

Tire Traction of Commercial Vehicles on Icy Roads

Anudeep K. Bhoopalam, Corina Sandu, and Saied Taheri
Virginia Tech

ABSTRACT

Safety and minimal transit time are vital during transportation of essential commodities and passengers, especially in winter conditions. Icy roads are the worst driving conditions with the least available friction, leaving valuable cargo and precious human lives at stake. The study investigates the available friction at the tire-ice interface due to changes in key operational parameters. Experimental analysis of tractive performance of tires on ice was carried out indoor, using the terramechanics rig located at the Advanced Vehicle Dynamics Laboratory (AVDL) at Virginia Tech. The friction-slip ratio curves obtained from indoor testing were inputted into TruckSIM, defining tire behavior for various ice scenarios and then simulating performance of trucks on ice. The shortcomings of simulations in considering the effects of all the operational parameters result in differences between findings of indoor testing and truck performance simulations. Thus, the need for state-of-the-art tire-ice models capable of predicting accurate friction levels taking into account all operational conditions becomes evident. Advanced simulation models reduce the heavy cost involved in experimental studies. A thorough understanding of the operational factors on braking and tractive performance of commercial vehicles with the aid of simulations and experiments will lead to specialized tire designs and safety systems for commercial vehicles operating on ice.

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INTRODUCTION

Motivation and Background

Commercial vehicles are widely used in the United States for hauling freight and passengers across the country. In 2008, truck shipments accounted for 67% of the 16.1 billion tons of freight shipped in the U.S., and it is estimated that by 2040, trucks will haul 68% of the 27 billion tons of freight shipped in the U.S. [1], an increase of about 70%.

Over 70% of the roads in the U.S. lie in regions that receive more than 0.13 m of annual snowfall [2]. The 10-year average for (2002-2012) accident data shows that vehicle crashes on ice accounted for 12% of the 1.3 million weather-related crashes [2]. 580 deaths occurred and 45,133 persons were injured while driving on ice, in between 2002-2012 [2]. The probability of accident occurrence increases with a decrease in surface coefficient of friction [3]. Icy roads are the worst driving conditions with the least available friction at the tire-ice interface.

Factors Affecting Friction at the Tire-Ice Interface

The factors that contribute to the complex frictional mechanism at the tire-ice interface were grouped into three main categories: the ice and ambient conditions, the tire

specifications, and the vehicle specifications [4]. Ambient conditions include ambient temperature and humidity present in the atmosphere. The ambient temperature decides if the frictional mechanism is of wet or dry in nature. At temperatures close to 0° C wet friction is predominant, while at lower temperatures dry friction is seen. The atmospheric humidity content leads to formation of a frost layer on the ice surface, thus the friction levels vary with change in humidity. Strong winds often carry dust and other impurities, which settle on the ice surface also altering the surface properties and thereby the friction coefficient.

The salt and impurity content of the water which freezes to ice, also had an effect on the friction levels of the resulting ice surface. Skouvakis et al. [5] showed from their experiments that water with higher salt and impurity content exhibits lower friction coefficients with a decrease of around 15% at low temperatures. At temperatures close to 0° C, a lesser percentage decrease was observed [5]. Eddie [6] observed a very significant variation in braking performance on ice, even when maintaining consistent weather conditions during testing; the variation in traction levels were observed with change in local surface texture of ice. Other ice parameters that affect the available friction levels are age of the ice track and the surface temperature. The experiments by Roberts [7] showed a reduction of friction with older ice tracks and higher friction

coefficients with lower ice surface temperatures. An increase of close to 100% was seen in the friction coefficient, in the temperature range -20 to -10°C in [7].

The properties of the ice formed on the asphalt roads differ from region to region, due to differences arising from water properties and rates of rainfall and snowfall. When local texture differences cause variation in braking performance [6], the challenges in a comprehensive experimental study and the development of a comprehensive tire-ice model, must be envisioned. In addition to the diversity of the ice formed on roads, the change in ice conditions with time due to vehicle passes and change in ambient conditions must also be accounted. The investigation of tire-ice mechanisms for development of vehicles and tires with consideration of all the affecting factors is a demanding task. Winter accident reconstruction is even more challenging, the time being the major factor that alters the properties of the ice-covered roads. Thus, learning from accidents on icy roads to design vehicles and tires for improved safety is a herculean task.

The tire is the only part of the vehicle that contacts the ice-covered road, and plays a major role in the tractive and braking performance of the vehicle. The tread pattern and compound are the main elements that determine the tire's performance on ice. The effect of the normal load on the tire and the tread depth during longitudinal traction on ice was studied in [8] and described in the later sections of this paper. An interesting study to understand the influence of tread pattern, during operation on ice was published by the Swedish Road and Transport Research Institute [9]; the presence of hard aggregates in the tread rubber yielded in an increase of friction coefficient by 70% during braking. Roberts [7] also observed that the higher the resilience of the rubber compound, the higher the available friction levels at low ice temperatures.

Diversity in today's available passenger cars and trucks also require the need to account for the vehicle type, the transmission type, the braking system, and other safety systems on the vehicle during analysis of the vehicle performance on ice. Tire-Rack's [10] tests on ice by driving an AWD and a RWD showed the minimal aid provided by the traction and stability control systems in increasing traction, the winter tires on the vehicle played a significant role in providing traction. The presence and absence of the ABS was studied in [6] and found not to be the governing factor in deciding braking performance, but it was the ambient temperature that had a major effect.

Indoor and Outdoor Testing

Indoor test rigs provide the advantage of experimental investigation with controlled and repeatable ice and ambient conditions. Indoor test rigs are usually quarter-car-based and employed to test tires and their interaction with different terrains, the disadvantage being that the effects of

suspensions, braking systems, powertrains, etc., cannot be captured. The only option to study the effects of all these vehicle systems is to conduct experiments using the vehicle in large indoor test facilities. Climate-controlled indoor vehicle test facilities capable of testing vehicles on ice are very few. Various indoor test facilities capable of evaluating tire performance on ice and other factors influencing outdoor testing are described in [4].

Outdoor testing is usually conducted on shallow fields; testing on frozen lakes could be dangerous at times, with cracking of the top layer of the frozen ice. Scheduling outdoor testing on ice is a major problem; sudden snowfalls usually require postponing the entire testing program to ensure repeatable ice surface conditions. Testing on ice is also usually conducted during the night, such that not to have the effect of solar load. ASTM-1572 [11] and ASTM-1805 [12] are standard outdoor test procedures for evaluation of tire performance on snow and ice-covered roads. ASTM-1572 describes procedures for testing different driving maneuvers during braking and lateral traction and ASTM-1805 outlines procedures for longitudinal traction during straight-line travel. Care must also be taken to keep the ice surface homogeneous and the settlement of impurities on the surface must be avoided.

In 2000, Pottinger et al. [13] experimented with a new approach to evaluate light truck tires. A semi-tractor and a light truck were attached to each other. The light truck was the test vehicle and the semi-tractor was the anchor vehicle that maintains the desired speed and orientation of the test vehicle. The proposed approach in [13] reduces the variability by maintaining desired test conditions with aid of the anchor vehicle. In order to be able to directly compare indoor and outdoor test results, all parameters that may affect the test results must be perfectly controlled and kept identical indoor and outdoor. This is a very challenging task. Instead, the outdoor test results are usually benchmarked against indoor test results just for a qualitative analysis, and not for a direct quantitative comparison.

Tire-Ice Models

Tire-ice models are vital in predicting tire performance on ice, with consideration of all the tire, ice, and ambient parameters. Minimal tire-ice models are available today, which consider all friction contributing factors into account for simulations. The challenges include consideration of the water content from which ice was formed; the cloudiness and texture of ice; the contamination and aggregates on the ice surface. Physical methods of modeling require consideration of large variety of conditions to be considered for the generation of simulations. Curve-fitting modeling techniques require execution of very large testing programs with all possibilities of test conditions. Analytical or semi-analytical approaches seem to be a preferred method of modeling tire performance on ice.

Peng et al. [14] model, based on the principle of thermal balance and theory of heat balance, simulates the tractive performance of tires on ice. The model considers the thermal parameters of the ice and the tread rubber and computes the heat generated in the contact patch. A heat balance is performed at the interface assuming the heat generated is conducted into the ice surface and the tread rubber, for an elliptical and rectangular contact patch. The simulations were validated against the experimental findings from the indoor test rig. Future recommendations included consideration of surface contamination, texture, and inflation pressure.

Comprehensive tire-ice models would also be very useful for reconstructing accidents on icy roads. All-inclusive tire-ice models are the need of the day and their integration with all-inclusive vehicle models would result in accurate simulations with negligible error as compared to field tests in realistic conditions.

A detailed literature review on the tire-ice studies, the friction contributing factors, percentage change in friction levels, test facilities, and tire-ice models can be found in [4].

EXPERIMENTAL STUDIES AT AVDL

The terramechanics rig shown in Figure 1, housed at the Advanced Vehicle Dynamics Laboratory [8, 15], is a unique, one-of-its-kind test facility developed to help study the interaction between tires and different terrains. The terramechanics rig was employed to conduct studies to investigate the friction levels at the tire-ice interface, during longitudinal driving. A buffed and a treaded P225/60R 16 97S Standard Reference Test Tire (SRTT) were the candidate tires as in Figure 2, and the test method and test conditions are described in [8]. The tests were conducted for 12 different slip ratios, data was recorded at steady state slip values for a time period of 20 seconds and the drawbar-pull-slip ratio curves were developed for multiple test conditions. The test rig is equipped with two motors; one controls the movement of the carriage along the terramechanics rig and the second controls the torque on the wheel. After the effective rolling radius is estimated [8], the speed of the motor is input into the motor control to achieve the desired slip ratio in the tire-ice contact patch. Initial procedures conducted before every test run included: resurfacing the ice surface and ensuring that the tire runs on fresh ice for every test run. The resurfacing procedure guarantees a repeatable ice surface condition for each and every test run. The tire was also cooled down to ice surface temperature before every test run using a cooling chamber, ensuring both the tire and the ice are at the same temperature during testing. Phase-I of the testing program included studying the effect of normal load and tread depth at different slip ratios. A detailed description of the test procedures, test conditions, and the drawbar-pull-slip curves for phase-I of the testing program can be found in [8].



Figure 1. Terramechanics rig at the Advanced Vehicle Dynamics Laboratory, employed for study of tire-ice interactions.

Phase II of the testing program consisted of experiments to study the effect of inflation pressure, ice temperature, and ambient temperature, the design of experiment matrix for the testing program is as in Table 1. The ice surface temperature was varied by changing the set point temperature of the ice making system. A cooler bag was built and installed around the tire that allowed evaluation of tire performance at different ambient temperatures. The influence of applying aggregates on the ice surface was also studied by conducting experiments on wet ice, dry ice, soil on ice and soil with slush on ice.



Figure 2. Tread pattern of the P225/60R 97S SRTTs tested on ice. The tire on the left has been buffed to have a tread depth of 1.6 mm and the tire on the right has full tread.

Table 1. Design of experiment matrix for indoor testing on the terramechanics rig. Each test condition was repeated three times and conducted at 12 different slip ratios

Conditions	No. of Levels	Level-1	Level-2	Level-3
Normal Load	3	60% Load Index- 4000 N	100% Load Index- 7000 N	120% Load Index- 8500 N
Tires	2	Treaded SRTT	Buffed SRTT	
Ice Temperature	2	-3°C	-10°C	
Inflation Pressure	3	60% Nominal Pressure 145 kPa	100% Nominal Pressure 242 kPa	120% Nominal Pressure 276 kPa