

Tire performance evaluation for severe snow traction

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Abstract: Snow traction is an important tire performance parameter for product applications in markets where snow is present for several months during the year. It is very difficult to perform multiple tests because proving grounds and consistent test conditions are available only for limited periods of time and due to prototyping and test expense. This paper deals with the simulation aspects of the snow traction test using Abaqus. The first part of this paper describes the chosen test method and offers a review of the available simulation technology. A modeling methodology for realistic snow interaction is examined using small-scale simulations, in order to evaluate its applicability to snow traction simulations. Next, simulations of snow traction are developed for a tire rolling over a snow surface. The tire models employ fine-resolution tread patterns so that a better approximation is obtained to the real-world event of tire/snow interaction. Physical phenomena such as snow shear, digging and friction are taken into account by an adaptive-explicit FEA. The proposed analytical procedure is validated through comparison with test data.

Keywords: Tire, snow, traction, adaptive-explicit FEA.

1. Introduction

Tire traction refers to the ability to transmit traction force from vehicle to ground in order to move that vehicle forward. Snow traction is an important tire performance parameter. Tires sold in North America must pass a certain traction test known as ASTM F1805 (ASTM, 2001) in order to bear the US Rubber Manufacturers Association snowflake-on-mountain symbol (RMA, 2008), shown in Figure 1, which rates the product as suitable for severe snow usage. In tire development programs, special attention is paid to snow traction because it is a critical OEM requirement. However, it is very difficult to have snow testing performed during three quarters of the year because the test grounds are not available. These tests are also time and resource consuming. Hence, there is need to help screen tires and tread patterns for snow traction through the application of FEA. In this way, the development curve can be shortened and costs associated with test, tire manufacturing and product qualification could be saved.

In order to perform a computer simulation, one has to carefully examine the test procedure so that the FEA can replicate the exact conditions while allowing for reasonable simplifications. A snow traction test in progress is depicted in Figure 1. The test tire is mounted on an instrumented vehicle and the desired load is applied by adjusting the ballast weight. The vehicle maintains a constant speed of 5 mph while the driver applies a driving torque on the test tire at a constant rate. The tire starts slipping on the snow surface when the applied traction force exceeds that of tire-snow interaction. In practice, when the tire starts spinning, there is visible trail of snow thrown behind the tire, which sometimes is referred to as “rooster tail”. When the spinning speed exceeds a prescribed value, the maximum torque transferred to the tire is found. The ratio of this torque to its

value of a reference tire run (for example, ATSM, 1986) on the same course is reported as a snow traction performance index. The procedure is repeated on three consecutive days and the average of these indices is provided to the customer.

The snow surface on the test track is prepared according to ASTM, 2001. At the beginning of the test season, a solid base is made by compacting natural snow to a prescribed hardness level. The snow in the base is known as “hard pack” snow. A second layer of snow is made by piling more material on top of the base and that layer is in turn compacted and groomed several times in order to achieve a different level of hardness, namely about 10% softer than the base. This snow is called a “medium pack” snow. In this way, when tests are run, rutting mostly occurs on the softer layer, and only that surface needs to be repaired for next runs.

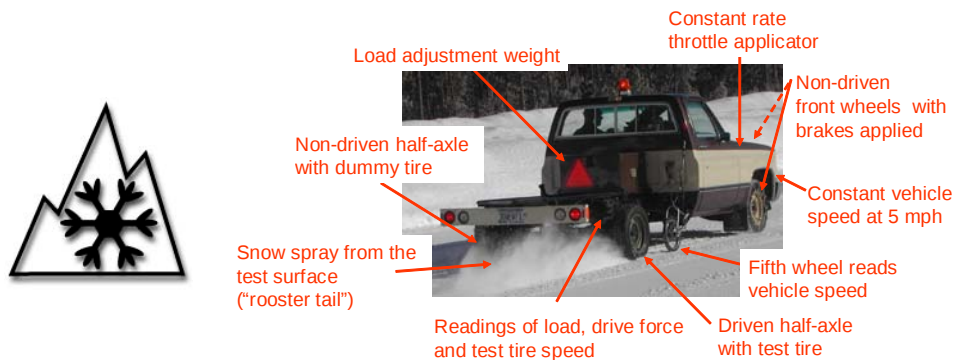


Figure 1: Test vehicle with instrumentation used in ASTM F1805 snow traction test and RMA’s snowflake-on-mountain severe snow traction symbol.

Thus, the challenges to the numerical analysis are not only to model correctly the snow medium and the tire properties, but also to pay particular attention to the interactions on the tire-snow interface accounting for phenomena such as snow material removal and sinkage.

The next section explores the prerequisites for the analytical method and the solver. Previously published materials on snow traction simulation and modeling are surveyed in the light of the above test method and software requirements. The choice to model the snow as an elastic-plastic material is verified by a simple numerical example of a plate sinkage test. Physical phenomena such as snow shear, digging and friction are taken into account by an adaptive-explicit FEA and are demonstrated using Abaqus/Explicit simulation of a single tread block. The validation of results is done by comparing the predicted snow traction force obtained from full-pattern analyses of three hand-carved tire patterns to those observed in the ASTM test, and by the relative tire rank-ordering for traction performance. Discussion on how the solver copes with large deformation, material removal and contact evolution is offered as well.

2. Prerequisites to snow traction simulation

Snow traction is a cumulative result of forces taking place in the tire footprint when it is rolled over the surface, as illustrated in Figure 2. The loaded tire sinks in the undisturbed snow terrain by a distance z , which results in snow resistance force F_A . Snow is entrapped between the wide openings (slots) in the tire tread, where it is sheared from the base surface to create a reaction force F_B in the direction of driving. Small features on the tread called “sipes” bend in the footprint and provide extra interaction edges which dig in the base generating additional driving force F_D . The frictional force F_C is standard in all traction cases. Therefore, the total driving force F_X is the result of all longitudinal forces in the footprint:

Equation 1

$$F_X = F_B + F_C + F_D - F_A$$

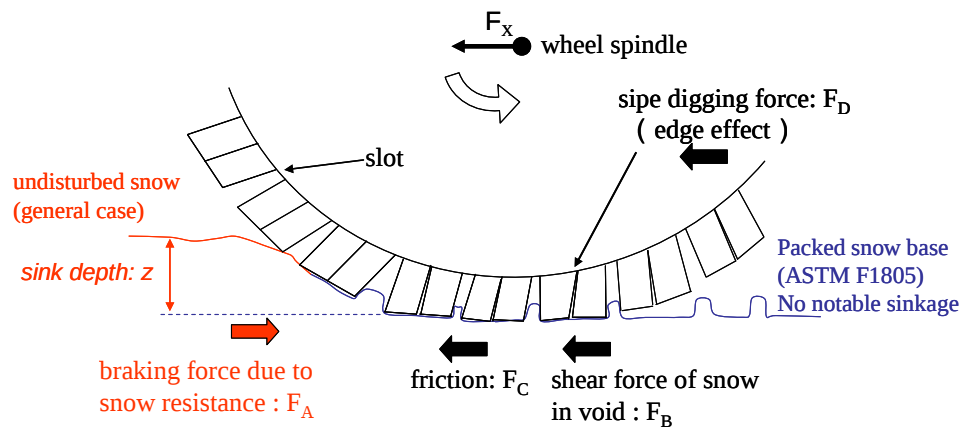


Figure 2: Interaction between tire and snow terrain.

In the ASTM test, because of surface preparation, there is no notable sinkage, and the snow resistance, F_A , is virtually non-existent. All other forces are effective and must be solved by FEA.

Publications on analytical methods can be found in the transport characterization research, in snow material properties test methods and in tire applications. The snow material models, the type of solvers and the level of complexity are selected from the point of specific applications. Commonly used snow material models are the Drucker-Prager model as reported by Mundl, 1997, Shoop, 1999 and, with modification, by Lee, 2006; the Cam-Clay model shown in Mundl, 1997, and Menschke, 1998; and the elastic-plastic Mohr-Coulomb model used by Seta, 2003. These models have been benchmarked for a plate sinkage test and it was found that snow compaction and depth-pressure “bulbs” were of acceptable quality for all models when compared to experiments on undisturbed snow (Seta, 2003). Richmond, 1995 and Shoop, 2001 compare the modified Drucker-Prager model and that of a crushable foam in applications to mobility analysis by Abaqus/Explicit and an in-house code PRONTO with the same effect.

The FE solver chosen to simulate snow traction must be able to deal with larger deformations, material compaction and element removal. This to a great extent depends on the material model chosen to model snow. In literature, Abaqus/Explicit has been widely reported in applications to trafficability (Shoop, 1999 and later in Shoop, 2006). In that research, attention is paid to compaction and tire sinkage along with the total driving force, while the tire tread detail is not modeled. The model accounts for snow compaction, but does not remove the snow elements resulting in a wave-like shape in front and on the sides of the tire. Another reference (Lee, 2006) extends the research to modeling of different sizes of commercial tires, which compares tire snow performance based on tire size (but not tread pattern) through the Drucker-Prager snow model. The simulation by Seta, 2003 employs MSC.Dytran for analysis of a tire with tread pattern. The tire is rolled over a medium pack snow and results in material separation from the snow surface, which is modeled with the Mohr-Coulomb elastic-plastic yield function.

Considering the existing capability in Abaqus/Explicit v.6.8, the following criteria were applied in the selection of the current material model:

- Availability of material data
- Modeling of strain hardening in snow
- Large deformation and contact modeling require explicit FE analysis
- Mesh adaptivity and element erosion function to remove medium pack snow volume sheared off in the tread void.

While large deformations are possible with the utilization of the Drucker-Prager and foam models, finite element erosion is not supported by the explicit solver for these materials. Since most sources describe natural loose snow, material properties of hard pack snow for this model were not readily available. Similarly, it was not possible to derive material data for the Cam-Clay models in laboratory conditions (as directed in Mundl, 1997). The Mohr-Coulomb plasticity, successfully applied in the MSC.Dytran analysis with the above requirements, is only available in Abaqus/Standard. It is noted (Simulia, 2009) that this material model has been recently implemented in Abaqus/Explicit v.6-9-EF. Such a capability should be considered for obtaining a detailed solution of the snow stress field in the contact zone.

An alternative to the latter analysis option that was not available at the time this work was completed is the classic elastic-plastic material model with prescribed stress-strain response (Figure 3). The material properties of this model can be extracted based on their reference to the snow density (Mellor, 1975). This model does support both adaptive remeshing and element erosion in the explicit formulation, and, as long as strain softening in failure is preceded by element removal, it should be computationally stable and a close approximation to the compacted snow behavior.

Figure 3 compares the constitutive material response of the current model to that of the Drucker-Prager model (Shoop, 1999), for a uniaxial compression case. The medium pack stress-strain curve is assumed at density of 510 kg/m^3 , following the data in Mellor, 1975, without taking into account density increase due to compaction. The snow density does increase in simulations with volumetric strain increase. The referenced Drucker-Prager model starts with an initial density of 200 kg/m^3 which gradually increases to over 300 kg/m^3 with deformation. Both responses are very

close although the density change is considered in the Drucker-Prager model through the volumetric pressure. The hard-pack snow has only 10% higher density than the medium pack, namely 560 kg/m^3 , but its stress response is about two times higher: the snow properties show exponential dependence on the snow density up to 800 kg/m^3 . Same is true for the Poisson ratios, which are defined by 0.1 and 0.3 for the medium and the hard-pack snow materials, respectively. The failure shear stress is the criterion applied to element removal: all finite elements exceeding this value would be removed from the stress calculations and from contact, but they still remain in the global model definition retaining the last known stress level and velocities at nodes. This feature permits the visualization of snow debris behind the tire, as shown in the test comparison below. Both the medium pack and hard pack materials have shear strain failure criterion of 50%, as illustrated in Figure 3. This strain corresponds to snow compaction to a density of 900 kg/m^3 , or just below that of solid ice.

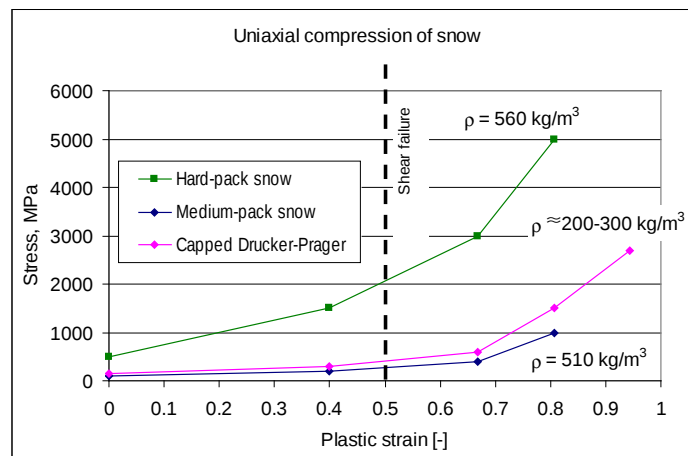


Figure 3: Comparison of the current model and the Capped Drucker-Prager from Shoop, 1999.

3. Verification of the current approach

3.1 Plate sinkage test

The first example used to verify the current approach is the plate sinkage test. The numerical setup is shown in Figure 4, where a rigid plate of 20 mm diameter is pushed up to 15 mm into snow with initial density of 150 kg/m^3 and Poisson's ratio of 0.1. As the volumetric pressure builds up in front of the plate, the density changes accordingly owing to the volumetric strain. The snow volume is deep and wide enough to avoid stress concentrations near the boundary planes. The objective of this exercise is to compare the snow density change with depth location in the snow and the overall deformation in order to verify the proposed elastic-plastic model for snow traction modeling.

The density distributions as a function of the distance from the plate front are compared to published values from the Drucker-Prager model in Table 1. It is noted that density values predicted by the current elastic-plastic model and the Drucker-Prager model are very close and that the density decreases in the material away from the plate face, although more compaction gradient is predicted by the current model. The analysis was found to be stable even for the large deformations in the vicinity of the plate edges, where the snow is pushed backwards. This example shows that we have a viable option for quick snow property characterization by referring to the density.

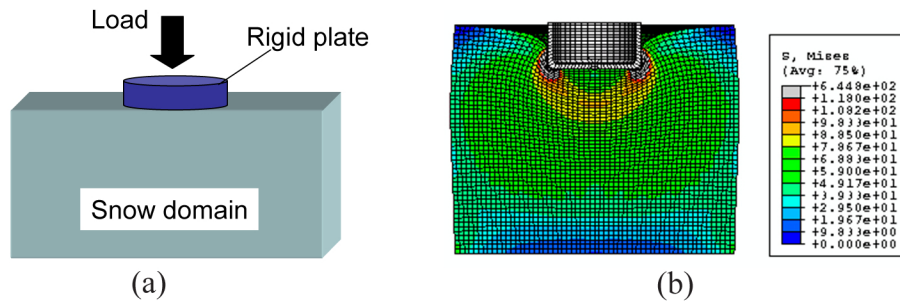


Figure 4: (a) Plate sinkage set-up; (b) von-Mises stress distribution using the current model.

Table 1: Comparison of predicted snow density [kg/m^3] by different models:
(a) current elastic-plastic model; (b) Shoop, 1999.

Distance, mm	(a) Current model	(b) Drucker-Prager
5	367	264
10	283	253
15	242	234

1.1 Tread block interaction with snow

Before performing a full-scale simulation, a single tread block interaction with snow is first analyzed. The setup, shown in Figure 5, considers a tread block of size 32x25x10 mm, with two sipes of 8 mm depth oriented transversely to the direction of motion. The block is loaded into the snow with prescribed displacement of 2 mm and moved along the contact surface under displacement boundary conditions. The two material models described above, elastic-plastic and Drucker-Prager, are applied to the snow to compare their ability to model snow deformations. A linear elastic modulus of 10 MPa is provided for the rubber tread block.

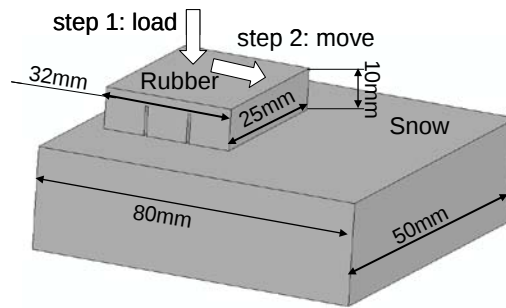


Figure 5: Setup in tread block-snow interaction example.

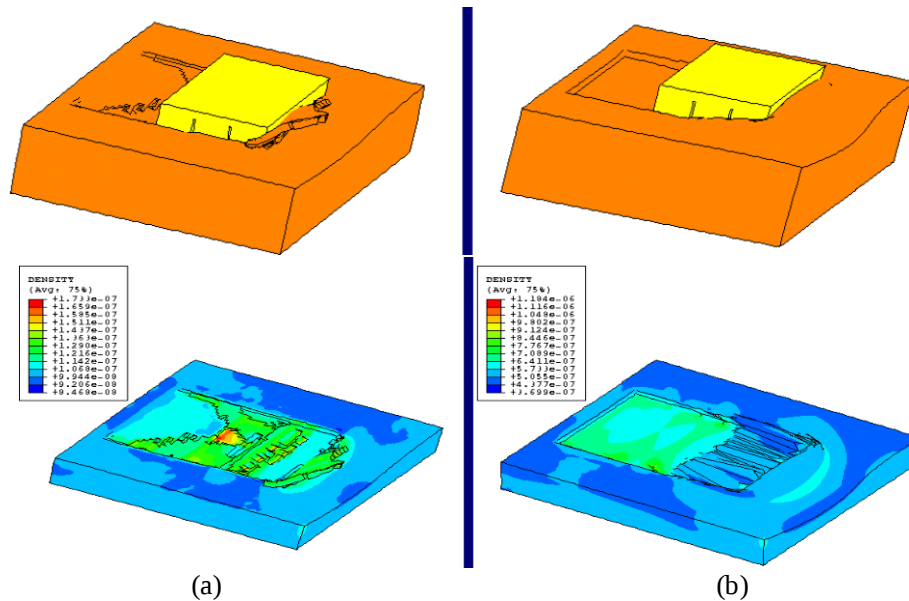


Figure 6: Last stage of tread block displacement (above) and snow deformation (below): (a) elastic-plastic model with snow element removal; (b) Drucker-Prager model, no element removal.

The snow deformation, as shown in Figure 6, is very severe: using the elastic-plastic model the density increases under the initial contact and slip initiation, and chunks break free from the snow volume. Because of the mesh adaptivity and element erosion, the snow elements are constantly refined and those that exceed the failure criterion are removed from the solution and from contact, remaining as debris in front of the moving tread block. The Drucker-Prager model cannot remove elements, but it rather applies a failure condition upon which the elements do not carry any stress, while still active in the analysis and in the contact definitions. This produces largely distorted elements in front of the tread block even when mesh refinement is utilized. The density distribution is very different from that of the current model prediction. This comparison shows

that, from the viewpoint of contact management and physics, the elastic-plastic model describes the snow interaction more practically.

4. Simulation of tire traction on snow surface

This section discusses the application of the developed methodology to tire snow traction simulation. Three tread patterns are simulated: a blank-rib tire, a one-slot pattern and a pattern with one slot and one sipe. This selection was based on their distinct snow performance, with respective snow traction indices of 35, 77 and 101 in the ASTM test respectively. Figure 7 displays the concept pitch sketch and the analysis setup of this numerical example. The tire body is made of a rigid ring (deck) on which the treads are modeled with a linear elastic material. For computational efficiency, center-line symmetry is assumed and only one-half of the problem is analyzed. The tire tread is attached on the deck surface by using “Tie” constraints. The snow domain is modeled as two layers, a medium pack and a hard pack, with resolution of two elements per tread slot void (a minimum of 2 mm) so that shear of entrapped snow can be simulated. Contact between the treads and the entire snow domain is prescribed through the General Contact definition with a Coulomb coefficient of friction of 0.2. This contact definition accounts for the friction force, digging and deformation of snow pushed into the tread slots, which results from the tire rolling over the snow. All snow elements are defined in self-contact with the same coefficient. These two definitions assure continuity of the snow response when the sides of the hexahedral snow elements are exposed due to erosion from snow shear and digging effects. This concept is illustrated in Figure 8. The snow and tread are modeled with C3D8R elements to which hourglass control “Enhanced” with default parameters is applied.

First, the tire is statically loaded up to a specified deflection corresponding to the load applied in test. During this step, some of the top-layer snow elements are removed due to excessive distortion while the density increases significantly in and near the remaining elements in the footprint. With some of the medium pack snow removed, the tread contacts the hard pack elements, as shown in Figure 8. Next, displacement boundary conditions are applied for the motion: a prescribed forward speed v_x on the X axis by 5 mph with a rotation about the Y axis ω , corresponding to a circumferential speed of 6.5 mph, or 30% higher than the translational velocity. These boundary conditions are chosen so that they can simulate a spinning tire. Further, to avoid high distortions in snow elements, the entire snow domain is subjected to adaptive remeshing with frequency of two increments.

A major difference with respect to the snow traction test is the time: about 2 s is recorded for each tire spin on the course while 0.1 s of analysis time is specified in FEA in order to have a reasonable run time. This approach affects the results for rate dependent quantities, such as acceleration, noise and damping as well as the overall analytical error measure, but should not have an effect on the magnitude of predicted force levels. It should also be noted that, while constant slip ratio is specified by the boundary conditions, in tests the slip increases because of the continuously increasing torque on the drive wheel. In both test and analysis, the reaction force F_x measured at the wheel spindle is reported.

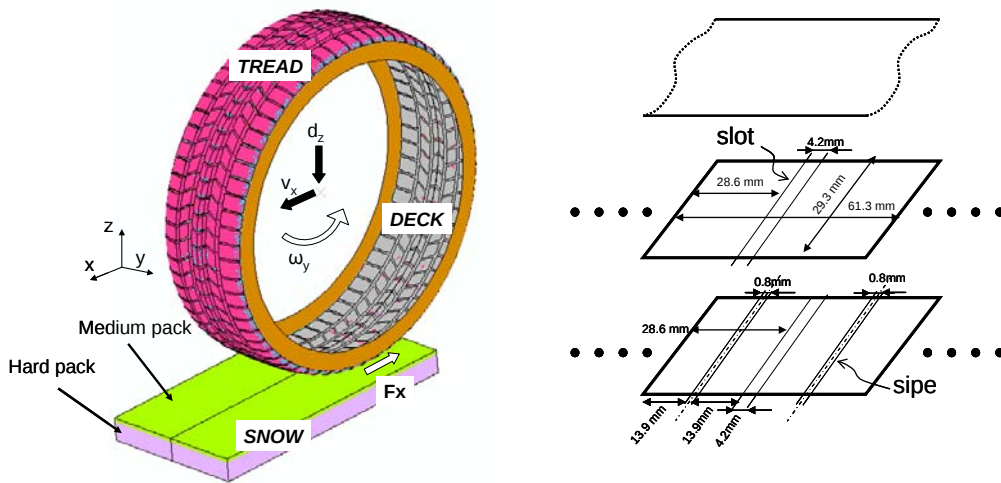


Figure 7: Tire-on snow example setup. A single pitch of each tread pattern is shown on the right.

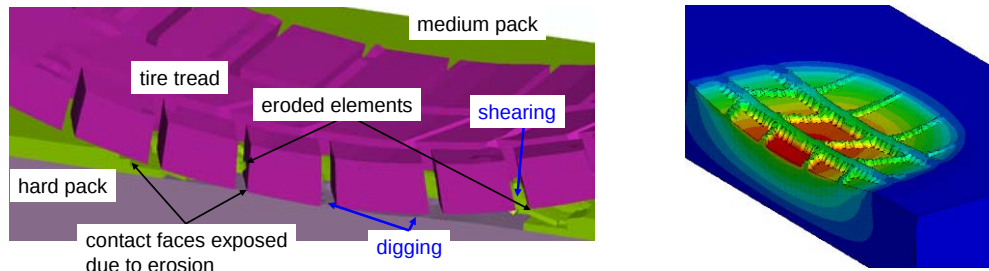


Figure 8: Tread-snow interactions in FEA and static footprint with density contours.

The three patterns interact differently with the snow. The comparison of the reaction spindle forces for these tires is offered in Figure 9 for the FEA and in Figure 10 for the test. There, several common effects can be seen. The test traction force increases with nearly constant slope when the tire accelerates. The same is observed in simulation, where the initial slopes are steeper due to time scaling. In test and FEA, the force peaks out at different levels, and then the response levels off at a steady-state “plateau”. The peak and the plateau predictions can be interpreted as peak traction and slide traction in test. As seen in the force-time plots, the lowest traction force is found for the blank-rib tire. It reaches the force peak earlier than the patterned tires, indicating the onset of earlier longitudinal slip. In turn, the one-slot pattern reaches the force peak earlier than the one-slot/one-sipe tire. Thus, there is time delay between the force signals, a characteristic also observed in the test data. The peak and plateau magnitudes of the three patterns are correctly rank-ordered by the simulations but the forces are somewhat higher than in test. The differences can be explained with the selected friction coefficient of 0.2 in the Coulomb friction model, assumptions of constant environment conditions and finite element discretization. An important factor is also

the choice of rigid tire carcass in the analysis, which would undoubtedly affect the footprint dimension and pressure distribution. Nevertheless, the analytical solution is in good agreement with the test data. Therefore, the presented model is deemed capable of differentiating between tire patterns.

The calculated maximum force corresponds to the traction force at a given longitudinal slip ratio, in this case 30%. The predicted traction forces are compared to the measured ones in Table 2. The simulated traction rankings, calculated by taking the one-slot tire as a reference at 100%, show a difference of 62% in traction performance between the highest and the lowest. The test values, in turn, when normalized to the reference tire, have a resultant spread in traction index of 81%. Since the only distinction between these analyses is the tread pattern, this means that the simulation is oversensitive to introduction of an extra sipe in the pattern, and that blank tire performance is overestimated. By adjusting friction, snow property values and applying appropriate acceleration during the spin, a reasonable correlation to test measurements can be obtained.

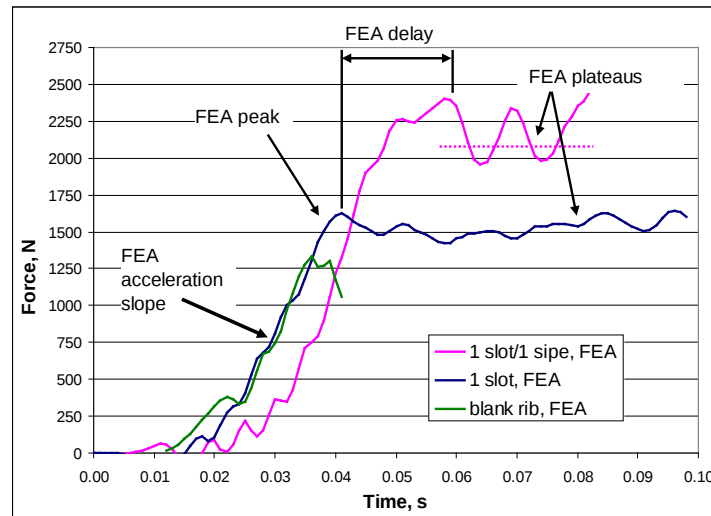


Figure 9: Predicted drive force by the FEA.

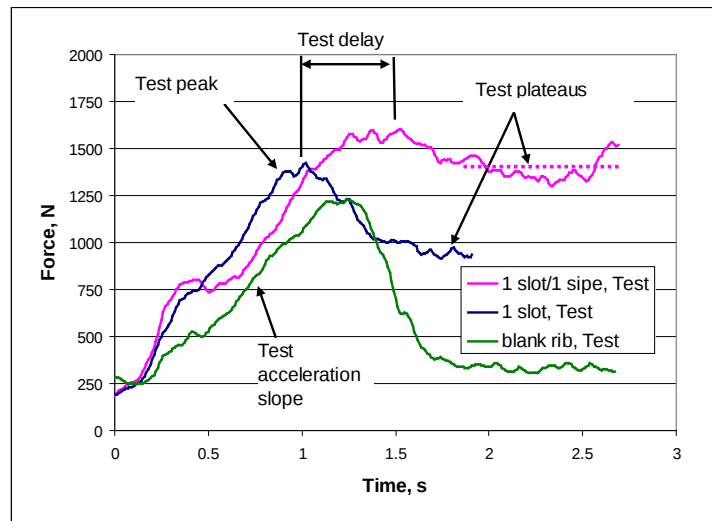


Figure 10: Measured drive force by ASTM test.

Table 2: Comparison of the predicted and the measured traction forces.

Tire ID	Peak, FEA(N)		Peak, Test(N)		Traction index	
1slot/1sipe	2317	145%	1560	110%	101	131%
1slot	1592	100%	1412	100%	77	100%
blank ribs	1330	83%	1211	86%	35	45%

5. Discussion

When the tire spins over the snow surface, several phenomena are found to take place. The FEA gives us the opportunity to examine these in detail, while observing certain points to improve the snow traction performance and the simulation accuracy.

5.1 Rolling tire footprints

The footprint is the place where all traction forces are generated. Thus, it is important to note the differences between the above patterns from that perspective. The snow surface images under the tires in the initial rolling stage (the acceleration slope in Figure 9) with shear stress contours are given in Figure 11. Higher absolute values of this measure produce higher reaction force with a higher snow removal rate. The blank tread mainly packs the snow in the tire groove, thus no shear forces are present in most of the footprint, leaving the friction forces as the only traction component in Equation 1. The footprint of the tire with one slot has smaller surface area in contact compared to the blank rib, because of introduction of slot voids. This can be seen by comparing the leading edges of both footprints. But the area is still larger compared to the one-slot/one-sipe

tire. A larger surface area would result in more friction force. On the other hand, the tire with one-slot/one-sipe shows more edge effect in the leading edge, illustrated with alternating high-low stress contours. These stresses produce a higher traction force due to the pattern digging effect compared to the one-slot tire. The slot-snow interaction is present in both patterns, and thus forces due to snow shear should be the same in both analyses. Therefore, it can be stated that the tire with sipes (more digging edges) would be more effective for snow traction than the tread pattern with a slot only.

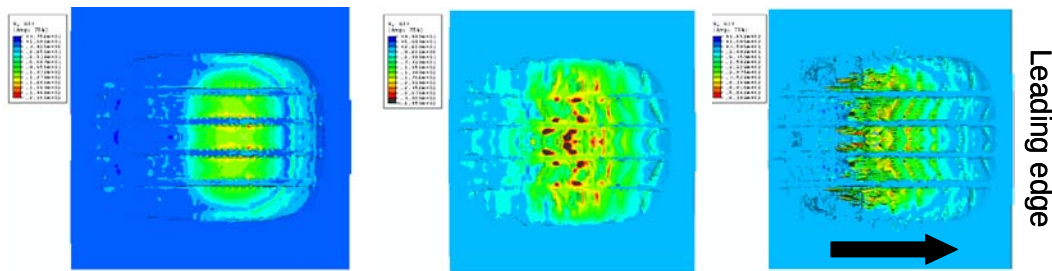


Figure 11: Footprints in the snow with shear stress distribution. Left to right: blank-rib tire, one-slot pattern, one-slot/one-sipe pattern.

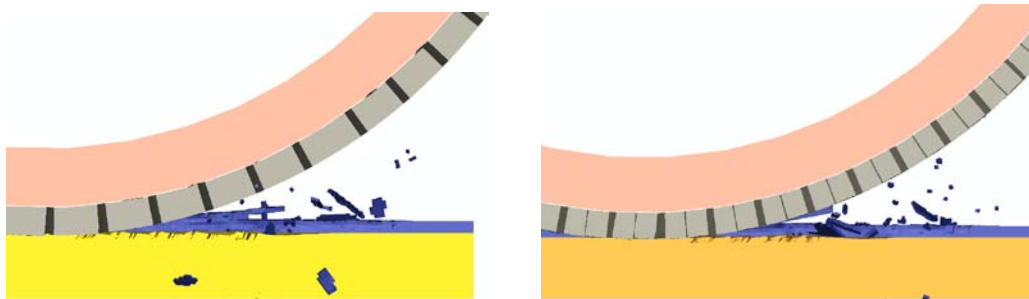


Figure 12: Centerline-view of snow sprayed behind the tire: Left: one-slot pattern; right: one-slot/one-sipe pattern.

5.2 Snow spray

The entrapped snow elements from the top-surface (medium pack) and some from the hard pack snow are removed from the snow volume due to large shear strain. These elements, seen as “debris” in the analysis, are removed from the contact formulation and from the energy balance while being retained with their last-known velocity and stress tensors. The illustration of this result is offered in Figure 12, where the snow thrown behind each of the carved patterns is compared. In the case of the of the single-slot tire, the snow “chunks” are large and well-spaced, while not traveling very high behind the tire. The size of the particles is attributed to the snow sheared inside the lateral slots. Some “delamination” of the softer medium pack elements from those of the hard

pack is observed, due to longitudinal compression-induced failure in the top snow layer and snow entrapped in grooves. In the case of the one-slot/one-sipe pattern, there is a mixture of small and large snow debris, because snow shearing in the tread slots and digging action by the sipe edges take place simultaneously. Through on-vehicle tests emulating the traction tests, the snow spray characteristics of the one-slot/one-sipe pattern were confirmed.

6. Conclusions

The above analyses required large CPU resource, with run times ranging over 24 hr on a 2-CPU 64 bit i686 EMT computer and memory demand of up to 2GB. Despite that, the described method can be adapted to a design-aiding tool when enhanced snow traction is needed.

Through a validation study, the analytical concept is proven as physically sound and allows future research to be based on the current method. Existing tread patterns could be modeled and modified to screen out designs for improved snow traction performance without having to make and test actual tires. The tread material in particular can also be evaluated for a given tread design.

There are several ways to improve the efficiency of the presented method. The analysis accuracy can be addressed by material model advances in Abaqus/Explicit which, as mentioned above, have made possible to use of the Mohr-Coulomb model. The Coupled Eulerian-Lagrangian (CEL) method can be utilized for tracing the snow behavior in and near tread features such as sipes and slots. Reduction in model complexity, especially model details outside the area of contact, could further reduce the resource demand and allow for better resolution in the footprint. Another key point could be modeling of the tire carcass response, as this was not possible due to numerical issues. This can be achieved through a global-local analysis technique.

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