Influencing factors on force transmission of tires on snow tracks

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1 Abstract

Studies on the internal drum test bench at the Universität Karlsruhe (TH) under constant and controllable conditions determine performance of transmittable side force coefficients on snow tracks. Performance is higher, when tire is low loaded under high inflation pressure and driving at low ambient temperatures. Hypothesis show that the mechanical potential of force transmission depends on shear resistance of snow. If tread pattern design supports interlocking and enclosure of snow, force performance of tire increases. Analysis of heat transfer at contact zone show that force transmission close to 0°C is reduced, when friction heat generates a liquid layer of melted snow.

2 Introduction

Active safety of cars is mainly depending on transmittable forces between tire and road. Within the process of winter tire development many test series have to be performed with big efforts using winter test areas all around the world (Outdoor). At Outdoor standard test conditions, tires have to demonstrate their true performance on snow and ice under extreme conditions and new design concepts can be compared.

Outdoor tests can be performed only within natural boundaries, including snow fall and temperature change. For that reason constant and controllable winter indoor tests using an internal drum test bench (Indoor) have been developed in cooperation between Continental AG and Universität Karlsruhe (TH) [1], [2]. This test rig - optimized for snow tests – provides the opportunity to determine pure tire performance of new tire designs and influencing parameters at any time of the year independent from car interaction (e.g. suspension, vehicle control systems). All important parameters can be adjusted and their influences studied systematically.

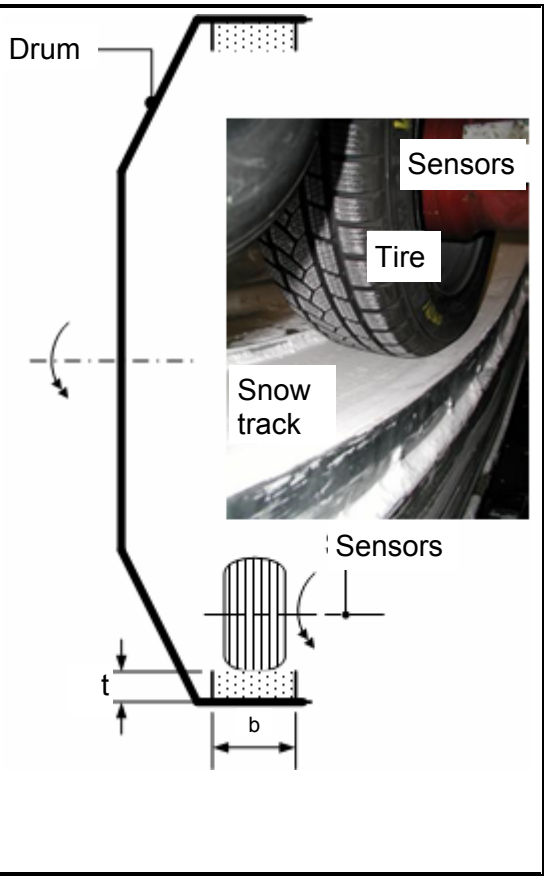
3 Indoor tests procedure

3.1 Technical specifications

At the test rig the tire is running inside a drum. For studying tire's static and dynamic characteristics, it can be driven free rolling by drum drive and for traction test additional by a wheel drive. Wheel is mounted on a special suspension, which allows change and control of camber angle, slip angle and wheel load. All 6 forces and moments are measured inside the wheel shaft and acquired and observed at the control room. Main technical data's of the test rig are shown in Table 3-1. Besides studies on snow tracks, the indoor drum test rig is used for tire performance tests on dry and wet tracks (safety walk, concrete and asphalt) and dynamic tests to develop F-Tire models. For studies on snow tracks the test rig is additionally equipped with two air conditioning systems to cool down to -20°C and track production devices like compact roller, surface cutter and snow gun.

Table 3-1: Technical data - Indoor drum test rig.

technical data	power of drum drive :	310 kW
	drum inner diameter :	3.80 m
	track surface :	safety-walk; concrete; asphalt; ice; **snow**
	max. speed :	200 km/h
	wet tracks with water depth :	0 ... 4 mm
	ambient temperature :	-20 ... +30 °C
	slip angle :	-20° ... +20°
	camber angle :	-10° ... +20°
	max. snow height t :	**80 mm**
	width of snow track b :	**270 mm**
measurement System	max. vertical, lateral, longitudinal force :	15 kN
	max. driving and overturning torque :	5500 Nm
	max. aligning moment :	1500 Nm



3.2 Standard test conditions

Inside the described test rig fresh snow is produced using a special optimized procedure. Afterwards the fresh snow is compacted by a roller. After a freezing period the snow surface

reaches a hardness of 88 – 91 CTI (measured with CTI – Penetrometer). Standard ambient temperature for snow tests is between -12 and -8°C. According to regulation ASTM 1805 track at the indoor drum can be classified as “hard pack snow”. Tire speed is 30 km/h.

3.3 Side force on snow

In this procedure the tire is free rolling under specified load and test speed on the rotating drum. Within a run-in sequence tire surface is cooled down to track surface temperature. For determination of side force characteristic, slip angle is changed periodically 2 times and reaches values of +6° and -6°. Within every force transmission on snow, snow crystals are melted, which creates closed ice. These areas are removed and track is reconditioned between every run by cutting off the used layer. Because force coefficient strongly depends on track temperature and hardness, the two sets are alternated tested and small change of conditions can be taken into account within the evaluation process. The definition of one set here is one tire under a certain condition (e.g. Fz, p). Finally an average characteristic curve for one set is evaluated out of four measurements (Fig. 3-1). Performance is rated comparing average force coefficients of both sets calculated from side and vertical forces within a slip angle range of ±(1-5°). In the shown example both sets develop ply steer force at slip angle 0°.

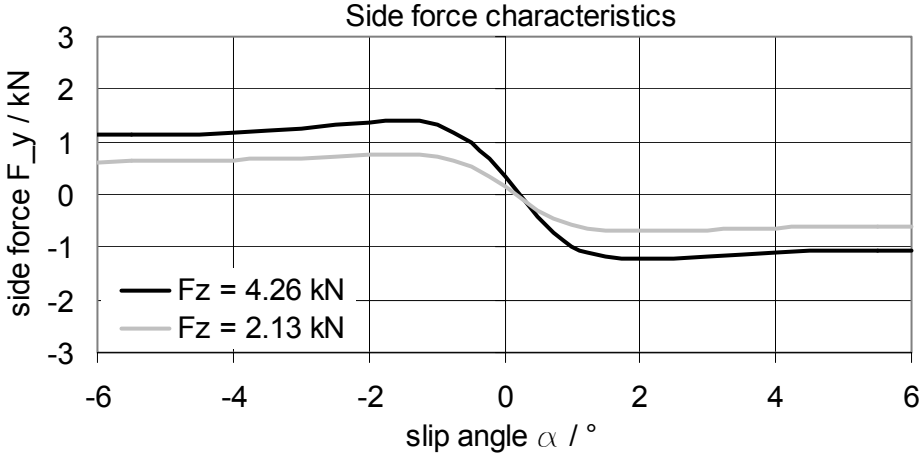


Fig. 3-1: Procedure for determination of side force characteristics of tire “Winter”.

3.4 Traction on snow

For traction tests on snow the wheel is driving the drum up to test speed using relative high load and low traction moment, so that icing of snow surface due to friction is avoided. Once test speed is reached, tire rolls with less traction force on the track in a short time period to stabilize contact temperature between tire and snow track. After this “Run-In” sequence the wheel moment is increased by changing the input for the wheel drive engine fast to a

constant level. This leads to an increase of traction force by a followed slip value. The offset of applied drive moment is chosen in that way, that tire slip reaches 40%.

Similar to determination of side force characteristics every set is tested in four runs and an average force coefficient is calculated for both sets taken values in slip range 10 to 40%. Main evaluation results are the characteristic curve (Fig. 3-2), maximum force coefficient, performance rating and statistical values (critical difference and standard deviation).

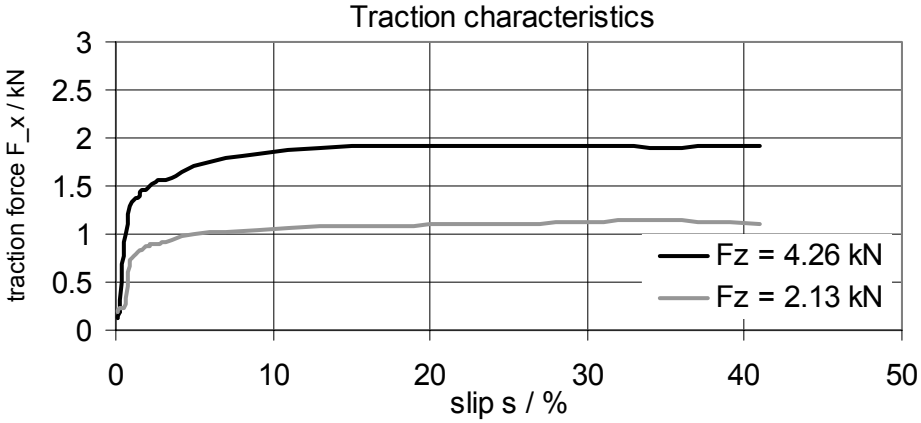


Fig. 3-2: Traction performance of tire “Winter” under 2 different loads.

3.5 Correlation

During the development of indoor traction tests, it was the main goal to achieve a high correlation to Outdoor results of Continental AG. In Fig. 3-3 results of two tire groups are shown. Within both groups, tires with different tread pattern and compound stiffness have been tested (y-axis) and compared to Outdoor results (x-axis).

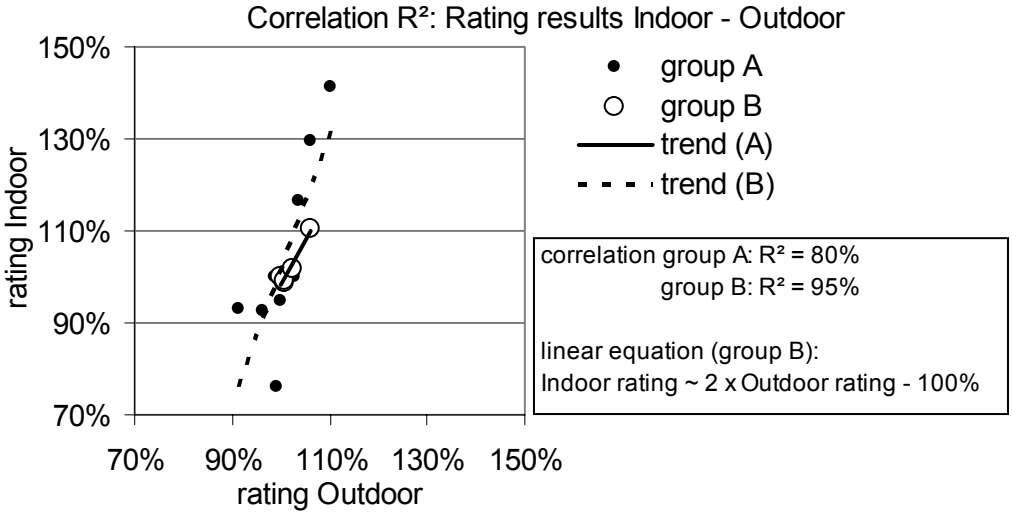


Fig. 3-3: High correlation of Outdoor and Indoor results. Higher spread of Indoor results.

For correlation analysis of group B only results with similar test conditions (mainly temperature) have been taken into account, which increased the correlation up to 95%. The diagram Fig. 3-3 shows that Indoor tests have a wider spread of rating values and therefore even small development steps can be detected. A factor of approximately 2 in a linear equation demonstrates the higher spread of Indoor results.

4 Parameter studies

4.1 Tested tires

Influences on force transmission on snow have been studied with several tires (Table 4-1). For these tires size, load index, inflation pressure and extra tire design informations about tread stiffness (shore value) and tread structure are listed. All selected tires can be found at middle class cars.

Table 4-1: Data for mainly studied tires.

Name	size	Load Index	Speed Index	ETRTO max. load	press. / bar	shore (A)	tread pattern
All Season	205/55 R16	91	H	5.4 kN	2.2	> 65	ripped, less small sipes
Winter Sport	205/55 R16	94	V	6.5 kN	2.5	60 – 65	band-shaped and many small sipes
Winter	205/55 R16	91	H	5.4 kN	2.2	60 – 65	less band-shaped, thicker sipes and many small sipes
Nordic	205/55 R16	91	Q	5.4 kN	2.2	< 60	high structured, blocks and high sipe density

4.2 Track characteristics

Outdoor tests are underlying changing track conditions. During the development of an efficient and reproducible snow track at the indoor test rig, influences of track parameters on tire performance were observed.

One important track parameter is hardness, which can be measured with the “Penetrometer”. Results of side force characteristics in Fig. 4-1 show, that at hard tracks maximum side force is more distinctive and side force at higher slip angle reaches lower values. At harder tracks less track deformation occurs, which leads to an increase of cornering stiffness. The average force coefficient is also influenced and decreases with increased track hardness. This decrease is tire dependent and has less influence for tire “All Season” with low absolute μ performance (Fig. 4-2).

For traction performance it’s even more important, on which snow conditions the tire has to work. Under same conditions concerning temperature (-7°C) and hardness (88 CTI), the tire

develops in case 1 (black curve in Fig. 4-3) high grip at high slip and in case 2 (grey curve in Fig. 4-3) the characteristic of the same tire has a distinctive maximum but with fast decreasing force coefficient at high slip. The snow layer, used in case 1, was produced with loose snow from mechanical grooming and packed to test hardness. In case 2 a snow layer with fresh produced snow was used. The difference between those two layers is the shear resistance of snow track. One time shear resistance is low (case 1), so the tire can dig into the snow. The other time shear resistance is that high (case 2), that less digging occurs and tire mainly reaches an interlocking and adhesion maximum. Both boundaries strongly depend on contact temperature and shear resistance of snow. Further Indoor tests show that traction performance similar to case 1 can be achieved on loose snow. For reproducible and efficient indoor drum tests snow tracks with high hardness and high shear resistance (case 2) are used. All parameter studies to influence on force characteristics have been performed on such tracks.

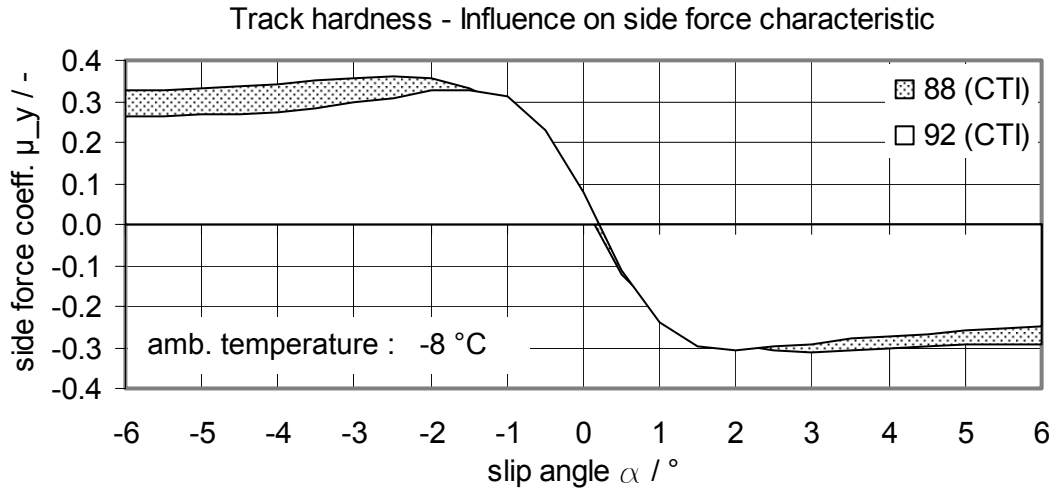


Fig. 4-1: Influence of track hardness on side force characteristics.

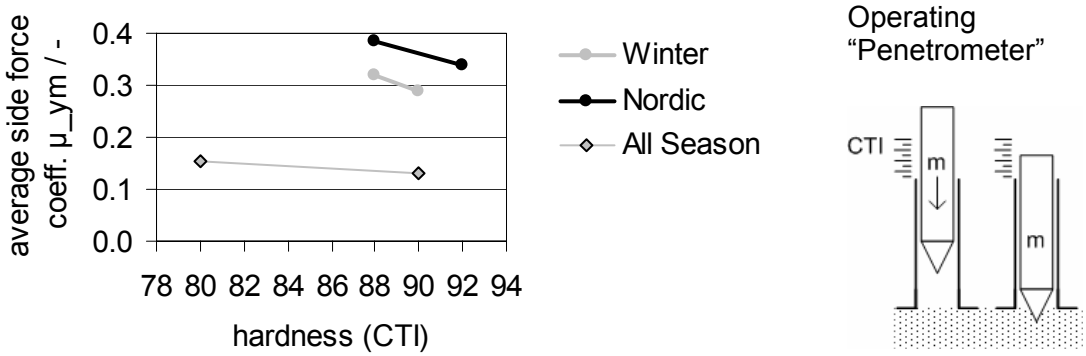


Fig. 4-2: Influence of track hardness on side force performance.

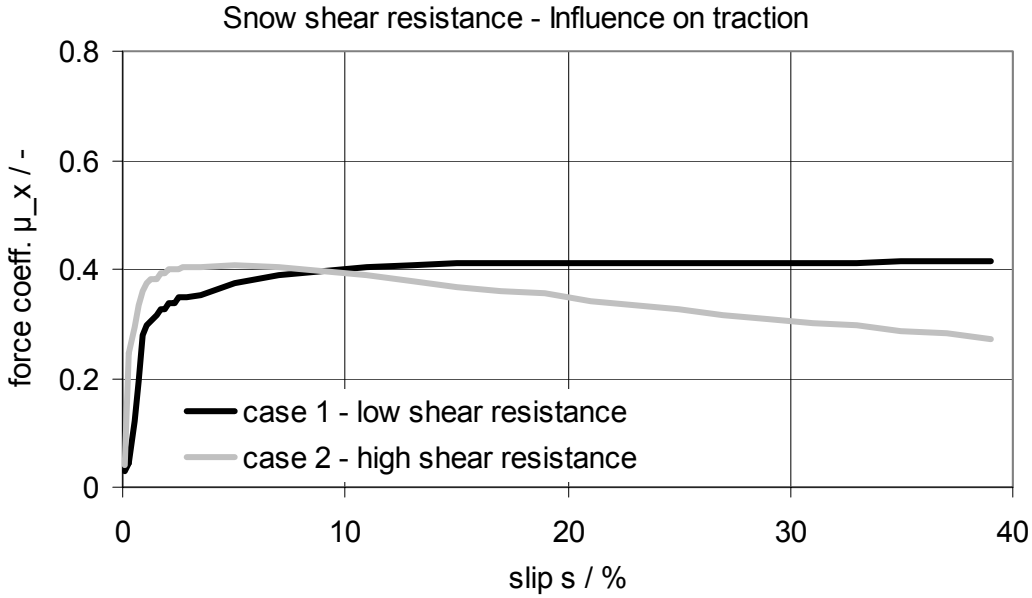


Fig. 4-3: Influence of snow shear resistance on traction force characteristic.

Since shear resistance of snow has a main effect on force transmission, the resistance force when cutting the first layer of snow track is measured. It is assumed that the measured cutting force is proportional to the shear resistance of the track. The comparison of this cutting force to results of side force performance at different track hardness's and ambient temperatures shows a high correlation of $R^2 = 90\%$ (Fig. 4-4). Compared to that, correlation between track hardness and side force performance can reach only $R^2 = 74\%$ (under same ambient temperature of -12°C). On tracks with high shear resistance, the force maximum due to transmittable interlocking forces between tire tread and snow track increase, but the transmittable traction forces at high slip decrease. Therefore cutting force is an additional parameter to characterize snow tracks.

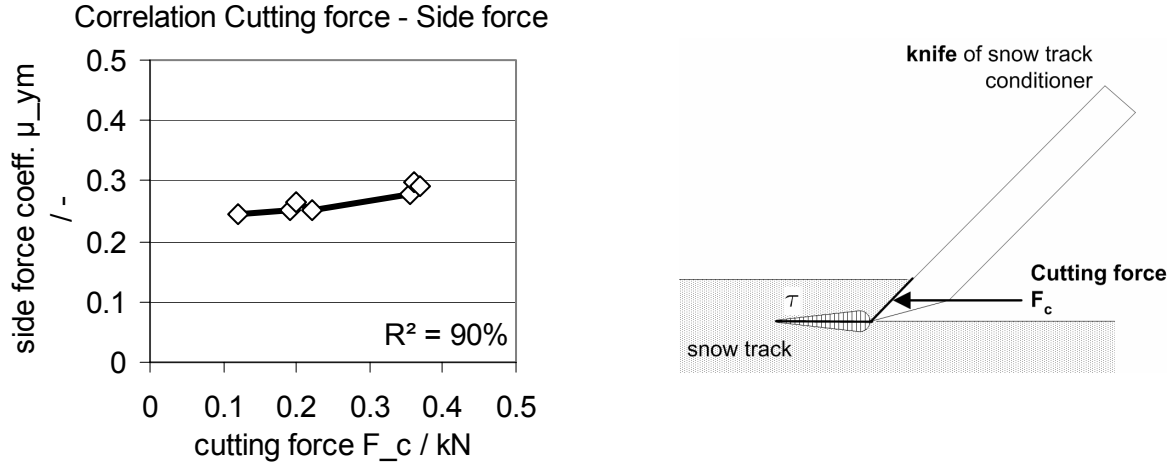


Fig. 4-4: Shear resistance measured as cutting force F_c correlates with side force performance (hardness: 88…92 CTI; amb. temperature -16…-13°C).

4.3 Ambient temperature

Temperature variations influence snow mechanics and heat transmission parameters. Laboratory experiments [3] for performance tests of skis are showing strong dependences of the snow temperature. The force coefficient of sliding polyethylene is increasing while the temperature is falling.

For tire performance similar effect can be observed (Fig. 4-5). In all studied cases force performance decreases when temperature rises. The rate of decrease is thereby strongly tire dependent.

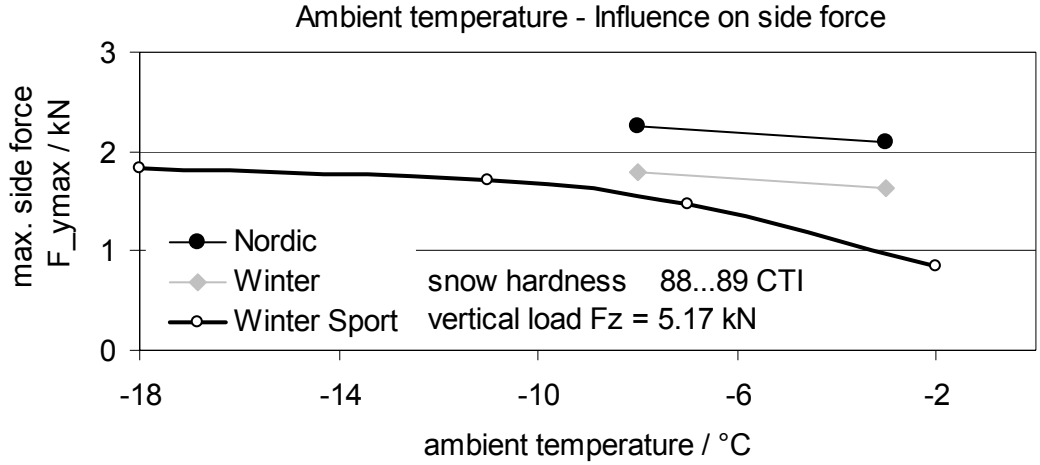


Fig. 4-5: Influence of ambient temperature on side force characteristics.

The tire type “Winter Sport” shows the most significant dependency on ambient temperature (Fig. 4-5). Under this aspect it has to be considered that the spread on the Indoor test rig is much higher than Outdoor. Therefore the temperature influence under real Outdoor condition is much lower. Side force performance of the other both tires is less effected by temperature increase.

4.4 Vertical load

Besides track parameters, tire performance depends on load and inflation pressure. Technical data sheets specify vehicle’s empty and maximum load. The resulting vertical forces of middle class cars for one tire are spreading between 2.8 kN and 5.3 kN. Vertical forces are changing with increasing side or drive acceleration and can spread even more. For that reason it’s important to know, how the vertical load influences transmittable forces.

Besides the expected increase of side force maximum and cornering stiffness, a degressive characteristic of side force maximum can be observed in Fig. 4-6. The tire “Winter” shows the highest cornering stiffness, which can be explained by an optimized solution of the target conflict between tread stiffness and winter grip under these specific conditions.

For tire performance a relative value like the force coefficient is more significant. The transmittable force coefficient μ_ymax is reduced, when increasing tire load. Experiments on dry tracks [4], [5] and of sliding forces on snow [3] have similar degressive characteristics when tire load is increased. For a stable car behaviour, it means that a heavy car can pass a curve with less driving velocity compared to a lightweight car, when both have the same tires mounted.

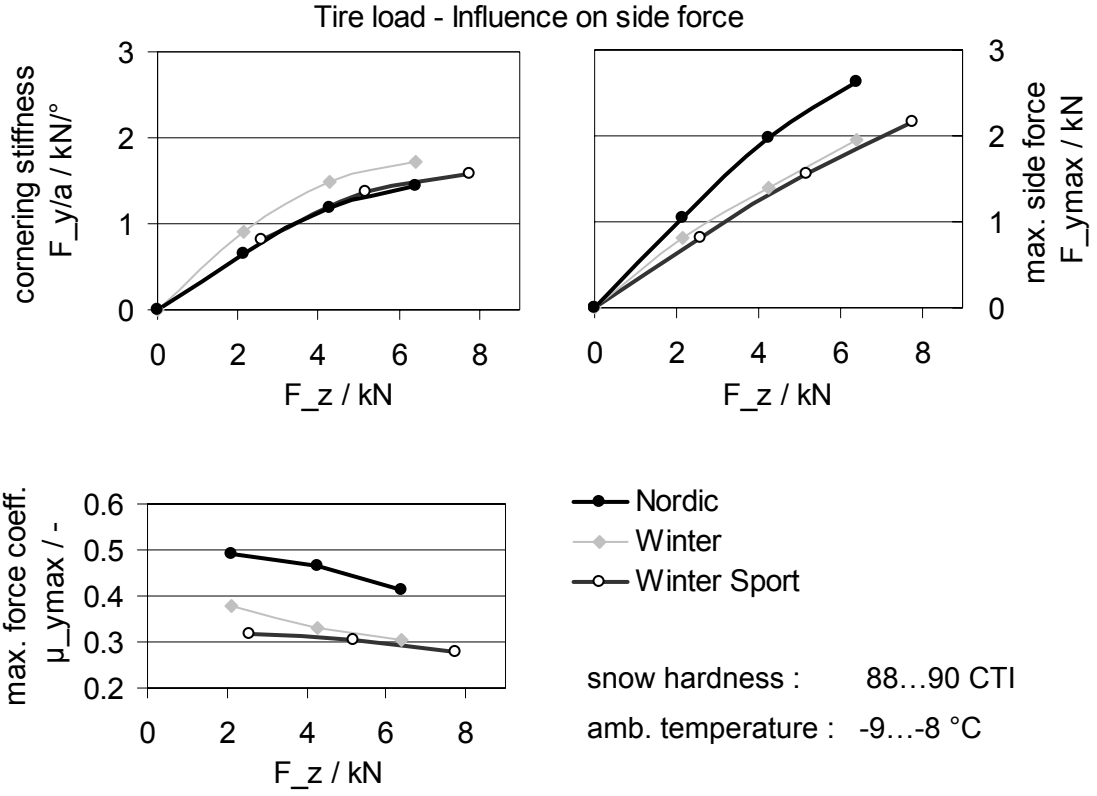


Fig. 4-6: Influence of tire load F_z on side force characteristic (cornering stiffness F_y/a, max. side force F_ymax and max. force coefficient μ_ymax).

When tire transmits side forces the tread velocity is reduced and a kind of braking situation occurs at each tire tread block. Compared to that we can find at the traction process tire tread velocity is increased and higher than driving speed. Indoor results are showing for traction force characteristics a progressive increase of force maximum in Fig. 4-7. Tire longitudinal stiffness and the traction performance (μ_xmax) increase degressive up to a limit.

The reason for that increase of force coefficient can be found in the traction optimized tread of tire “Winter Sport”, which has a lot of sipes orientated in lateral direction and interlocking with snow track increases with increased load.

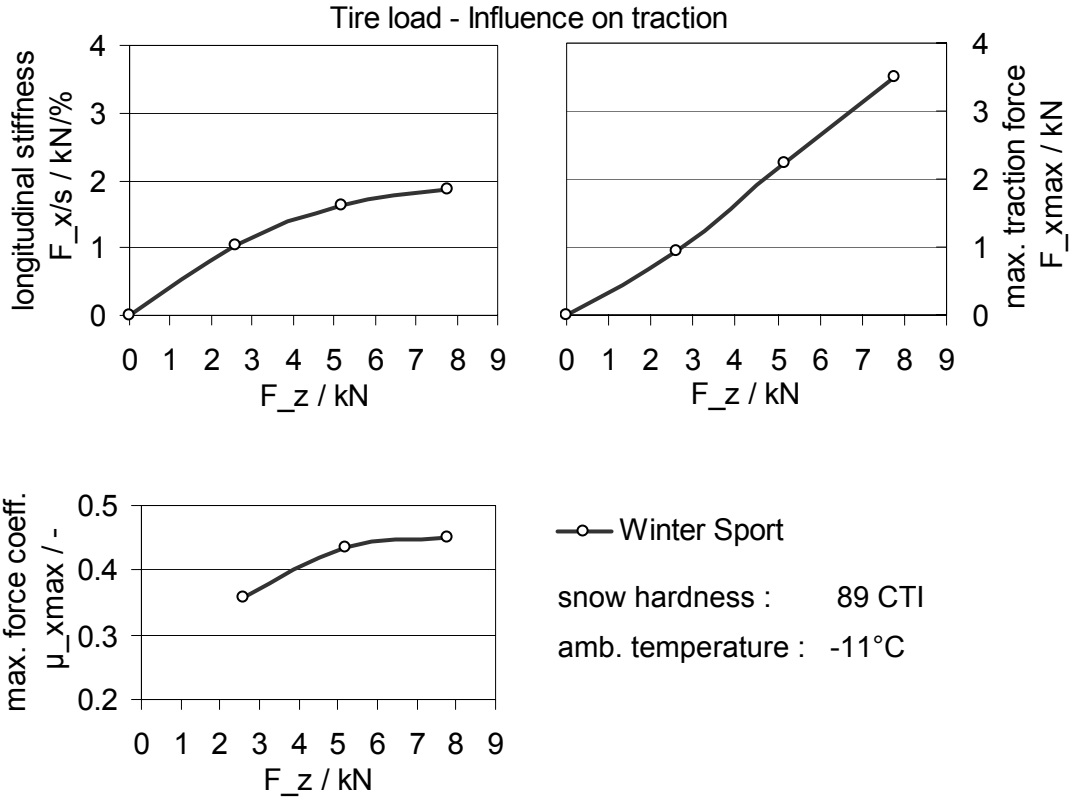


Fig. 4-7: Influence of tire load F_z on traction force characteristics (longitudinal stiffness F_x/s, max. traction force F_xmax and max. force coefficient μ_xmax).

4.5 Inflation pressure

The normal tire inflation pressure is car and load depending. Normal range is between 2 and 3 bar. It is well known from off-road situations that lower inflation pressure is used to get more grip by an increased contact zone. Studied pressure influence on hard packed snow track do not support choice of low pressure to increase performance. With high pressure values cornering stiffness is increasing (shown in Fig. 4-8). Side force and force coefficient maximum are less influenced, but also reaching higher values. Traction performance is increasing with higher inflation pressure (dashed line in Fig. 4-8). Less effect of changed tire inflation can be found for longitudinal stiffness.

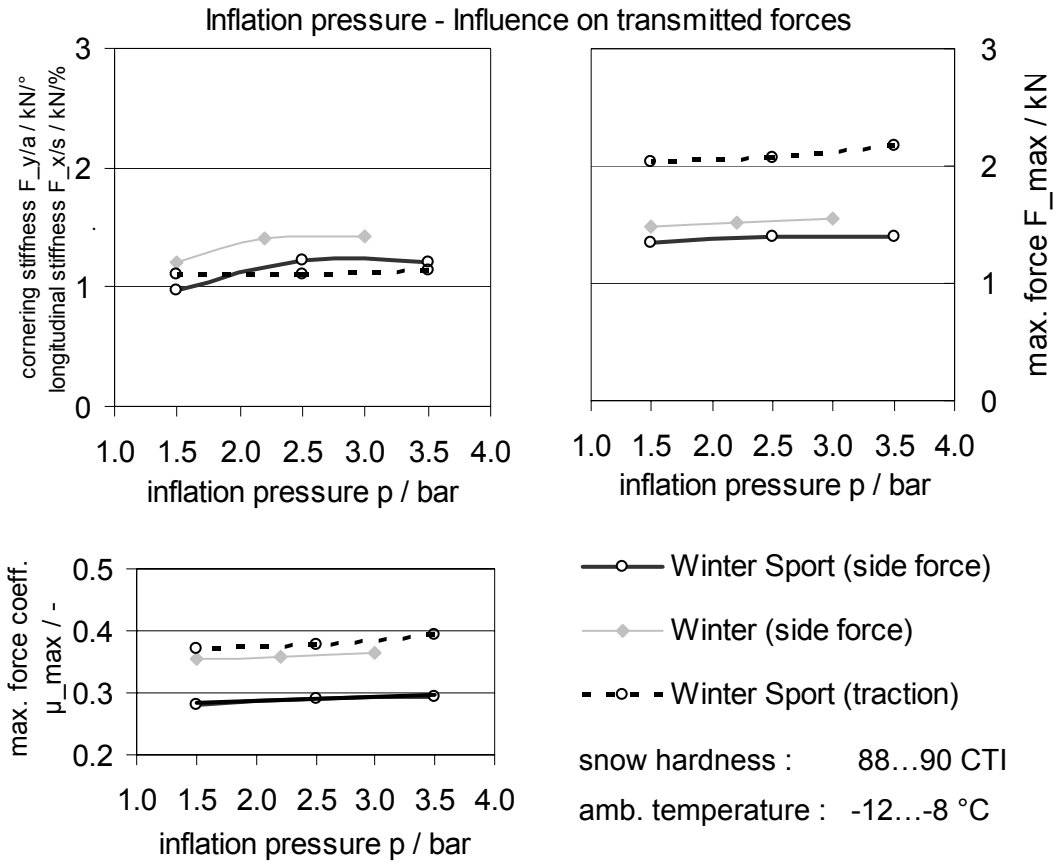


Fig. 4-8: Influence of tire inflation pressure p on force characteristic.

4.6 Comparison of influencing factors

Picking out one tire the rate of influence on the max. force coefficient can be cleared out. Fig. 4-9 shows that ambient temperature has the highest effect on side force performance, followed by load and inflation pressure (evaluated within the given range and for a max. difference).

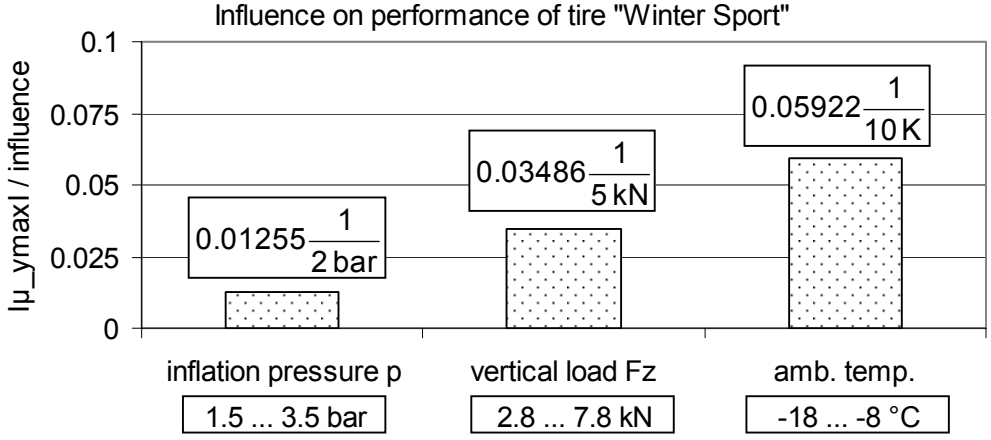


Fig. 4-9: Influence of different parameters on side force characteristics of tire „Winter Sport“.

5 Hypothesis of force transmission on snow

5.1 Force elements

The parts of force transmission have been described already by several authors [6], [7]. Based on these publications and our experiences with Indoor snow tests, 4 main mechanisms for force transmission exist.

At low slip values snow – rubber adhesion and interlocking force (Fig. 5-1) between snow and tread exist. The transmittable interlocking force is depending on the tread pattern and on the shear resistance of the snow track, which can be measured as cutting force (see chapter 4.2).

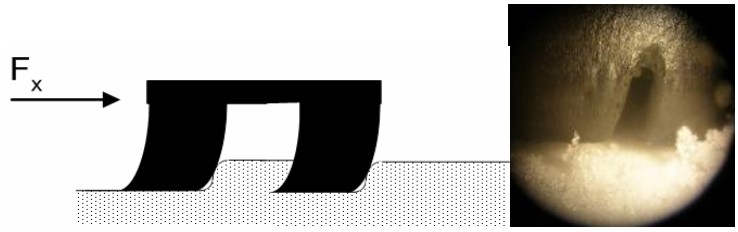


Fig. 5-1: Interlocking force tire tread – snow.

Force transmission at high slip values uses 3 mechanisms on snow depending on mechanical track properties and ambient temperature. If the shear resistance of the snow surface is very high (e.g. on high compacted snow tracks) tire forces reach the interlocking maximum and start to slide very fast. Traction force then drops to low μ values (grey curve in Fig. 4-3). Friction heat is generated, which increases drop of transmittable forces due to the liquid layer.



Fig. 5-2: Friction – Sliding of rubber at snow produces friction heat.

The generated friction heat leads to an increase of contact temperature. The contact temperature is not only depending on the amount of friction heat resulting from transmitted force F_x and sliding velocity. Temperature is also depending on heat loss over snow layer, shaved snow, compacted snow and tire tread. If a snow layer or shaved snow exist, heat loss over these parts can be high, therefore tire force reaches high μ under high slip. Melting of snow is reduced and tire tread can dig into snow. Force transmission at this state is mainly depending on properties of shaved snow material and uses forces within the snow (snow / snow friction) and between rubber and snow (sliding friction) (Fig. 5-3).

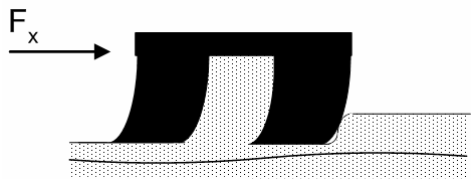
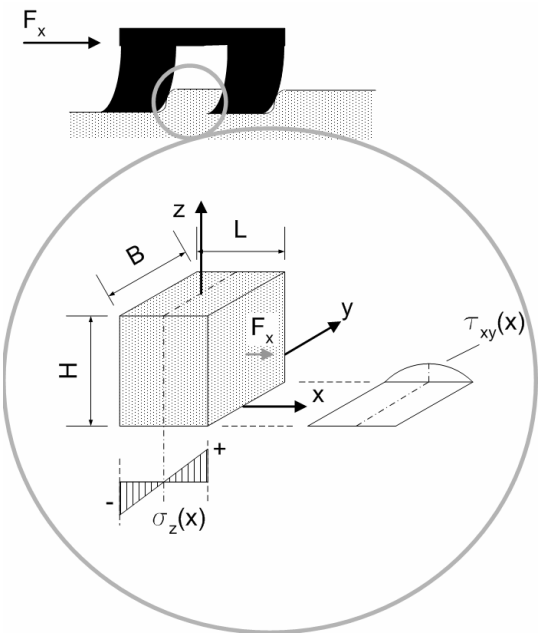


Fig. 5-3: Sliding force between rubber and snow as well as snow / snow friction between gripped snow and snow track.

5.2 Physical Model – Interlocking

Tire tread is pressing into snow surface and transmits one part of force stressing the enclosed snow block. Bending and shear stress occurs within the snow block and can be described with equation given in Fig. 5-4. Assuming force is applied at the middle of the enclosed snow block, we get a max. bending stress at the outer surface of the enclosed snow block. With increasing of length L the occurring bending stress decreases more than shear stress. Since block height H is limited at hard tracks and bending stress is highly reduced by the length L, the main load is the shear, which has to be transmitted by the snow block and finally leads to a break of enclosed snow block. Shear resistance of snow or its cohesion carry these stresses. Snow cohesion under no normal load reaches values between 1 to 1000 kN/m² [8] depending on density. When normal stress compacts the snow block (e.g. in case of filled sipes) even higher shear resistance can be reached [7]. The traction characteristic show in Fig. 5-5 a high dependence to the enclosed area for a analyzed tire group with same tread compound stiffness.



Bending stress:

$$|\sigma_z(x)| = \frac{M_b}{I_y} \cdot x$$

$$\left|\sigma_{z_max}\left(x = \frac{L}{2}\right)\right| = 3 \cdot F_x \cdot \frac{H}{B \cdot L^2}$$

$$\lim_{L \to oo} \sigma_{z_max} = 0$$

Shear stress:

$$\tau_{xy_max}(x) = \frac{3}{2} \cdot \frac{F_x}{B \cdot L} \cdot \left[1 - \left(\frac{x}{B/2}\right)^2\right]$$

$$\tau_{xy_max}(x = 0) = \frac{3}{2} \cdot \frac{F_x}{B \cdot L}$$

Fig. 5-4: Stress analysis at enclosed snow block.

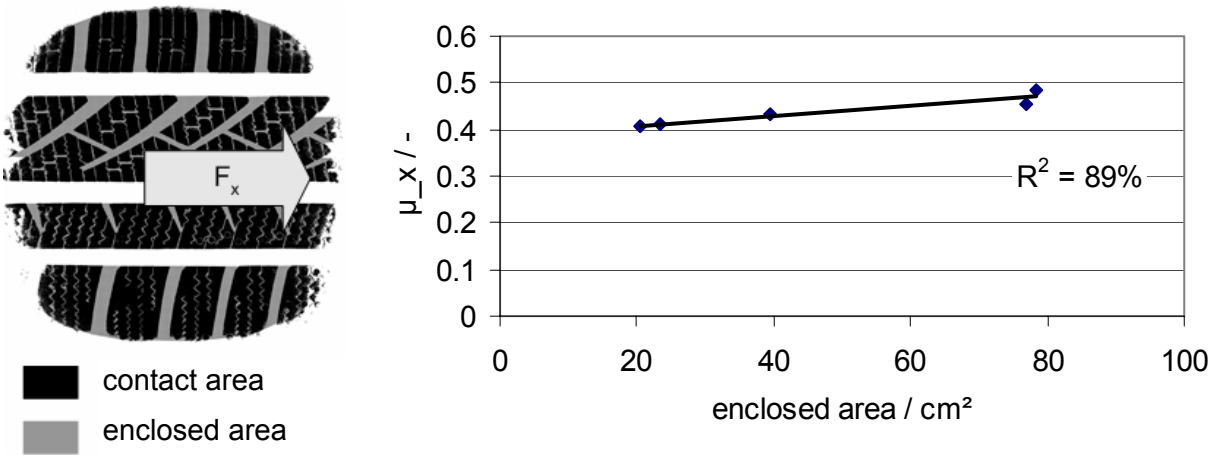


Fig. 5-5: High correlation of enclosed area with measured traction force coefficients.

5.3 Determination of contact temperature

One boundary of force transmission on snow is given by snow mechanic parameters. As results in Fig. 4-5 illustrate another boundary is ambient temperature, which influences contact temperature. Since heat transfer coefficient of snow and rubber is very low (Table 5-1), the contact temperature on snow surface can rise to 0°C during transmission of friction force and melts snow crystals to a thin liquid layer, which is refreezing to small local ice areas. Heat transfer has been studied using a simple model. In this model the tire foot print is a simplified rubber block, which slides at the snow surface and produces friction heat within the contact zone.

Table 5-1: List of heat transfer coefficients.

tire compound λ_R	0.245 W / (m K) – nordic compound (0.2…0.3 W / (m K)
snow λ_S	0.46 W / (m K) (0.1…1 W/ (m K) increase with higher density [8]
ice λ_I	2.3 W / (m K), [9]
steel λ_{St}	14…58 W / (m K), [9]

Heat loss increases, contact temperature reduces.

The effective contact time when observing one certain point of the snow surface and the sliding rubber is given by driving velocity and footprint length. During this time friction heat is transmitted to the snow surface. The transmittable friction heat flow density can be described in dependence of heat transfer coefficient, contact time and specific heat. The generated friction heat density is calculated from transmitted force (side or traction force), slip velocity and contact area (footprint). Assuming that all heat flows to the snow, transmittable and generated friction heat density are equal and a thermic boundary as function μ(s) can be

determined. At this thermic boundary (Fig. 5-6) contact temperature reaches 0°C and a liquid layer is generated, which causes low μ values.

For two cases the boundaries have been calculated as shown in Fig. 5-6 and compared to the side force results. For the analyzed tire the footprint was that small, that all friction heat have been transmitted over a small area and the contact temperature rises to 0°C. Maximum side forces are limited by thermic boundaries. Compared to the characteristic μ(s) at -11°C, where the friction coefficient beyond the maximum is dropping, the friction coefficient at -3°C reach not such a high maximum and stays on a low level. At a contact temperature of 0°C the generated heat energy leads to a “phase” change from snow to water.

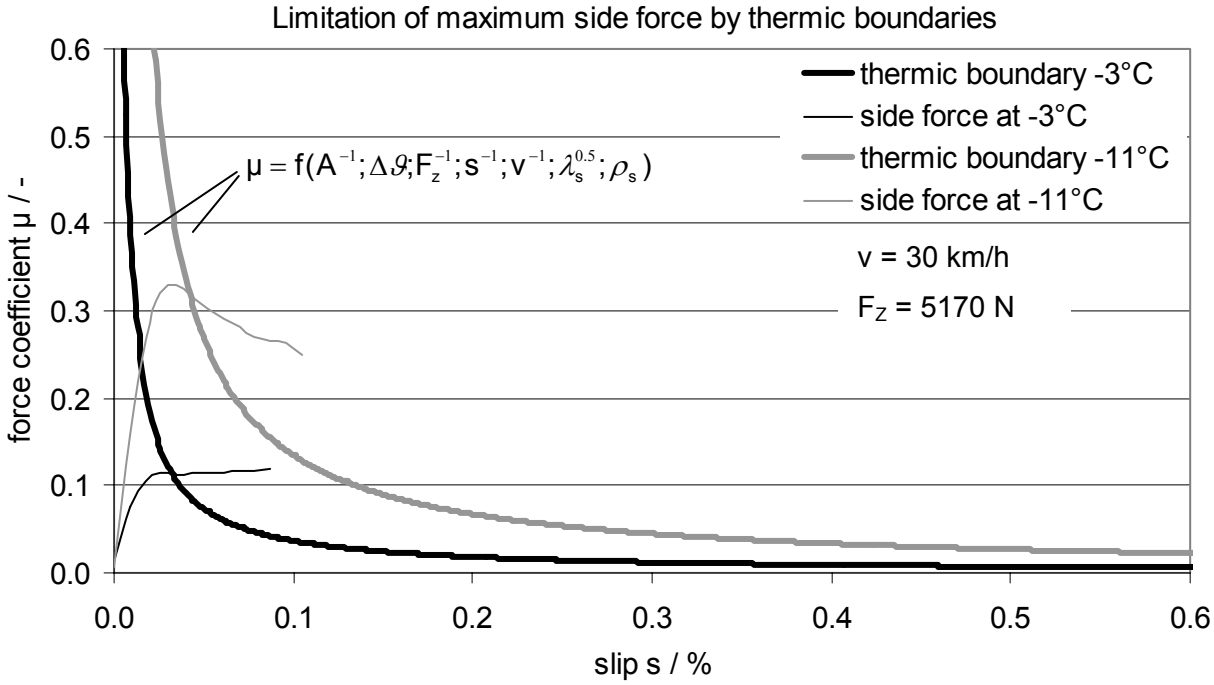


Fig. 5-6: Side force maximum reaching thermic boundary value.

6 Conclusion

Indoor test procedures for measurement of side force and traction force characteristic on snow tracks have been developed at the internal drum test bench of Universität Karlsruhe (TH). Results of the Indoor test procedure have a high correlation to Outdoor results. The performed studies of influencing factors of force transmission on hard packed snow tracks show that tires generate higher force coefficient with increasing inflation pressure and decreasing load. The influence of track characteristics is very high. The results show that transmittable forces are increasing with decreasing ambient temperatures. The physical analysis of heat transfer in the contact zone shows that maximum forces are generally limited

by thermic boundary values. On hard snow tracks a tire characteristic with distinctive side force maximum exists. Additionally to track hardness the shear resistance of the snow track is an important parameter. Traction performance is highly influenced by shear resistance of snow. If shear resistance is low, tire can dig into the snow and transmit high traction forces at high slip. On the other hand a high interlocking force maximum can be reached at snow tracks with high shear resistance and therefore side force performances increases. The stress analysis of an enclosed snow block supports the theory that shear resistance is the main mechanical property of a snow track. Tire tread designs with a high amount of enclosed snow blocks (e.g. sipes) are developing higher force performance.

7 Literature

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