

Experimental Investigation of the Tractive Performance of Pneumatic Tires on Ice

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ABSTRACT: This investigation was motivated by the need for performance improvement of pneumatic tires in icy conditions. Under normal operation, the pneumatic tire is the only force-transmitting component between the terrain and the vehicle. Therefore, it is critical to grasp the understanding of the contact mechanics at the contact patch under various surfaces and operating conditions. This article aims to enhance the understanding of the tire-ice contact interaction through experimental studies of pneumatic tires traversing over smooth ice. An experimental design has been formulated that provides insight into the effect of operational parameters, specifically general tire tread type, slip ratio, normal load, inflation pressure, ice surface temperature, and traction performance. The temperature distribution in the contact patch is recorded using a novel method based on thermocouples embedded in the contact patch. The drawbar pull is also measured at different conditions of normal load, inflation pressure, and ice temperatures. The measurements were conducted using the Terramechanics Rig at the Advanced Vehicle Dynamics Laboratory. This indoor single-wheel equipment allows repeatable testing under well-controlled conditions. The data measured indicates that, with the appropriate tread design, the wheel is able to provide a higher drawbar pull on smooth ice. With an increase in ice surface temperature, a wet film is observed, which ultimately leads to a significant decrease in traction performance.

KEY WORDS: tire-ice interface, contact patch, traction on ice, drawbar pull, temperature, friction

Introduction

The purpose of this article is to enhance the understanding of the tire-ice contact interaction at the contact patch through experimental studies for pneumatic tires traversing over smooth ice. The outcome of the work conducted is divided into several sections, detailing the experiment and the correlation of some of its results. First, a literature review of the topic under investigation will be summarized. Next, the experimental methodology will be explained. This includes a design of experiment matrix highlighting all testing levels, the apparatus used for testing, and the preparation of the ice surface prior to the beginning of each test. Next, the results followed by a brief discussion will be

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presented, including temperature measurements at the contact patch during direct contact with the ice. The results for different scenarios are presented to illustrate the effects of the specific parameters investigated on the tire performance. Finally, the conclusion section highlights the major findings of this study.

Background

The interaction between tire and ice is a highly complex phenomenon that has a direct influence on the overall performance of the pneumatic tire. From tire-terrain interaction dynamics, it is evident that icy road conditions and tire operational parameters play a vital role in determining the overall performance of the vehicle, including the drawbar pull. The friction at the tire-ice contact varies, as it is dependent on the ice surface conditions. The main factors of ice parameters that directly influence the amount of friction available at the tire-ice interface are the following [1]:

1. The ambient and ice surface temperatures
2. The effect of the ice surface growth rate and track age
3. The effect of impurities in the ice surface
4. The effect of the ice surface texture

The ambient and the ice temperatures are two of the most difficult variables to control to ensure consistent testing conditions. In most cases, the lowest ambient and ice surface temperatures resulted in the highest levels of friction, as the low temperatures promote bonding between the tire and ice surfaces. This was investigated by Giessler et al. [1] and Roberts [2]. Giessler et al. [1] studied the effects of friction transmissibility at various ice and ambient temperatures, while Roberts [2] performed studies regarding the friction generation and bonding at the contact interface.

Roberts [2] also investigated the influence of the age of the ice track and its effect on the available friction. The investigation determined that as the track ages, the ionic impurities that are created with time eventually break down the top layer of the ice [2]. As the impurities accumulate, the layer of the ice weakens because of the lack of bonds being formed in the micro-surface of the ice. This weakening of the ice surface leads to a reduction in the available friction [2], which has a direct effect on the temperature rise in the contact patch during operation. The effect of the ice surface growth rate was investigated by Shimizu et al. [3]. In this study, it was found that the size of the crystals in the ice is influenced by the growth rate of the ice surface. The size of the crystals determines the texture of the ice, which has a direct effect on the tire's longitudinal characteristics.

The mechanical properties of ice (i.e., the capacity of ice to resist the influences of external forces) change considerably depending on temperature. The closer the temperature of the ice is to the melting point, the more dominant are the effects of the plastic properties of the ice and the lower its overall strength [3]. This phenomenon is explained by the weakening of the cohesion of the ice molecules in the lattice of the crystals. On the other hand, the lower the temperature is, the more difficult it is for the bonds of the hydrogen and oxygen atoms to become rearranged in the space lattice. This results in the elastic and brittle properties of ice becoming more apparent.

Although the temperature of the ice surface is critical in determining how the tire will perform on ice, the rise in temperature in the contact patch due to normal tire operations has a more dominant effect on the tractive performance. The temperature distribution in the contact patch needs to be established to properly characterize a pneumatic tire, since thermomechanical properties of rubber materials are strongly dependent on temperature [4]. The temperature rise at the contact patch is due to various factors influencing the tire during operation. A large fraction of the total work done in rolling tires under normal operation conditions is made up of hysteresis. This deformation of the tire causes heat to be distributed throughout the tire, where most of the heat generation is found to be located near the tread of the tire [5]. To acquire sufficient temperature information in a rolling tire, a new wireless temperature measurement system was set up for this study.

Experimental methods are common methods of investigation for evaluating tractive performance. The experiments are usually a result of a direct evaluation conducted in the field [6]. Therefore, the data collected are valid only for the particular terrain, and it is hard to extrapolate to other types of terrain. Furthermore, such results are dependent on the tire tested, and this also makes extrapolating the results to other types of tires difficult. There are relatively few studies that investigate experimentally the effect of the temperature distribution at the contact patch with an imposed slip and under various steering configurations [6].

Motivation

The investigation is motivated by the need for improvement in tire performance in icy conditions. From 1995 to 2005, there were 193 899 crashes due to adverse weather and pavement conditions directly related to ice in the United States. The average accident data [7] presented that 34% of those resulted in injuries to a person. To traverse over icy terrain, which has a low level of friction, vehicles need specific characteristics that promote traction. This includes proper brake applications, increased friction at the contact patch to provide better traction, and the ability of the tire to minimize the temperature increase at the contact patch to reduce the presence of water at the contact interface. Therefore, it is imperative to fully characterize the pneumatic tire in

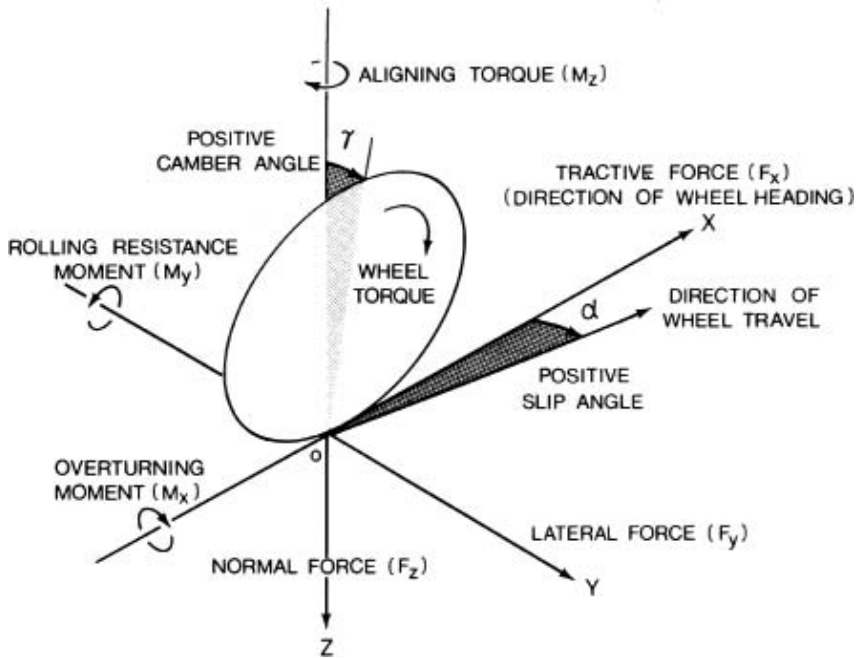


FIG. 1 — Axis system of a tire according to SAE J670e and SAE J2047. Adapted from [8] under fair use.

such conditions to provide improvements to the tire regarding its safety and performance on ice.

Experimental Methodology

An experimental investigation of pneumatic tires on smooth ice was conducted to enhance the understanding of the tire-ice contact interaction. An experimental design was formulated that provides insight into the effect of operational parameters, namely, tread type, wheel slip, toe angle, camber angle, normal load, inflation pressure, ice surface temperature, and traction performance. The coordinate system used in this investigation is shown in Fig. 1. For this experimental study, an indoor testing facility was used to investigate the performance of pneumatic tires on ice.

Test Parameters and Variables

To investigate the various pneumatic tires, two experimental designs were prepared to capture the tires' performances under various controlled operating conditions. The two candidate tires for the first investigation were the 225/



FIG. 2 — Tread design of candidate tires used for the study.

60R16 97S Uniroyal (Michelin) Standard Reference Test Tire (SRTT; tire A) and a 235/55R19 asymmetrical tire (tire B). The second investigation consisted of a new SRTT (tire C), a 215/60R16 asymmetrical winter tire (tire D), and a 215/60R16 directional all-season tire (tire E). The tread designs are shown in Fig. 2.

The effects of camber and toe on solid ice were investigated using interchangeable toe and camber rods of various lengths on the Terramechanics Rig at the Advanced Vehicle Dynamics Laboratory (AVDL) at Virginia Tech [9]. Three levels of camber angles were chosen to be investigated: nominal value 0° , as well as $+2^\circ$ and -2° . Three levels of toe angles were also chosen: nominal value 0 , $+2$, and -2° . Three inflation pressures were investigated as 60, 80, and 100% of the maximum inflation pressure for the respective tire. The

TABLE 1 — *Design of experiment for first investigation.*

Test condition	Number of levels	Level 1	Level 2	Level 3	Level 4
Tire type	2	Tire A (symmetrical)	Tire B (asymmetrical)		
Camber angle	3	0°	2°	−2°	
Toe angle	3	0°	2°	−2°	
Normal load	3	60% LI	100% LI	120% LI	
Inflation pressure (% of rated max)	3	60%	80%	100%	
Ice surface temperature	2	−3 °C	−10 °C		
Slip ratio	8	0% 20%	5% 25%	10% 30%	15% 40%

normal load applied was 60, 100, and 120% of the load index (LI), using an active normal load control on the Terramechanics Rig developed by Naranjo [10]. The LI is a number assigned to a tire to identify the tire’s ability to carry a load. The higher the LI, the greater the load carrying capacity. Tire B was rated at 105 with a speed rating of V, tire D was rated at 99 and H, and tire E was rated at 94 and T, respectively.

The design of the experiment matrix including all test conditions is presented in Table 1 for the first investigation. The parameters varied for the second investigation and can be found in Table 2. For the first investigation, the main purpose of the study was to record temperature measurements at the contact interface as well as to gather tractive measurements. The second investigation focused on the effects of the tread pattern design. The ice surface temperature was maintained at either −3 or −10 °C using a thermocouple to measure the ice surface temperature for both sets of experiments. The ambient temperature in the laboratory was maintained between 9 and 12 °C, while the humidity was typically between 30 and 40% for all of the conditions tested. One

TABLE 2 — *Design of experiment for second investigation.*

Test condition	Number of levels	Level 1	Level 2	Level 3	Level 4
Tire type	3	Tire C (symmetrical)	Tire D (asymmetrical)	Tire E (directional)	
Camber angle	1	0°			
Toe angle	1	0°			
Normal load	2	4 kN	100% LI		
Inflation pressure (% of rated max)	2	80%	100%		
Ice surface temperature	2	−3 °C	−10 °C		
Slip ratio	8	0% 12%	2% 15%	4% 20%	8% 30%

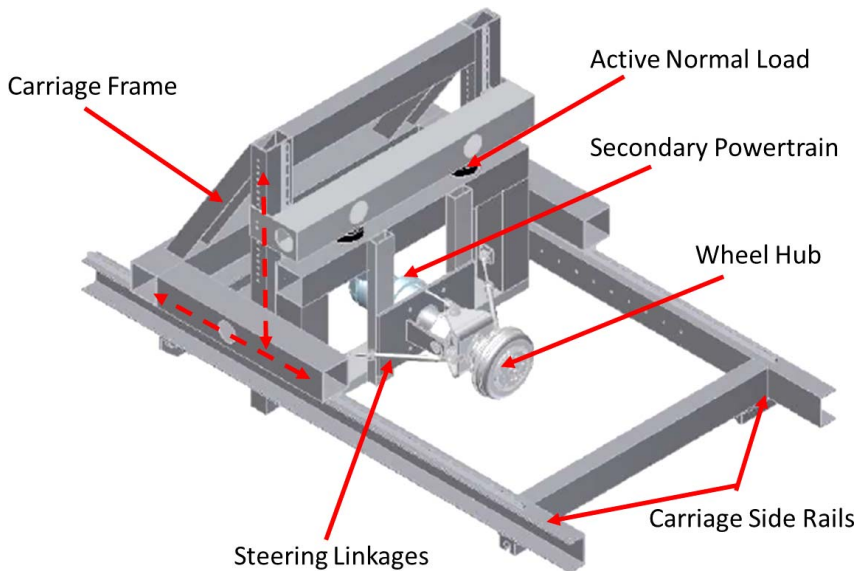


FIG. 3 — *Terramechanics Rig at AVDL with water on top of solid ice.*

run consisted of a tire traveling a straight line for 120 seconds. During these 120 seconds, two different slip ratios were tested and held for a constant 60 seconds each to ensure that the steady-state conditions were reached. After comparing the results for three runs and ensuring minimal differences between the runs, the drawbar pulls from the three runs were averaged. In general, the largest standard deviation observed from the normalized drawbar pull was 0.06. Once all of the conditions were tested for one tire, the next tire was mounted for testing.

Test Equipment

The investigation was conducted on the Terramechanics Rig at the AVDL at Virginia Tech. Figures 3 and 4 show the Terramechanics Rig as a model and before/after ice preparation, respectively. The single wheel tester was mainly designed and fabricated by Biggans et al. [9]. Interchangeable rods of various lengths allow the tire to be set at various toe and camber angles prior to beginning each run, thus simulating steering maneuvers. The Terramechanics Rig has been shown to provide repeatable results under various operating conditions that can be defined by the user.

With the opportunities to test on various terrains, the unique rig allows the tire performance to be measured under various operating conditions. The rig uses two separate motors to control the angular rotation of the wheel and the longitudinal velocity of the carriage assembly, thus allowing the user to impose a controlled slip at the contact patch. The speed of the carriage was set to 7 cm/s

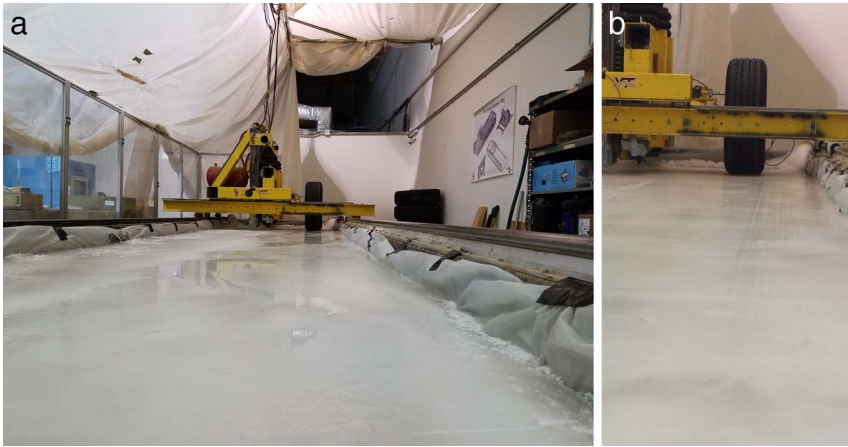


FIG. 4 — *Terramechanics Rig at AVDL with water on top of solid ice.*

for this study. The carriage assembly contains two pneumatic springs and a flow control valve that allows control of the normal load at the wheel center.

The normal load on the tire is controlled using the active normal load control system developed by Naranjo [10] at the AVDL. The system is a closed-loop proportional-integral-derivative control system consisting of a rapid pneumatic flow control valve. While the forces and moments at the contact patch are collected via a KISTLER P650 force hub, the pneumatic flow control valve regulates the amount of air in the pneumatic springs to control the normal load.

The ice was formed on top of foam insulation boards, which were placed in the Terramechanics Rig on a steel rigid surface. Custom tubing made out of linear low-density polyethylene material was laid out the entire length of the test bed. Using an external compressor and five thermocouples to record the ice surface temperature throughout the travel length, the system was preset to a specified temperature, and coolant was pumped through the tubes until the preset temperature was reached. Once the temperature stabilized at the preset value, the system powered off and operated only if the temperature moved away from the preset value. Once the system was initiated and allowed sufficient time for the pump to warm up, water was sprayed at a low rate through a garden hose connected to a tap. Once the water froze, another layer of water was sprayed on top of the ice. This was repeated at regular intervals until the desired ice thickness of 127 mm was reached.

The 825a American Slip Meter, as seen in Fig. 5, was used to measure the static coefficient of friction of the ice after it had been conditioned. This was necessary to ensure that the conditions of the ice surface were consistent and the



FIG. 5 — Static coefficient of friction of the pressure pad measuring system that mimics the smooth ice surface used for traction measurement.

same as the others by measuring and evaluating the static coefficient of friction at the surface.

To match real-world scenarios, the tire was also cooled down from room temperature to the same temperature as the ice surface. This was done by placing the tire in a Thermotron Chamber, which is a temperature chamber that can be controlled to a constant temperature well below freezing. The tire was placed in the chamber, and the bulk temperature was periodically measured using an infrared thermometer until the tire reached the desired temperature before each test trial.

Tire Instrumentation

To record the bulk temperature distribution at the contact interface, thermocouples were instrumented in between the tread blocks. The positioning of the thermocouples allows for the temperature distribution in between the tread blocks to be measured. With the temperature measurement, it is possible to determine the conductive heat transfer at the middle of a tread block. This is possible due to Fourier's Law of Conduction and because the exact locations of the thermocouples relative to the contact patch are known.

The thermocouples were calibrated by simply placing one of the metal junctions in a medium of a known temperature and the other metal junction on the object of interest. The voltage change can be measured and used in a calibration equation to precisely calculate the temperature of an object. The

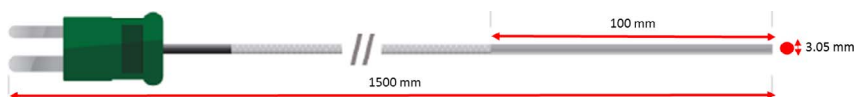


FIG. 6 — Dimensions of the K-type thermocouples used for the investigation.

thermocouples used were of K-type, with a resolution of $0.1\text{ }^{\circ}\text{C}$, where their individual dimensions are shown in Fig. 6.

The thermocouples were inserted as shown in Fig. 7, and 100% silicone was used to adhere the thermocouples to the tire. To ensure that the thermocouples made direct contact with the ice surface, the tips of the thermocouples were exposed to the contact surface. The main challenge in the instrumentation of pneumatic tires is in the transmission of data between the measurement device and the logger during tire operation. To account for the transmission of data, four wireless data loggers were attached to the sidewall of the tire. The temperature was measured at each point where the thermocouples were placed, as indicated. Figure 8 represents the exact locations of the measurements. Note that thermocouples 2 and 7 have been inverted to capture the temperature at the middle of the contact patch.

Test Preparation

To maintain a consistent testing environment and reduce the variation in tire conditions, a repeatable ice-surfacing procedure must be followed before the start of each test. The first step was to remove all the debris left behind on the ice surface using a metal scraper, as shown in Fig. 9. Scraping was done in the lateral direction for the entire path of the wheel, which created a testing surface of $0.91\text{ m} \times 4.89\text{ m}$. This step also created a smooth surface as it cleared out the asperities present after the water freezes. The second step consisted of cleaning the surface using a squeegee, as shown in Fig. 9. This process removed all ice and tread particles off the test track. This step also removed any water that was present. After the ice surface was prepared, it was tested at various locations using an American Slip Meter. The average coefficient of friction was between 0.14 and 0.16 for all of the tests conducted.

The tires were also conditioned before each test. Before each test, the tire was completely dried, and any debris was removed from the tread. Afterward, the tires were cooled to the same temperature as the ice surface using the Thermotron Chamber. In addition to conditioning the tire prior to each test, all of the tires used during this study were mounted on the same car and used under normal operating conditions for a period of 160 km at highway speeds. This was done to remove lubricants or oils that may have been left behind on the tire during manufacturing.

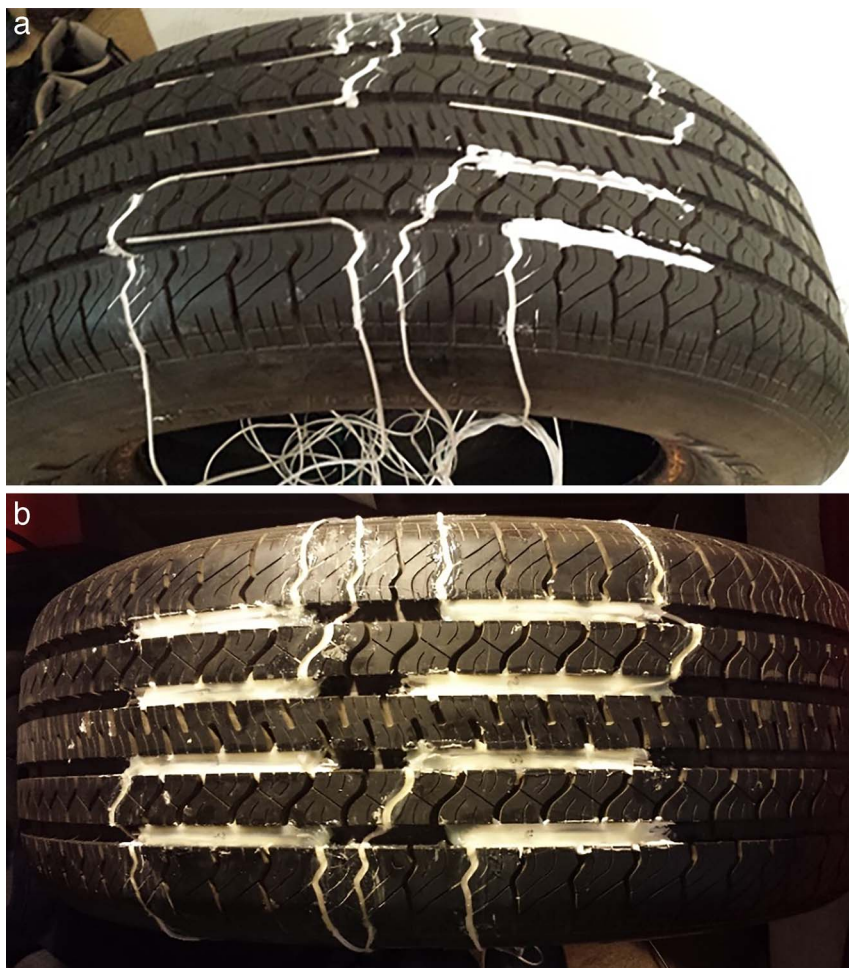


FIG. 7 — Instrumentation of the standard reference test tire (SRTT).

Results

Drawbar Pull

The drawbar pull is defined as the difference between the longitudinal thrust developed at the tire-ice interface and the resistive forces acting on the tire. Resistive forces include, but are not limited to, frictional properties of the terrain and resistive forces present in the testing facility. The difference in the slip ratio where the maximum drawbar pull occurs could be helpful in assessing the impact of the adhesion and of the sliding portion of the contact patch on the tractive capability of the tire, as shown in Fig. 10. It is hypothesized that, as the

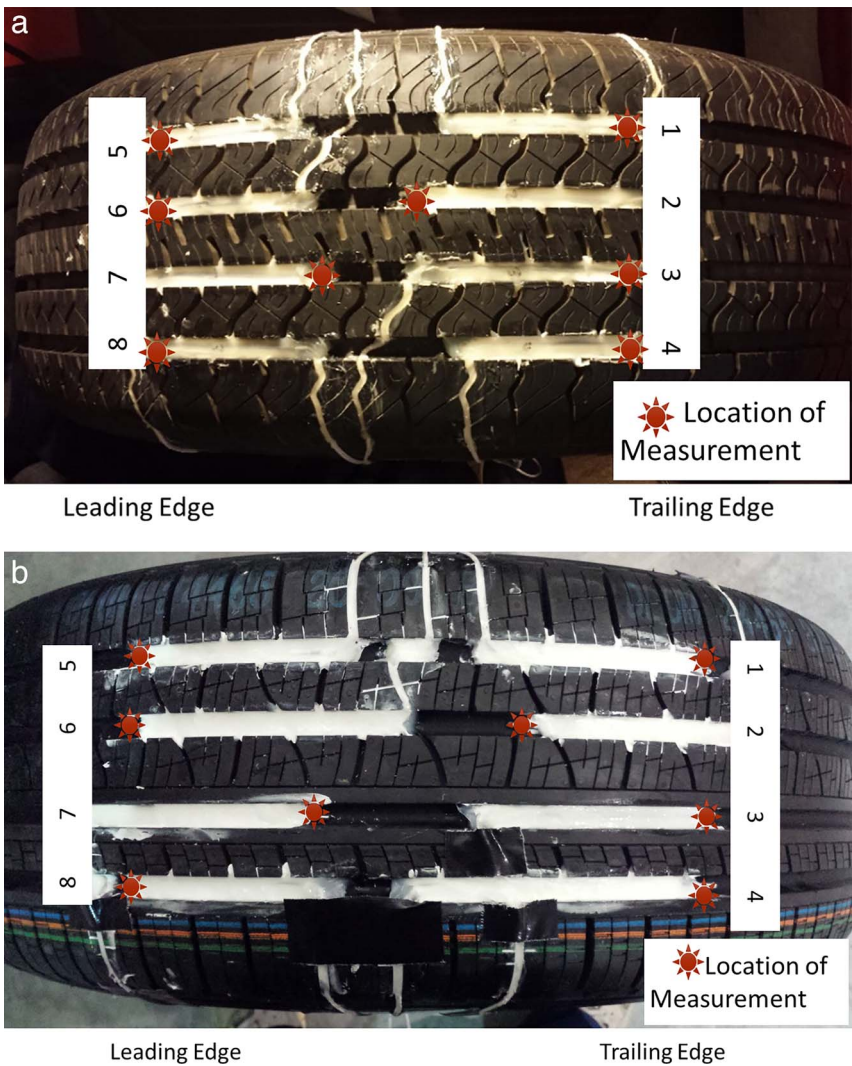


FIG. 8 — Measurement and identification of thermocouples.

tread wears down, the maximum drawbar pull occurs at a lower slip ratio value due to the contact patch becoming mostly a region of slip.

Slip Ratio Calculation

The longitudinal velocity of the carriage assembly of the Terramechanics Rig, as shown in Fig. 11, was set to 7 cm/s. An electric step motor controlled the angular velocity of the wheel separate from the carriage assembly. To control

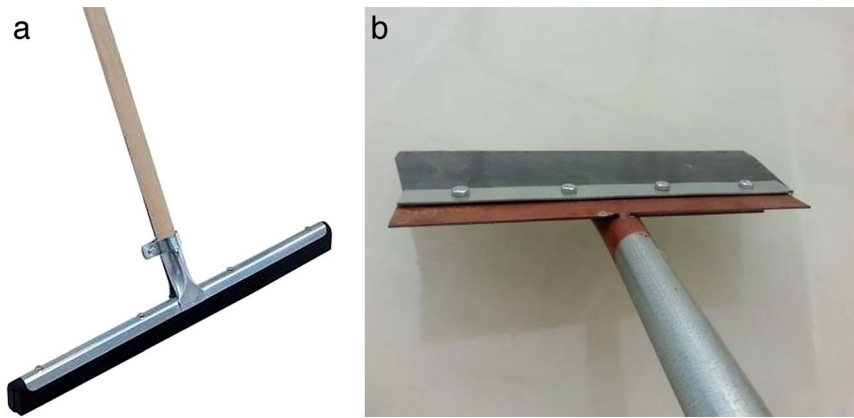


FIG. 9 — Metal scraper and rubber squeegee used for ice preparation prior to each test.

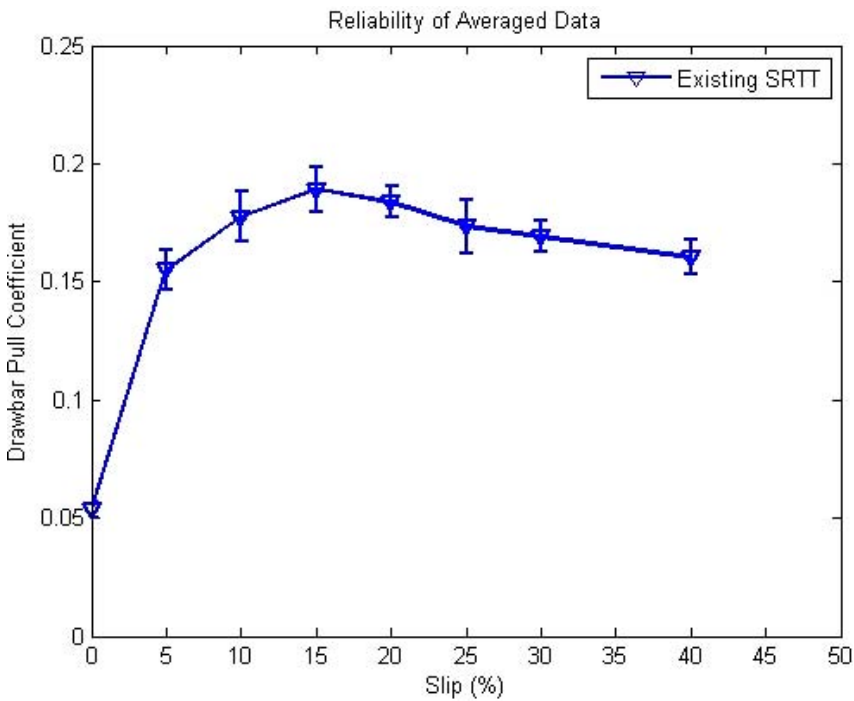


FIG. 10 — Measured drawbar pull of the SRTT. The ice surface temperature was -10°C , the inflation pressure was 242 kPa, and the tire was operating at 100% LI. The error bars show the largest standard deviation of 0.03.

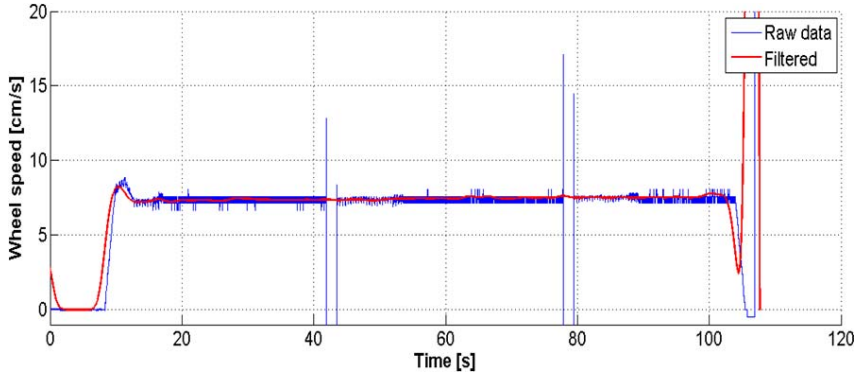


FIG. 11 — Calculated longitudinal velocity of the carriage assembly.

the slip, the effective rolling radius of the tire must be known, as shown in Eq. (1). The rolling radius of the tire was measured using an in-house wireless internal tire sensor [10]. The system uses cameras mounted on the inside of the tire to measure the deflection of the carcass. The measurements were taken at different normal loads and inflation pressures and were used for the calculations of the slip ratio at the contact patch. All of the tires tested underwent this test to measure the effective rolling radius.

$$\text{Calculated Slip Ratio} = 1 - \frac{V_{\text{carriage}}}{R_{\text{eff}} \cdot \omega} \quad (1)$$

Effect of Toe Angle

When a toe angle or cornering maneuver is introduced into the configuration of the tire, a slip angle is developed at the contact patch due to

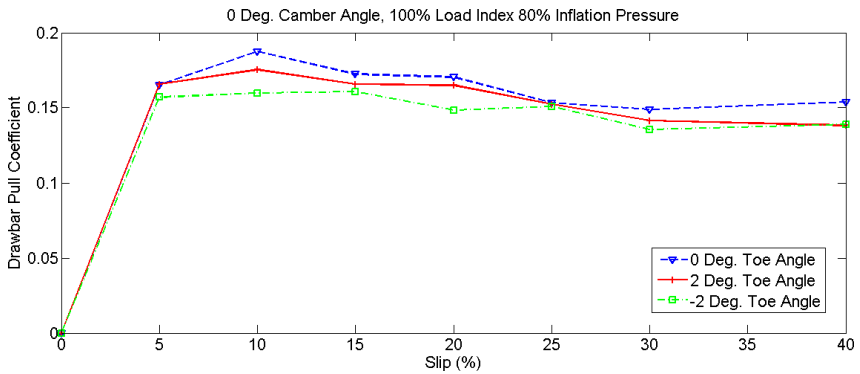


FIG. 12 — Drawbar pull measurement of the SRTT at an ice surface temperature of -10°C for the examination of the effects of the toe angle.

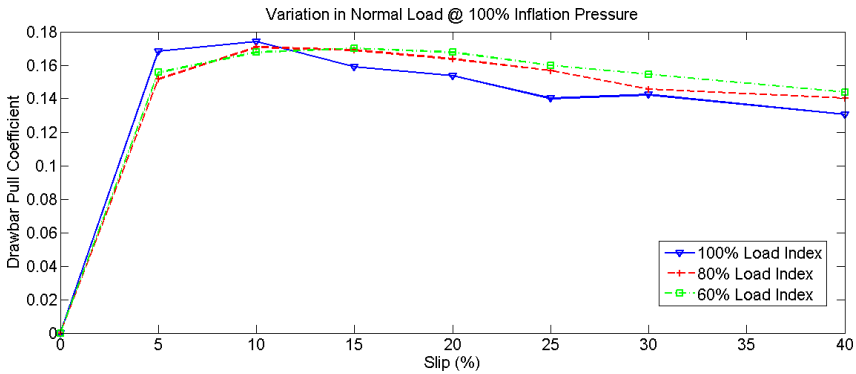


FIG. 13 — Drawbar pull coefficient of the SRTT at various normal loads with 0° camber angle and 0° toe angle when the inflation pressure is at 100% of the maximum and the ice surface temperature is at -10°C .

the lateral elastic properties. The presence of a slip angle produces a side force F_Y that is perpendicular to the wheel plane. This angle is caused by the deflection of the tire plies and tread elements.

The effect of the toe angle on the performance of the tire was investigated for 0 , $+2$, and -2° . The toe angle was set at the beginning of each test and was held constant throughout the run. Figure 12 represents the drawbar pull coefficient for the SRTT obtained from testing various toe angles. From the figure, it is evident that as the slip angle is increased, the maximum drawbar pull decreases. Because of the assembly of the carriage, the Terramechanics Rig simulates the left front tire. A negative toe angle value represents a toe-in geometry that produces a drawbar force performance lower than the one produced by the positive toe angle configuration, or toe-out geometry. The difference in the results between the toe-in and toe-out condition may be explained by conicity [11]. With the application of a toe angle, the contact patch becomes asymmetrical. In addition, because of the design of the testing facility, a boundary condition is placed on the tire when a slip angle is applied. This causes the shape of the tire to change and forces the tire to roll like a cone. Figure 12 shows that the SRTT may have been manufactured with a slightly higher conicity in one direction as the tire belts may not have been perfectly aligned during manufacturing.

Effect of Normal Load

Per Table 1, three normal loads were used to simulate a quarter car at various operating conditions. The steering configuration for this test was 0° for the toe and for the camber angle. From Fig. 13, it is evident that the peak drawbar pull coefficient decreases with a reduction in normal load. It is hypothesized that this is due to the change in the contact area at various normal

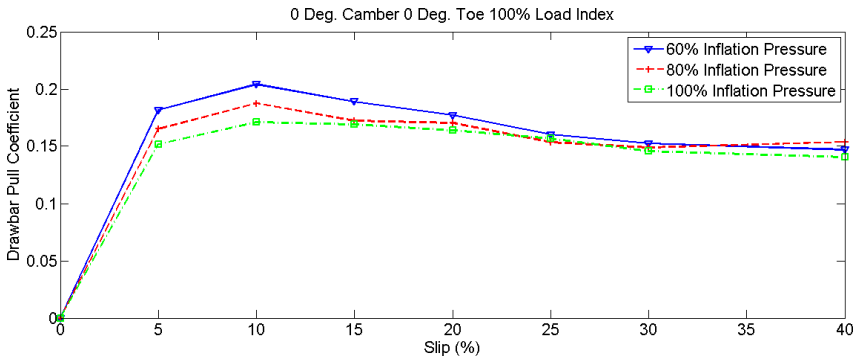


FIG. 14 — Drawbar pull coefficient of SRTT at various inflation pressures with 0° camber angle and 0° toe angle and an ice surface temperature of −10 °C.

loads. When the normal load is increased, the tire is able to deform more. The increased amount of deformation will result in a larger contact area, which will ultimately lead to an increase in friction, mainly in the linear region of Fig. 13. As the slip ratio and normal load increase, more heat is generated at the contact patch. This will ultimately lead to a formation of a thin water film at the contact interface and impact the overall friction. In Fig. 13, it is shown that at higher loads, the tire will experience the least amount of friction at high slip ratios, because of the formation of the thin water film. In the conditions of lower normal loads, the water film that is created is not as influential as in the higher loads, and the friction remains greater than 0.14. It is also important to note the location of the maximum drawbar pull as this has a direct effect on the handling of the vehicle. The peak normalized drawbar pull occurred between a slip ratio of 5 and 10%. This is important since, by comparison, the maximum drawbar force occurred at 20% slip ratio during experiments on sandy loam [12]. As the peak drawbar pull occurs at a lower slip ratio, handling of the vehicle becomes more difficult. Once the peak drawbar pull has been achieved, the contact patch will be completely made up of a sliding region as the friction becomes saturated. Therefore, the location of the peak drawbar pull relative to the slip ratio will provide information regarding when the contact patch moves from adhesion/sliding regions to completely sliding [11]. The tire will lose traction faster if the peak drawbar pull occurs at a lower slip ratio, as the adhesion region in the contact patch diminishes faster than if the peak drawbar pull occurred at a higher slip ratio.

Effect of Inflation Pressure

The effect of the inflation pressure on the tire was taken into consideration during this study at various slip ratios. Figure 14 represents the measured drawbar pull on the SRTT for tire inflation pressures of 145, 193, and 241 kPa at

100% LI for the normal load. The maximum drawbar pull measured for the scenarios investigated occurred between a coefficient value of 0.21 and 0.16, and the saturated value occurred between a drawbar pull coefficient of 0.17 and 0.14. The experimental data show that the drawbar pull has a higher peak at lower inflation pressures. A tire with a lower inflation pressure is observed to have a larger contact area and thus will produce more traction during operation on ice. Furthermore, as shown in Fig. 14, as the inflation pressure decreased, the longitudinal stiffness of the tire in the linear region increased. This may cause the maximum drawbar pull to occur at a lower slip ratio value and affect the handling of the vehicle [11]. Future active tire inflation systems could provide a function for controlling the inflation pressure depending on how much traction is required for the given driving conditions.

In general, tire pressure varies significantly with temperature because air takes up more volume at higher temperatures and less volume at lower temperatures. Lower temperatures lead to lower tire pressure, and higher temperatures to higher tire pressure. Therefore, it is crucial to understand the effect that the inflation pressure has on the traction performance of tire.

Effect of Water Film

The influence of a thin water layer on top of the ice was also investigated experimentally. Tap water was sprayed from a hose directly on the ice surface prior to each test run to simulate wet conditions. The thickness of the water layer is determined from the amount of water that is sprayed onto the ice. With a known flow rate and surface area of the water and ice layer respectively, the volume sprayed can be used to determine the thickness. For this study, the water layer was maintained between 2 and 3 mm.

When the contact patch remains dry, several outcomes may happen, depending on the ice surface temperature. If the temperature of the ice is low enough, the tire tread adheres to the ice surface. This was observed as the tire skipped along its path during travel. As the tire rotates, microscopic parts of the tread rubber are left behind in the track, as the tire skids. The phenomenon occurred when the tread blocks deflected toward the trailing edge and snapped back to equilibrium, causing increased wear and a peel-stick condition [13]. However, when the ice surface temperature gets close to the melting point, the medium between the ice and the tire will be made up of water. Therefore, the viscous friction will dominate the tractive efforts of the tire on ice.

As shown in Fig. 15, the peak drawbar pull value of the 16-in. SRTT (tire A) decreased significantly, by approximately 11%, when the water film was applied and the ice surface temperature was close to the melting point. When tire B was tested, the tire was able to approximately maintain the traction as a result of its tread pattern design, as shown in Fig. 16. The ice surface temperature was at -3°C for the wet film conditions.

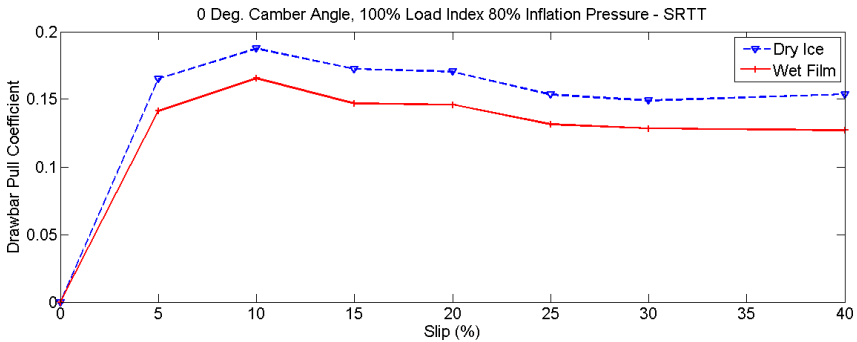


FIG. 15 — Drawbar pull coefficient of SRTT at 80% inflation pressure, 100% normal load, with 0° camber angle and 0° toe angle.

Tire B is considered an all-season tire, and the difference between the dry ice performance and wet film was not as significant. The introduction of grooves and sipes allowed for the water to be removed from the contact patch and to penetrate (bite) the ice surface to promote traction, as shown in Fig. 16. When the edge of the sipes bite into the ice surface, the ice is not destroyed. The sipes instead help to propel the tire forward by acting against the microscopic peaks and ridges present on the ice surface. The SRTT had bulk tread blocks without sipes, and its design did not allow for the water to move away from the contact patch during operation.

Effect of General Tread Pattern Design

Figure 17 compares three distinct tread patterns. These tread patterns are composed of the most common types of tread pattern designs. The directional tire is labeled DT (tire E), and the asymmetrical tire (tire D) is labeled WT. On a dry ice surface with a temperature of −10 °C, the SRTT and the winter tire (tire

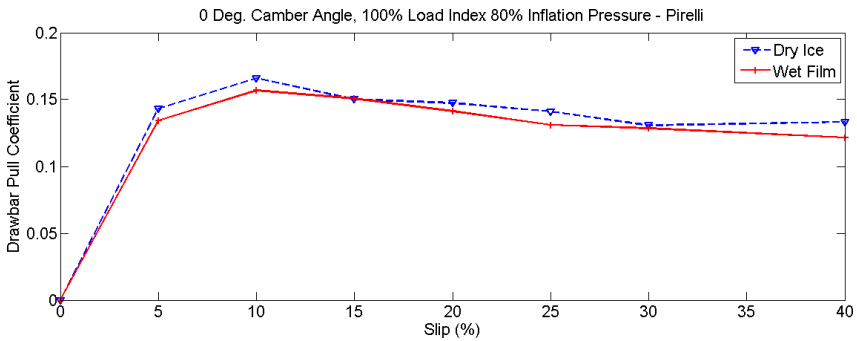


FIG. 16 — Drawbar pull coefficient for tire B at 80% inflation pressure, 100% normal load, with 0° camber angle and 0° toe angle.

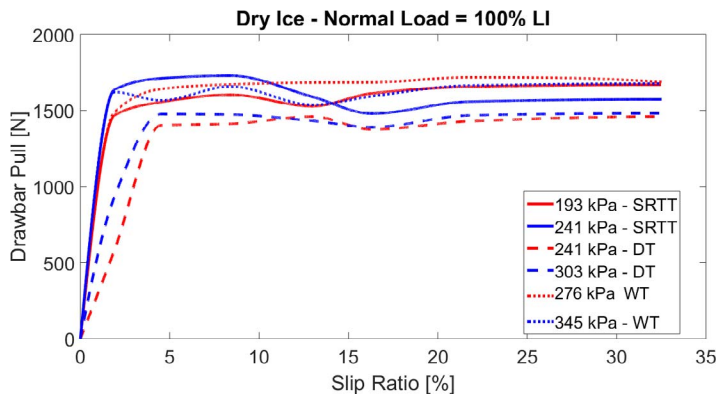


FIG. 17 — Drawbar pull measurement of three tires at an ice surface temperature of -3°C .

D) shared the highest drawbar pull. This occurred at an inflation pressure of 100% of the rated maximum. The design of the asymmetrical winter tire led to an increase in traction compared with the DT. On dry ice, it was evident that the biting effect was present as the measured drawbar pull was higher than others in Fig. 17. Even in the high slip ratio range, the design of the tire led to a higher tractive performance, while the results for the other tires diminished in this region. The winter tire was made of several sipes aligned in succession at the shoulder of the tire. By introducing sipes into the tread design, more individual tread blocks are created, which allows for a higher ratio of edges for the tire to use to produce traction [14]. Tire B is also composed of an asymmetrical tread pattern. When this tire was loaded with a camber angle, the angle will selectively load the wider or narrower ribs of the tire, depending on the orientation of the angle. Imposing a camber angle on the tire results in more or less contact on those ribs, which will ultimately yield more or less traction. By increasing the area in contact, the tire is able to generate more tractive forces. In other tread pattern designs such as tire A (symmetrical), a change in camber angle resulted in no significant change in the tractive performance.

The hardness of the tires was measured at room temperature using a Shore A durometer and is presented in Table 3. The locations of the measurements are at the center of a tread block, the shoulder of the tire, and at the sidewall. The sidewall was measured to capture a measurement that resembles the bulk property of the tire when averaged with the other measurement locations. The rubber of the winter tire is softer compared with that of all the tires tested, as shown in Table 3. Using a Shore A durometer shows that the hardness of the DT (tire E) was higher than that of the winter tire, as shown in Table 3. This shows that the hardness of the rubber is also significant with regard to the traction performance. The design of the tread pattern and the hardness of the rubber will

TABLE 3 — Shore A hardness measurement.

Test condition	Tread block	Side wall	Shoulder	Average	Tire temperature
Tire A	60.5	61	72.5	64.7	19.9 °C
Tire B	66	65.5	67.5	66.3	
Tire D	58.5	56.5	54.5	56.5	
Tire E	65.5	66.5	72.5	68.2	
Tire A	66.5	57.5	78	67.3	−3 °C
Tire B	65	67	66.5	66.2	
Tire D	53.5	48	54.5	52.0	
Tire E	65	66.5	74	68.5	
Tire A	69	62	77	69.3	−10 °C
Tire B	69	67	68.5	68.2	
Tire D	55.5	50	51.5	52.3	
Tire E	70	64	71	68.3	

be the dominating factors that dictate the traction performance of pneumatic tires on ice.

When the ice surface temperature is reduced to −3 °C and a water film is observed, the drawbar pull is reduced, as shown in Fig. 18. In this scenario, the DT recorded the highest drawbar pull. The all-season DT had deep grooves running in an unidirectional pattern, as well as along the middle of the contact patch, as shown in Fig. 2. This design of the tread pattern was effective in removing the water from the contact patch and providing higher traction performance on ice, which explains why the drawbar pull increases again before falling to the saturated value in Fig. 18. The winter tire measured the lowest drawbar pull. This shows that once a thin water film serves as the contact interface, an emphasis of water removal must be made during the design of the tread pattern. Therefore, comparing Fig. 17 and Fig. 18 shows that a design

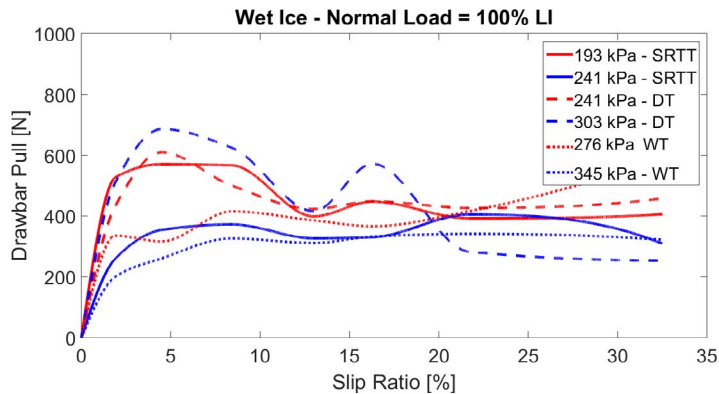


FIG. 18 — Drawbar pull measurement of three tires at an ice surface temperature of −3 °C.

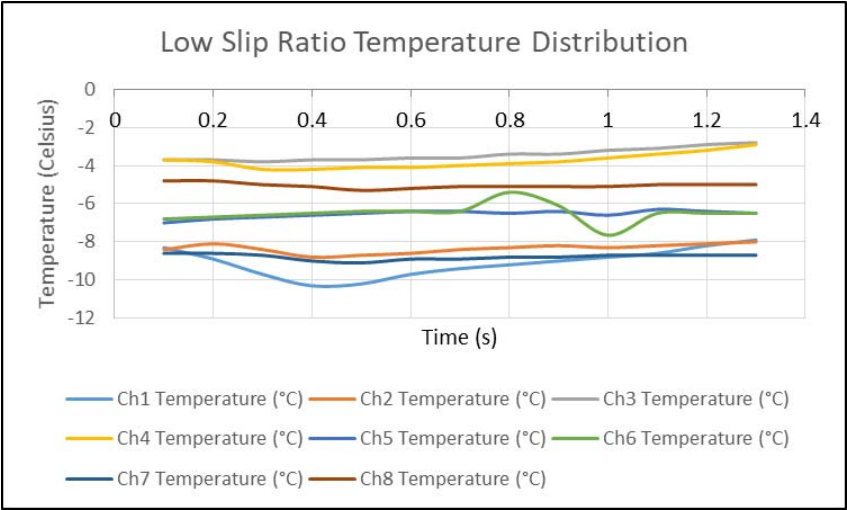


FIG. 19 — Temperature time history measurements displaying the effect of 60% inflation pressure for the 235/55R19 tire B at low slip ratio. The testing conditions were set at 0° toe angle and 0° camber angle at 100% load index.

compromise must be made for a tire traversing smooth ice. The design must be effective in removing the water away from the contact interface, as well as providing a biting effect on dry ice by using sipes.

Tire Temperature Measurement

All the conditions listed in Table 1 were investigated to determine the temperature rise at the contact patch using thermocouples. The channel number corresponds to those of Fig. 8 for all of the scenarios presented. During operation, the leading edge is cooler than the trailing edge, which is why the different starting temperatures for the thermocouples are shown. As the tire rolls, the increase in temperature from friction is shown only for when the tire is in contact with the ice, for Fig. 19 and Fig. 20. To ensure a steady-state condition, the tire is cooled to the same temperature as the ice surface and covered within an insulated shell to maintain the tire at the specified temperature. The tire rolls approximately 6 m under a single specified slip ratio, and the measurement is taken only once it has stabilized. This is repeated three times and averaged to account for repeatability of the test.

First, the effect of varying the inflation pressure on the temperature rise was studied. As shown for the 19-in. tire B in Figs. 19 and 20, as the inflation pressure decreases, the temperature rise in the contact patch becomes more significant. Heat generation is proportional to the total surface area. Therefore, as the inflation pressure decreases, the contact area increases, which promotes heat generation.

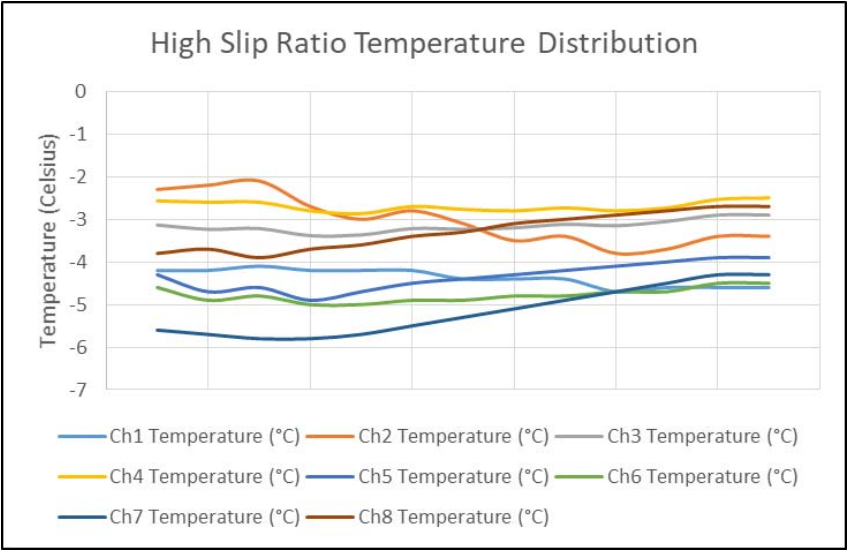


FIG. 20 — Temperature time history measurements displaying the effect of 60% inflation pressure for the 235/55R19 tire B at high slip ratio. The testing conditions were set at 0° toe angle and 0° camber angle at 100% load index.

The effect of varying the slip ratio at the contact patch was also investigated. From Fig. 20, it is evident that there is a higher variation in temperature with respect to the high slip ratio, as the thermocouples try to reach an equilibrium. As the rate of friction generation increases, the tire tends to reach steady state slower than in the low slip ratio. The temperature rise was also more evident in experiments with a higher normal load on the tire, especially in the case of high slip values. This is assumed to be the result of the increased area in the contact patch as well as the increased pressure distribution at higher normal loads.

Tires are rated to their resistance to heat and their ability to dissipate heat when tested under controlled laboratory test conditions. These ratings are referred to as temperature grades. The grades from highest to lowest are A, B, and C. Grade C corresponds to the minimum performance required by federal safety standards. In winter applications, especially ice, the warmer the tire is able to get, the higher the height of the melted fluid layer at the contact interface. This height of water fluid has a direct influence in the overall traction available [15,16]. As the height increases, the tire will lose direct contact with the ice, and the traction will be reduced [16]. Therefore, winter tires must be designed to control the temperature rise at the contact patch during operation.

Conclusion

This study aims to enhance the understanding of the tire-ice contact interaction at the contact patch through experimental studies for a pneumatic tire traversing over smooth ice. This study investigates the effects of various parameters at the tire-ice interface, including the effect of normal load, inflation pressure, and toe angle during the operation of the candidate tires. A novel method to measure the temperature directly at the tire-ice interface was introduced, which is based on the instrumentation of the tire tread with thermocouples and their respective locations relative to the contact patch.

A reduction in drawbar performance was observed with a decrease in normal load for the entire slip ratio range investigated. A decrease in the slip ratio value at which the maximum normalized drawbar pull is achieved was detected when the inflation pressure was increased. When operating at lower inflation pressures, an increased contact area was observed that led to increased friction levels at low slips. However, at high slips, with an increased contact area there is also an increased heat generation, which enhances frictional melting of the ice surface; thus, the friction levels are lower at higher slips. With the addition of a thin water film, there is a significant decrease in the available traction at the contact patch, found for the SRTT, as expected. Tire B performed better than the SRTT with a thin liquid layer present at the interface. When a camber angle is applied, the contact area of the tire changes with respect to the applied angle. This reduction in area led to nonsignificant changes on the tractive performance of the car. However, an increase in toe angle led to a decrease in peak drawbar pull coefficient, but it also led to an increase in the lateral force at the tire-ice interface.

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