

Longitudinal Interfacial Forces of the Interaction of a Treaded Tire with Snow

Jonah H. Lee

University of Alaska Fairbanks

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ABSTRACT

Although it is intuitively and qualitatively known that a treaded tire has a larger drawbar pull than a smooth tire, little is known *quantitatively* about *all* the interfacial forces *and* the origins of these forces of a treaded tire traversing a snow cover. There have been relatively few studies regarding the quantitative effects of tread pattern on tire-snow interaction due to the complexity of the tread pattern, the enormous amount of computational resources needed for high-fidelity numerical simulations, and the difficulty of measuring all the interfacial forces between a tire that is much harder than snow. The purpose of this paper is to understand the effects of a simplified tread pattern of a two-dimensional rigid tire on the interfacial forces between a tire and low-density snow. The parameters to vary included the wheel load, as well as a full-range of longitudinal slip. Snow sinkage, snow density, traction, motion resistance and drawbar pull were obtained as a function of input parameters and parts of the tire; the results were compared with those of a smooth tire. It was found that a larger shear force on the void at higher slip ratios contributes significantly to the increase of traction of a treaded tire. The treaded tire has a larger drawbar pull than the smooth tire at higher slip ratios due to a larger decrease in motion resistance relative to traction. It was also shown that the positive normal contact force on the flank increases with slip ratio, as a result of the larger torque, and is the dominant cause of the decrease of the motion resistance at higher slip ratios leading to a higher and desirable drawbar pull.

INTRODUCTION

The interfacial forces due to the interaction between soft terrain and tire are important for vehicle performance such as maneuverability, controllability and safety. Modeling of ground vehicles on soft terrain is more complicated than on hard ground due to the complexity of material properties of the terrain and its interactions with the vehicles. Additional challenges to vehicle-snow interaction involve drastic changes of material properties due to environmental conditions as well as the layered nature of snow, among other factors. These challenges

need to be addressed from both modeling and experimental point of view.

From modeling point of view, these challenges are being addressed on one hand by using probabilistic methods such as interval analysis [1], polynomial chaos [2] and metamodeling [3], and on the other hand by developing better deterministic constitutive laws of snow [4] and the detailed understanding of the mechanics of tire-snow interaction [5]. Advancement in deterministic understanding of tire-snow interaction can be cast in a probabilistic light for practical vehicle design. From methodology point of view, computational methods are often employed to conduct numerical experiments to understand the physics of vehicle-terrain interaction such that the insight gained can be used for analytical modeling which is more suitable for real-time simulation [6]. From validation point of view, the current modeling results can be used as a guideline in planning physical experiments of tire-snow interaction which are notoriously difficult to conduct due to the highly heterogeneous and soft nature of different types of snow.

The author's research group in recent years has developed tire-snow interaction models that consider the effects of snow depth, wheel load, longitudinal and lateral slip, uncertainty in snow properties, snow depth, and tire flexibility. These and other existing studies [5, 7-11], however, are all for a smooth tire without tread pattern. Tread pattern is known to improve the performance of tire for a specified function such as reduction of noise, reduction of wear and improvement of traction on different surfaces. Seta et al. [12] seem to be the first to conduct three-dimensional numerical simulations to predict tire-snow interaction forces for a rolling tire with tread pattern. Their simulations were conducted on a very shallow snow (3 cm) with one slip ratio (0.3) and for a very short period of time (< 90 ms). For a very shallow snow, the behavior of tire is similar to that on rigid ground, consequently less representative of tire-snow interaction. Although drawbar pull (called *traction* by them) was obtained, the traction and motion resistance were not separated from the drawbar pull. In

addition, the relative contributions of interaction forces due to the tread pattern were not considered as in the analytical tire-snow model [13] such that cause and effect could not be assessed.

Comprehensive three-dimensional modeling of tire-snow interaction is challenging due to the large computational resources required as well as the large amount of data that need to be analyzed and understood. For example, the detailed mechanistic studies of tire-snow interaction using three-dimensional (smooth) pneumatic tires under combined slips and different vertical wheel load [5] take more than a month CPU time for the final production run on a 4-processor computer excluding the time involved in designing, building, testing and verifying models, as well as in developing customized software to expedite the preprocessing and postprocessing of jobs. Although building a three-dimensional pneumatic tire model with realistic tread pattern is feasible [14], to include such a pattern into comprehensive simulations is difficult due to the extremely fine mesh needed to discretize snow. While it is foreseeable that computational methods will improve in the future to overcome this difficulty, scaled-down simulations may provide insight in tire-snow interaction with tread pattern to advance the development of validated analytical models, the goal to achieve for practical vehicle design.

The analytical model in [13] seems to be the first to consider tread pattern for longitudinal tire-snow interaction. Using their terminology, with our terminology in parentheses if different, the traction (drawbar pull) was considered to have four components:

1. Braking force as a result of snow compression due to tread and void (motion resistance)
2. Shear force of snow in void (traction in void)
3. Frictional force (traction on tread block)
4. Digging force

Qualitative considerations of the regimes of slip ratio were discussed but the slip ratio itself was not explicitly included. Many assumptions were made in the analytical model such that it is difficult to assess the results quantitatively.

It is then the purpose of this paper to conduct comprehensive two-dimensional studies of a rigid treaded tire on low-density snow to understand the effects of tire tread on the interfacial forces. It has been shown previously that, as a first order approximation, the deformation of tire can be ignored for low-density snow which is very soft such that the tire can be modeled as rigid. To study longitudinal behavior only, a two-dimensional analysis is justified.

Our research is novel as it differs from existing works of the interaction of treaded tire with snow in the following aspects:

1. Longitudinal slip is explicitly controlled over a large range of slip ratio.

2. The interfacial forces as a function of slip ratio and vertical wheel load are separated such that the relative contributions of motion resistance and traction are obtained.
3. The wheel states are identified.
4. The relative contributions of motion resistance and traction due to different parts of the treaded tire are quantitatively evaluated.
5. Comparisons of interfacial forces for treaded versus smooth tire are made.

In the following, we first present the finite element tire and snow model and the simulation procedure. Detailed results in interfacial forces, snow sinkage, and snow density are then presented. The paper closes with discussion and conclusion.

FINITE ELEMENT MODEL AND PROCEDURE

FINITE ELEMENT TIRE AND SNOW MODEL

We used the general purpose finite element program Abaqus Explicit 6.6 [15] for all the simulations. The rigid tire has a radius of 0.365 m using element R2D2. The smooth tire is discretized into 208 nodes and elements. The treaded tire has 30 evenly distributed tread blocks where each tread block has a nominal depth of 1 cm. Fillets were introduced at the intersections between the void and the side (flank) of the tread block, as well as between the side and top of the tread block to alleviate stress concentration. The tire was discretized into 810 nodes and elements. It is noted that the rigid tire has the nominal dimensions of the 3-D high-fidelity pneumatic tire used previously in [5]. The snow model used in this paper, discussed in the Appendix, is the Modified Capped Drucker-Prager model developed for 200 kg/m^3 low-density snow described in [16] and also utilized in [5] where a high cohesion value of 30 kPa was used to represent snow that has undergone some bonding. The snow cover has a depth of 20 cm, length of 2.3 m and a width of 0.2 m modeled under plane strain condition (element CPE4R). For smooth tire, the snow domain was discretized into 4,503 nodes and 4,248 elements where the nominal length of each element is 1.11 cm. For treaded tire, the nominal length of each element of the snow model is 0.44 cm resulting in 26,595 elements and 27,232 nodes. The bottom and sides of the snow were fixed in the simulations. The coefficient of friction between the tire and the snow is 0.3. The Arbitrary Lagrangian Eulerian (ALE) feature of Abaqus was used.

SIMULATION PROCEDURE AND CONDITIONS

The simulation procedure is the same for smooth and treaded tire and consists of two steps:

1. Indentation of the rigid tire on snow with a given vertical wheel load in 0.3 second

- Rolling of the tire over snow in 1 second with the same constant vertical load in step 1 with a given linear velocity (2 m/sec) and angular velocity depending on the slip ratio

The simulation conditions are given in Table 1.

Table 1 Simulation conditions.

Tire	Load (N)	Slip Ratio
smooth	4,500	-0.12, -0.16, -0.2, -0.3, -0.4, -0.04, -0.08, 0.0, 0.1, 0.15, 0.2, 0.4
smooth	6,240	-0.12, -0.16, -0.2, -0.3, -0.4, -0.04, -0.08, 0.0, 0.1, 0.15, 0.2, 0.4
treaded	4,500	-0.12, -0.16, -0.2, -0.3, -0.4, -0.04, -0.08, 0.0, 0.1, 0.15, 0.2, 0.25, 0.3
treaded	6,240	same as smooth

The slip ratio, i , is defined by

$$i = 1 - \frac{v_x}{r\omega} \quad (1)$$

where v_x is the longitudinal velocity of the wheel center, ω is the angular velocity of the wheel and r is the radius of the tire. For treaded tire, r is the radius of the outer surface of the tread. Step 1 is run only once for a given wheel load and tire type (smooth or treaded). Step 2 is run for each slip ratio for a given load and tire type.

SUMMARY OF MODELING ASSUMPTIONS

The major assumptions made in this paper are as follows:

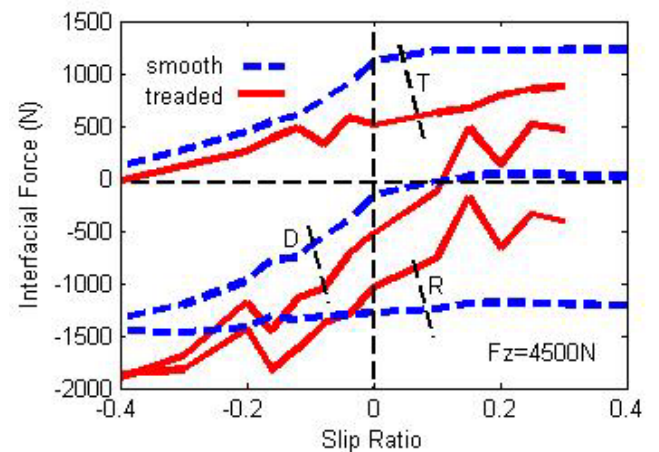
- Snow is fresh, homogeneous of 200 kg/m^3 with moderate cohesive strength representing a modest amount of bond formation (sintering).
- Snow can harden when compacted but failure of snow is not considered.
- The tire is rigid and two-dimensional with a single tread pattern.
- The coefficient of friction between tire and snow is constant.

INTERFACIAL FORCES AND WHEEL STATES

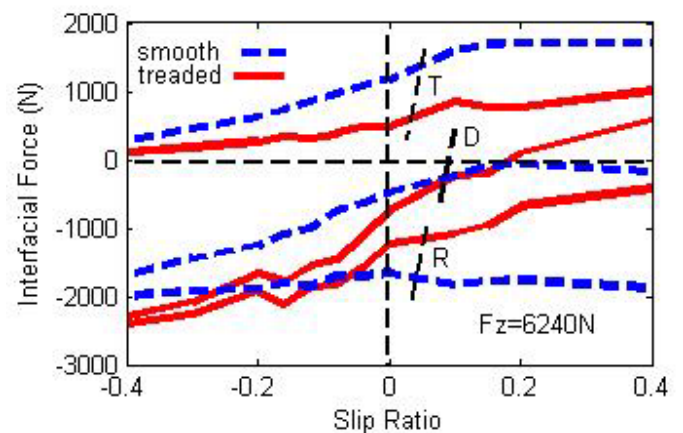
The simulations are fully dynamic such that all variables of interest are a function of time. The intent of the current research is to obtain quasi-static conditions to understand the cause and effect of input parameters such that analytical formulations can be advanced. Consequently, the results are averaged over a time window close to the end of the simulations or at a representative quasi-static time.

There are three interfacial forces, positive to the right in the positive x-direction: traction (T), motion resistance (R) and drawbar pull (D) related by [17]

$$D = T + R \quad (2)$$



(a) $F_z = 4,500\text{N}$



(b) $F_z = 6,240\text{N}$

Figure 1 Interfacial forces for smooth and treaded tire versus slip ratio.