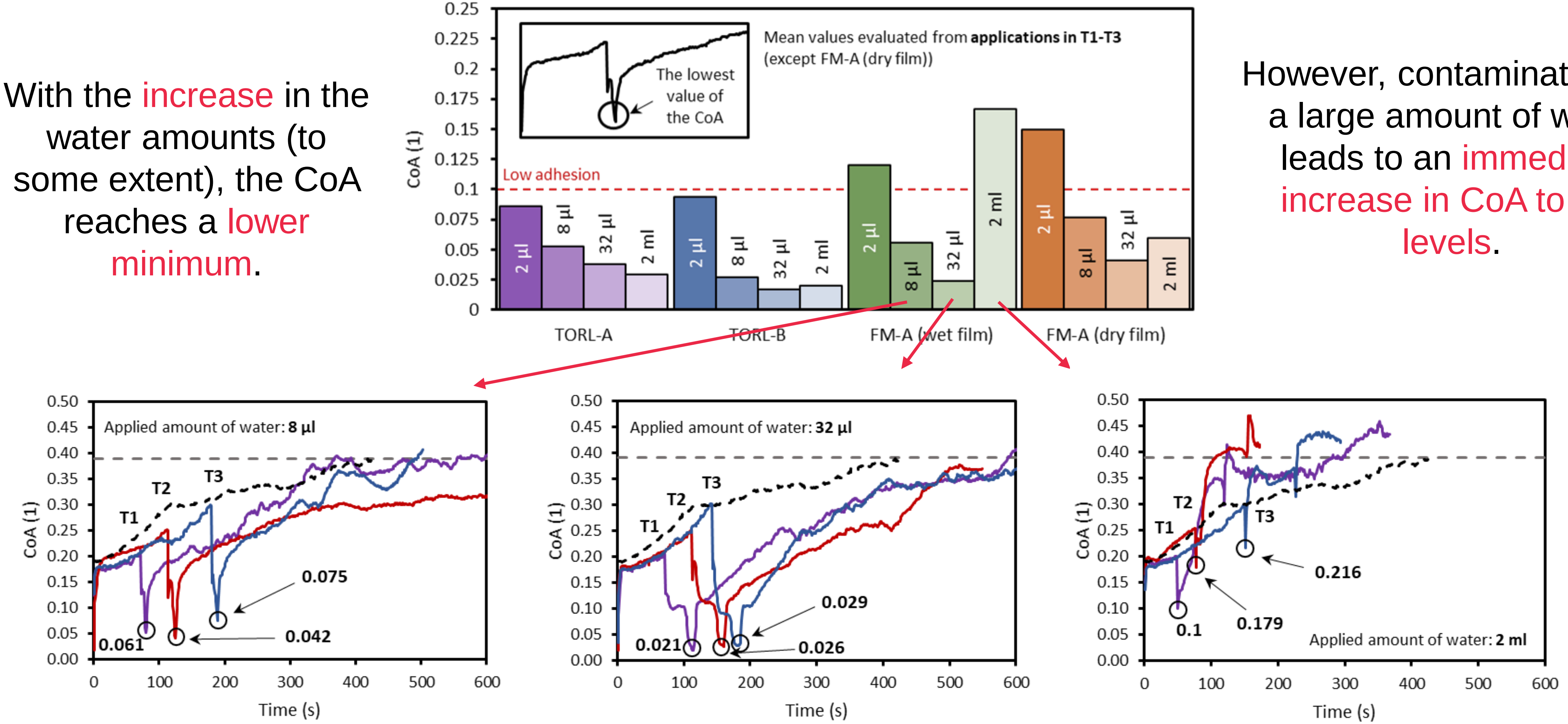


Contamination of TOR lubricants by a large amount of water resulted in a long-lasting period of low adhesion.

THE EFFECT OF WATER CONTAMINATION

RESULTS

With the increase in the water amounts (to some extent), the CoA reaches a lower minimum.

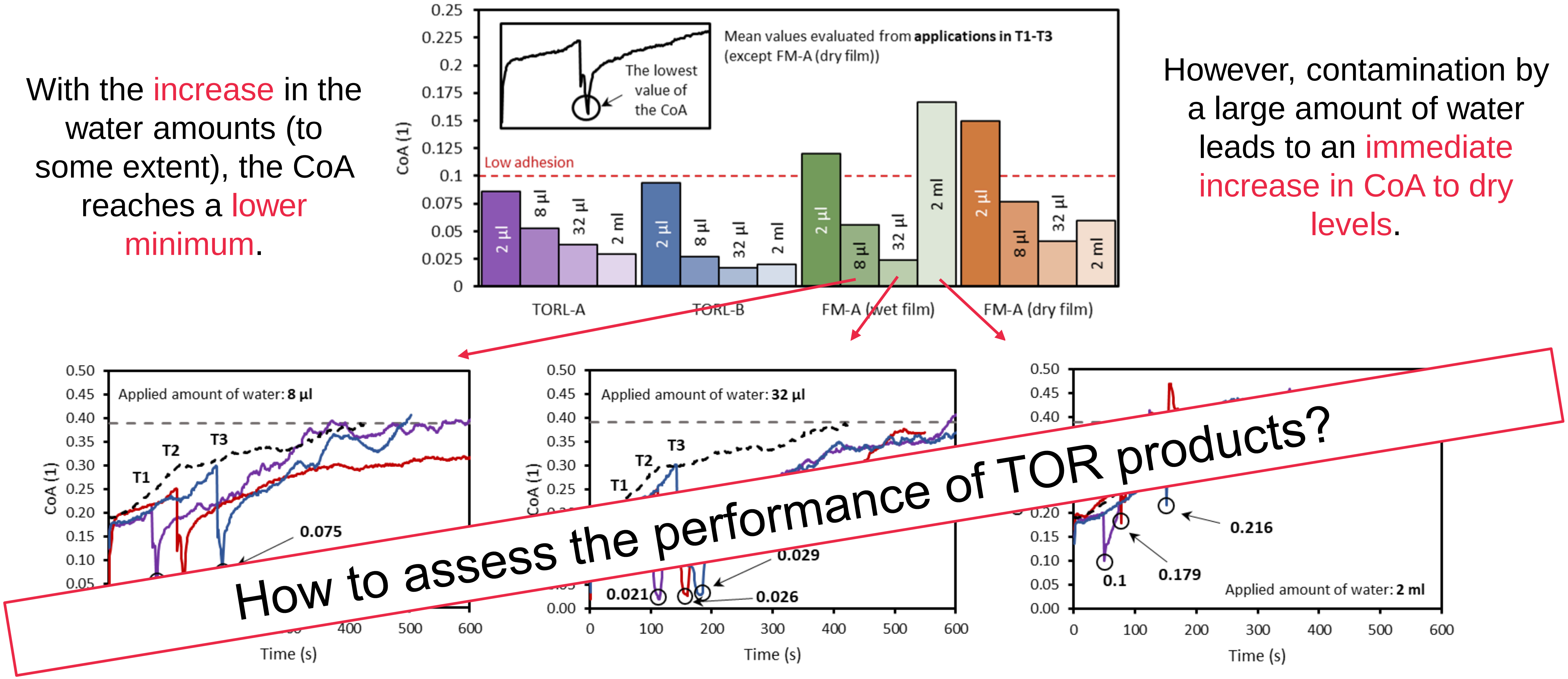


However, contamination by a large amount of water leads to an immediate increase in CoA to dry levels.

THE EFFECT OF WATER CONTAMINATION

RESULTS

With the increase in the water amounts (to some extent), the CoA reaches a lower minimum.



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METHODOLOGIES AND STANDARDS

„Start of my PhD Journey“

Early 1990s | 2000s | 2016 | 2017 | 2018 | 2021

METHODOLOGIES AND STANDARDS

Also, the first standard on the TOR product testing was published:

CEN/TS 15427–2-2
Railway applications - Wheel/Rail friction management - Part 2–2: Properties and Characteristics Top of Rail materials
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A Benchmarking Methodology for Top-of-Rail Products


Tribology International 189 (2023) 108910

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A benchmarking methodology for top-of-rail products

Radovan Galas[a,*], Simon Skurka[a], Martin Valena[a], Daniel Kvarda[a], Milan Omasta[a], Haohao Ding[b], Qiang Lin[b], Wen-jian Wang[b], Ivan Krupka[a], Martin Hartl[a]

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ARTICLE INFO

Keywords:
Rail-wheel tribology
Rolling-sliding
Friction modifier
Top-of-rail lubricants

ABSTRACT

Top-of-rail (TOR) products are designed to optimize adhesion, reduce wear and mitigate noise from the wheel-rail interface. Prior to testing these products in field conditions, a laboratory approach is suitable because it is not time-consuming and expensive. This study aims to design a benchmarking methodology to investigate the performance of TOR products using a standard tribometer in a ball-on-disc configuration. The resulting methodology is based on a multi-parameter approach enabling the assessment of TOR products from multiple perspectives. The core of the methodology is formed by traction tests and a robust evaluation phase resulting in a performance map dividing TOR products into four performance classes, Q1-Q4, based on which a suitable TOR product can be chosen for further testing.

1. Introduction

TOR products represent a progressive approach to modification of friction between the wheel tread and the rail head. In contrast with other conventional methods, such as sanding and flange lubrication, TOR products are designed to control friction at a desired level, referred to as an intermediate level of friction [1]. Besides that, the presence of TOR product in the contact should avoid a negative slope of the creep curve occurring in untreated contact [2]. According to the state of matter, TOR products are classified into solid and liquid. Solid TOR products are usually called "solid sticks" or "HPF solid sticks", while there are different, sometimes confusing, terms for liquid products. Water-based products (drying products) are called friction modifiers (FMs), while oil- or grease-based products (non-drying products) are called TOR lubricants (TORLs). There is also a third category of TOR products containing both water and oil/grease. These products are called TOR hybrids [1,2].

The possible benefits of TOR products have been intensively studied since 1992, when Kalousek et al. [3] published a pilot study on railway friction management. This study was conducted on the Vancouver mass transit system line, where severe short pitch wheel and rail corrugation developed only a few months after its opening. This investigation showed that applying a solid stick to the wheel tread prevented corrugation formation as roll-slip oscillations were eliminated due to a positive creep curve. The ability to reduce or completely avoid the corrugation growth for different mass transit systems was later confirmed for FMs [4–7]. Other field studies [7–11] showed that suppression of roll-slip oscillations …

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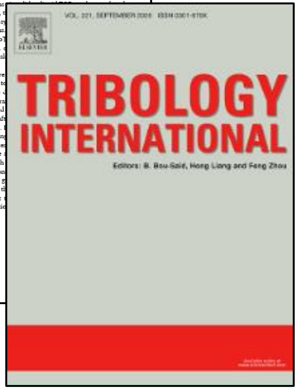

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Although field studies have proved many benefits of TOR products, some negative effects related to their application have been revealed as well. One of the most severe drawbacks is the risk of a very low CoT compromising traction and braking. This undesirable phenomenon was observed for both FM [17] and TOR lubricants [18–20]. FMs may cause a very low CoT immediately after their application when a high amount of FM enters the contact [21]. In addition, a significant drop in the CoT was observed during the drying of FM when a viscous film was formed between the contacting surfaces [22]. In the case of TOR lubricants as oil or grease-based products, the applied amount strongly affects product performance [23,24]. A high amount of these non-drying products (TORLs and TORHs) in the contact can lead to the extension of braking distance and can promote the growth of pre-existing cracks and spalling formation [19,25]. Besides these security risks, recently published studies [26–28] showed that the expected benefits of TOR products, such as squeal noise reduction and long carry distance, cannot be

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A Comparison of both Methodologies:

	Wear-in[1)] parameters	Run-in parameters	Test parameters	# of sets	Total time[2)]	Performance parameters	Overall assessment
Article II	0.8 GPa 1 m/s 2% SRR 60 min	0.8 GPa, 1 m/s, 2% SRR, 30 min	0.8 GPa 1 m/s 0–20% SRR 20–40 min	5	5–8h	I, OLF	Performance map (Q1–Q4)
CEN/TS standard	1 GPa 0.1 m/s 50% SRR 30 min	–	1 GPa 1, 3.8 m/s 0.25–10% SRR 22 min	1	1h	CoT at 10% SRR	Good/bad

1) CEN/TS standard uses run-in in the same way as wear-in in the proposed methodology.
2) Estimation, the exact time is dependent on the number of creep curves.

\+ A robust multi-parameter approach

\- Time-consuming

Early 1990s | 2000s | 2016 | 2017 | 2018 | 2021

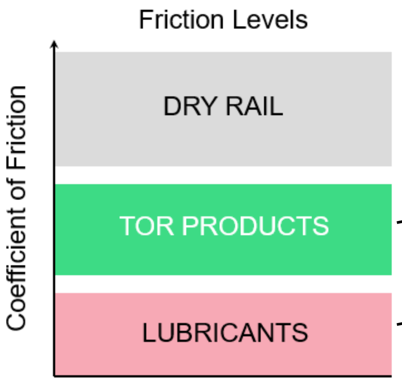
METHODOLOGIES AND STANDARDS

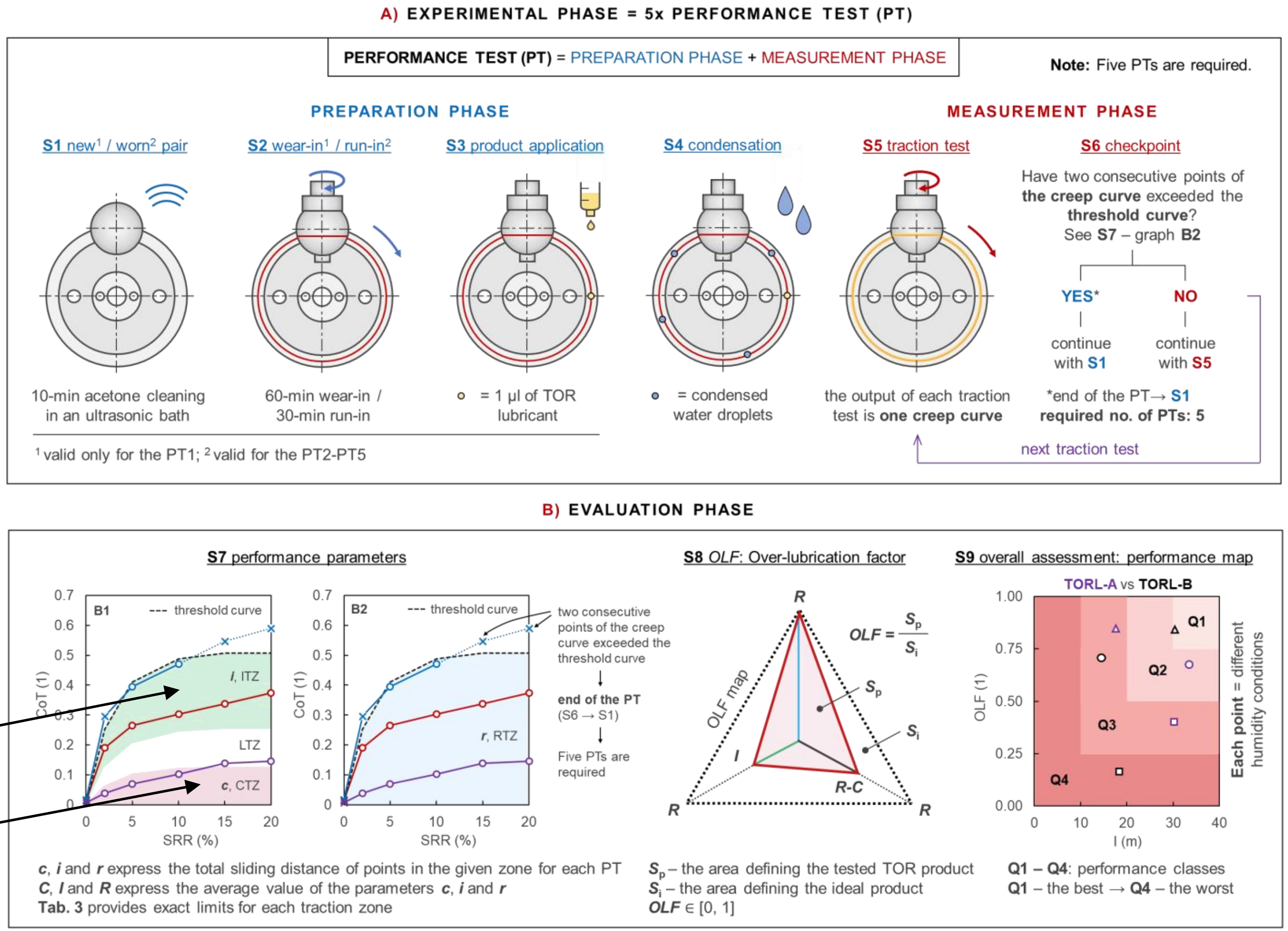
THE DEVELOPED METHODOLOGY

Performance parameters:

C – Critical Traction
I – Intermediate Traction
R – Retentivity

Based on these parameters, the over-lubrication factor (**OLF**) is calculated.

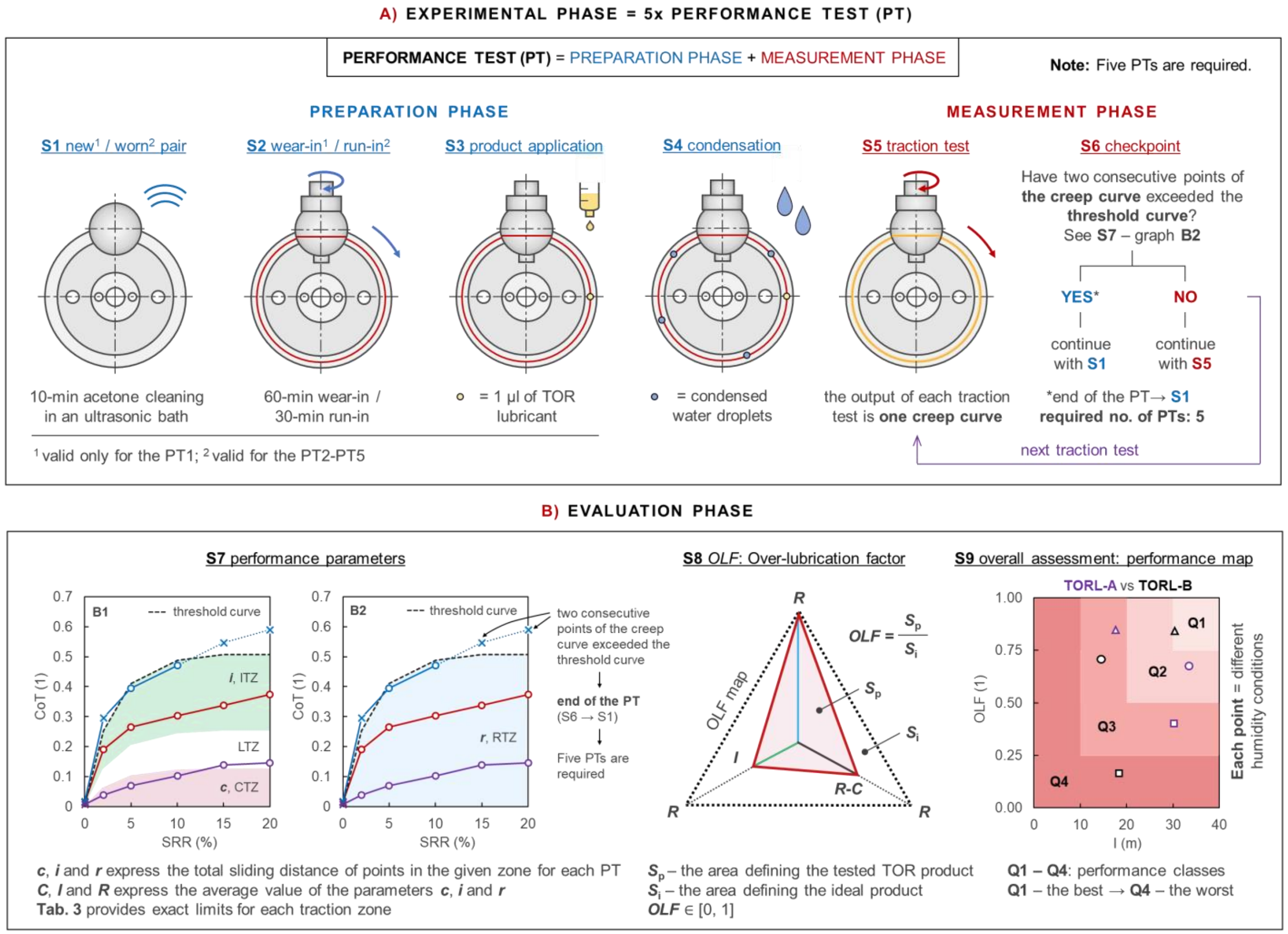


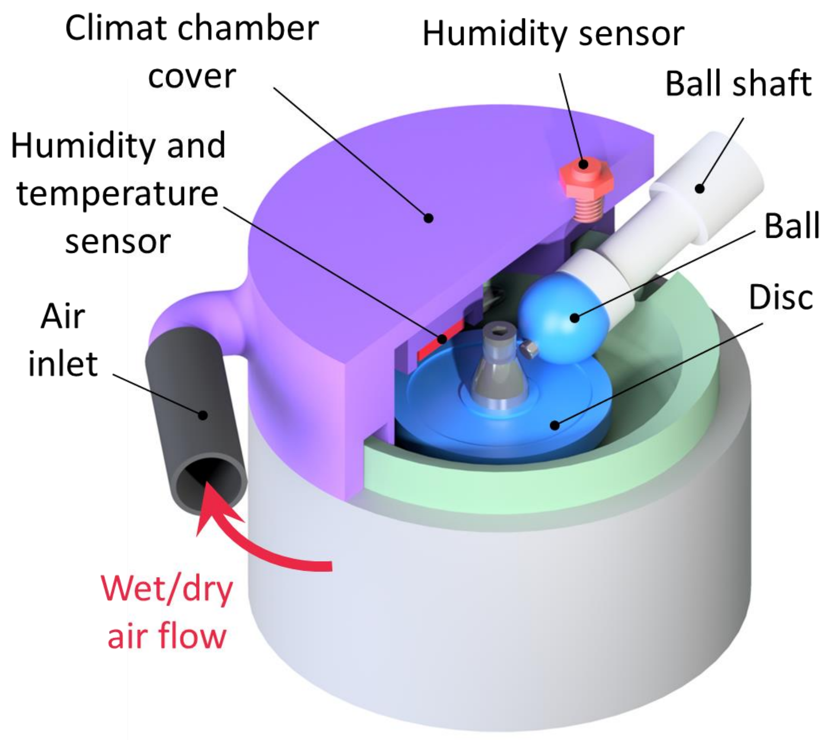


OLF and **I** are used to construct a performance map divided into four performance classes, Q1-Q4

METHODOLOGIES AND STANDARDS

THE DEVELOPED METHODOLOGY





AISI 52100 0.8 GPa 1 m/s SRR 0–20%

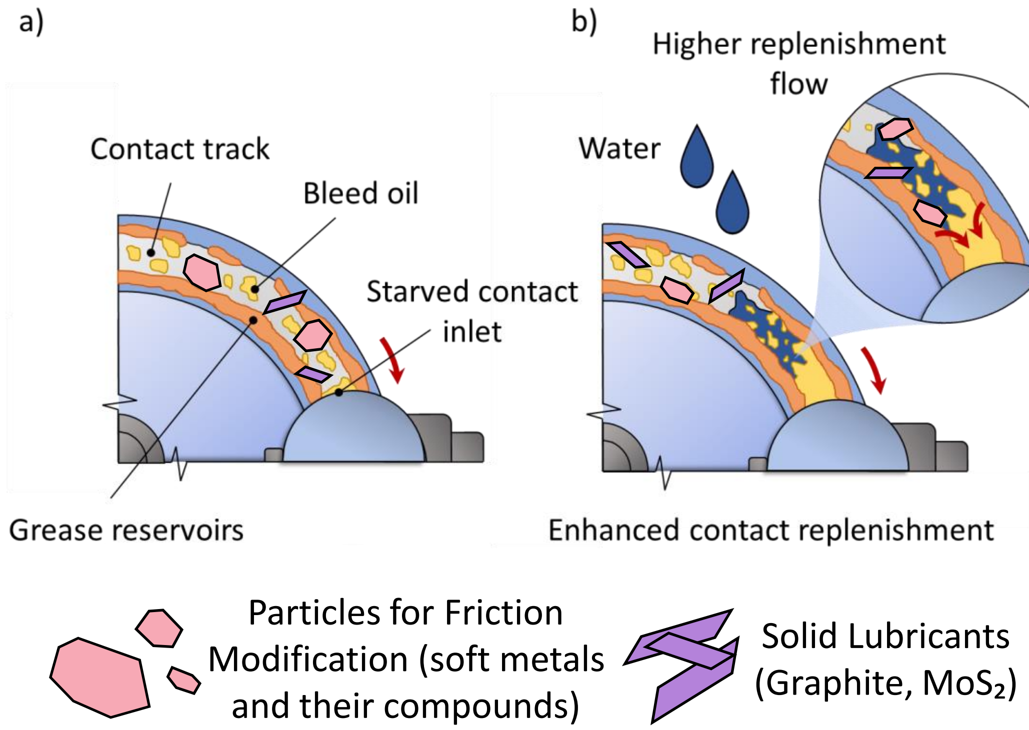
2x TOR Lubricant RH levels: 34%; 70%; 100%

THE EFFECT OF HUMIDITY AND DEW

THE EFFECT OF HUMIDITY AND DEW

QUESTION AND HYPOTHESIS

Q2: How does the performance of TOR lubricants change with increasing ambient humidity and under dew conditions?



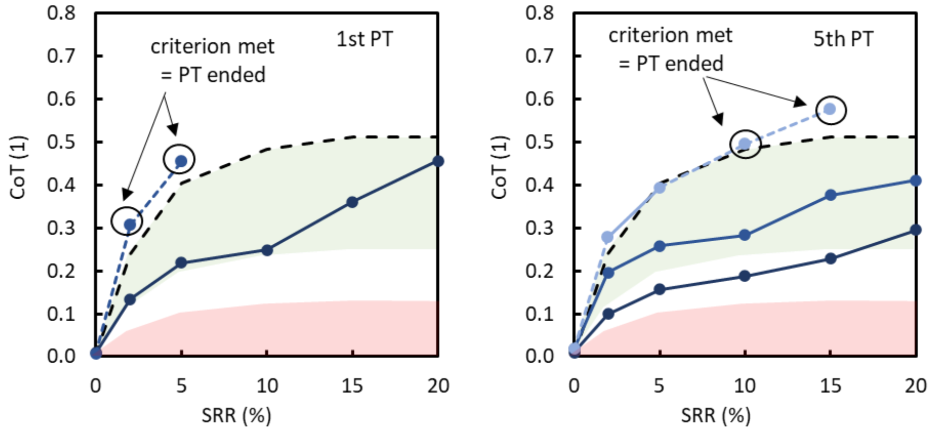
H2: Ambient humidity alone is expected to have only a minor effect on friction and, therefore, is unlikely to influence the performance of TOR lubricants significantly.

A substantial change is expected when the dew point is reached, and water condenses on the rail surface. In this case, the condensed water can mix with TOR lubricants and cause over-lubrication.

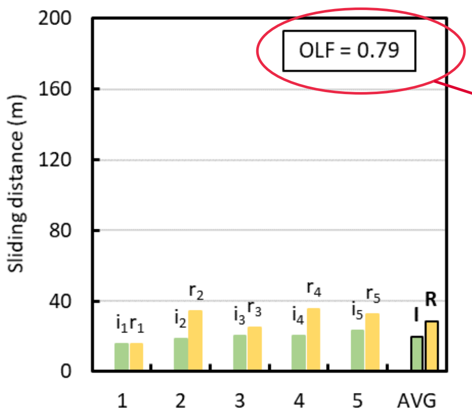
THE EFFECT OF HUMIDITY AND DEW

RESULTS

Standard performance of TORL-A



RH = 35%, ambient temperature



0.79 = **Very Good**

OLF:
1 = the Best
0 = the Worst

Per one dosage, 2-3 creep curves were measured without any risk of low adhesion.

THE EFFECT OF HUMIDITY AND DEW

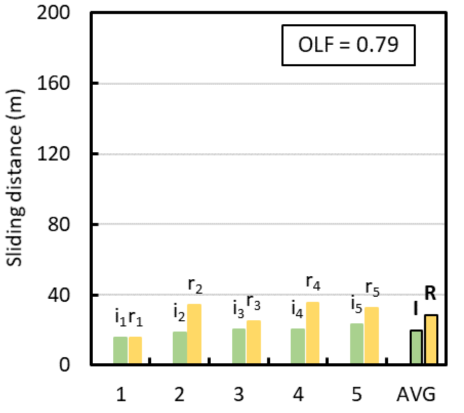
RESULTS

OLF:
1 = the Best
0 = the Worst

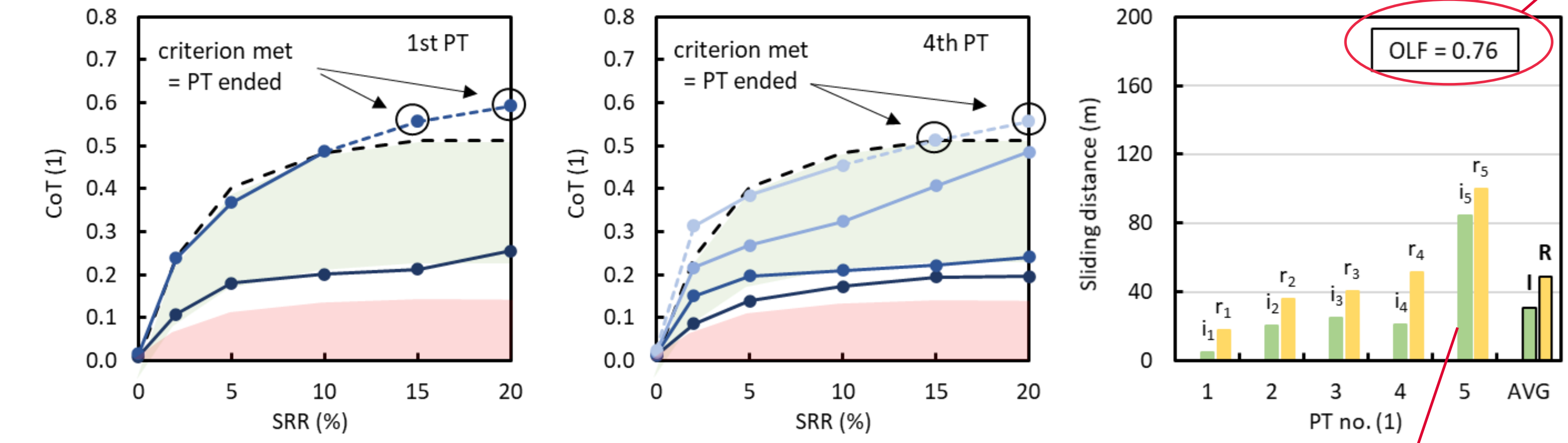
Performance of TORL-A in Humid Environment

0.76 = **Very Good**

RH = 35%, ambient temperature



70% RH, ambient temperature



A slight positive effect of humidity was observed, but with reduced repeatability.

Prolonged Period of Intermediate Friction

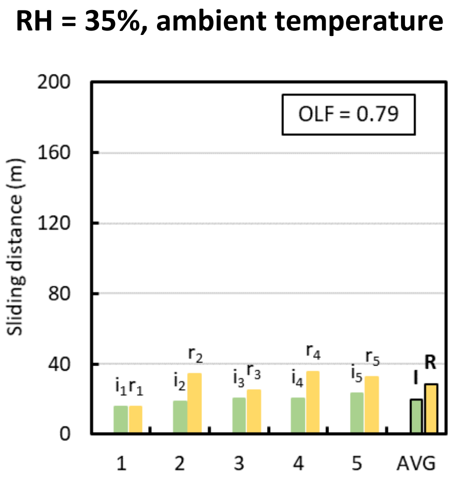
THE EFFECT OF HUMIDITY AND DEW

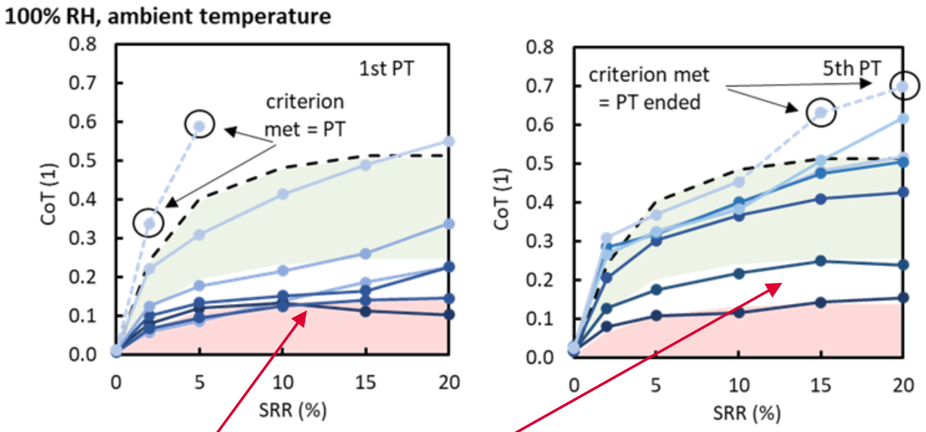
RESULTS

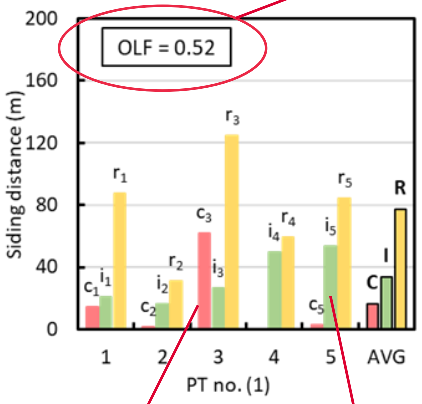
OLF:
1 = the Best
0 = the Worst

0.52 = **Sufficient**

Performance of TORL-A under Dew Conditions







Water changed the trend of some creep curves to negative.

Period of Low Adhesion

Prolonged Period of Intermediate Friction

THE EFFECT OF HUMIDITY AND DEW

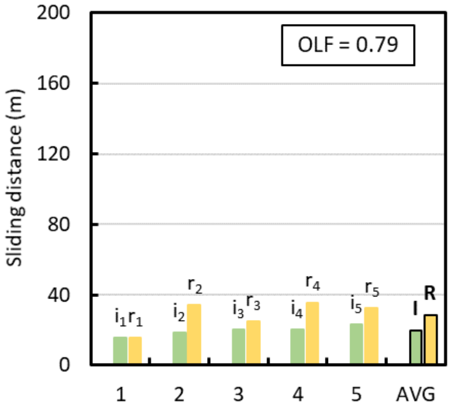
RESULTS

OLF:
1 = the Best
0 = the Worst

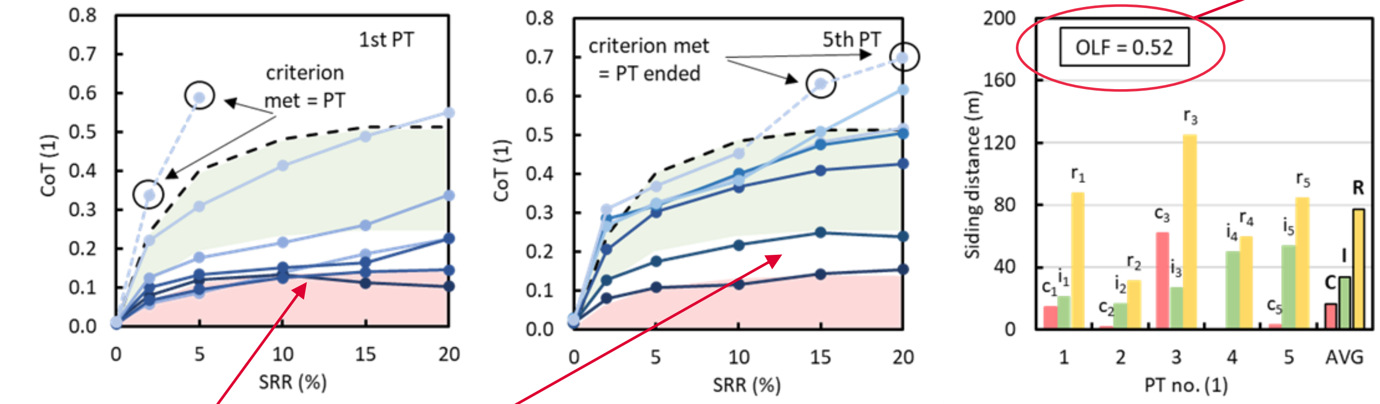
0.52 = **Sufficient**

Performance of TORL-A under Dew Conditions

RH = 35%, ambient temperature

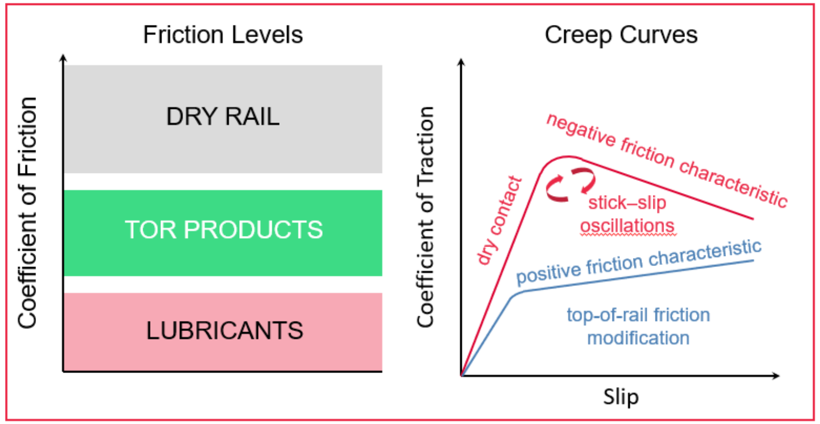


100% RH, ambient temperature



Water changed the trend of some creep curves to negative.

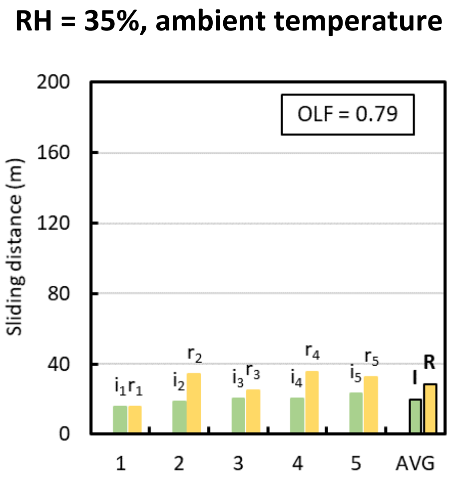
The Main Function of TOR Products

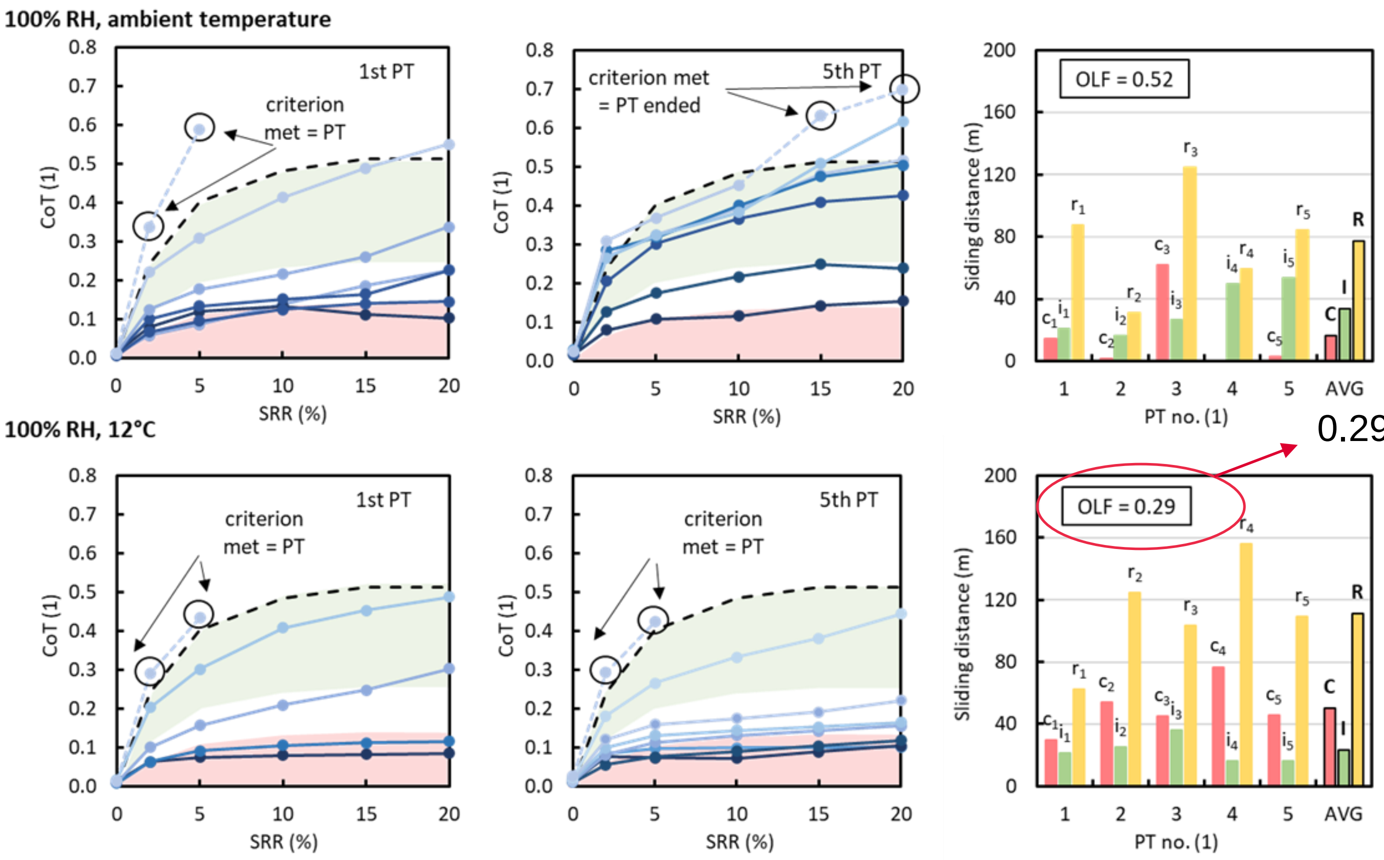


THE EFFECT OF HUMIDITY AND DEW

RESULTS

Performance of TORL-A
under Dew Conditions





0.29 = **Very Bad**

OLF:
1 = the Best
0 = the Worst

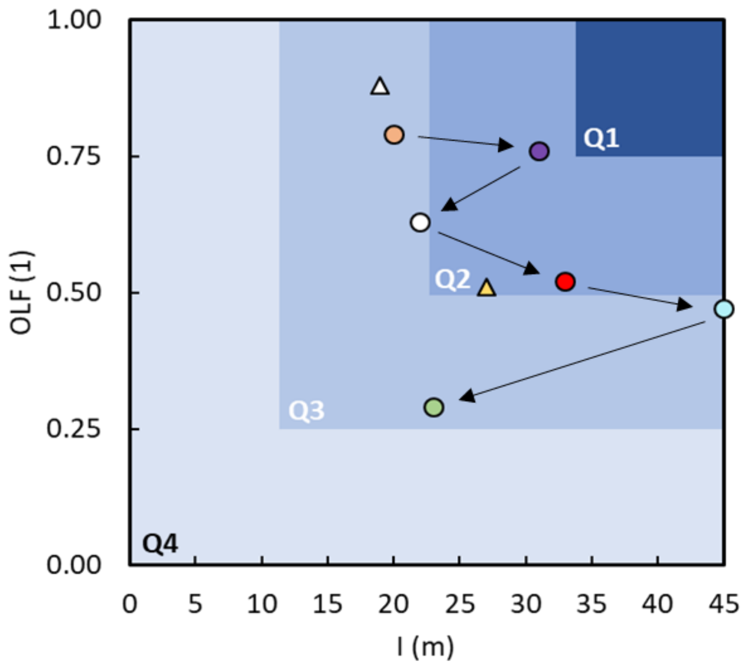
Long-lasting Period of
Low Adhesion

THE EFFECT OF HUMIDITY AND DEW

RESULTS

Humidity and small amounts of water may have a slightly positive effect on the performance, as it increases retentivity.

The Performance Map



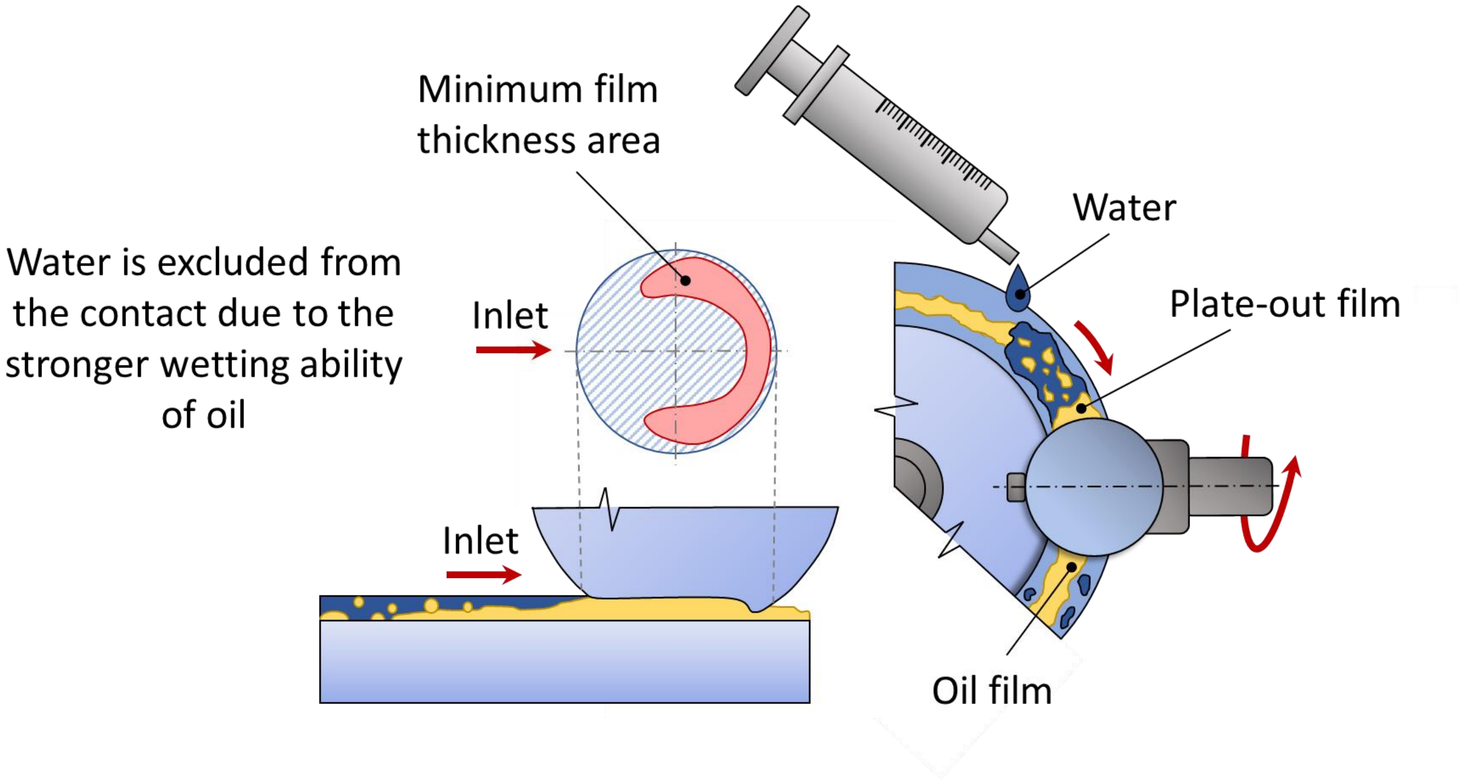
However, higher water amounts come at the cost of a prolonged low-adhesion period, which may result in a lower performance category.

THE EFFECT OF MOISTURE ON ADHESION

DISCUSSION

THE EFFECT OF MOISTURE ON ADHESION

DISCUSSION



<u>Fluid film regime</u>

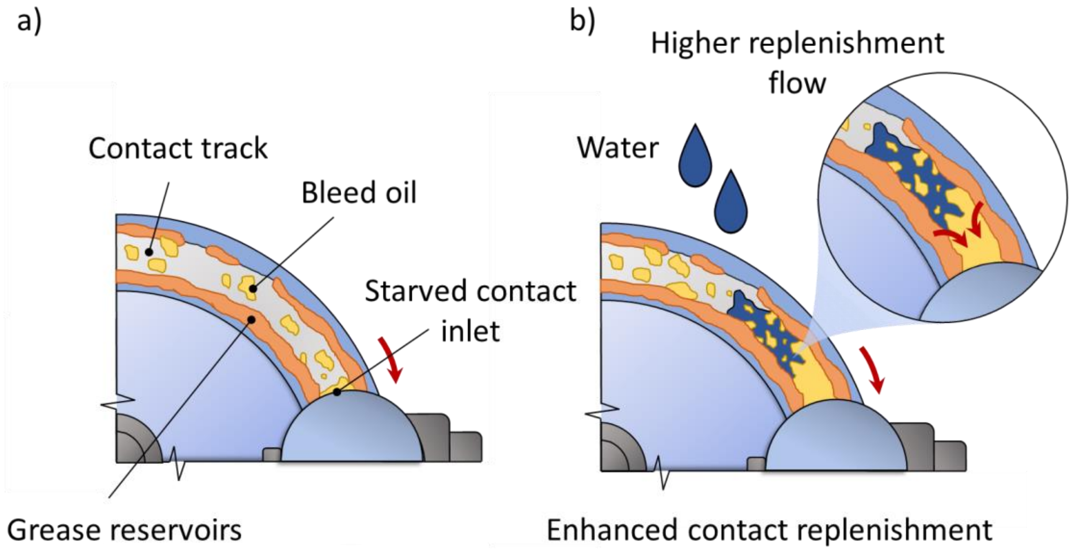
O/W emulsion theories can explain the water contamination of the EHL contact.

Plate-out theory shows that due to the stronger wetting ability of oil, water is excluded from the contact.

That means: Despite water being present in larger quantities, the contact is still dominantly lubricated by the oil.

THE EFFECT OF MOISTURE ON ADHESION

DISCUSSION



Grease absorbs water → Oil-bleeding Lower viscosity → Higher contact replenishment → Thicker lubricating film

<u>Starved fluid film regime</u>

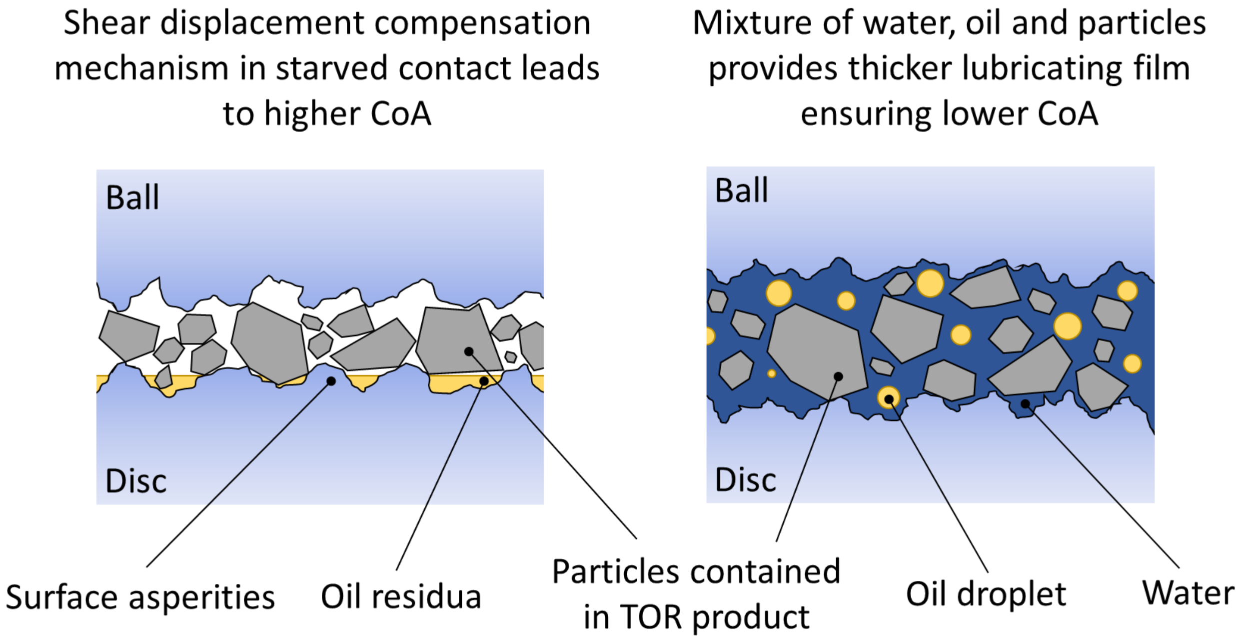
Unlike oil, grease can absorb a larger amount of water due to the polar nature of its thickener and additives.

Absorbed water influences stiffness and oil-bleeding, i.e., the ability to replenish the contact.

That means: Water could enhance contact replenishment, resulting in a thicker film and thus lower CoA.

THE EFFECT OF MOISTURE ON ADHESION

DISCUSSION



<u>Mixed/Boundary regime</u>

When severe starvation occurs, lubricant film thickness further decreases, resulting in a mixed regime and CoA increases.

When mixed with a small amount of water, solid particles create a paste that causes a transient decrease in friction („wet-rail“ phenomenon).

That means: A mixture of water and particles forms a thick lubricating film, ensuring low CoA.

THE EFFECT OF MOISTURE ON ADHESION

DISCUSSION

Q1: How does water contamination influence the ability of TOR products to modify friction?

H1.1: TOR lubricants are expected to cause over-lubrication because the presence of water disrupts the balance between the liquid and solid phases, shifting it in favour of a stronger lubricating effect. (…)

„The mechanism was more complex than initially assumed. While the disturbed ratio between the liquid and solid phases contributes to the effect in near-dry, starved conditions, the dominant influence arises from the interaction between water and the oil base, which together enhance the lubricating action of the liquid phase.“

PARTIALLY VERIFIED

THE EFFECT OF MOISTURE ON ADHESION

DISCUSSION

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PARTIALLY VERIFIED

H1.2: For FMs, the effect of water is expected to depend on the amount of water. Small amounts of water may enhance lubrication by slowing evaporation of the base medium. In contrast, larger quantities are likely to disrupt film formation and result in higher and less stable friction.

VERIFIED

THE EFFECT OF MOISTURE ON ADHESION

DISCUSSION

Q2: How does the performance of TOR lubricants change with increasing ambient humidity and under dew conditions?

H2: Ambient humidity alone is expected to have only a minor effect on friction and, therefore, is unlikely to influence the performance of TOR lubricants significantly.

A substantial change is expected when the dew point is reached, and water condenses on the rail surface. In this case, the condensed water can mix with TOR lubricants and cause over-lubrication.

VERIFIED

THE EFFECT ON WEAR AND RCF

THE EFFECT ON WEAR AND RCF

QUESTION AND HYPOTHESIS

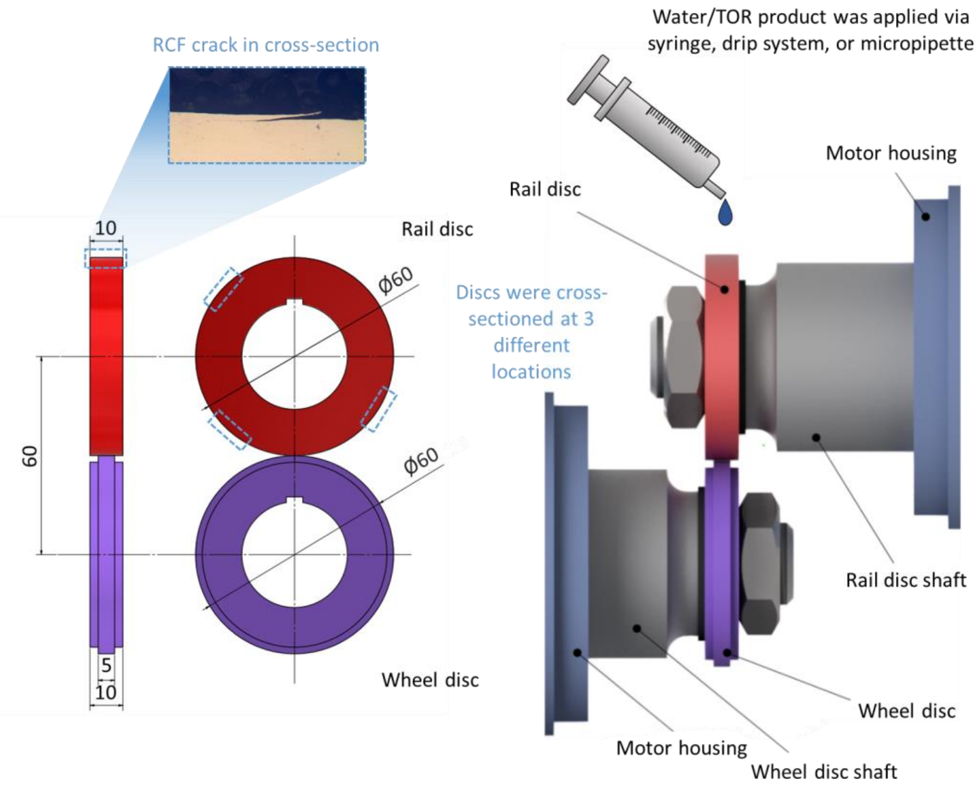
Q3: How do TOR products affect wear and rolling contact fatigue in the presence of oxide layers under wet conditions?

H3.1: In wet conditions, TOR lubricants are expected to influence RCF in a way similar to TOR hybrids. The only difference is that water is intentionally added in the latter, whereas in the former, it enters the contact as an unwanted contaminant. This combination is expected to promote severe RCF due to the coexistence of high friction and liquid-assisted crack propagation.

H3.2: When mixed with friction modifiers, oxides are expected to disrupt film formation, reducing the effectiveness of the product and increasing wear. In contrast, the presence of water may partially counteract this effect by helping to rebalance the liquid–solid ratio by slowing the evaporation of the base medium, thereby prolonging the lubricating effect.

THE EFFECT ON WEAR AND RCF

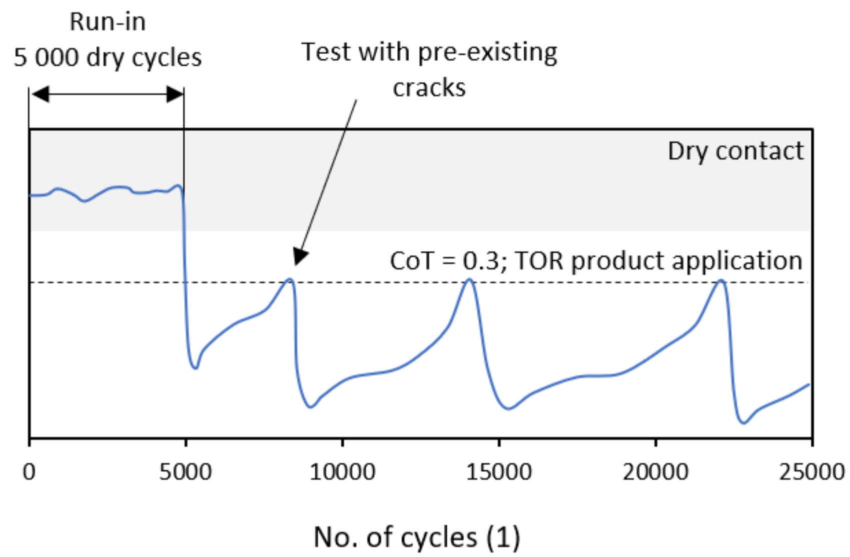
MATERIALS AND METHODS



U71Mn (rail) C-Class (wheel) 1.1 GPa 1.5 m/s slip 2%

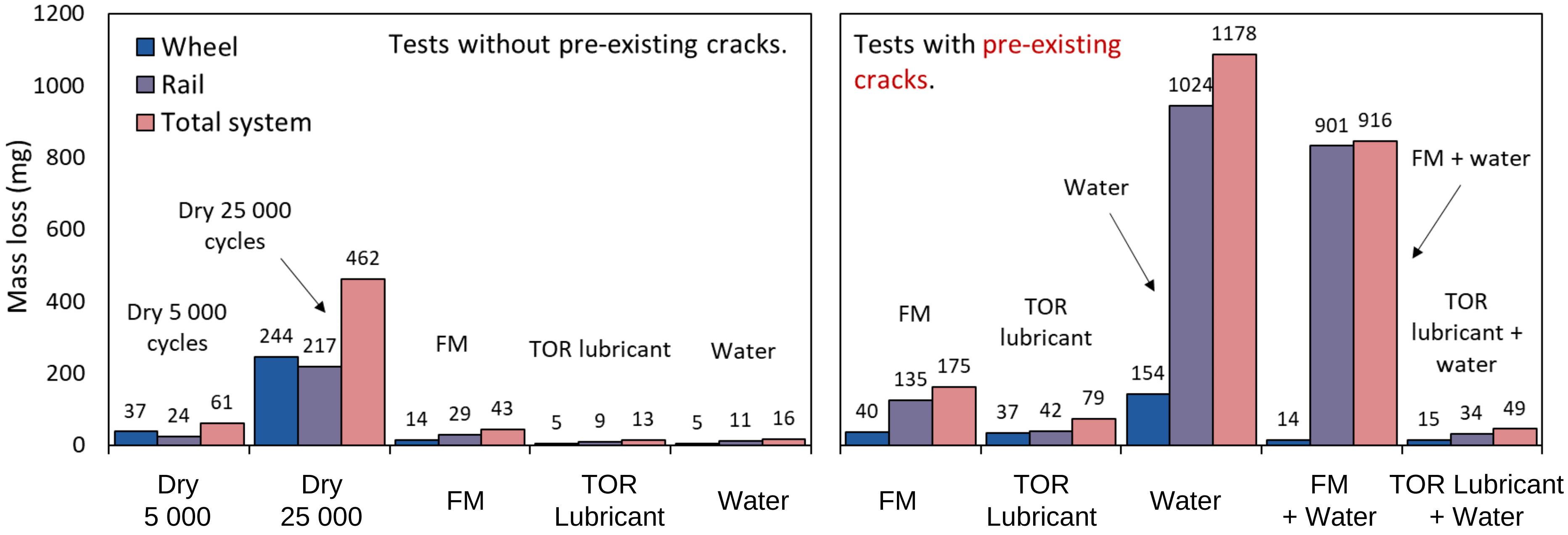
1x TOR Lubricant 1x Friction Modifier

The TOR product was applied when CoA = 0.3 was reached. Water was applied at a rate of 1 drop/s.



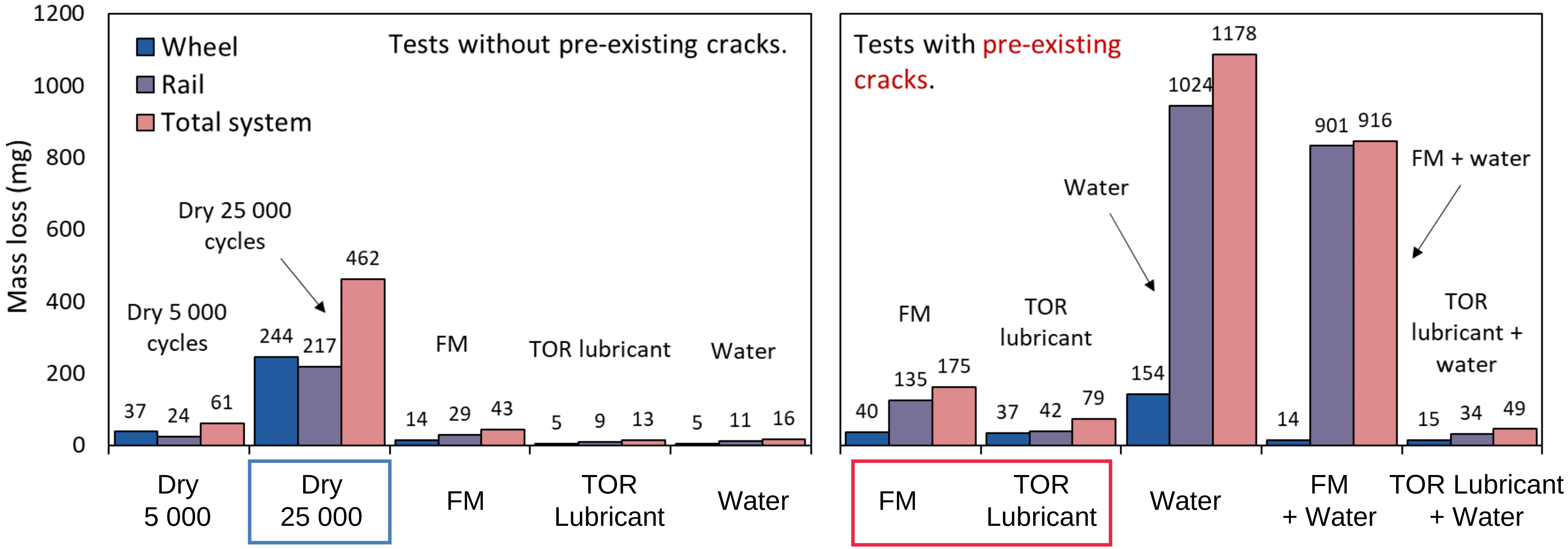
THE EFFECT ON WEAR AND RCF

RESULTS



THE EFFECT ON WEAR AND RCF

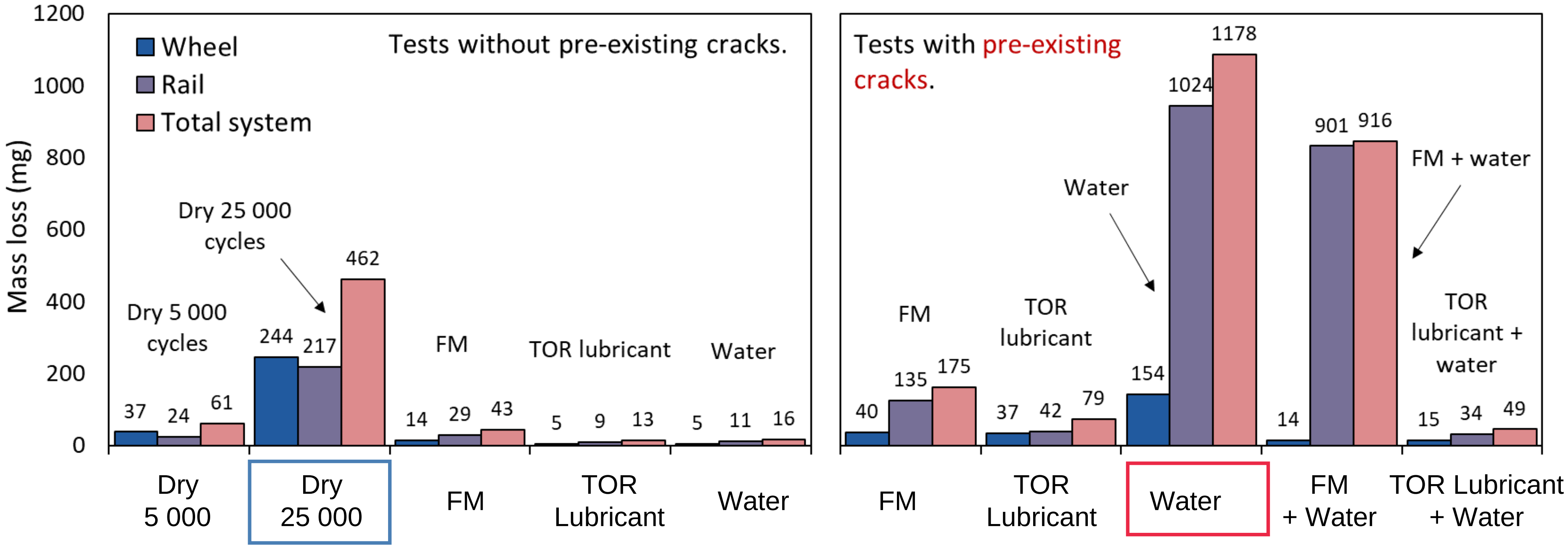
RESULTS



TOR products were effective in reducing wear in comparison with unlubricated conditions.

THE EFFECT ON WEAR AND RCF

RESULTS

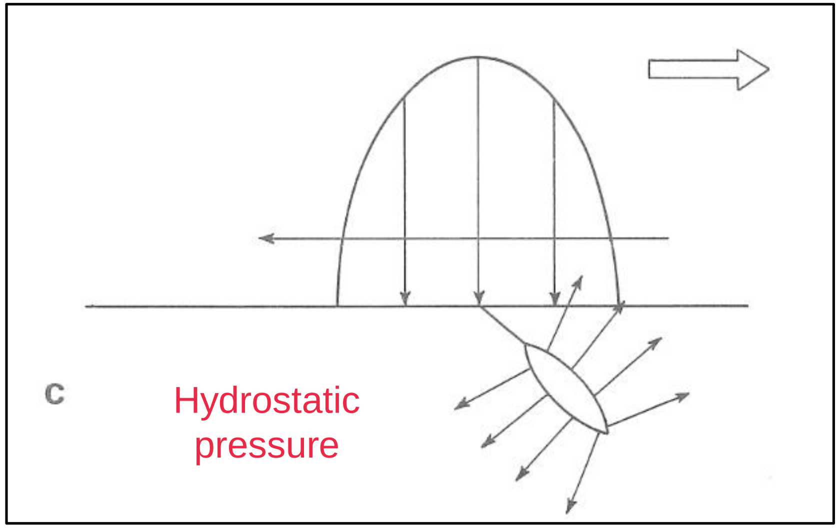


Water caused massive material removal and delamination.

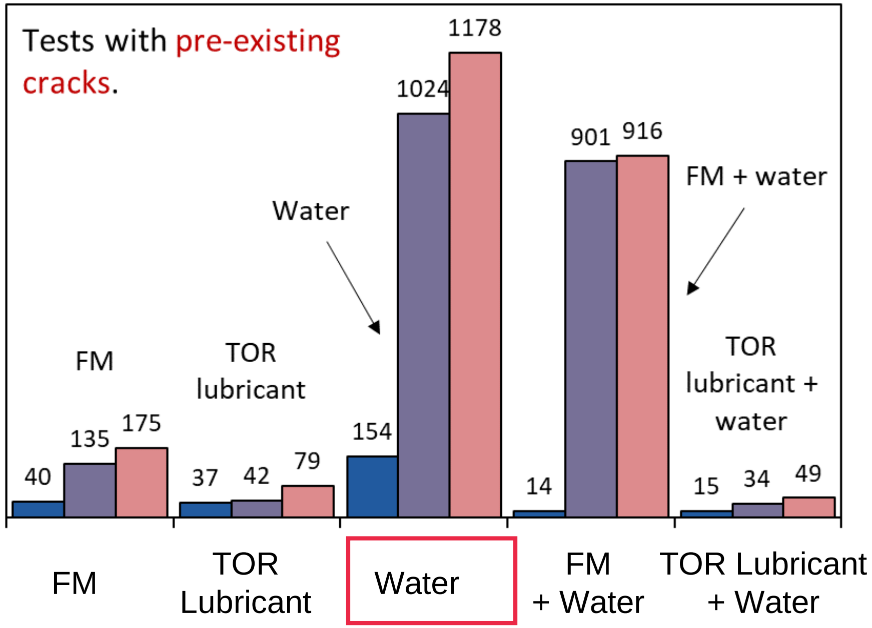
THE EFFECT ON WEAR AND RCF

RESULTS

Liquid-assisted Crack Propagation



Kaneta et al. (1987)



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THE EFFECT ON WEAR AND RCF

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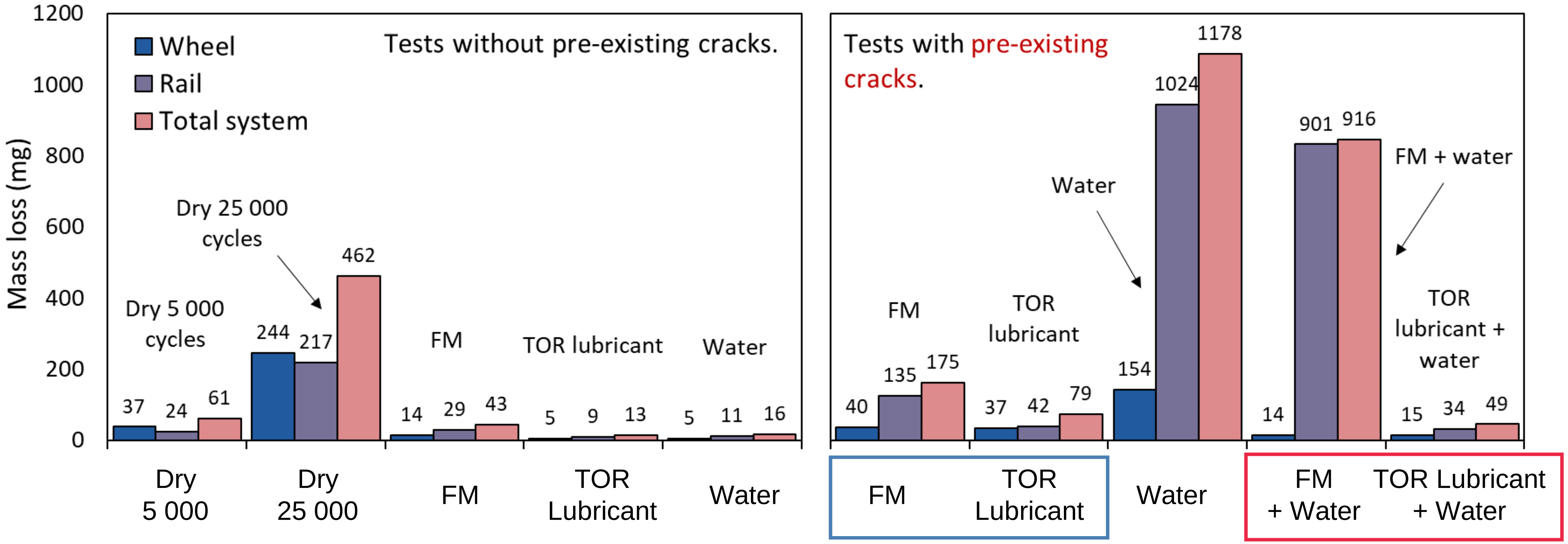
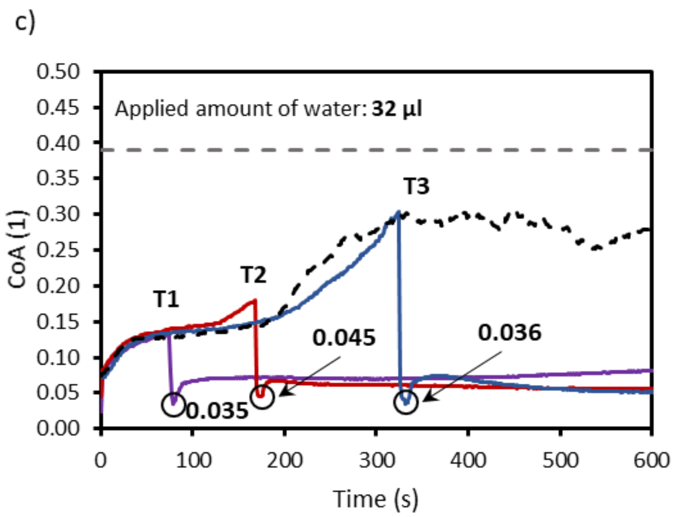


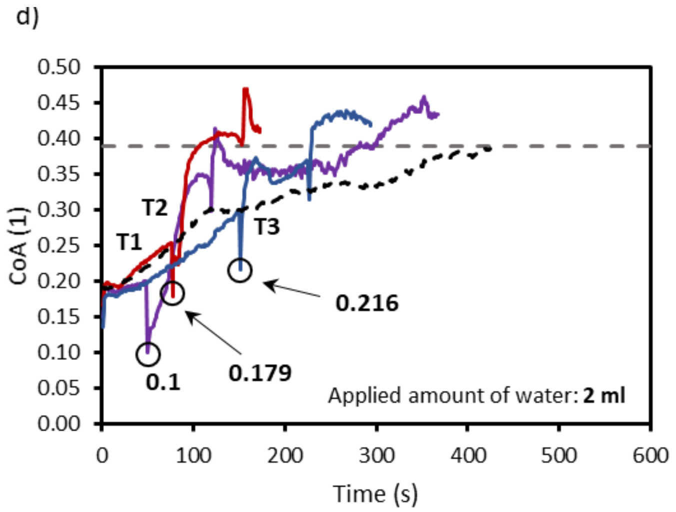
Unlike TOR lubricant, FM could not maintain its function in wet conditions.

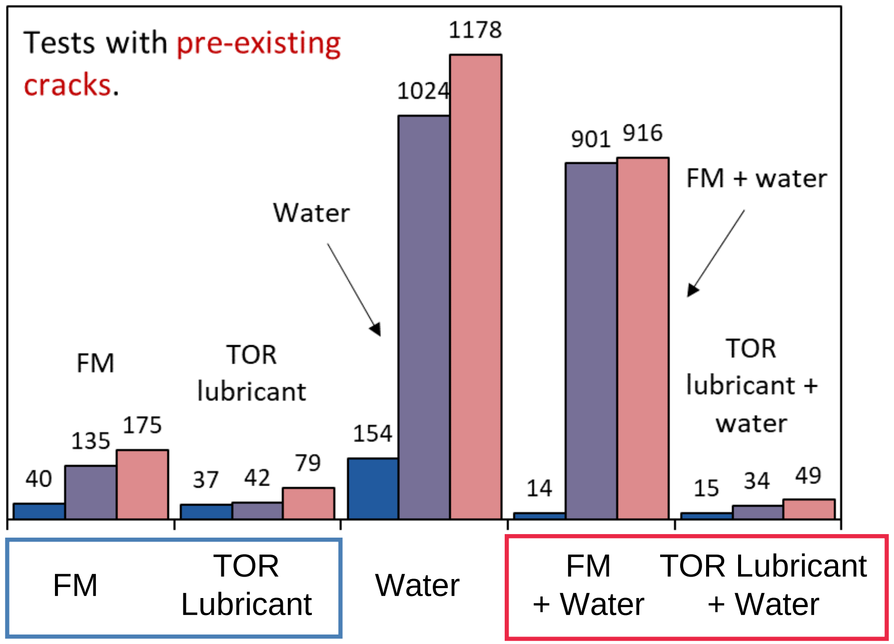
THE EFFECT ON WEAR AND RCF

RESULTS

FM film is easily removed by water, and thus, in case of contamination, the surface remains unprotected.





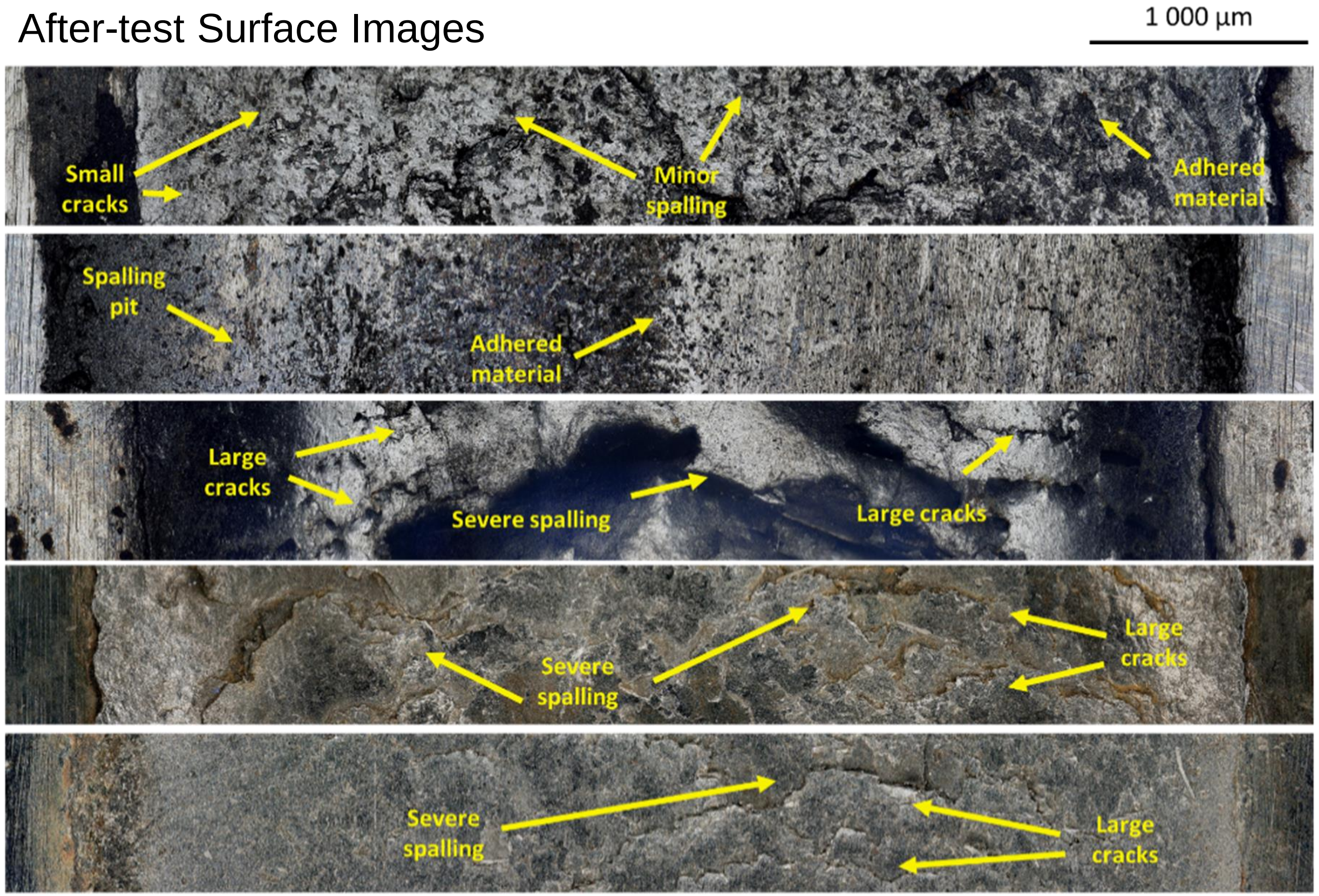


Unlike TOR lubricant, FM could not maintain its function in wet conditions.

THE EFFECT ON WEAR AND RCF

RESULTS

After-test Surface Images



Friction Modifier
(25 000 cycles, pre-existing cracks)

TOR Lubricant
(25 000 cycles, pre-existing cracks)

Water
(25 000 cycles, pre-existing cracks)

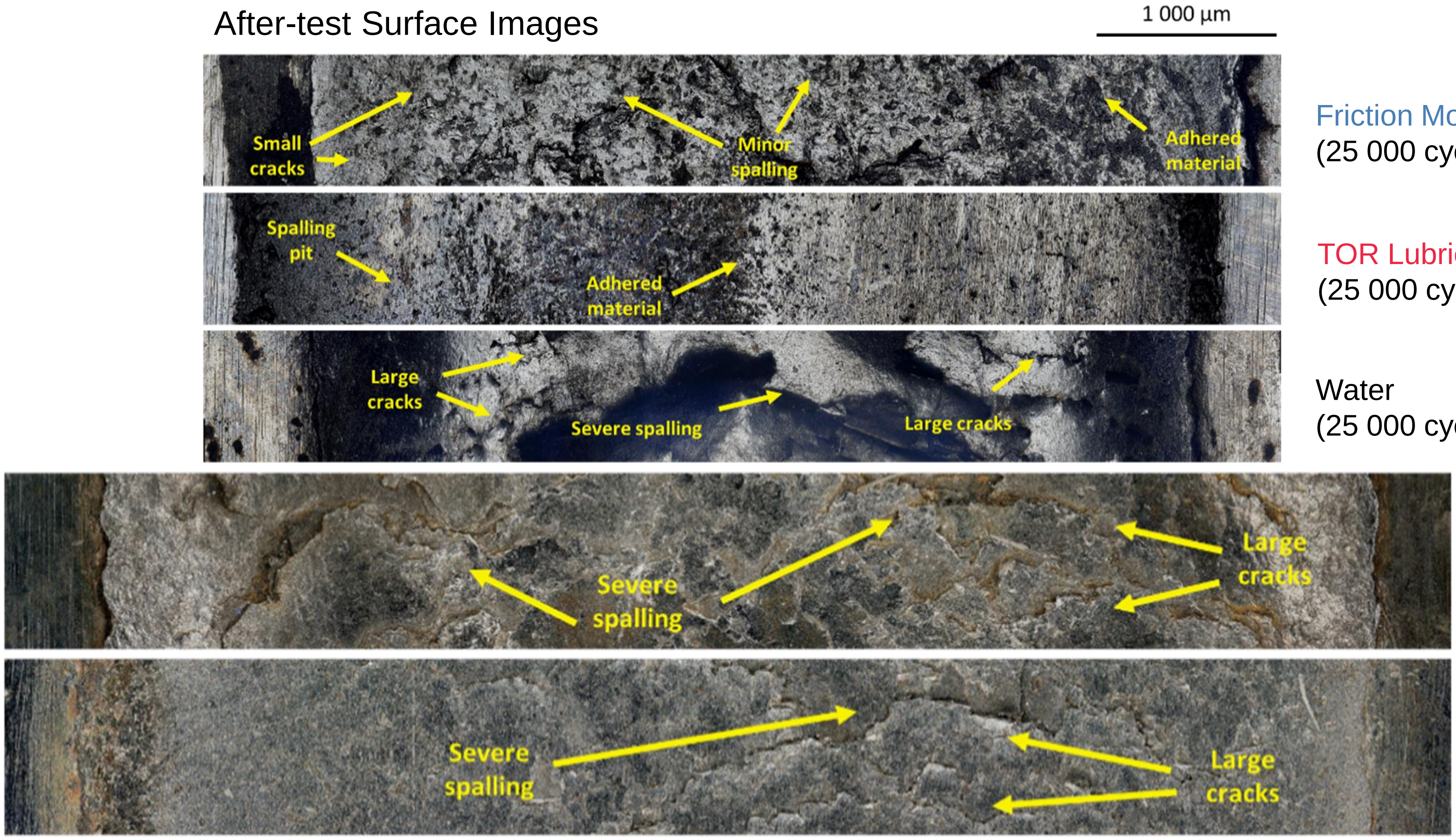
Friction Modifier in Wet Conditions
(25 000 cycles, pre-existing cracks)

TOR Lubricant in Wet Conditions
(25 000 cycles, pre-existing cracks)

THE EFFECT ON WEAR AND RCF

RESULTS

After-test Surface Images



Friction Modifier
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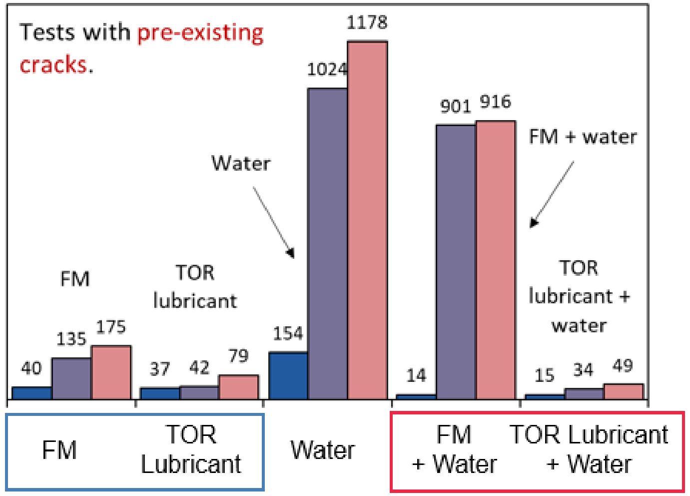
Friction Modifier
in Wet Conditions
(25 000 cycles,
pre-existing cracks)

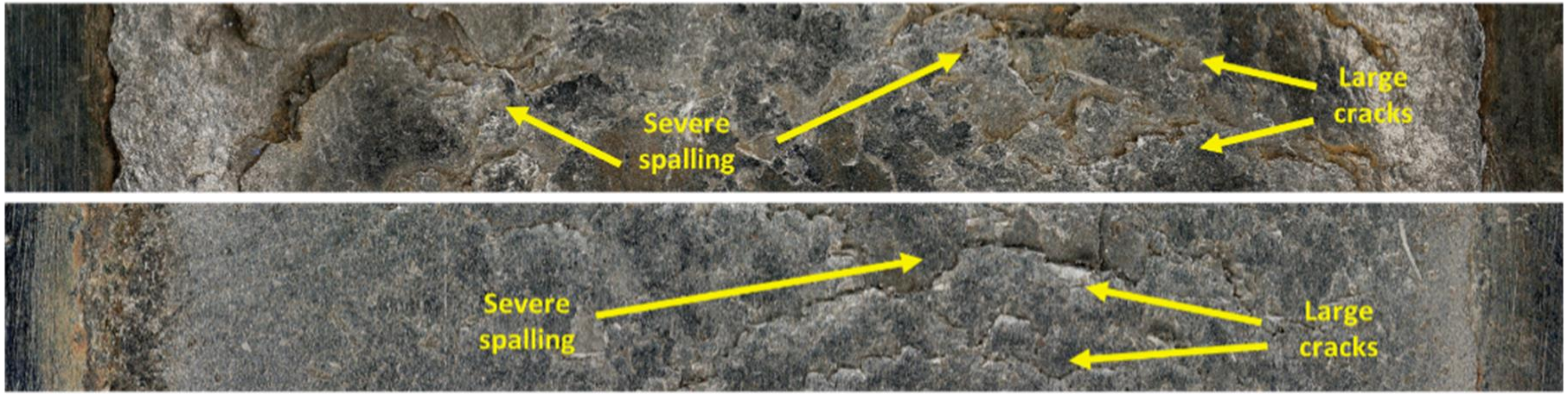
TOR Lubricant
in Wet Conditions
(25 000 cycles,
pre-existing cracks)

THE EFFECT ON WEAR AND RCF

RESULTS

Although there was almost no material loss under the TOR lubricant in wet conditions, large cracks were spotted on the surface.



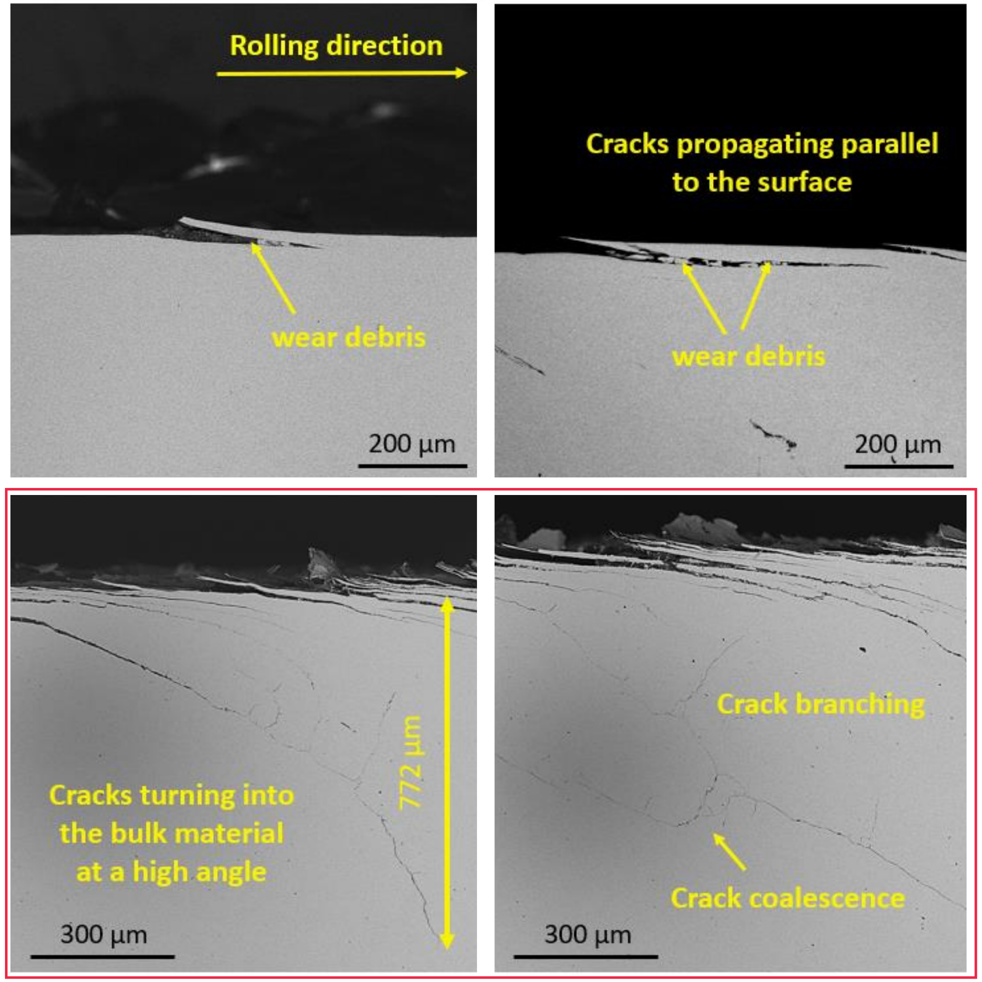


Friction Modifier in Wet Conditions (25 000 cycles, pre-existing cracks)

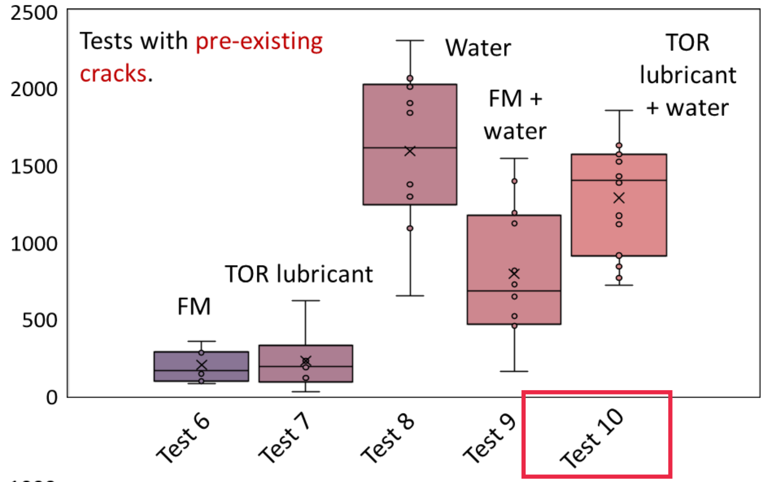
TOR Lubricant in Wet Conditions (25 000 cycles, pre-existing cracks)

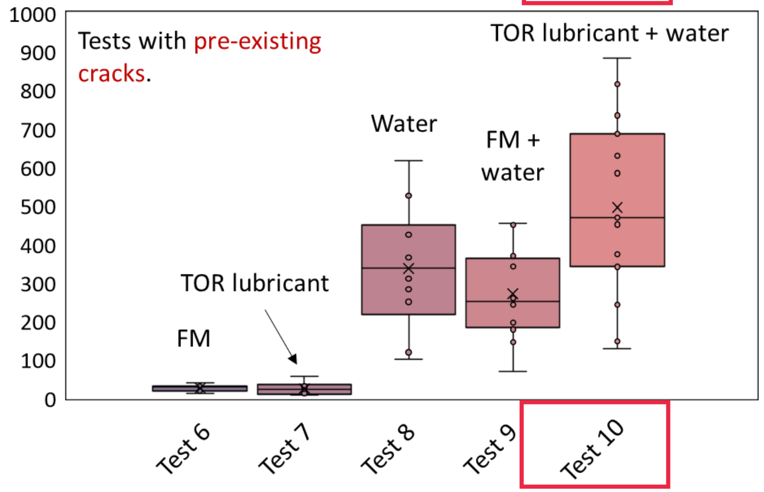
THE EFFECT ON WEAR AND RCF

RESULTS



TOR Lubricant in Wet Conditions



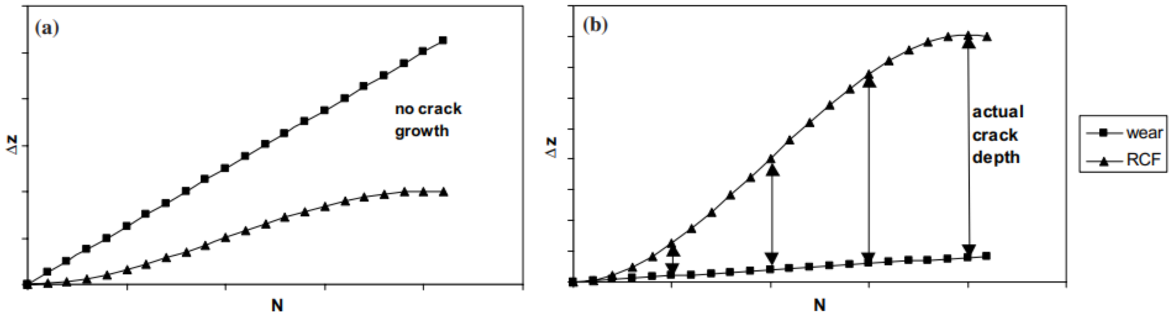


Out of all tests, the TOR lubricant under wet conditions led to the development of the deepest cracks.

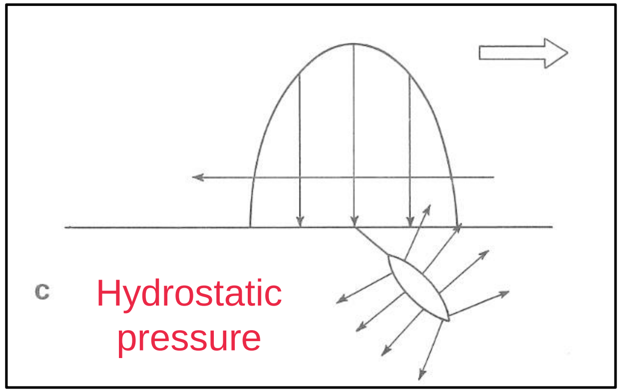
THE EFFECT ON WEAR AND RCF

RESULTS

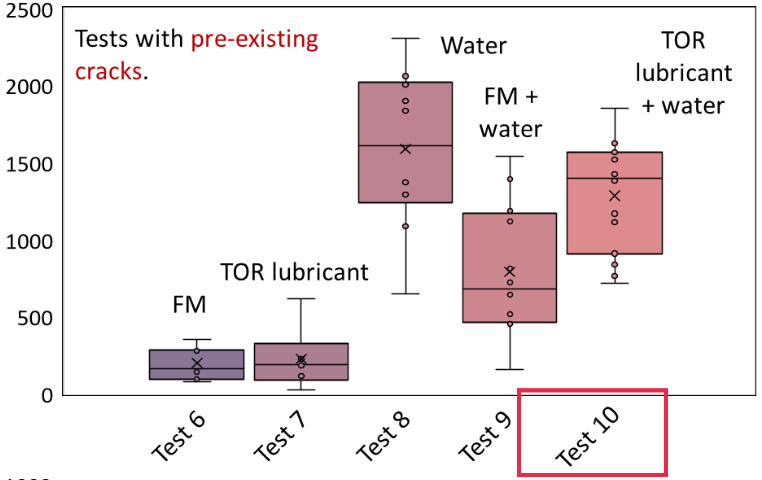
„Competition“ between Wear and Crack Growth

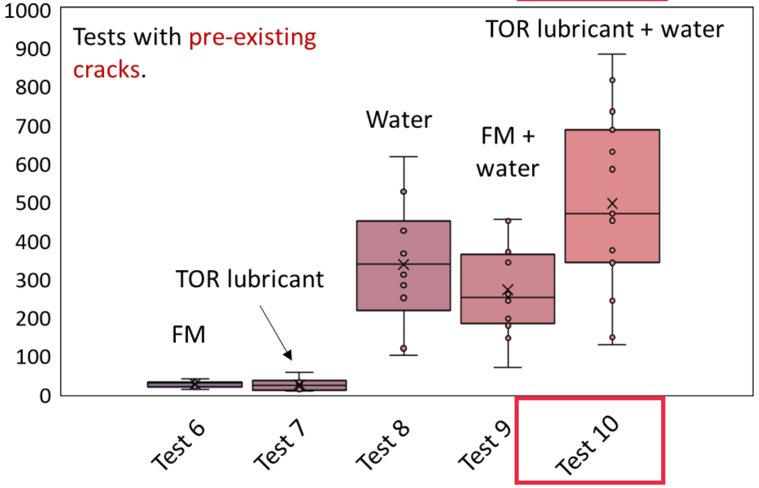


Liquid-assisted Crack Propagation



upper: Donzella et al. (2005); lower: Kaneta et al. (1987)





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THE EFFECT ON WEAR AND RCF

QUESTION AND HYPOTHESIS

Q3: How do TOR products affect wear and rolling contact fatigue in the presence of oxide layers under wet conditions?

H3.1: In wet conditions, TOR lubricants are expected to influence RCF in a way similar to TOR hybrids. The only difference is that water is intentionally added in the latter, whereas in the former, it enters the contact as an unwanted contaminant. This combination is expected to promote severe RCF due to the coexistence of high friction and liquid-assisted crack propagation.

The proposed mechanism did not occur. Instead, water amplified the lubricating effect of the TOR lubricant, suppressing surface wear and preventing the natural removal of developing cracks. Simultaneously, water and oil penetrated open cracks, promoting growth through hydropressurisation and crack face lubrication. Nevertheless, the predicted outcome was confirmed, although through a different mechanism than anticipated.

PARTIALLY VERIFIED

THE ROLE OF OXIDES

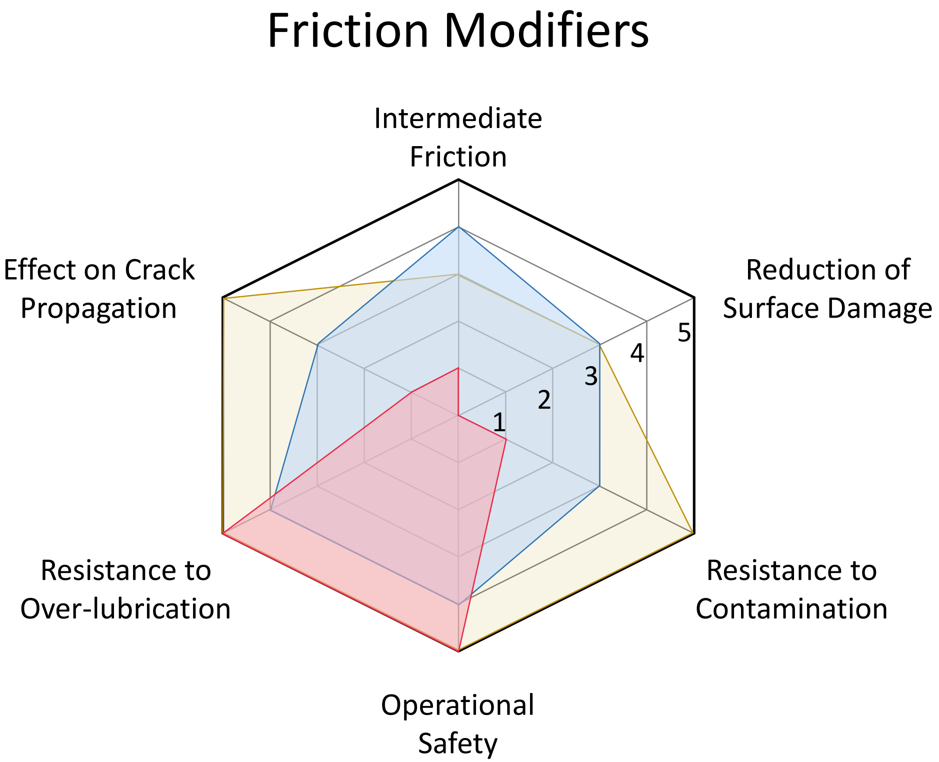
THE EFFECT OF OXIDES

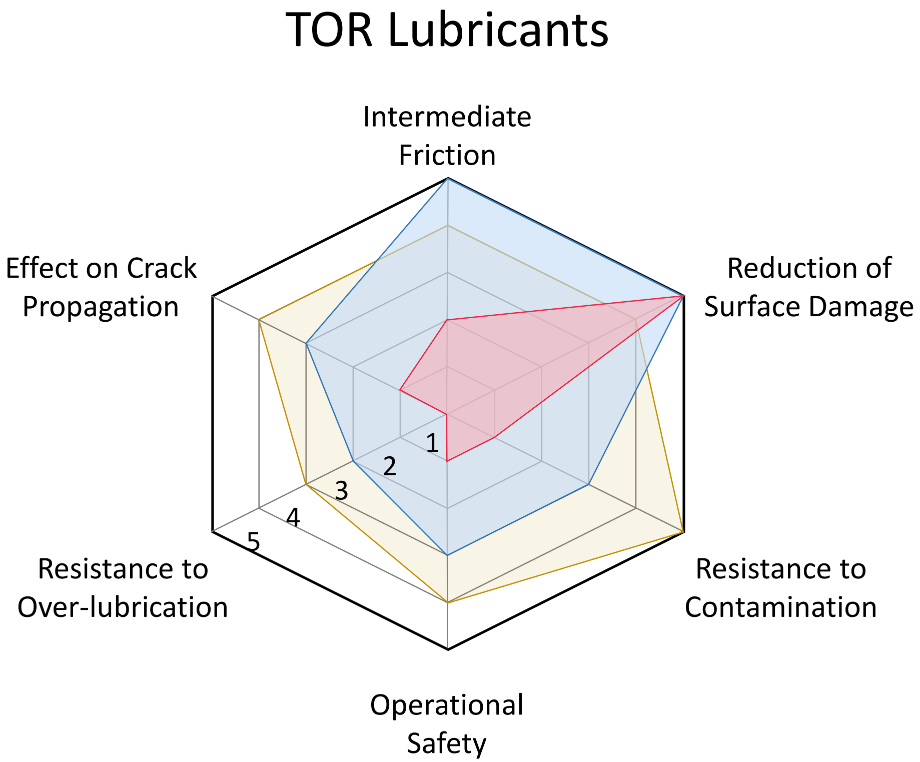
RESULTS

REMOVED PENDING PUBLICATION

THE EFFECT OF CONTAMINATION ON FRICTION MODIFICATION

THE EFFECT OF CONTAMINATION ON FRICTION MODIFICATION





<u>Contamination scenarios:</u>

Dry and Clean Rail

Light Moisture (humidity, dew)

Water (precipitation)

1 = the worst (e.g. severe wear); 5 = the best (e.g. virtually no wear)
The scale is illustrative only and serves to indicate qualitative trends. No weighting between individual criteria is implied.

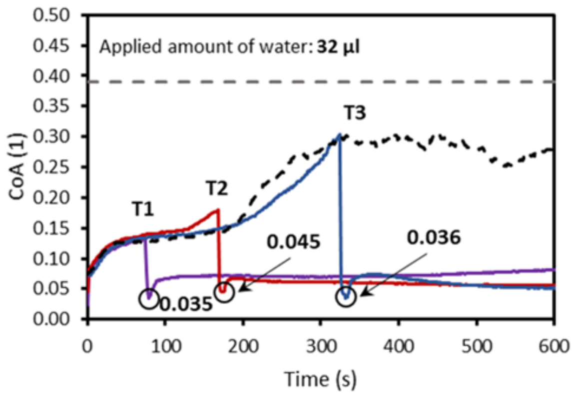
THE EFFECT OF CONTAMINATION ON FRICTION MODIFICATION

THE MAIN TAKEAWAY

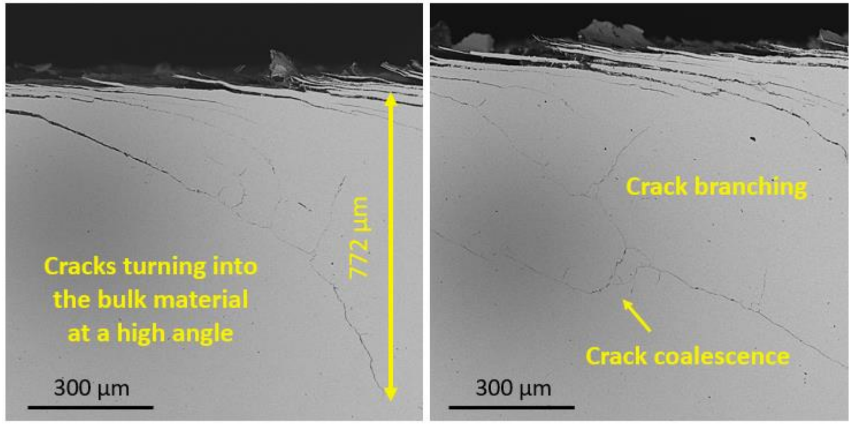
„For friction modifiers, contamination is a matter of cost.
For TOR lubricants, it's a matter of safety.“

THE EFFECT OF CONTAMINATION ON FRICTION MODIFICATION

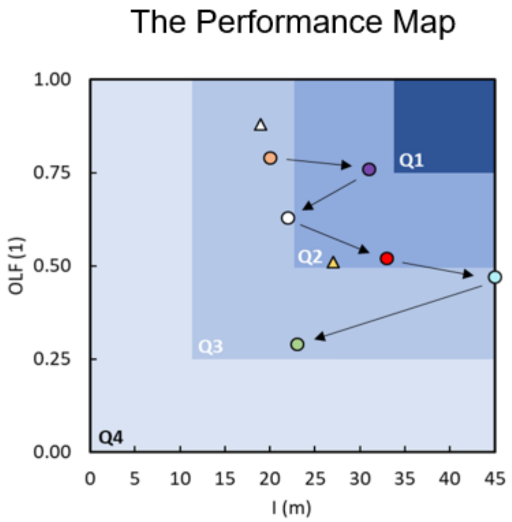
THE MAIN CONCLUSIONS

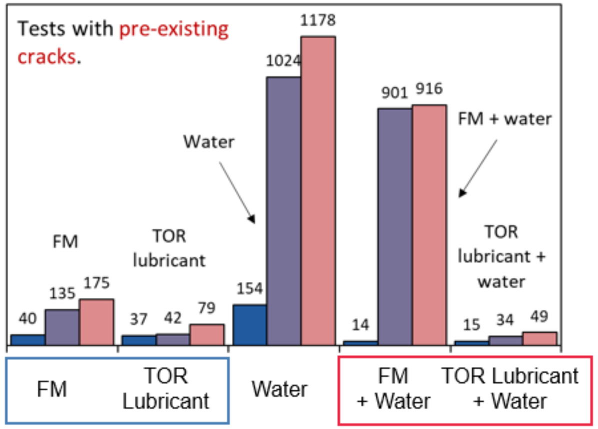


1) TOR lubricant contamination can lead to severe low-adhesion conditions, eliminating wear while simultaneously accelerating crack growth and RCF.



Out of all tests, the TOR lubricant under wet conditions led to the development of the deepest cracks.





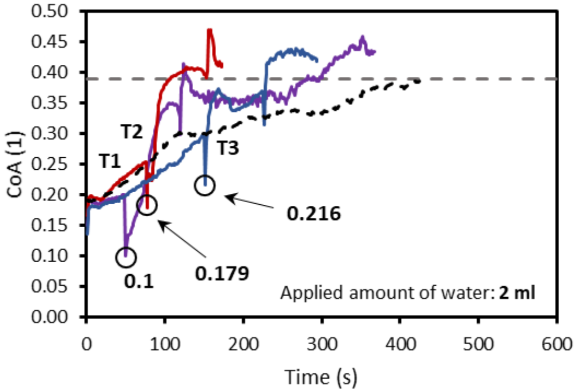
Unlike TOR lubricant, FM could not maintain its function in wet conditions.

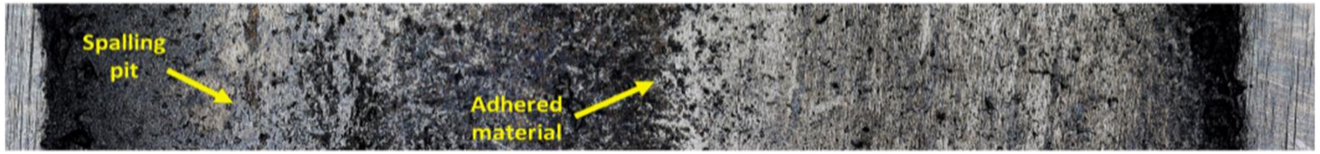
THE EFFECT OF CONTAMINATION ON FRICTION MODIFICATION

THE MAIN CONCLUSIONS

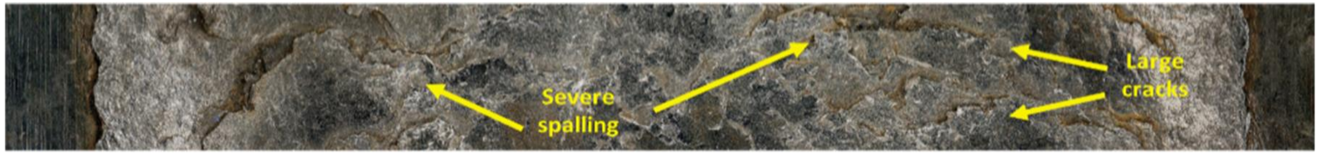
1) TOR lubricant contamination can lead to severe low-adhesion conditions, eliminating wear while simultaneously accelerating crack growth and RCF.

2) Friction modifiers perform slightly better under mild moisture conditions, but excessive water causes wash-off and complete loss of effectiveness, leaving wear and RCF uncontrolled.

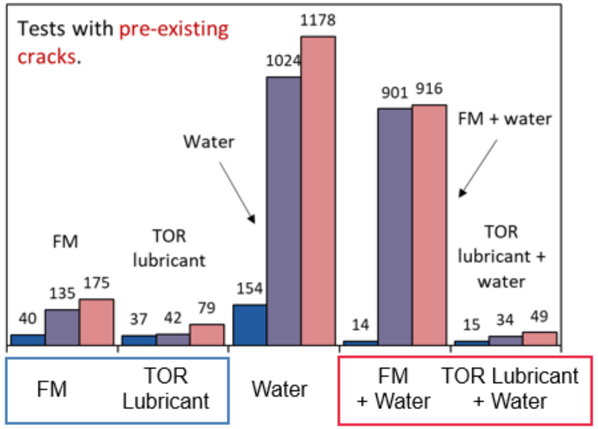




FM in dry conditions



FM in wet conditions



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THE EFFECT OF CONTAMINATION ON FRICTION MODIFICATION

THE MAIN CONCLUSIONS

1) TOR lubricant contamination can lead to severe low-adhesion conditions, eliminating wear while simultaneously accelerating crack growth and RCF.

2) Friction modifiers perform slightly better under mild moisture conditions, but excessive water causes wash-off and complete loss of effectiveness, leaving wear and RCF uncontrolled.

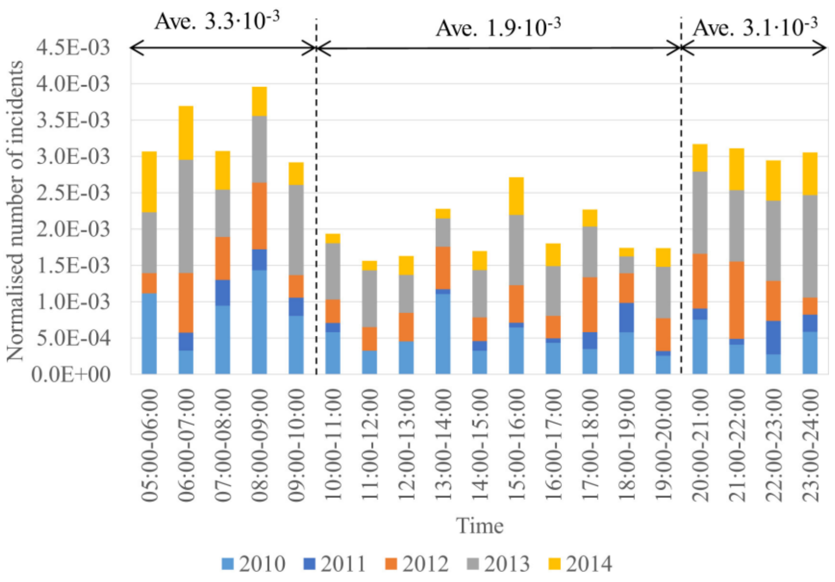
3) Iron oxides had a negligible effect on the performance of TOR products. However, they had a surprising effect on crack growth through oxygen-assisted crack propagation.

REMOVED PENDING PUBLICATION

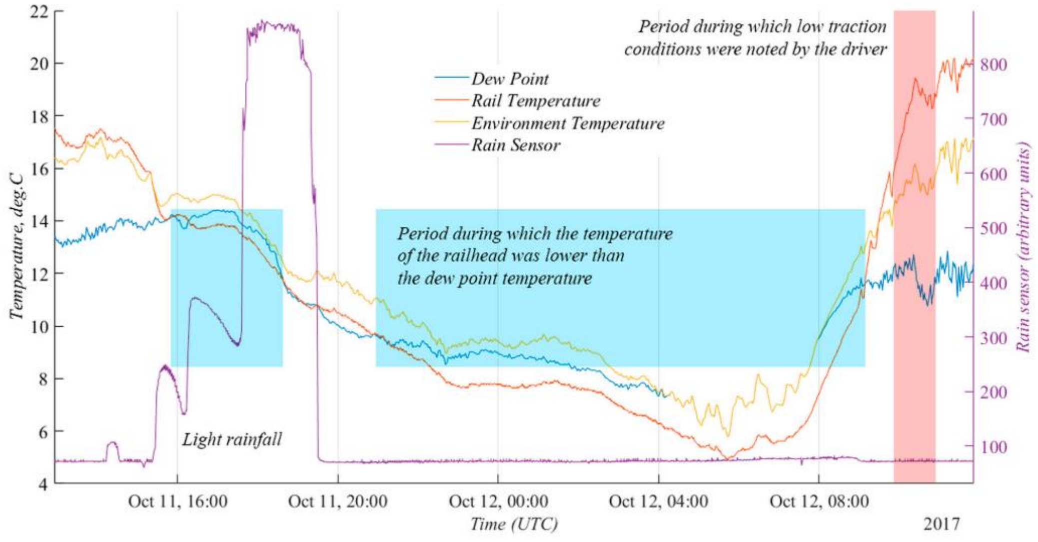
THE EFFECT OF CONTAMINATION ON FRICTION MODIFICATION

PRACTICAL APPLICATION

Low Adhesion Incidents



The Link between Low Adhesion and Weather

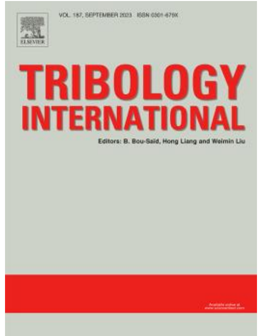


left: Ishizaka et al. (2017); right: Kempka et al. (2021)

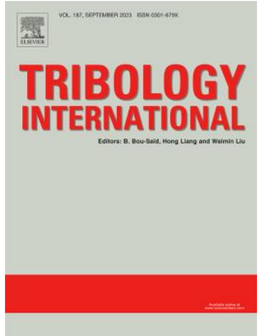
OPERATIONAL RECOMMENDATIONS

To mitigate the risk of low adhesion, TOR applicators should be equipped with meteorological sensors monitoring temperature, humidity, and precipitation. When environmental conditions exceed defined thresholds, the application should be automatically reduced or suspended.

OVERVIEW OF THE RESEARCH OUTCOMES

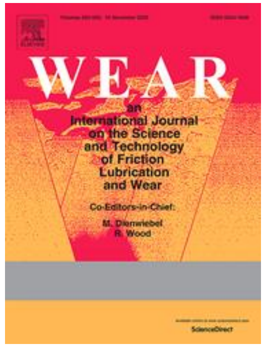


2023



2023

2024



2026

2026

International Research Stay

- Southwest Jiaotong University, Chengdu, China, March–August 2024. Supervisor: Prof. Wenjian Wang. *Oxidation as a factor in rail crack damage.*
- Southwest Jiaotong University, Chengdu, China, May–August 2025. Supervisor: Prof. Wenjian Wang. *Performance of TOR products under contaminated conditions with pre-existing cracks.*

Scientific Conferences

- 48th Leeds-Lyon Symposium on Tribology, Tribology for a Sustainable and Resilient Future, 5–7 September 2023, University of Leeds, UK.
- 3rd International Conference on Rail Transportation (ICRT), 7–9 August 2024, Shanghai, China.
- 13th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM 2025), 22–26 September 2025, Tokyo, Japan.

THANK YOU!

Šimon Skurka

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