

Influences of Friction Heat on Tire Traction on Ice and Snow

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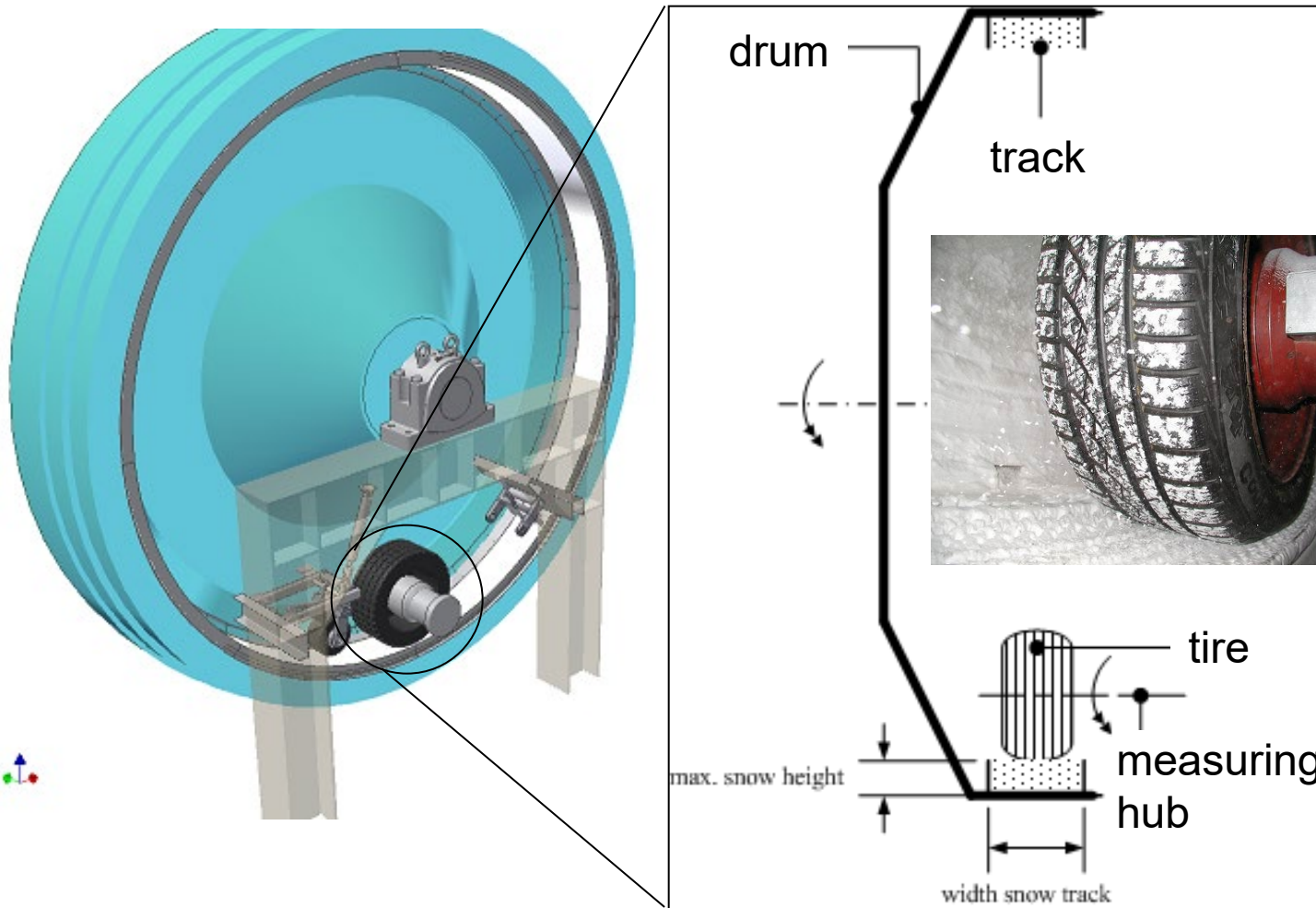
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Inner Drum Test Rig

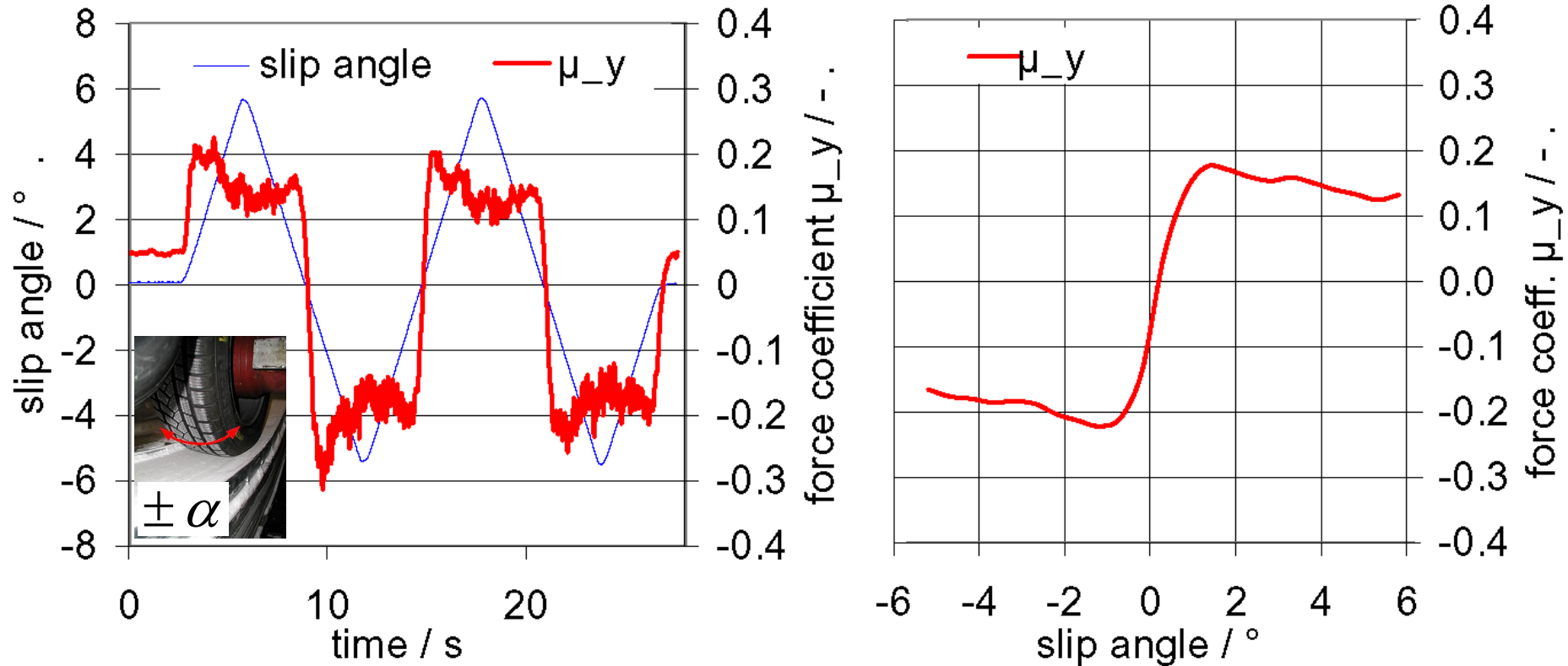


Further tests:
on asphalt,
concrete,
and wet tracks.

Further research:
acoustic, wear,
dynamics.

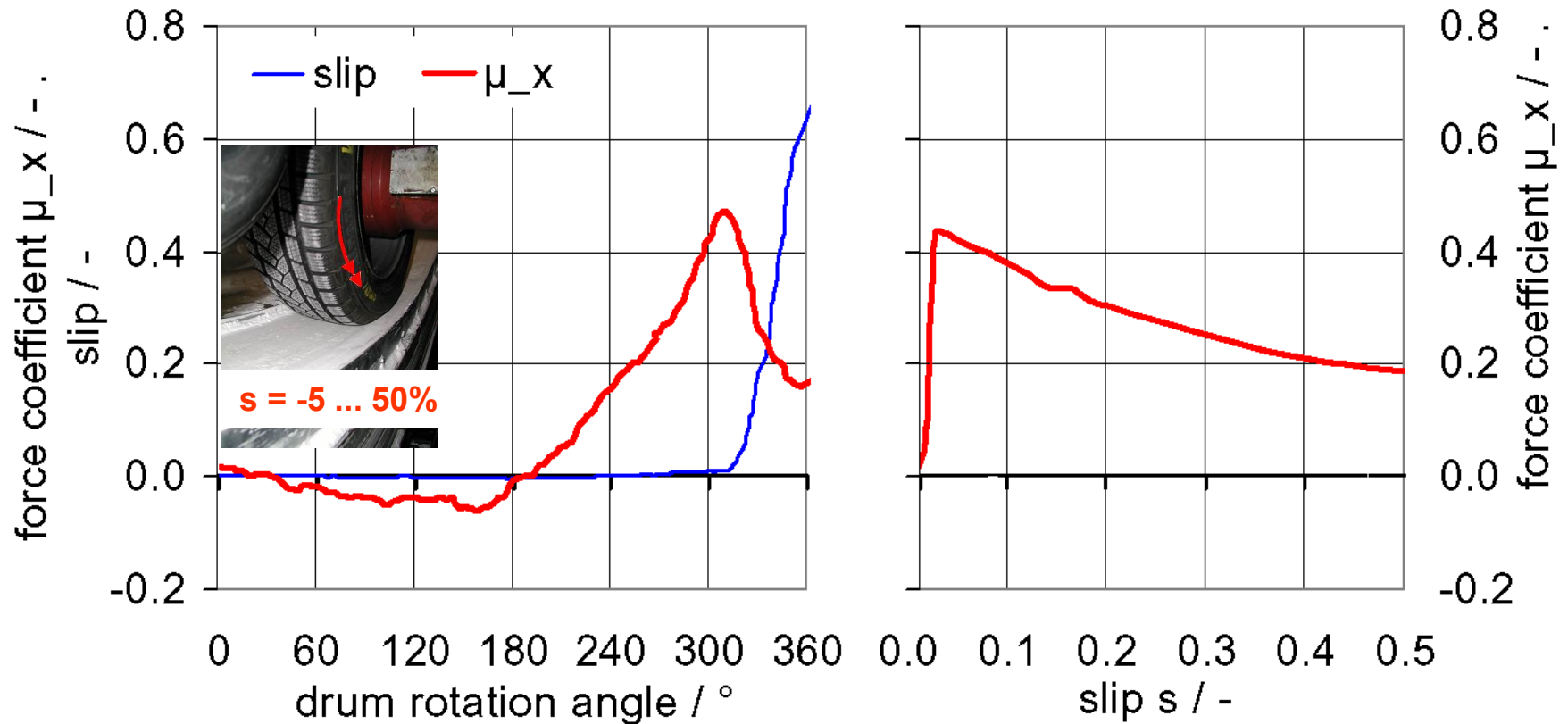
Inner drum test rig for tire tests on ice and snow under controllable conditions.

Test Procedures - Lateral Traction on Snow



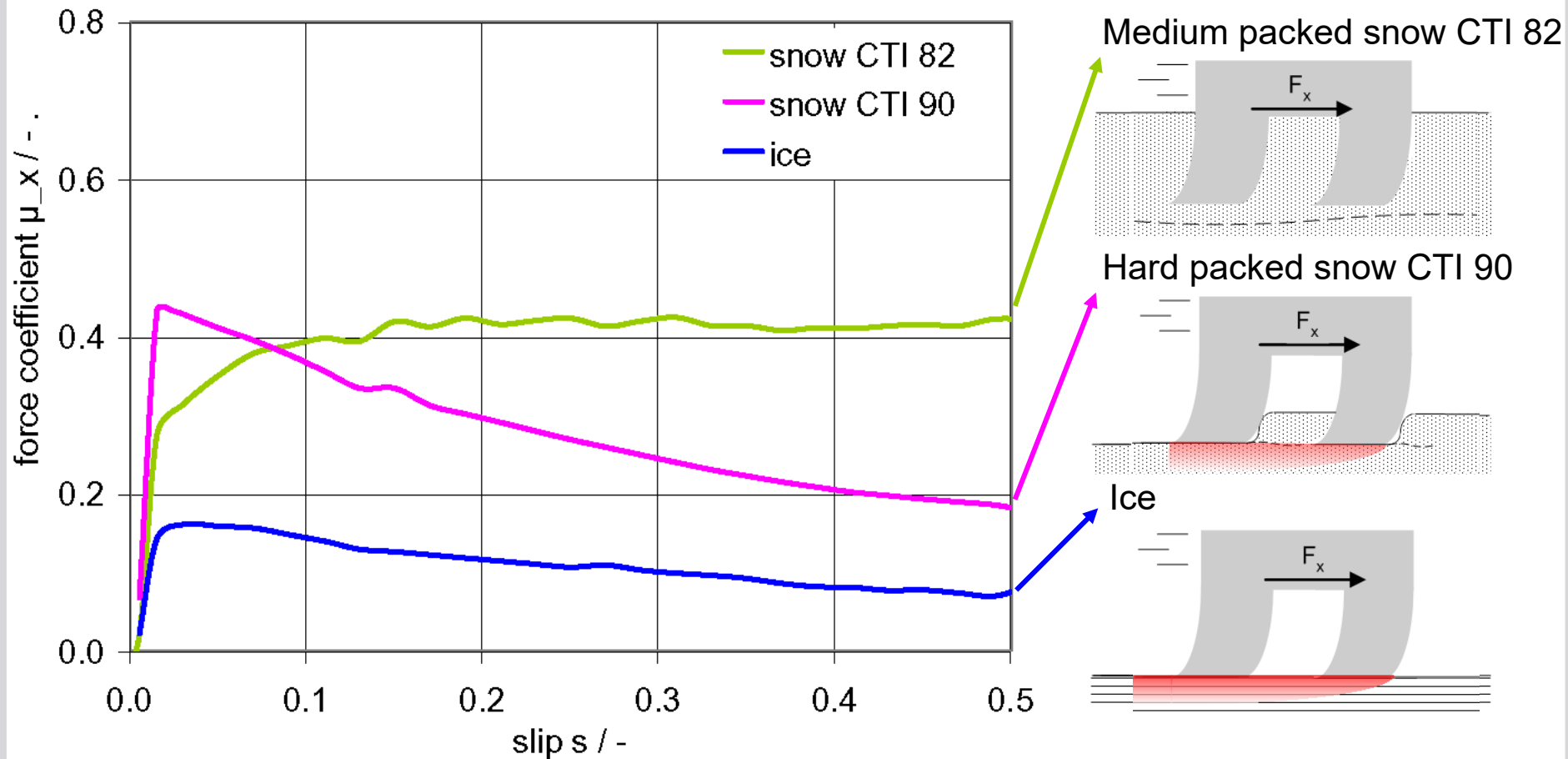
Lateral traction determined in 2 cycles by varying the slip angle.

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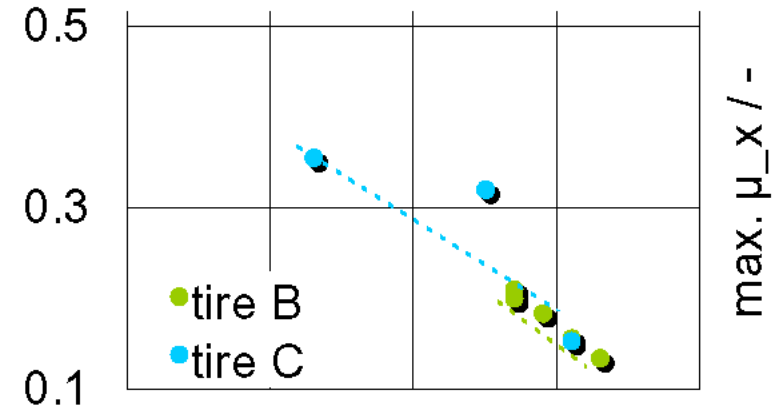
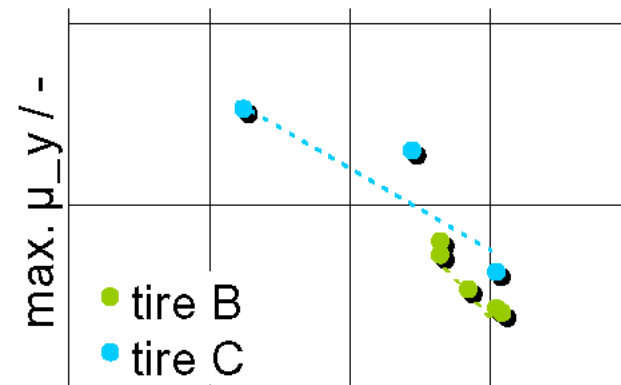
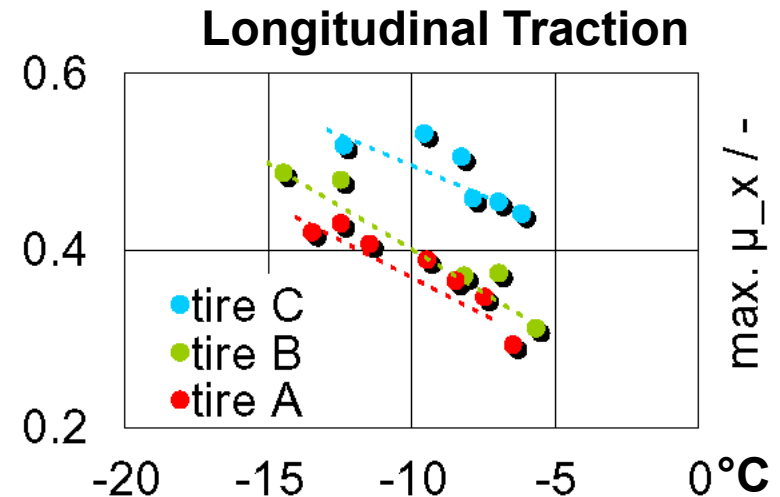
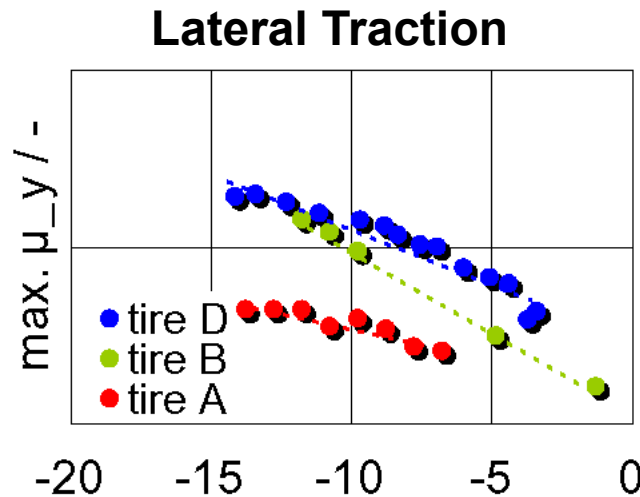
Longitudinal traction performance is determined within one drum turn to avoid rolling over of iced surfaces.

Influence of Track Hardness



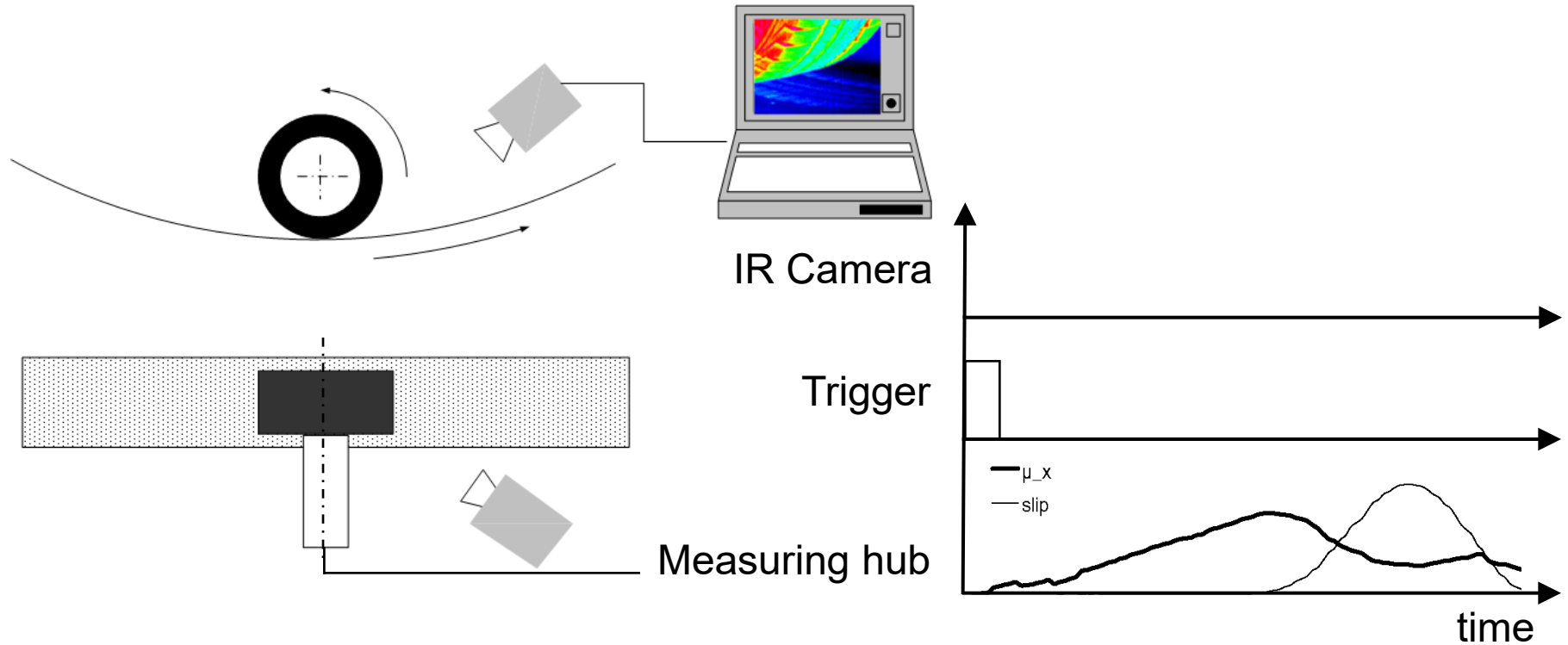
On tracks with low hardness, high traction forces can be transmitted under high slip. Distinctive force maximum on hard packed snow and ice.

Influence of Ambient Temperature



Maximum of transmittable forces decreases, when temperature rises.
Average μ - gradient is higher on ice.

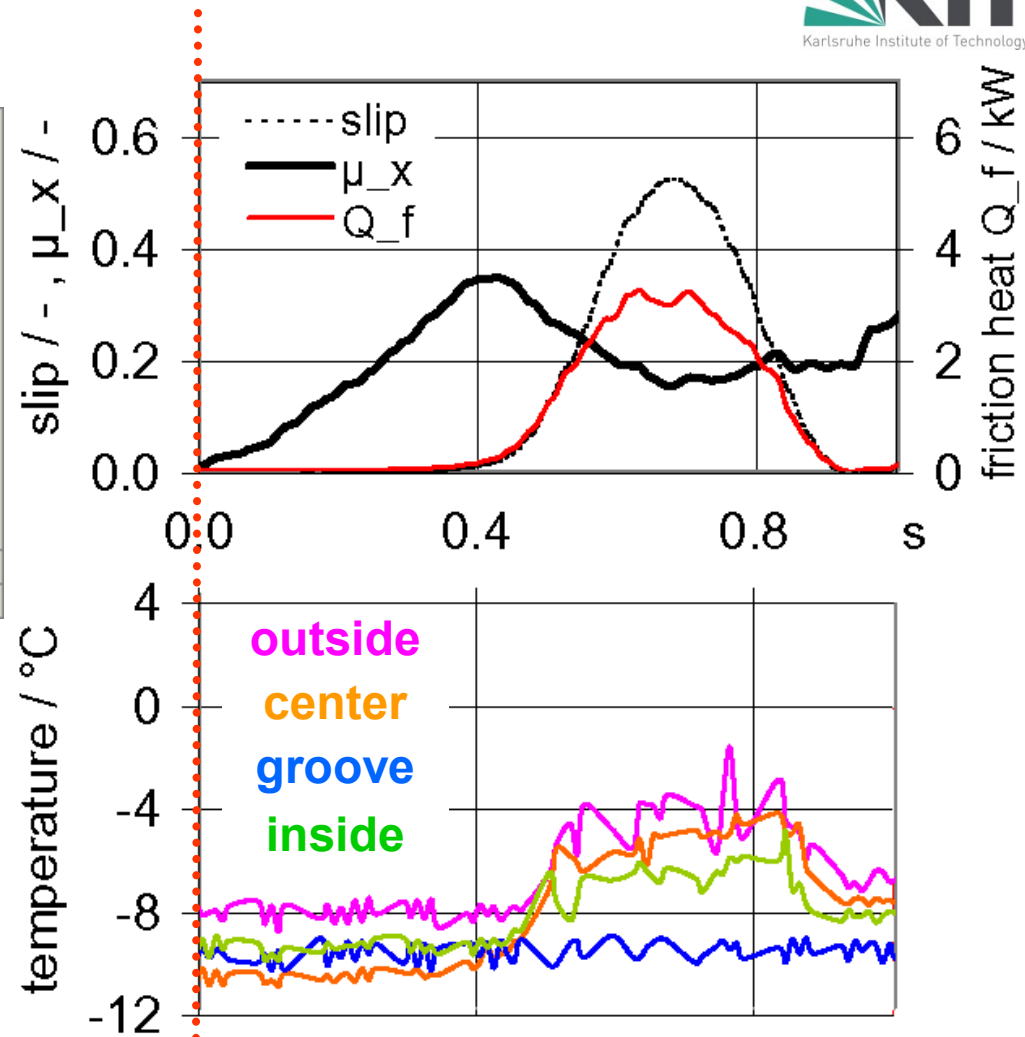
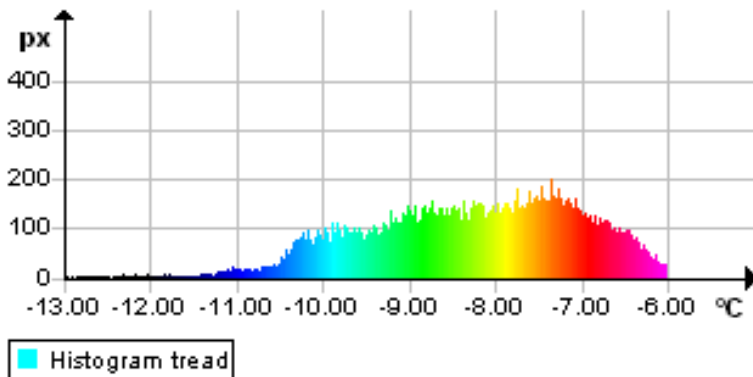
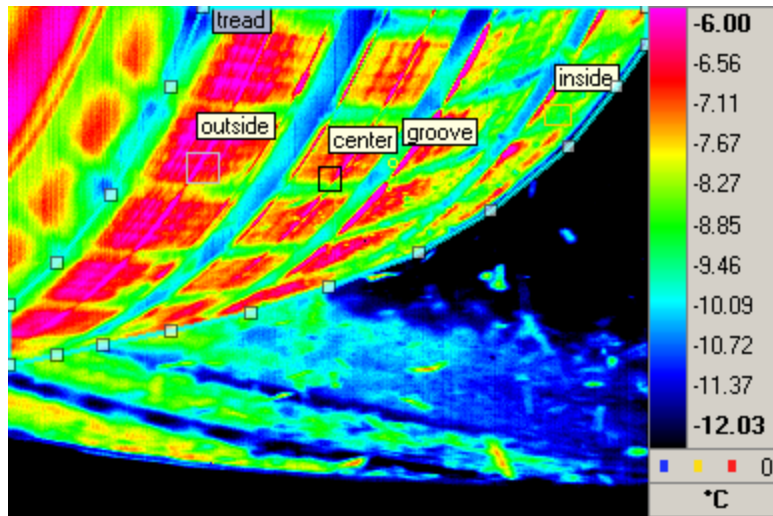
High Speed Infrared Camera



The high speed infrared camera focuses on the run out of the tire.
Trigger used for synchronization of the measured forces and the IR images.

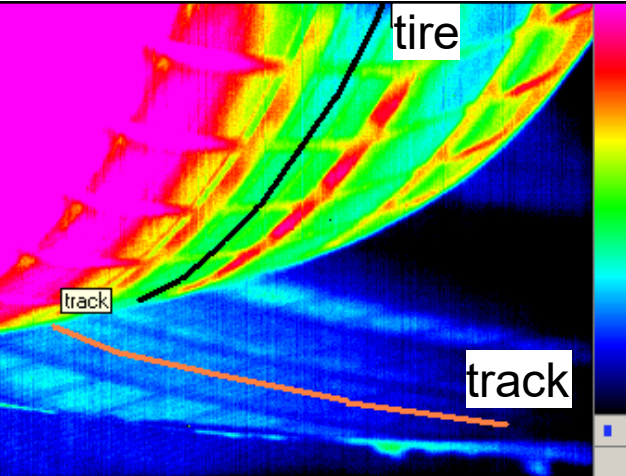
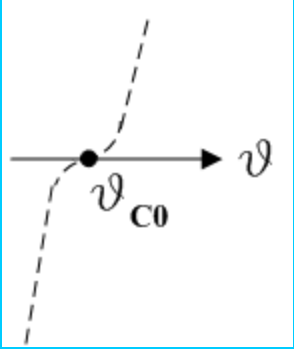
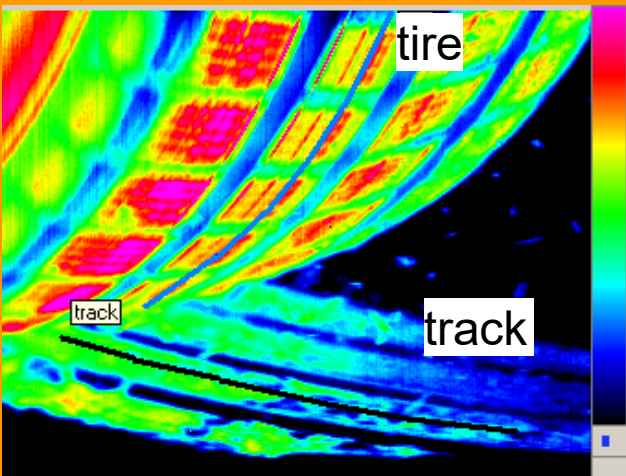
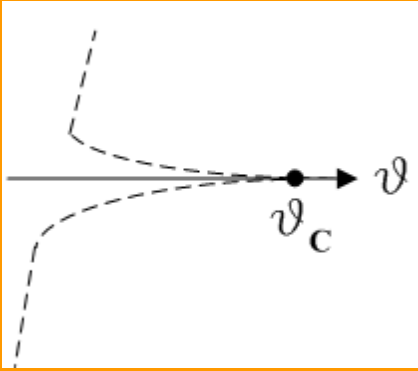
Influence of Friction Heat

t3 = 0.64s : max. Q_f

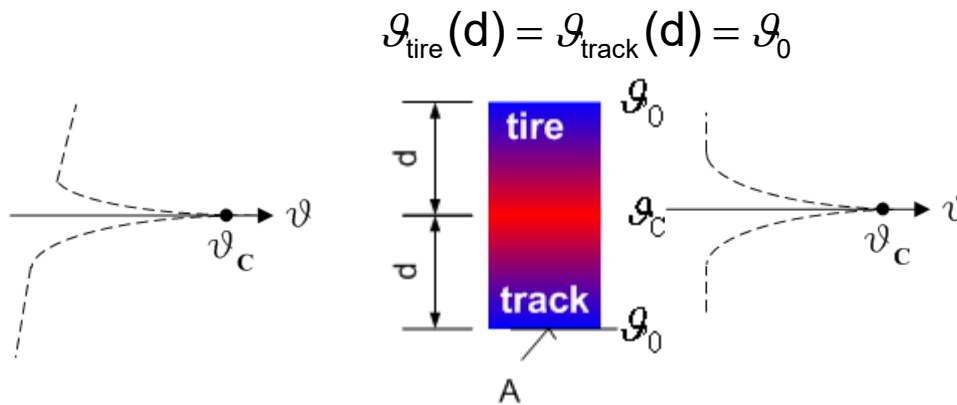


t1 → t2: Adhesion & interlocking force between tire and track under low slip.
t2 → t3: Sliding tire develops friction heat → increase of surface temperature within a thin layer → melting of snow and drop of transmitted force.

Free Rolling and Sliding Tire

	Experiment	Result	Theory
Free rolling	 - 9°C - 14°C	Warm tire Cool track	 v_{c0}
Sliding	 - 5°C - 12°C	Heating of thin layer of the tire. Groove temperature not influenced.	 v_c

Theory	Assumption	Stationary Heat Flux
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$$\dot{Q}_{\text{Tire}} = \frac{\lambda_{\text{Tire}} \cdot A}{d} \cdot (g_C - g_0)$$

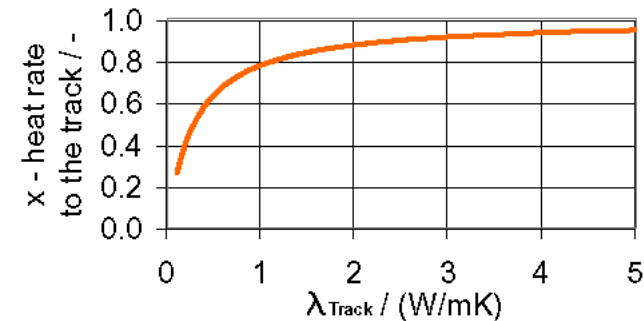
$$\dot{Q}_F = \mu_X \cdot F_Z \cdot s \cdot v$$

$$\dot{Q}_{\text{Track}} = \frac{\lambda_{\text{Track}} \cdot A}{d} \cdot (g_C - g_0)$$

$$\dot{Q}_{\text{track}} = x_S \cdot \dot{Q}_F$$

1st estimation of heat ratio to the track:

$$x_S = \frac{\dot{Q}_{\text{track}}}{\dot{Q}_{\text{track}} + \dot{Q}_{\text{tire}}} = \frac{\lambda_{\text{track}}}{\lambda_{\text{track}} + \lambda_{\text{tire}}}$$



Analysis of quasi stationary heat flux $\rightarrow$ 1st estimation: Heat ratio x_S to the track depends on heat transfer coefficients of track and tire.

1st Law of thermodynamic

$$\rho \cdot c_p \cdot \frac{\partial \vartheta}{\partial t} = -\nabla \dot{q}$$

Fourier's law of heat transfer

$$\dot{q} = -\lambda \cdot \nabla \vartheta$$

$$\rho \cdot c_p \cdot \frac{\partial \vartheta}{\partial t} = \nabla \lambda \cdot \nabla \vartheta$$

Transient heat flux:

$$\frac{\partial \vartheta}{\partial t} = \frac{\lambda}{\rho \cdot c_p} \cdot \nabla^2 \vartheta$$

For a temperature field
e.g. in cartesian coordinates:

$$\nabla^2 \vartheta = \frac{\partial^2 \vartheta}{\partial x^2} + \frac{\partial^2 \vartheta}{\partial y^2} + \frac{\partial^2 \vartheta}{\partial z^2}$$

$$\lambda_x = \lambda_y = \lambda_z = \lambda$$

Based on source: Prof. Martin, VDI Wärmeatlas 2002.

Description of time depending temperature field.

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Transient heat Flux

$$\frac{\partial \vartheta}{\partial t} = \frac{\lambda}{\rho \cdot c_p} \cdot \nabla^2 \vartheta$$

Start temperature

$$\vartheta(r,0) = \vartheta_0$$

Friction heat

$$-\lambda \left(\frac{\partial \vartheta}{\partial n} \right) = \frac{\dot{Q}_F}{A}$$

Thermal penetration coefficient:

$$b = \sqrt{\lambda \cdot \rho \cdot c_p}$$

Surface temperature
during heat development:

$$\vartheta_c(x=0,t) = \vartheta_0 + \frac{2 \cdot \dot{q}_w}{b} \cdot \sqrt{\frac{t}{\pi}}$$

Based on source:

Dittmann: Repetitorium der Technischen
Thermodynamik.
Teubner Verlag, Stuttgart, 1995.

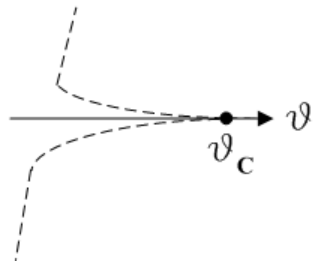
valid for
short term temperature change within a small layer

Transferred
heat flux density:

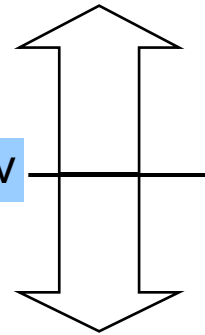
$$\hat{q}(x=0,t) = (\vartheta_c - \vartheta_0) \cdot \frac{b}{2} \cdot \sqrt{\frac{\pi}{t}}$$

Formula for the increase of surface temperature, when the surface is exposed to a constant heat flux.

Theory	Generated heat density	Heat flux to tire and track
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$$\dot{q}_F = \mu_x \cdot p \cdot s \cdot v$$



$$\hat{q}_{\text{tire}}(x=0, t) = (\vartheta_c - \vartheta_0) \cdot \frac{b_{\text{tire}}}{2} \cdot \sqrt{\frac{\pi}{t}}$$

$$\hat{q}_{\text{track}}(x=0, t) = (\vartheta_c - \vartheta_0) \cdot \frac{b_{\text{track}}}{2} \cdot \sqrt{\frac{\pi}{t}}$$

Assumption:
equal temperature at $t=0s$

$$\vartheta_{0_track} = \vartheta_{0_tire}$$



**Heat ratio
to the track:**

$$\dot{q}_{\text{track}} = x \cdot \dot{q}_F$$



2nd estimation:

$$x = \frac{b_{\text{track}}}{b_{\text{track}} + b_{\text{tire}}}$$

Transient heat flux → 2nd estimation: Heat ratio x to the track depends on thermal penetration coefficient of tire and track.

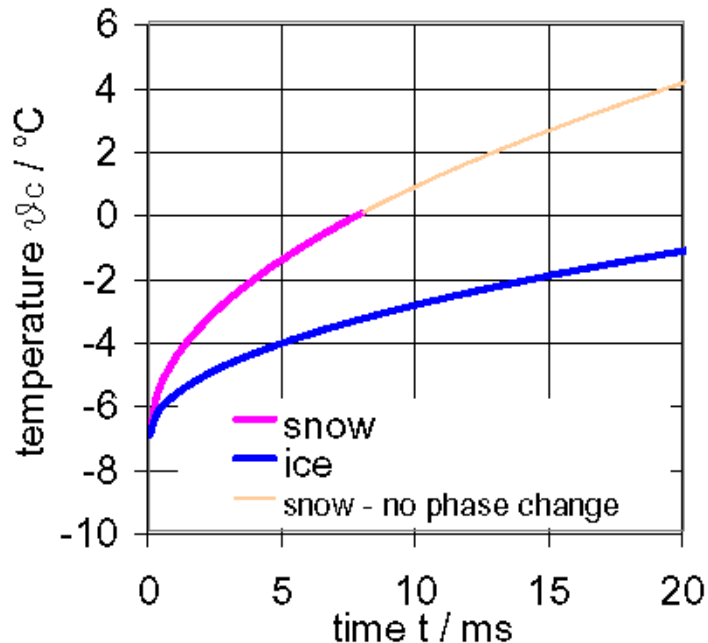
Transient Heat Flux

Surface temperature
during heat development :

$$\vartheta_c(x=0, t) = \vartheta_0 + \frac{2 \cdot x \cdot \dot{q}_w}{b_{\text{track}}} \cdot \sqrt{\frac{t}{\pi}}$$

valid for

$$Fo = \frac{\lambda \cdot t}{\rho \cdot c_p \cdot d^2} \leq 0.0972$$



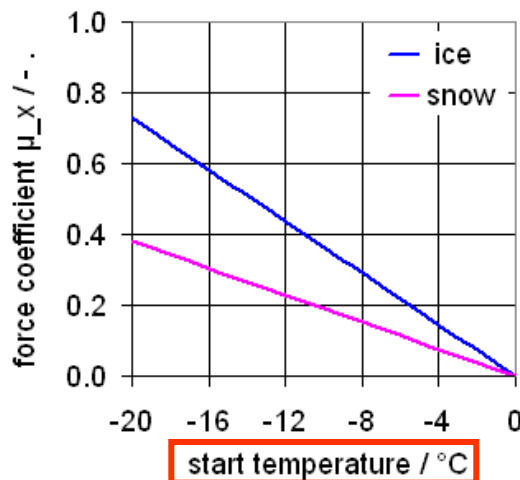
		rubber	snow	ice	
λ	heat transfer coeff.	0.28	0.46	2.25	W / mK
ρ	density	1207	560	917	kg / m ³
c_p	spezific heat	1450	2100	2040	J / (kg K)
b	thermal penetration coeff.	705	735	2052	W s ^{0.5} / (m ² K)
x	heat to the track		0.51	0.74	-
ϑ_0	start temp.		-7		°C
$\dot{q}_w$	heat flow density on the surface		100		kW / m ²

Example: Fast increase of surface temperature, when the surface is exposed to a constant heat flux.

Influence of Ambient Temperature

$$\hat{q}_{\text{track}}(x=0,t) = (\vartheta_c - \vartheta_0) \cdot \frac{b_{\text{track}}}{2} \cdot \sqrt{\frac{\pi}{t}} \quad \dot{q}_{\text{track}} = x \cdot \dot{q}_F = x \cdot \mu_x \cdot p \cdot s \cdot v \quad \vartheta_c = 0^\circ\text{C}$$

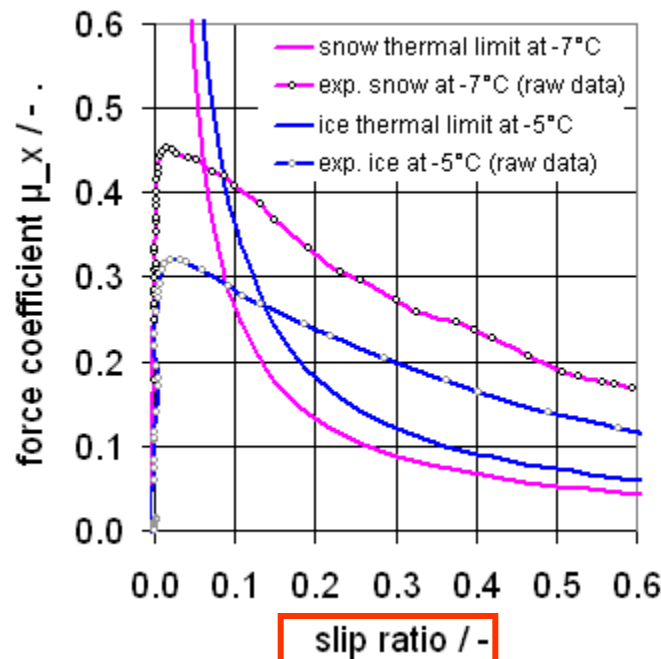
$$\mu_x(s) = -\vartheta_0 \cdot \frac{b_{\text{track}}}{2} \cdot \sqrt{\frac{\pi}{t}} \cdot (x \cdot p \cdot s \cdot v)^{-1}$$



		rubber	snow	ice	
λ	heat transfer coeff.	0.28	0.46	2.25	W / mK
ρ	density	1207	560	917	kg / m ³
c_p	spezific heat	1450	2100	2040	J / (kg K)
b	thermal penetration coeff.	705	735	2052	W s ^{0.5} / (m ² K)
x	heat to the track		0.51	0.74	-
p	contact pressure		300		kN / m ²
v	driving velocity		8.3		m / s
s	slip ratio		0.20		-
l	footprint length		0.15		m
t	contact time		0.018		s

Thermal force limit: contact temperature reaches 0°C $\rightarrow$ snow and ice melt
 $\rightarrow$ decrease of transmittable force coefficient, when initial temperature increases.
Comparison theory vs. experiment: Higher gradient on ice

$$\mu_x(s) = -\vartheta_0 \cdot \frac{b_{\text{track}}}{2} \cdot \sqrt{\frac{\pi}{t}} \cdot (x \cdot p \cdot s \cdot v)^{-1}$$



		rubber	snow	ice	
λ	heat transfer coeff.	0.28	0.46	2.25	W / mK
ρ	density	1207	560	917	kg / m ³
c_p	spezific heat	1450	2100	2040	J / (kg K)
b	thermal penetration coeff.	705	735	2052	W s ^{0.5} / (m ² K)
x	heat to the track		0.51	0.74	-

p	contact pressure	300	kN / m ²
v	driving velocity	8.3	m / s
l	footprint length	0.15	m
t	contact time	0.02	s

Tire interlocks and sticks with the track up to μ_{max} . When sliding starts, friction heat is generated and thermal force limit will be reached. At the thermal force limit, total sliding and heat production within the contact zone is assumed and contact temperature reaches the melting point of snow and ice, which speeds up sliding process.

Comparison theory vs. experiment:

Measured force characteristic drops before thermal limit is reached.

Summary & Conclusion

Experiment

Laboratory tests on snow and ice: Controllable conditions for tire tests.

Track hardness: Distinctive $\mu_{\max}$ on ice and hard packed snow.

Adhesion and interlocking forces are major parts before $\mu_{\max}$ is reached under low slip.

The tire slides shortly after $\mu_{\max}$ and produces friction heat, which reduces transmittable μ .

Ambient temperature: Transmittable $\mu_{\max}$ is reduced, when temperature increases.

Friction on ice and snow heats up the surface within a thin layer and a short time.

The used high speed IR camera proved the theory.

Theory

Stationary analysis: → 1st estimation: Heat ratio to the track = f (heat transfer coeff.).

Transient analysis: → 2nd estimation: Heat ratio to the track = f (thermal penetration coeff.).

→ Temperature increase for constant heat source.

→ Thermal limit for force transmission on ice and snow.

Summary & Conclusion

Increase of transmitted force coefficient up to its maximum under very low slip
= Adhesion and Interlocking effect.

Tire starts to slide, when $\mu_{\max}$ is exceeded and produces friction heat.

Fast increase of surface temperature, when friction heat is generated.

Friction heats up body temperature within a thin layer.

On hard packed snow and ice the surface melts and a water film is produced at the thermal force limit.

Ambient temperature increase reduces transmittable $\mu_{\max}$.

Average gradient of transmittable $\mu_{\max}$ vs. temperature on ice much higher.

Measured force characteristic drops before thermal limit is reached.

Thank you for your attention!

