

**ADA Notice**

For individuals with sensory disabilities, this document is available in alternate formats. For information call (916) 654-6410 or TDD (916) 654-3880 or write Records and Forms Management, 1120 N Street, MS-89, Sacramento, CA 95814.

1. REPORT NUMBER CA16-2732	2. GOVERNMENT ASSOCIATION NUMBER	3. RECIPIENT'S CATALOG NUMBER
4. TITLE AND SUBTITLE Evaluation of Devices for Improving Traction Control in Winter Conditions		5. REPORT DATE July 31, 2016
		6. PERFORMING ORGANIZATION CODE AHMCT Research Center, UC Davis
7. AUTHOR George W. Burkett & Steven A. Velinsky		8. PERFORMING ORGANIZATION REPORT NO. UCD-ARR-16-07-31-01
9. PERFORMING ORGANIZATION NAME AND ADDRESS Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center Department of Mechanical & Aerospace Engineering University of California, Davis Davis, California 95616-5294		10. WORK UNIT NUMBER
		11. CONTRACT OR GRANT NUMBER 65A0568 Task 2732
		13. TYPE OF REPORT AND PERIOD COVERED Final Report June 15, 2015 – July 31, 2016
12. SPONSORING AGENCY AND ADDRESS California Department of Transportation PO Box 942873, MS #83 Sacramento, CA 94273-0001		14. SPONSORING AGENCY CODE Caltrans
15. SUPPLEMENTARY NOTES		
16. ABSTRACT Winter storms can deposit snow and ice on California's highways, which results in a significant loss of friction at the tire-road interface. The reduced friction in turn reduces the ability of vehicles to maintain stability and control, thus creating hazardous conditions. Accordingly, many states, including California, require the use of traction control devices, such as tire chains, on travelling vehicles to improve safety under winter conditions. A wide variety of winter traction control devices are available, and many devices are under development. While traction control devices are required in numerous states under extreme winter conditions, no uniform standards exist for their use or for their qualification testing. This report documents a survey of winter traction control devices and categorizes them according to their structures. Second, this report discusses the various methods used to measure road friction under winter conditions with the aim to understand how traction control devices can be tested and thus qualified for use. This work has investigated the methods used by transportation agencies, and we have found that only three government agencies use qualification testing. Each method uses a comparative approach, with the traditional snow chain serving as the baseline device.		
17. KEY WORDS tire friction; traction control device; tire chains; vehicle testing	18. DISTRIBUTION STATEMENT No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.	
19. SECURITY CLASSIFICATION (of this report) Unclassified	20. NUMBER OF PAGES 48	21. COST OF REPORT CHARGED

Reproduction of completed page  
authorized.

## DISCLAIMER/DISCLOSURE STATEMENT

The research reported herein was performed by the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center, within the Department of Mechanical and Aerospace Engineering at the University of California – Davis, for the Division of Research, Innovation and System Information (DRISI) at the California Department of Transportation. AHMCT and DRISI work collaboratively to complete valuable research for the California Department of Transportation.

The contents of this report reflect the views of the author(s) who is (are) responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the STATE OF CALIFORNIA or the FEDERAL HIGHWAY ADMINISTRATION. This report does not constitute a standard, specification, or regulation.

The contents of this report do not necessarily reflect the official views or policies of the University of California. This report does not constitute an endorsement of any products or services described herein.

For individuals with sensory disabilities, this document is available in Braille, large print, audiocassette, or compact disk. To obtain a copy of this document in one of these alternate formats, please contact: the Division of Research, Innovation and System Information, MS-83, California Department of Transportation, P.O. Box 942873, Sacramento, CA 94273-0001.



# **Advanced Highway Maintenance and Construction Technology Research Center**

Department of Mechanical and Aerospace Engineering  
University of California at Davis

## **Evaluation of Devices for Improving Traction Control in Winter Conditions**

George W. Burkett: Development Engineer  
Steven A. Velinsky: Principal Investigator

Report Number: CA16-2732

AHMCT Research Report: UCD-ARR-16-07-31-01

Final Report of Contract: 65A0568

Task ID: 2732

July 31, 2016

## **California Department of Transportation**

Division of Research, Innovation and System Information

## ABSTRACT

Winter storms can deposit snow and ice on California's highways, which results in a significant loss of friction at the tire-road interface. The reduced friction in turn reduces the ability of vehicles to maintain stability and control, thus creating hazardous conditions. Accordingly, many states, including California, require the use of traction control devices, such as tire chains, on travelling vehicles to improve safety under winter conditions. A wide variety of winter traction control devices are available, and many devices are under development. While traction control devices are required in numerous states under extreme winter conditions, no uniform standards exist for their use or for their qualification testing. This report documents a survey of winter traction control devices and categorizes them according to their structures. Second, this report discusses the various methods used to measure road friction under winter conditions with the aim to understand how traction control devices can be tested and thus qualified for use. This work has investigated the methods used by transportation agencies, and we have found that only three government agencies use qualification testing. Each method uses a comparative approach, with the traditional snow chain serving as the baseline device.

## EXECUTIVE SUMMARY

Winter driving is inherently more hazardous due to a reduction in friction (also known as traction) at the tire-road interface caused by snowfall and ice formation on the road surface. The California Department of Transportation (Caltrans) has procedures in place that help improve vehicle traction by mechanically clearing the road and applying surface treatments such as de-icers, and/or abrasives. Many states, including California, require the use of traction control devices, such as tire chains, on vehicles travelling along specific road locations to improve safety under winter conditions. In California, vehicles are visually inspected to ensure that such devices are installed for use on these roads.

A wide variety of winter traction control devices are available, and many devices are under development. This research has compiled and classified both available traction control devices and those under development. Traditional traction control devices include mud and snow tires, studded tires, traditional tire chains, and cable chains. Additionally, numerous nontraditional devices exist, including, but not limited to, variations on traditional tire chains, textile devices, and various cleated systems.

While traction control devices are required in numerous states under extreme winter conditions, no uniform standards exist for their use or for their qualification testing. This report discusses the various methods used to measure road friction under winter conditions with the aim to understand how traction control devices can be tested and thus qualified for use. As such, this report provides a brief overview of tire friction to help understand the requirements for road friction testing. While there are specific methods and products for measuring friction, any general qualification test procedure must be physically compatible with the variety of traction control devices currently available and under development. This presents a significant challenge considering the variety of products and test instrumentation must allow for the mounting of the various devices while still providing accurate measurement.

This work identifies the guidelines for traction control devices in all states. Some states merely articulate the permitted traction control devices, whereas other states have enforceable chain control requirements. This work also considers the methods employed by government agencies to accept the use of a particular traction control device. Only three government agencies use detailed qualification testing for traction control devices. In all of these test guidelines, a traction control device must perform at least as well as the traditional tire chain. The direct comparison of devices is a challenge, as test procedures need to account for changing environmental conditions from one test to the next.

This research provides several recommendations for future traction control device research. First, it is necessary to develop very specific test procedures and associated performance criteria

to assess and ultimately accept any traction control device. Second, methods need to be developed to disseminate information on accepted devices to the travelling public, DOT employees, and law enforcement officers in order to ensure that proper use and enforcement takes place.

Concerning test procedures, existing approaches require that traction devices perform at least as well as the reference, the traditional tire chain. Since road conditions vary continually according to environmental conditions, the comparison between any device and chains needs to occur on the same road at the same time. Thus, it would be ideal to perform such a comparison in real time, which requires the development of new measurement devices. Moreover, many of the commercially available friction measurement devices are not geometrically compatible with the variety of available and future traction devices; new measurement devices therefore need to be developed to overcome this issue.

In addition to the development of measurement devices, performance requirements should be established for the minimum acceptable friction between the traction control device and the road under a variety of conditions. This will facilitate the development and future acceptance of new traction control devices based on quantifiable data.

Once sound methods for the acceptance of traction control devices are implemented, these standards should be disseminated to traction control product manufacturers for the purpose of certifying their products. Lists of approved products then could be made readily available to the travelling public in order to remove their uncertainty. Moreover, Caltrans chain inspectors and law enforcement would all have the same knowledge of the accepted products and their proper use. Optimally, such an approach would be implemented nationally.

In summary, using traction devices under winter conditions helps to maintain the safety of the motoring public when travel is required. This is accomplished due to the improved frictional characteristics at the vehicle-road interface when traction devices are implemented. Developing a detailed test method and associated approval process will lead to the proper use of devices, safer roadways, and fair enforcement, thus benefiting all.

## TABLE OF CONTENTS

Abstract.....	iii
Executive Summary.....	iv
Table of Contents.....	vi
List of Figures.....	viii
List of Tables.....	ix
List of Acronyms and Abbreviations.....	x
Chapter 1. Introduction.....	1
1.1 Report Outline .....	2
Chapter 2. Traction Control Products and Availability.....	4
2.1 Introduction .....	4
2.2 Traditional Traction Devices.....	4
2.2.1 Mud and Snow Tires.....	4
2.2.2 Tires for Use in Severe Snow Conditions .....	5
2.2.3 Studded Tires .....	5
2.2.4 Traditional Chains .....	6
2.2.5 Cable Chains.....	6
2.3 Nontraditional Traction Devices .....	6
2.3.1 Variations of Traditional Chains .....	6
2.3.2 On-demand Chains .....	7
2.3.3 Temporary Studded Tire.....	8
2.3.4 Textile Devices .....	9
2.3.5 Continuous Surface Cleat Systems.....	10
2.3.6 Cleated Systems Using Discretely Attached Elements .....	11
2.3.7 Miscellaneous Devices .....	12
2.4 Summary.....	14
Chapter 3. Investigation of Testing Methods for the Measurement of Coefficient of Friction in Winter Conditions .....	15
3.1 Friction Background and Key Terms .....	15

3.1.1 An Overview of Tire Friction .....	15
3.2 Tire Testing Methods .....	17
3.2.1 The Direct Method for Tire Friction Testing.....	17
3.2.2.1 The Fixed Slip Angle Approach.....	18
3.2.2.2 Longitudinal Methods .....	19
3.2.2 The Indirect Method for Tire Friction Testing .....	22
3.2.2.3 Skid Pad Testing.....	22
3.2.2.4 The Pull Test.....	23
3.2.2.5 Spin Up Testing.....	24
3.3 Normal Load Measurement.....	24
3.4 Environmental Considerations .....	24
Chapter 4: Acceptance Methods Used in Transportation Agencies .....	26
4.1 Existing Test Methods.....	26
4.2 Summary of Approved Traction Devices.....	28
Chapter 5. Conclusions and Recommendations .....	33
5.1 Conclusions .....	33
5.2 Recommendations .....	33
References .....	35



## LIST OF FIGURES

Figure 1. Typical Cable Chain.....	6
Figure 2. (a) TRAK Sport, (b) Spikes Spider (Sport and Alpine Pro), and (c) Thule K-Summit Low-Profile Passenger Car Snow Chain.....	7
Figure 3. Generalized ATD Installation (Onspot, Similar to Insta-Chain and Roto-Grip) .....	8
Figure 4. Spikes-Spider Compact.....	8
Figure 5. Michelin Easy Grip Composite Tire Snow Chain.....	9
Figure 6. Nokian Hakkapeliitta 8 Concept Tire Showing Stud Retracted and Deployed [7].....	9
Figure 7. (a) AutoSock, (b) Shark Classic Issue Snow Sock, (c) Fit and Go Tech Sox.....	10
Figure 8. Snobootz Installation Image.....	11
Figure 9. MITA Chain System .....	11
Figure 10. (a) ZipGripGo, (b) SnowGripz, (c) Truck Super Sector Schneeketten, (d) Bang Theory Universal Car Snow Chain, (e) AUMO-mate® Car Snow Tire Anti-skid Chains and (f) Carsun 2015 .....	12
Figure 11. Typical Wheel Sander .....	13
Figure 12. Tyre-Grip - Spray to enhance tire traction on snow/ice.....	13
Figure 13. (a) Go Claws/Flex-Trax, (b) Terragrips, (c) Proyecto Snow Chain, (d) TASAT Snow Chain, and (e) Snow Monkey .....	13
Figure 14. The Tire Friction Ellipse .....	16
Figure 15. SCRIM Layout [20] .....	19
Figure 16. Mu-Meter: (a) Unit Close Up, (b) Unit With Water Tank.....	19
Figure 17. (a) GEM Hub, (b) RT3 Grip, and (c) RT3 Curve .....	19
Figure 18. SAAB Friction Tester .....	20
Figure 19. Dynatest 1295 Pavement Friction Tester (PFT).....	21
Figure 20. International Cybernetics System (Variable Slip System).....	21
Figure 21. ViaFriction Winter Trailer: (a) Without Water System and (b) With Water System .....	22
Figure 22. Grip Tester .....	22
Figure 23. Generalized Pull Test Configuration.....	24

## LIST OF TABLES

Table 1. Caltrans Chain Control Designations and Requirements [2] .....	5
Table 2. Summary of Traction Devices.....	14
Table 3. Friction Values From NCHRP Report [32].....	27
Table 4. Summary of Information for Other States.....	32

## LIST OF ACRONYMS AND ABBREVIATIONS

<b>Acronym</b>	<b>Definition</b>
ABS	Anti-lock Braking System
AHMCT	Advanced Highway Maintenance & Construction Technology Research Center
ASTM	American Society for Testing and Materials
ATD	Automated Traction Device
Caltrans	California Department of Transportation
DOT	Department of Transportation
ESC	Electronic Stability Control
M+S	Mud and Snow
NCHRP	National Cooperative Highway Research Program
NRS	Nevada Revised Statute
ÖNORM	Österreichisches Normungsinstitut, English: Austrian Standards Institute
PIARC	Permanent International Association of Road Congresses
SCRIM	Sideway-Force Coefficient Routine Investigation Machine
TCS	Traction Control System
TÜV	Technischer Überwachungsverein, English: Technical Inspection Association
WAC	Washington Administrative Code

## CHAPTER 1. INTRODUCTION

Winter storms that include precipitation have the potential to impact nearly every aspect of daily life. Even a temporary shutdown of transportation infrastructure can have long-lasting effects on the goods and services on which people rely. On a local and regional level, winter storms impede people's ability to commute to work and participate in the economy, leading to lost wages and a decrease in productivity. On a national scale, they slow the movement of goods and resources traveling over roadways. As such, the California Department of Transportation (Caltrans) attempts to keep as many routes open as possible during winter storm events, while ensuring, as much as possible, the safety of the travelling public. Caltrans has a winter maintenance plan designed to manage the road surface in order to provide the public with safe driving conditions [1]. Their plan includes a combination of methods including, but not limited to, clearing snow, deicing, and using abrasives to enhance road friction.

Water, snow, and ice on the roadway surface reduce the frictional properties of the tire-road interface as compared with dry pavement. Since all vehicle control forces pass through the tire-road interface, it is important to maximize the road's surface friction to ensure safe vehicular operation. Tires are designed to channel water away from the tire-road interface to help maintain a maximum level of friction in wet conditions. Additionally, a class of products referred to as "tire traction devices" have been developed in order to help improve friction in snowy and/or icy conditions. At times, Caltrans requires the use of tire traction devices, and detailed guidelines on the utilization of these devices is provided on its website [2].

Tire traction devices generally surround a vehicle's power driven tires in order to improve the friction between the vehicle and the road. Traditionally, the term "tire traction device" has been synonymous with "chains." Moreover, storm events in which Caltrans requires the use of tire traction devices for vehicles to travel on impacted roads are commonly referred to as "chain controls." Recently, however, new products have been developed that differ from the general description of chains. Developers of these new tire traction devices would like their products to meet legal requirements so that their use is allowed during winter storm events. Because some of these new devices are manufactured from nontraditional materials such as plastics, there is concern about both their efficacy as traction devices and their durability.

The California vehicle code section 605 defines tire traction devices as follows:

*"Tire traction devices" are devices or mechanisms having a composition and design capable of improving vehicle traction, braking, and cornering ability upon snow or ice-covered surfaces. Tire traction devices shall be constructed and assembled to provide sufficient structural integrity and to prevent accidental*

*detachment from vehicles. Tire traction devices shall, at the time of manufacture or final assembly, bear a permanent impression indicating the name, initials, or trademark of the assembling company or primary manufacturer, and the country in which the devices were manufactured or assembled in final form.*

While the above vehicle code defines traction devices, it provides no quantification of the expected improvement in tractive forces, nor does it establish any associated standards. Additionally, there is no unifying federal policy on traction control devices, and states typically have independent acceptance criteria. Establishing a federal policy on product acceptance could have a positive impact on the interstate transportation of goods.

The aim of this study is to develop methods for the evaluation of traction control devices. A more quantitative approach is necessary to establish clear standards and promote the qualification of these devices. Moreover, such standards could promote the development of new and improved traction control devices.

The Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center was tasked with performing an extensive study of traction control devices, with an emphasis on quantifying the friction characteristics between the vehicle and the roadway. The specific tasks of this research were:

1. The investigation of traction control products and their availability
2. The investigation of testing methods for the measurement of the coefficient of friction in winter conditions
3. The development of the experimental approach and detailed experimental design
4. Data acquisition and processing
5. Engineering analysis
6. Documentation

This report is the primary deliverable for task 6 and documents the results of the research.

## **1.1 Report Outline**

The goal of this research was to develop an understanding of the efficacy of traction control devices in winter driving conditions. Since the project was terminated at the end of tasks 1 and 2, only the results of those two tasks are discussed herein. Accordingly, Chapter 2 addresses the types of traction devices that are commercially available. Chapter 3 discusses the results of a detailed literature search aimed at understanding the current methods used for testing the tire-road coefficient of friction in winter conditions. Chapter 4 presents the methods employed by the

various transportation agencies for accepting tire traction control devices and summarizes the approved products. Chapter 5 provides the conclusions and recommendations of this research.

## CHAPTER 2. TRACTION CONTROL PRODUCTS AND AVAILABILITY

This chapter provides the results of a search aimed at identifying the variety of traction control products, the degree of their use, and their availability. The goal was to identify the most widely available and used devices with the most likely possibility for application in California. This chapter also includes a discussion of traction control policies and standards from California and other states.

### **2.1 Introduction**

Tire traction devices have been widely available for many years. Traditionally, four main groups of products have been used. However, numerous new products have recently become available or are being developed. Some of these new devices satisfy European traction aid requirements for road use and have been accepted by European transportation agencies. There are also products that are specifically intended for use in emergency situations. The following sections summarize the variety of traction control products.

### **2.2 Traditional Traction Devices**

There are essentially four traditionally used groups of traction devices, which include mud and snow tires, studded tires, steel chains, and cable chains. Snow tires and studded tires have design features incorporated into the tire carcass in order to improve traction. Given the nature of these devices, the tires are typically installed at the beginning of the snow season and removed at its conclusion. Steel chains and cable chains are also regularly employed in low traction conditions. Since these devices are mounted on the outside of the tire, they are installed on an as-needed basis.

#### **2.2.1 Mud and Snow Tires**

Mud and snow tires, which are designated by “M+S”, “MS,” or ”M/S,” are known to improve traction in winter conditions. These tires satisfy the California chain requirements for all vehicles under R-1 conditions and the R-2 requirements for four-wheel and all-wheel drive vehicles [3]. The chain requirements for the various “R” designations are presented in Table 1.

**Table 1. Caltrans Chain Control Designations and Requirements [2]**

Designation	Requirements
R-1	Chains are required on all vehicles except passenger vehicles and light-duty trucks under 6,000 pounds gross weight and equipped with snow tires on at least two drive wheels. Chains must be carried by vehicles using snow tires. All vehicles towing trailers must have chains on one drive axle. Trailers with brakes must have chains on at least one axle.
R-2	Chains are required on all vehicles except four-wheel drive vehicles under 6,500 pounds gross weight and equipped with snow tires on all four wheels. Chains for one set of drive wheels must be carried by four-wheel drive vehicles using snow tires.
R-3	Chains are required on all vehicles without exception.

### 2.2.2 Tires for Use in Severe Snow Conditions

The American Society for Testing and Materials (ASTM) E-1136 standard reference test is regularly used to evaluate tires. In particular, tires that receive a traction index of 110 or greater with the ASTM F-1805, 2006 snow traction test are termed tires for use in severe snow conditions[4]. In addition to a mud and snow designation, they are marked with a pictograph of a mountain with a snowflake to clearly indicate their rating. These types of tires are manufactured with a more aggressive tread and typically a softer rubber compound than traditional tires and these aspects allow for higher frictional properties at the contact patch. These types of tires are used seasonably since they tend to wear more rapidly and provide lower overall dry road performance than tires without such a designation.

### 2.2.3 Studded Tires

Studded tires are basically mud and snow tires with embedded small metal cleats to provide additional traction. Unfortunately, the embedded metal spikes tend to damage the roadway. There is no way to remove and reinstall the spikes while keeping the tires intact. Given the nature of the traditional studded tires, unless the tires are removed following storm events, it is inevitable that road damage will occur during the winter driving season. Accordingly, some states do not allow the use of studded tires at any time, while other states specify date ranges during which these tires can be used. Some states, including California, do not consider studs as a traction device.



### **2.2.4 Traditional Chains**

Snow chains are the most common tire traction devices used, and they are allowed in many states. There are very few detailed specifications provided on the chain construction, and some states merely dictate that vehicles must use chains of reasonable proportion. The construction of snow chains consists of two circular rings connected by a series of cross-link strands. The two rings are placed on opposite sides of the tire, whereas the cross-link strands extend across the tire periphery that contacts the road. Several states specify the number of cross-link strands; the most common number is nine.

### **2.2.5 Cable Chains**

Cable chains, as shown in Figure 1, are very similar in construction to traditional snow chains. In the case of cable chains, however, the two rings are constructed of cable. The cross-link strands are also primarily constructed of cable, but, additionally, have a number of generally cylindrical steel parts that surround the cable and provide further tractive ability. Cable chains are significantly lighter than traditional chains and are also slightly easier to mount.



**Figure 1. Typical Cable Chain**

## **2.3 Nontraditional Traction Devices**

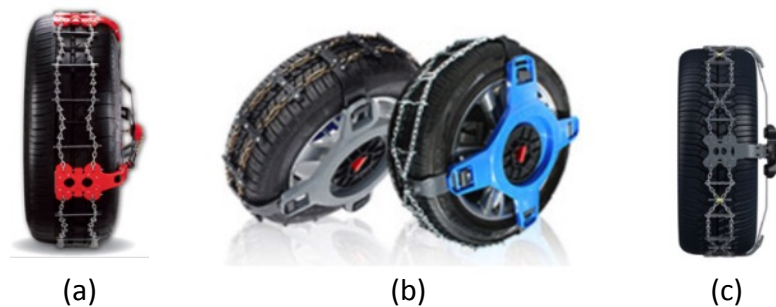
In recent years, numerous new devices have been developed, although many are not in widespread use and have not been formally approved. If testing protocol is ultimately developed, it should allow for the assessment of all types of tire traction control devices, including those described to follow. These nontraditional traction devices are grouped into four general categories in the following sections.

### **2.3.1 Variations of Traditional Chains**

As noted above, both traditional chains and cable chains have a ring on either side of the tire. As such, their installation requires that the chain installer be able to reach into the vehicle's wheel well in order to secure the inner ring. Some companies have developed products that completely eliminate the inner ring. This is accomplished by using a generally rigid component, similar to a modified hubcap, on the outside of the wheel that entirely supports the traction components on the tire periphery that contacts the road. TRAK manufactures such a device [5],

and they have a full line of products for various vehicles. Similar products are available through Spikes-Spider and Thule. All three are shown in Figure 2.

All three of these products are similar. Each contains two bands of chains that go around the perimeter of the tire on the tread surface, and these bands are held in place by a plastic arm that connects to the wheel hub. While the primary traction aid mechanism is the same as chains, the cross-support arms are augmented with metal studs, which have a similar construction to those used on traditional studded tires. Since the chain forms a continuous band around the tire's perimeter, the frictional properties are quite consistent as the tire rotates, in comparison with traditional tire chains for which the cross-link strands' contact with the road varies according to the tire's rotational position.



**Figure 2. (a) TRAK Sport, (b) Spikes Spider (Sport and Alpine Pro), and (c) Thule K-Summit Low-Profile Passenger Car Snow Chain**

### **2.3.2 On-demand Chains**

Automated traction devices (ATDs) include a mechanism for deploying chains on demand and are otherwise stowed to prevent contact with the road. The ATDs Onspot, Insta-Chain, and Roto-grip function in a similar manner. In typical installations, a pneumatic actuator is used to put a rubber wheel in contact with the tire's sidewall. Enough contact pressure is applied to the sidewall in order to force the wheel to rotate with the tire utilizing a friction drive. As the wheel rotates, the centrifugal force causes a strand of chain to be slung across the tire face and it is then trapped under the tire's contact patch. Figure 3 illustrates the basic ATD installation, which is similar for all three products. The chain strand then acts like a traditional chain. These devices are more permanently installed than traditional devices, and they can be deployed (or stowed) from the confines of the vehicle. ATDs are almost entirely limited to use by heavy trucks since the actuation typically relies on compressed air. A shortcoming of these systems is that their performance is greatly compromised if deployment occurs after the vehicle is stuck. These systems can only be used on the inside tire on axles with dual wheels on each side. These products are generally accepted by Caltrans, although Caltrans does reserve the right to require additional chains on the outside tire.



**Figure 3. Generalized ATD Installation (Onspot, Similar to Insta-Chain and Roto-Grip)**

### **2.3.3 Temporary Studded Tire**

Some products have been developed that take advantage of the improved traction effects of studded tires but are not permanently installed. Because the temporary studs are much more easily removed, these devices have the potential to reduce the excessive road damage experienced when studded tires are left on a vehicle operating on dry pavement.

Spikes-Spider's Compact product line utilizes the same attachment mechanism as their chain system shown in Figure 4, but instead of using chains, the portion running around the periphery of the tire has a higher density of arms and relies solely on the embedded studs to create added traction. In the previously mentioned designs, the studs augmented the chains as a secondary system, while in this system, the metals studs are the primary traction-aid mechanism.



**Figure 4. Spikes-Spider Compact**

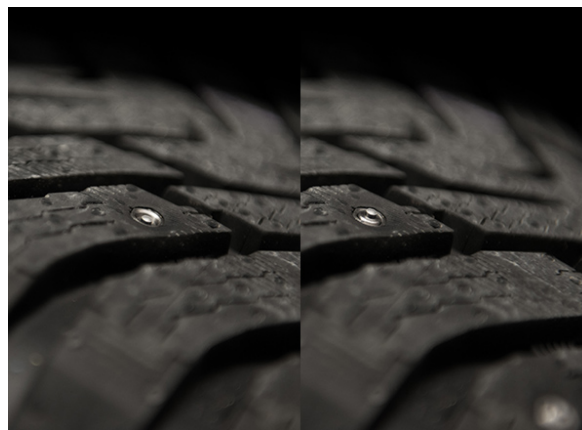
Michelin's Easy Grip Composite Tire Snow Chain, shown in Figure 5, also works on the principle of creating a temporary studded tire. Although the company describes it as a chain, the

system has a mesh of abrasion-resistant polyamide and polyurethane cords that surround the tire. Galvanized metal cleats are located where the various mesh strands come together and add traction in a process similar to that of the studded tire.



**Figure 5. Michelin Easy Grip Composite Tire Snow Chain**

Some companies are working on advanced versions of studded tires. The Nokian Hakkapeliitta 8, shown in Figure 6, has studs that can be retracted as needed. The manufacturer does not release information on the detailed mechanisms to accomplish retraction and deployment. References from 2008 were found for the Q Tire Celsius [6], which used wireless technology to extend or retract the studs. However, there are no indications that this product is available for purchase.

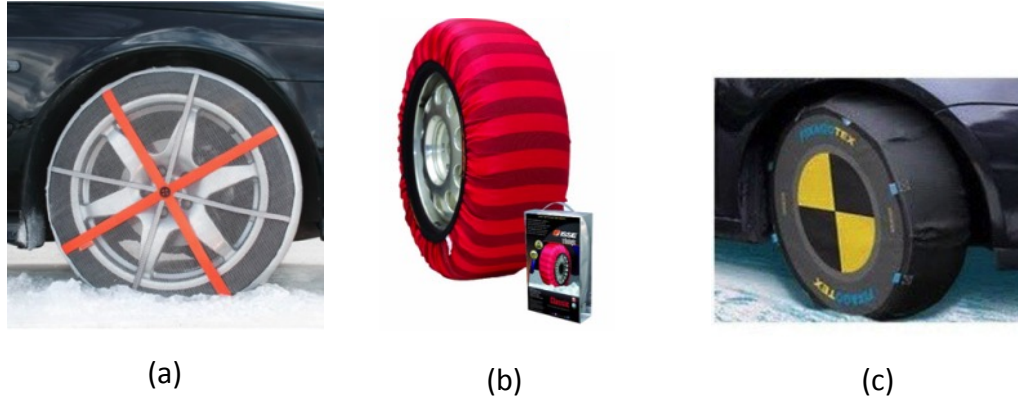


**Figure 6. Nokian Hakkapeliitta 8 Concept Tire Showing Stud Retracted and Deployed [7]**

### **2.3.4 Textile Devices**

Recently, there has been much development of textile traction control devices. The AutoSock is the first known textile traction control device. Generally, these systems are similar to a shower

cap for the tire. An in-depth explanation of the AutoSock's operating principle is available on the manufacturer's website [8]. Since the AutoSock was developed, other products have entered the market with a similar construction, such as the Shark Classic Issue Snow Socks and the Fit & Go Tech Sox. Figure 7 shows images of all three products. There is concern about these devices' degree of tire traction improvement due to their significantly different structure than traditional devices. Moreover, based on the type of material used, there is large concern for product durability with this class of devices.



**Figure 7. (a) AutoSock, (b) Shark Classic Issue Snow Sock, (c) Fit and Go Tech Sox**

The possible use of textile traction control devices introduces several additional concerns. The manufacturers recommend that these devices be removed when not in use for numerous reasons. First, since the textile traction devices do not significantly adversely affect vehicle ride, operators may be unaware of their installation and exceed the maximum recommended speed. Second, if these devices remain on a vehicle that is driven over dry pavement for an extended period, then excessive wear of the textile traction device is likely to occur, which will degrade its performance. Third, the performance of these devices degrades if they are allowed to freeze on a motionless tire. To that end, it is more difficult for a driver to perceive the failure of the textile traction control devices, which can result in unaided vehicle operation. Each of these issues needs to be considered when establishing policies for their use.

### **2.3.5 Continuous Surface Cleat Systems**

The Snobootz and the MITA chains primarily consist of a cleated band that goes around the perimeter of the tire. These two products rely on similar mechanical geometry but employ different materials.

Snobootz consist of a directional rubber cleat that is held onto the tire using a cloth-based backing [9], as shown in Figure 8. *Consumer Reports* tested this device in 2009. Based on the review, this product tends to work well on ice and hard-packed snow, but its performance is



degraded when operated on soft snow. Efforts to identify other references to this product were unsuccessful, and it is not commercially available.



**Figure 8. Snobootz Installation Image**

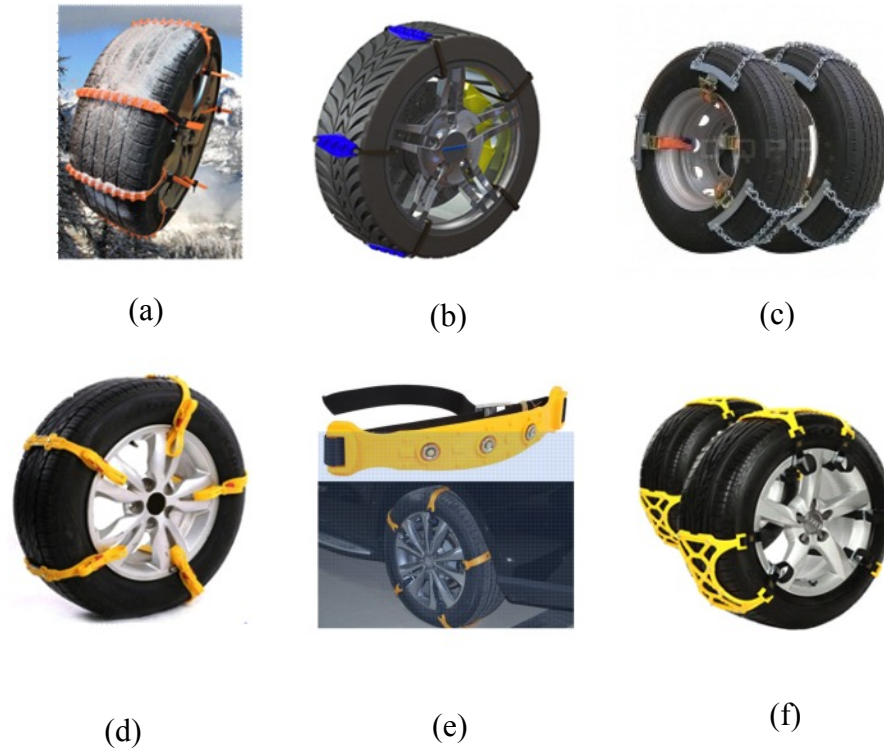
The MITA chain system, shown in Figure 9, consists of a series of steel plates that follow the perimeter of the tire. This system requires a groove around the perimeter of the tire that is at least 0.24 inches wide and 0.16 inches deep to locate the device [10]. Once installed, tension in the system keeps it seated on the tire. Research shows that this is an active product, but with limited availability in Europe.



**Figure 9. MITA Chain System**

### **2.3.6 Cleated Systems Using Discretely Attached Elements**

Another unique group of products consists of cleats that are attached to the tire through the rim. These products take advantage of the fact that many modern rims have a more open design. The ZipGripGo is a single-use, cleated zip-tie that can be attached to the tire. The current version of this product is intended for emergency situations where the car is stuck, but it is not intended for use as a replacement when chains are required. The SnowGripz, Truck Super Sector Schneeketten, Bang Theory Universal Car Snow Chain Tire Chain, and AUMO-mate® Car Snow Tire Anti-skid Chains all function in a similar manner as the ZipGripGo, but can be used multiple times. There are several products that are very similar to the Truck Super Sector Schneeketten shown in Figure 10. The Carsun 2015 anti-slip chain consists of three separate modules that are evenly spaced around the tire. This product utilizes nylon webbing to secure the system in place. All six of these products are shown in Figure 10.



**Figure 10. (a) ZipGripGo, (b) SnowGripz, (c) Truck Super Sector Schneeketten, (d) Bang Theory Universal Car Snow Chain, (e) AUMO-mate® Car Snow Tire Anti-skid Chains and (f) Carsun 2015**

### **2.3.7 Miscellaneous Devices**

This section discusses products that are unique and cannot be grouped with those above. Figure 11 shows a wheel sander device, which allows sand to be placed on the road near the tires at the driver's command. The spray-on traction aid is another novel product and is available from Tyre-Grip. This product, shown in Figure 12, is sprayed onto the traction surface on an as-needed basis. The Go Claw/Flex-Trax system is very similar to the Carsun product, except that instead of having straps that pass through the rim, there are additional components along the tire's sidewall that help keep the traction aid in place. The Terragrips chain is very similar to the classic chain in how it connects to the tire; however, the steel cross-link strands of traditional chains are replaced with rubber slats. This product is typically geared towards use in farm tractors but could be applicable to road-going vehicles. The Proyecto Snow Chain was identified in a YouTube video that presents a conceptual product demonstration [11]. The TASAT snow chain is another product for which only a conceptual product YouTube video [12] could be found. This device is geared towards larger commercial trucks and is essentially a larger, more robust version of a discrete cleated system permanently mounted on the wheel's hub. The Snow Monkey was also only found on YouTube and consists of 4 arms that are evenly spaced around the wheel [13]. Many of the miscellaneous products mentioned here and shown in Figure 13 are not developed as consumer products at this time. However, all of the products mentioned in this section could have value in the future as tire traction control devices for road-going vehicles.



**Figure 11. Typical Wheel Sander**



**Figure 12. Tyre-Grip - Spray to enhance tire traction on snow/ice**



(a)



(b)



(c)



(d)



(e)

**Figure 13. (a) Go Claws/Flex-Trax, (b) Terragrips, (c) Proyecto Snow Chain, (d) TASAT Snow Chain, and (e) Snow Monkey**



## 2.4 Summary

Many devices have been developed to help improve winter traction, and this chapter has discussed those that are currently available. Traditional devices have been used for many years. Recently, a variety of new traction control devices have become available, yet there is much uncertainty about their acceptance for regular use in winter low-traction conditions. Moreover, no guidelines have been established which facilitate the acceptance or rejection of future products for use in California. Table 2 summarizes the tire traction control devices discussed in this chapter.

**Table 2. Summary of Traction Devices**

Class	Group	Product
Traditional Traction Devices	Mud and Snow Tires	Multiple manufacturers and products
	Studded Tires	Multiple manufacturers and products
	Traditional Chains	Multiple manufacturers and products
	Cable Chains	Multiple manufacturers and products
Nontraditional Traction Devices	Variations of Traditional Chains	TRAK Sport, Spikes Spider (Sport and Alpine Pro), and Thule K-Summit Low-Profile Passenger Car Snow Chain
	On-demand Chains	Onspot, Insta-Chain, and Roto-Grip
	Temporary Studded Tire	Spikes-Spider Compact, Michelin Easy Grip Composite Tire Snow Chain, Nokian Hakkapeliitta 8, and Q Tire Celsius
	Textile Devices	AutoSock, Shark Classic Issue Snow Sock, Fit and Go Tech Sox
	Continuous Surface Cleat Systems	Snobootz, Mita
	Cleated Systems Using Discretely Attached Elements,	ZipGripGo, SnowGripz, Bang Theory Universal Car Snow Chain, Carsun 2015, Truck Super Sector Schneeketten, and AUMO-mate® Car Snow Tire Anti-skid Chains
	Miscellaneous Devices	Go Claws/Flex-Trax, Terragrips, Proyecto Snow Chain, TASAT Snow Chain, and Snow Monkey, Wheel Sander, Tyre-grip

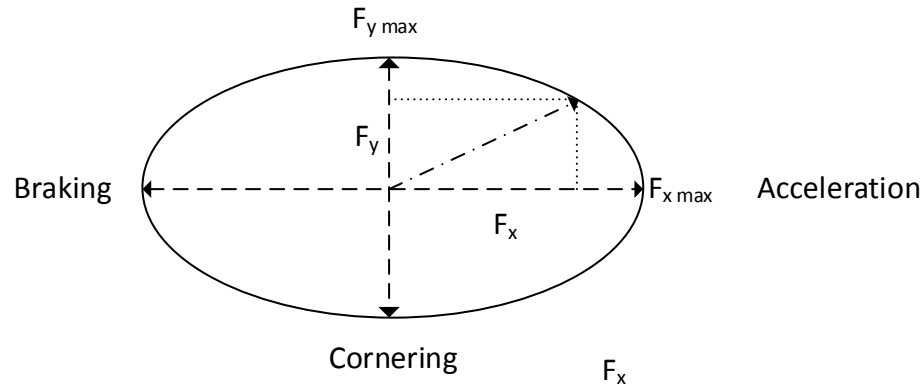
## CHAPTER 3. INVESTIGATION OF TESTING METHODS FOR THE MEASUREMENT OF COEFFICIENT OF FRICTION IN WINTER CONDITIONS

### 3.1 Friction Background and Key Terms

This chapter provides the results of a literature search aimed at identifying the various methods for tire friction measurement. First, some basic concepts of tire friction are discussed. This is followed by a categorization of the various tire testing methods. Lastly, each tire testing category is discussed in detail, including the many specific approaches employed. This material is intended to provide the background knowledge required to ultimately select a measurement method for use by Caltrans in their evaluation and acceptance of tire traction devices for winter conditions.

#### 3.1.1 An Overview of Tire Friction

First and foremost, all vehicle control forces are generated through friction at the interface between the tires and the road surface. As such, vehicle performance under winter conditions significantly degrades due to the reduced friction between the tires and the road surface. The characterization of tire friction has been the subject of many studies over the years. Rather than herein providing an exhaustive discussion of tire friction in general, the following sections instead describe the tire's behavior through the use of the commonly recognized friction circle, or the friction ellipse approach [14]. Figure 14 illustrates the friction ellipse concept. Essentially, the maximum friction that a tire can generate is represented by an ellipse in the friction plane. The axes of the ellipse represent the fore and aft, or longitudinal direction, of the tire and the cornering, or lateral direction, of the tire, respectively. In the absence of any longitudinal (i.e., braking or tractive) forces, the maximum cornering force is denoted as  $F_{y \max}$ , as shown on the vertical axis. In the contrary absence of cornering force, the maximum braking or tractive force is denoted as  $F_{x \max}$  on the horizontal axis. For combined braking (or traction) and cornering force, the tire force is bounded by the ellipse. Any demands on the tire that lie outside of this ellipse result in sliding and thus a reduction of forces available for vehicle control. The values for  $F_{y \max}$  and  $F_{x \max}$  are a function of several variables, including the normal load on the tire and the coefficient of friction between the tire and the surface with which it is in contact.



**Figure 14. The Tire Friction Ellipse**

Other terms germane to the following discussion in this chapter include the skid number, or SN, which is often used to represent the coefficient of friction between the tire and the road surface and is merely the coefficient of friction multiplied by 100.

The tire's slip angle describes the condition leading towards the tire's generation of a lateral or cornering force. In order to generate cornering force, a tire must be pointed in a direction other than that in which it is traveling. Essentially, the tire's contact patch—the portion of the tire in contact with the road surface—must be displaced relative to its static position for it to generate lateral force. This displacement is denoted by the slip angle, which is the angle between the heading direction and the tire's longitudinal direction.

Tires generate longitudinal (i.e., braking or tractive) forces due to tire slip, which is the difference between the tire's forward speed and its rotational speed multiplied by its radius. When the forward speed and the rotational speed multiplied by the radius are equal, then the tire is merely rolling, and no braking or tractive force is generated. If the rotational speed multiplied by the radius is greater than the tire's forward speed, then tractive forces are generated; likewise, if the rotational speed multiplied by the radius is less than the tire's forward speed, then braking forces are generated. Tire slip is typically expressed as a slip ratio in which 0 denotes pure rolling and 1 (or 100%) denotes pure sliding.

The most important aspect of the concise description presented herein is that the friction ellipse helps to define the maximum force resultant that the tire can generate to control a vehicle. If a driver demands more force than the maximum as defined by the friction ellipse through a combination of lateral and longitudinal control inputs, the vehicle will slide, and the operator will have significantly less control over the vehicle. Vehicle control systems such as anti-lock braking systems (ABS), electronics stability control (ESC), and traction control systems (TCS) have been developed to help keep the vehicle's friction demand within the tire's capabilities while still allowing operation near the boundary as defined by the tire friction ellipse.

## **3.2 Tire Testing Methods**

Many methods have been developed to evaluate the coefficient of friction between the road surface and a vehicle's tires. Many of the common methods utilize a well-characterized tire and are thus aimed at evaluating the specific road surface's coefficient of friction. Such an approach is commonly used to assess the frictional characteristics of airport runways. The intent is to ensure that the runway is capable of providing sufficient traction to support safe landing, and, as such, the longitudinal friction characteristics of the contact patch are the major concern. Similar methods are used for determining a specific road surface's coefficient of friction during the course of accident investigations. The assessment of tire traction control devices clearly differs from such approaches because the intent is to assess the traction device as opposed to the road surface.

Tire/road surface coefficient of friction test methods can be divided into two fundamental categories. The first category, referred to as the direct method, measures actual tire forces in order to evaluate the coefficient of friction. The second category, referred to as the indirect method, calculates the coefficient of friction from the measurement of the overall vehicle system parameters such as acceleration and displacement. For example, the coefficient of friction could be ascertained by applying simple dynamics to a vehicle's measured stopping distance.

### **3.2.1 The Direct Method for Tire Friction Testing**

All direct measurement methods rely on measuring the actual force generated by a specific tire. There are many different direct methods, but all require specialized equipment for measurement. The following material presents the various methods applicable to testing tire traction control devices. Given the range of testing methods and the variation of the available equipment, both the Permanent International Association of Road Congresses (PIARC) [15] and the National Cooperative Highway Research Program (NCHRP) have attempted to correlate the various approaches [16]. Pendulum-style stationary test methods are discussed in the NCHRP report, but this method does not seem applicable to testing different traction control devices and is thus omitted from the discussion below.

The most common approaches for direct tire friction testing are fixed slip angle, fixed slip, variable slip, and locked wheel testing. For each method, the load on the tire is found either through a one-time calibration or continuous measurement. ASTM E2340 [17] explicitly states that up to a 1% variation in vertical load is permissible without the need for an additional force sensor. Conversely, if more than a 1% variation is predicted, dynamically measuring the load is required.

These testing methods typically utilize one of two standardized tires. ASTM E501 [18] defines the specifications for a ribbed tire, while ASTM E524 [19] defines the specifications for a smooth testing tire. The standardized tire is then used to evaluate the frictional characteristics of the pavement. Measurement is more challenging for the testing of tire traction control devices

when the road surface conditions and the tire's tractive characteristics are uncertain. The various approaches to direct tire friction testing are described below.

### **3.2.2.1 The Fixed Slip Angle Approach**

One method of direct tire friction testing uses a fixed slip angle to estimate the coefficient of friction. In this approach, the tire is pulled forward with a set slip angle and the lateral force is measured. The Sideway-Force Coefficient Routine Investigation Machine (SCRIM) is an example of a fixed slip angle system; it operates at a slip angle of approximately 20 degrees [20], as shown in Figure 15. Another system, the Mu-meter, shown in Figure 16, is specifically mentioned by ASTM E670 [21] and applies a 7.5 degree slip angle to two wheels. Other fixed slip angle systems include the Pave CTF, which also meets the E670 standard, and the Halliday roadway friction tester, which fixes the slip angle to 1.5 degrees [22]. The Halliday system employs its Grip Evaluation and Management (GEM) hub, shown in Figure 17(a), to measure the axial force on the wheel; its various systems for mounting are shown in Figure 17 (b) and (c), as well. The state of Ohio has assessed winter road friction properties using the Halliday device [23]. In general, in the fixed tire slip angle approach, the measured tire wears at a lower rate with small slip angles.

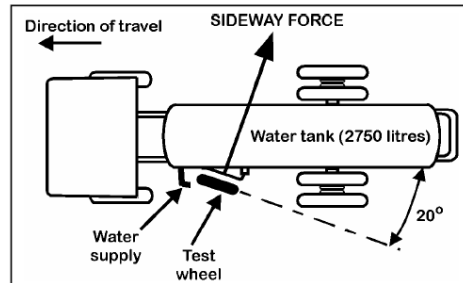


Figure 15. SCRIM Layout [20]



(a)



(b)

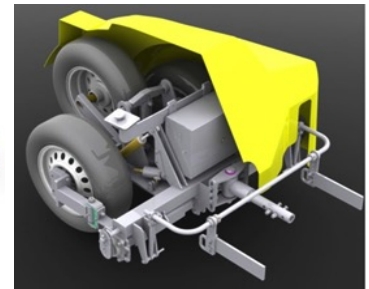
Figure 16. Mu-Meter: (a) Unit Close Up, (b) Unit With Water Tank



(a)



(b)



(c)

Figure 17. (a) GEM Hub, (b) RT3 Grip, and (c) RT3 Curve

### 3.2.2.2 Longitudinal Methods

The longitudinal method for tire friction testing measures the longitudinal force of a wheel with some amount of longitudinal slip and the tire oriented in its travel direction (i.e., with no slip angle). Generally, the method systematically applies the wheel's brake in order to vary the slip ratio and measures the resultant force. There are three general longitudinal methods: those

with fixed slip, a locked wheel, and variable slip. These methods are distinguished according to their respective levels of slip. ASTM E274 [24] describes the protocol associated with a locked wheel test. As such, ASTM E274 measures the forces generated in the 100% slip condition and averages the readings over a given time. ASTM E2340 is assessed in a similar manner to E274, with the exception that instantaneous values are used instead of average values over a given time interval. ASTM E1337 [25] denotes the protocol for assessing the maximum force that occurs at a low percentage of slip. The three methods are discussed in more detail in the following sections.

#### **3.2.2.2.1 The Fixed Slip Method**

In this method, a fixed amount of slip is imposed on the measuring wheel. The SAAB friction tester, shown in Figure 18, is one device that uses this method. In this system, the test wheel's slip is developed by gearing its drive system to the rear wheel of the measuring vehicle. The Dynatest 6875H also uses the fixed slip friction method, and it operates at 14% slip.



**Figure 18. SAAB Friction Tester**

#### **3.2.2.2.2 The Locked Wheel Method**

In this method, the tire is locked up, which results in a 100% slip condition; the resulting force is then measured. Accordingly, the testing tire used in this system has the shortest life of the three approaches. While the method is relatively simple, the peak tire friction occurs at slips less than 100%, typically at slips of about 15%, and thus this method does not measure peak friction. The state of Florida researched the precision of this method [26] and found that the results were repeatable with minimal variation. ASTM E274 outlines the guidelines for this method, which includes the use of a water system. Texas [27] also performed a detailed study of the ASTM E274 method. At the time of the report, Texas utilized locked wheeled testers with only a single force transducer. The focus of this work was understanding the test error caused by non-ideal road surfaces. The variations in road surface cause changes to the vertical load on the measuring wheel, which in turn causes errors in the assessment of the frictional properties. The results of this testing indicated that adding a second force sensor to measure the vertical load creates a more robust measuring system and more accurate results. The Dynatest 1295 shown in Figure 19 is an example of a dual-channel measurement system that measures vertical load and tire longitudinal force.



**Figure 19. Dynatest 1295 Pavement Friction Tester (PFT)**

### **3.2.2.2.3 The Variable Slip Method**

Systems based on the variable slip method have a means to vary the amount of slip. This is typically implemented through a control system that monitors the vehicle speed and adjusts the angular velocity of the tire accordingly through the application of a braking system. ASTM E1859 [28] defines the test specifications for data collection and the ultimate comparison of the friction number and slip ratio. ASTM E1337 is also a variable slip test method, but ultimately determines the peak force. The International Cybernetics system shown in Figure 20 conforms to the ASTM E1337 standard.



**Figure 20. International Cybernetics System (Variable Slip System)**

### **3.2.2.2.4 Hybrid Systems**

While there are three general longitudinal tire friction measurement approaches, as discussed above, there are commercial systems that are capable of implementing multiple approaches. For example, the Viafriction system, shown in Figure 21, is marketed as a variable slip system, but it is also capable of performing locked wheel and fixed slip tests. Also, the Grip tester, shown in Figure 22, is able to conduct both fixed slip and locked wheel tests.





**Figure 21. ViaFriction Winter Trailer: (a) Without Water System and (b) With Water System**



**Figure 22. Grip Tester**

### **3.2.2 The Indirect Method for Tire Friction Testing**

Indirect tire friction testing methods rely on measuring some aspect of vehicle performance and then use engineering principles to correlate that measurement with the frictional interface at the tire and road surface. Several specific indirect methods are discussed below.

#### **3.2.2.3 Skid Pad Testing**

Skid pad testing involves the measurement of a vehicle's kinematic parameters as it performs a maneuver on a closed section of test track. This typically involves measuring such parameters as vehicle speed, travel distance, and time and then employing principles of engineering dynamics to calculate the associated forces. Depending on the type of test, one can assess either lateral or longitudinal forces, and the amount of necessary instrumentation can be relatively low. Concerning longitudinal force evaluation, the vehicle speed is acquired as the vehicle accelerates in a straight line, and the force is calculated from the acceleration and the vehicle's mass. The vehicle can either be undergoing positive or negative acceleration to establish the tractive or braking forces, respectively. The coefficient of friction is then easily estimated from the resulting force and the vehicle's mass.

For coefficient of friction testing with braking, all four of the vehicle's tires are involved. Furthermore, modern cars with ABS inherently attempt to maximize the coefficient of friction and avoid locking the wheels. As such, the testing is relatively simple, as the operator merely attempts maximum braking and the vehicle ensures that lockup does not occur. Without ABS, the operator would need to modulate braking to ensure that maximum deceleration occurred. For the evaluation of tire traction devices, all tires would need to be so equipped.

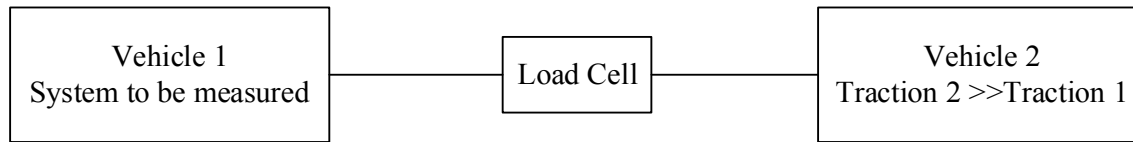
For coefficient of friction testing under acceleration, only the driven tires need to be equipped with the traction device. The force necessary to allow the vehicle acceleration is calculated with the full vehicle weight, but the portion of the weight carried by the driven tires is used to calculate the coefficient of friction. Vehicles equipped with a traction control system (TCS) allow less operator involvement in ensuring that tire sliding does not occur. Further, rapid acceleration causes longitudinal weight transfer, which may need to be accounted for.

The road/tire coefficient of friction can also be determined through lateral performance testing. In such a case, the vehicle is driven in a constant radius circle; the speed of the vehicle is increased until the wheels begin to slip laterally and controllability is reduced. The coefficient of friction is easily calculated from the centripetal acceleration; only the vehicle speed and turn radius are needed. When evaluating traction devices, the device must be placed on all tires.

#### **3.2.2.4 The Pull Test**

The pull test is another indirect method of tire friction testing. This method requires the use of two vehicles and a force transducer and focuses on longitudinal performance. In the skid pad method, the longitudinal traction is assessed computationally based on time and travel distance data. The pull test is used to measure the longitudinal force of the vehicle with lower friction; that is, vehicle 1 is measured while vehicle 2 maintains a higher tractive ability. This method is considered indirect since the overall vehicle performance is measured rather than that generated by a single tire.

Figure 23 presents an overview of the pull test method, which has two possible functional configurations. The first configuration involves measuring the maximum braking force. During the test, vehicle 2 moves the system forward. Once a steady speed is reached, vehicle 1 applies its brakes and the load cell force is measured. Since vehicle 2 is configured to ensure its greater traction than that of vehicle one, the limits of the installed device can be reached. The second configuration involves measuring the maximum acceleration force. In this test, vehicle 1 pulls vehicle 2. Once a test speed is reached, vehicle 2 applies its brakes. To counteract this effect, vehicle 1 generates additional force in order to maintain speed. This test is also referred to as the "maximum tractive force" test [29].



**Figure 23. Generalized Pull Test Configuration**

### **3.2.2.5 Spin Up Testing**

In this method, the vehicle is brought to a specific test speed, at which time the testing tire (with a well-defined rolling radius and moment of inertia) is lowered to the ground in a locked condition. Once in contact with the surface, the brake is released and the wheel is allowed to accelerate. During the process, the angular acceleration is measured and, based on the measurements, the force as a function of slip is determined through the dynamic equations of motion. This method was referenced in a presentation by the Michigan Technology University [30], but no other information on it could be found.

### **3.3 Normal Load Measurement**

One of the key challenges in all of the methods, and particularly the direct measurement methods, is having an accurate estimate of the normal load on the wheels. The normal load value is very difficult to isolate from the influence of vehicle dynamics. In some of the direct measurement systems, such as the RT3 curve (see Figure 17 (c)), much of the design details concern isolating the system from the vehicle. Continuous friction measurement equipment often has the capability to measure the dynamic load in real time. ASTM E2340 6.1.2 [17] states that up to a 1% variation in vertical load is acceptable before the measuring device is required to have a vertical load measuring system.

### **3.4 Environmental Considerations**

The traction generated by a tire is highly dependent on the road surface conditions and, correspondingly, the environmental conditions. There are two important aspects of the environment to consider in order to understand a tire's performance in winter conditions through testing. First, it is necessary to identify the environmental condition, such as snow, ice, etc. Second, it is necessary to understand and quantify the testing environment well enough to allow for comparison of results from different test events.

Characterizing the typical use environment is important. Specifically, traction devices are normally used during snowstorms; additionally, sections of ice will likely appear under such conditions. It may also be appropriate to characterize slushy road conditions. Ultimately, a minimal set of environmental conditions for testing is required in order to provide sufficient information to assess the overall performance of a given product.

Two main strategies have been used to address environmental variations during testing. One strategy, which was suggested by Halliday Technologies, is to perform a large number of tests and include not only friction assessment data, but also environmental characterization data. The environmental data can be used to identify similar environmental test conditions, and thus the most comparable test results. ÖNORM approach instead compares various products to a baseline product (in their case, a typical tire chain). During testing, the reference chain's performance is assessed at the outset and at the end of the test procedure. Then, a comparison is made between the values of the product of interest and those of the interpreted baseline chain, which have been corrected for environmental fluctuations throughout the day. ASTM F1650 [31] describes the mathematics required to make such a correction. Another possible approach, which has not been previously reported, is to make measurements of the traction control device (e.g., typical chains) and the device of interest simultaneously. This would allow immediate correlation between the data.

## CHAPTER 4: ACCEPTANCE METHODS USED IN TRANSPORTATION AGENCIES

Traction control devices are used throughout the world to aid in vehicle performance during winter storm events. As such, it is of benefit to Caltrans to understand the methods used to assess the efficacy of traction control devices and to identify the products accepted for use outside California. This chapter reports detailed search results for these purposes.

### 4.1 Existing Test Methods

Assessing traction performance is challenging in general, but is further complicated by the conditions in which traction devices are used. Thus, testing by regulatory agencies typically compares the performance of a specific device to that of a standard tire chain, and specific coefficient of friction values are rare.

NCHRP is one of the few agencies that explicitly reports coefficient of friction values for traction devices [32]. The preliminary investigation performed for Caltrans was unable to identify specific reported data outside of this report [33]. The stated goal of the NCHRP report was "... to develop standard procedures for evaluating the relative performance and pavement wear effects of various types of winter-driving traction aids." The report presents a brief description of the test with very little information on how the friction values are ultimately computed. The report gives representative values, as shown in Table 3. Interestingly, the data shows no difference between the locked-wheel braking performance of a vehicle with only highway tires and a vehicle with anti-lock brakes. This report clearly shows that the need to develop an evaluation procedure for traction devices has existed for some time.

In Europe, the ÖNORM V5121 standard was developed to help assess the performance of a traction device. The ÖNORM procedure compares all devices' performance to that of a reference chain, which meets the V5117 standard. The testing involves performance assessments on snow and ice for braking, acceleration, and cornering. This testing procedure was performed by Technischer Überwachungsverein (TÜV) for the AutoSock [34].

An internal document from the Colorado DOT, obtained through communication with AutoSock, outlines a test procedure that served as the basis for acceptance of the AutoSock. Similar to ÖNORM tests, this test procedure includes a series of acceleration, braking, and cornering tests on both snow and ice surfaces. The Colorado Code of Regulations, 2 CCR-601-14 [35], defines an alternative traction device as a "... traction device differing from metal chains in construction, material or design but capable of providing traction equal to or exceeding that of such metal chains under similar conditions." Essentially, Colorado DOT also compares traction devices to a standard chain. Moreover, accurate comparison requires the testing of the traction devices and standard chains under similar environmental conditions. Colorado testing of the

AutoSock was done in accordance with specifications outlined by the ÖNORM V5121 [46] (car) and V5119 [45] (truck) standards. The ÖNORM V5117 [44] standard defines the acceptance criteria for chains and serves as the benchmark for the V5121 standard. A YouTube video [36] shows some of the testing that took place. Ultimately, the testing results led to the approval of AutoSocks for use in Colorado [13].

**Table 3. Friction Values From NCHRP Report [32]**

	Locked-Wheel Braking			Traction			Controllability		
	Ice	Snow	Wet	Ice	Snow	Wet	Ice	Snow	Wet
Highway tires (no traction aid)	.08	.15	.4	.024	.03	.19	.08	.15	.4
Snow tires (on rear only)	.08	.175	.4	.024	.055	.19	.08	.175	.4
Steel tire chains (on rear only)	.19	.27	.4	.13	.17	.19	.19	.27	.4
Plastic tire chains (on rear only)	.065	.27	.4	.011	.17	.19	.06	.27	.4
Studded snow tires (on rear only)	.09	.175	.4	.032	.055	.19	.09	.175	.4
Four-wheel drive	.08	.15	.4	.064	.12	.37	.16	.30	.8
Anti-lock brakes (4-wheel system)	.08	.15	.4	.024	.03	.19	.16	.30	.8
Anti-lock brakes (2-wheel system)	.08	.15	.4	.024	.03	.19	.12	.23	.6

The Washington State Patrol’s policy towards traction devices is outlined by Chapter 204-24 of the Washington Administrative Code (WAC) [37]. WAC 204-24-035 explicitly defines a testing protocol for the acceptance of alternative traction devices. This policy was used to determine AutoSock’s acceptance. The Washington acceptance policy states that the device of interest should meet or exceed that of the designated reference chain. The code outlines a series of tests that includes acceleration, deceleration, and cornering.

The test procedures from the three agencies discussed above all require a direct comparison between a traction control device and a standard reference chain on both ice and snow. The traction control device’s durability is also of concern, and thus the procedures include some durability tests on dry, bare pavement. Additionally, all three test procedures discuss compatibility concerns between a traction control device and the vehicle’s electronic control systems—for example, ABS and TCS.

In the state of California, Caltrans [2] refers to the following vehicle code 26104 as that which covers the laboratory testing of chains:

*(a) Every manufacturer who sells, offers for sale, or manufactures for use upon a vehicle devices subject to requirements established by the department shall, before the device is offered for sale, have laboratory test data showing compliance with such requirements. Tests may be conducted by the manufacturer. (b) The department may at any time request from the manufacturer a copy of the test data showing proof of compliance of any device with the requirements established by the department and additional evidence that due care was exercised in maintaining compliance during production. If the manufacturer fails to provide such proof of compliance within 30 days of notice from the department, the department may prohibit the sale of the device in this state until acceptable proof of compliance is received by the department.*

The above vehicle code, however, does not provide clear, quantifiable metrics that traction devices must meet. The California code only states that products must improve traction. The codes from Colorado and Washington explicitly require comparable performance to a widely accepted product: the standard tire chain. The lack of specifics in the California code presents significant challenges to the developers of new products and the motoring public since there is tremendous uncertainty about the efficacy of any specific product.

#### **4.2 Summary of Approved Traction Devices**

In addition to the lack of a quantitative basis in the above vehicle code, the applicable policies used to determine whether a specific product can be accepted for use remain vague. For example, California vehicle code 605 merely states that a traction aid must improve traction. Moreover, there is no standard certification mark on approved traction devices at the state and federal levels. As such, it is difficult from the simple inspection of a product to determine whether it is in fact acceptable for use. On the contrary, in Europe, the TÜV [34] marks accepted devices “Winter traction aid.”

The American Trucking Association published a document in 2014 [38] that summarizes the chain laws in various states. The only states omitted from this report were Florida, Hawaii, Missouri, New Hampshire, and Vermont, as they did not have any chain regulations when the document was created. Many states allow both chains and studded tires. The website [39] [www.tirechainsrus.com](http://www.tirechainsrus.com) notes that traction aids are allowed in some states, while they are required in other states. However, the acceptability of other types of traction devices is not clear.

Mud and snow tires are widely accepted and are deemed sufficient for road travel based on the road conditions. In California, mud and snow tires are universally accepted for passenger vehicles under R-1 conditions. Under R-2 conditions, these tires are allowed for all-wheel drive vehicles. In R-3 conditions, mud and snow tires are not sufficient alone, and additional traction devices are required.

Studded tires are also accepted in many states, yet most restrict their use to a specific period of the year based on the state's snow season. Such regulations balance the public's ease of use of studded tires, while reducing the extent of the damage caused by these products to dry pavement. Many states include physical design limits for studded tires; that is, limitations are placed on the length by which the stud protrudes from the tire (typically about .063 inches) and the percentage of the tire's area that consists of metal studs. California allows the use of studded tires between November 1 and April 30. However, the installation of studs in tires does not ensure that they automatically meet the requirements associated with R-1, R-2, or R-3 conditions. Studs are typically installed only in mud and snow tires, which do meet the R-1 requirements.

Snow chains are the most widely accepted traction control device. The National Association of Chain Manufacturers provides guidelines for the construction of snow chains (NACM-92805 (TC)) [40]. These guidelines do not contain information related to friction performance, but instead focus on the chain's physical construction. In some states, such as Wyoming, the detailed construction of chains is explicitly defined. Wyoming statute 31-5-956 section (k) states [41]:

*As used in this section, "tire chains" means metal chains which consist of two (2) circular metal loops, one (1) on each side of the tire, connected by not less than nine (9) evenly spaced chains across the tire tread and any other traction devices differing from metal chains in construction, material or design but capable of providing traction equal to or exceeding that of metal chains under similar conditions.*

Due to the wide adoption of snow chains, the use of the term "tire chain" has expanded to denote a variety of traction devices. For example, the California chart that depicts proper methods for the installation of chains explicitly states [42], "When the term 'chains' is used here, it means any 'tire traction device' (not necessarily link type chain)...." Such broad use of the term tire chain adds to the uncertainty in determining whether a specific product is allowable.

Cable chains are also widely accepted, and both California and Washington permit their use for passenger cars and light trucks. However, both California and Washington suggest that traditional link-style chains or quality cable chains are preferable for large commercial vehicles.

Section 2.3.1 discussed several products that are variations of traditional chains. Many of these traction devices are also widely accepted. Contact was made with both Spikes-Spider and Thule to investigate the acceptance of these products for use in California. According to the respective companies, both products are classified as chains in California. These products are also available for sale in many other states. The TRAK system, which is grouped with these two products above, is not available in the United States. However, the TRAK system is certified under ÖNORM V5117, which is the certification standard for chains. This appears consistent with California policy, as stated above.



On-demand chains, or automated traction devices (ATDs), are widely accepted throughout the United States. These systems require sufficient space under the vehicle for their deployment mechanism; their use is therefore limited to large commercial vehicles. Typically, these systems are installed on non-steerable axles, as it is much more difficult to install them on steerable axles. These systems are treated like a traditional chain with respect to regulation enforcement. On vehicles that have dual tires, these systems meet the chain requirements in some conditions by aiding the inside tire only. This meets the California requirement for semi-trailers according to the California chain installation chart [42]. However, this chart also contains language that suggests all of the drive wheels (i.e., the inside and outside wheels on a tandem axle) may need to be chained in severe circumstances. Nevada Revised Statute (NRS) 484D.530 [43] requires that an ATD's chain cross member cover at least 85% of the width of the tire's contact patch.

There are two temporary stud products. The Spikes-Spider compact series seems to meet the California requirements, as well as those of many other states. The Michelin product, which physically operates more like a studded tire but has a form factor more like a chain, does not seem to be acceptable [44]. The Michelin website states that their product is not approved in California. Finding additional information about the Michelin product was challenging, and it is likely a discontinued product.

Textile-based traction devices are relatively new and have become more readily accepted in various states. The AutoSock was the first such commercial product in this classification. This product was tested by TUV using the ÖNORM standard. Colorado and Washington each performed additional testing. Colorado allows AutoSocks to be used for both large vehicles and passenger cars [45]. Washington has explicitly approved AutoSocks by name [46]; however, Washington guidelines restrict any vehicle combination over 10,000 lbs with 6 or more axles from using AutoSocks. While both Washington and Colorado explicitly name AutoSocks as an approved traction device, California's regulation is less specific and refers to textile-based devices as "...synthetic material devices" [47]. This language opens up the door for other products while not providing any explicit guidelines for acceptance or rejection.

The MITA snow chain, sold by the Italian company Blumec, is a continuous surface cleated system. No literature has been found to suggest that this device is allowed in any state. Additionally, the manufacturer's website states that this product, which has won various awards, is not ÖNORM certified [10].

The various discrete cleated systems do not seem to be allowed for general use as traction control devices. The ZipGripGo does not claim to meet California requirements, but the device is marketed for use in emergency situations to free a stuck vehicle. Conversely, numerous online comments state that the SnowGripz mechanism is allowed in California based on the strict interpretation of the California vehicle code [48]. No additional information on the acceptance of the Bang Theory Universal Car Snow Chain could be found. The frequently asked questions for

the Carsun product on the Amazon website [49] suggest that the legality of the product is unclear based on the vague description given in the California vehicle code.

Numerous unique products discussed in Chapter 2 are currently under development and thus are not commercially available. Based on the lack of specific performance criteria for acceptance, their ultimate acceptance remains uncertain. However, some wheel sanders are allowed. For example, Colorado permits the use of wheel sanders but requires that such systems carry sufficient sand to allow the vehicle to travel through the entire chain control area [50].

Overall, a wide range of traction control products is available. Unfortunately, regulations between states conflict, and no specific performance criteria to evaluate a device exist. California vehicle code is not exact in how it describes traction devices and leaves room for interpretation. Moreover, states classify identical products differently; for instance, the Spikes-Spider is classified as a chain under California regulations, but clearly is not considered a chain according to the Wyoming statute, based on the explicit language in the law regarding the physical construction of a chain.

Concerning the installation of traction devices, California [42], Washington [51], Nevada [52], and Colorado [45,53] provide pictorial information showing the required configurations for both commercial and passenger vehicles.

In summary, almost all states have policies concerning the use of tire traction devices. Table 4 summarizes the associated information provided to the public by each state. While there is an abundance of policy, very few states have any specific test procedures and acceptance criteria for the traction devices themselves.

**Table 4. Summary of Information for Other States**

State	Enforced Chain Control? (Y/N) [54],[39]	Tire Chains Permitted? (Y/N) [55]	Studded Tires Permitted? (Y/N) [56]	Textile Devices Permitted? (Y/N) [57]	State	Enforced Chain Control? (Y/N) [54],[39]	Tire Chains Permitted? (Y/N)	Studded Tires Permitted? (Y/N) [56]	Textile Devices Permitted? (Y/N) [57]
Alabama	N	Y	Y	Y	Nebraska	N	Y	Y	Y
Alaska	N	Y	Y	Y	Nevada	Y	Y	Y	Y
Arizona	N	Y	Y	Y	New Hampshire	N	Y	Y	Y
Arkansas	N	Y	Y	Y	New Jersey	N	Y	Y	Y
California	Y	Y	Y	Y	New Mexico	N	Y	Y	Y
Colorado	Y	Y	Y	Y	New York	Y	Y	Y	Y
Connecticut	N	Y	Y	Y	North Carolina	N	Y	Y	Y
Delaware	N <sup>1</sup>	Y	Y	Y	North Dakota	N	Y	Y	Y
Florida	N	Y	Y	Y	Ohio	N	Y	Y	Y
Georgia	Y	Y	N	Y	Oklahoma	N	Y	Y	Y
Hawaii	N	N	N	Y	Oregon	Y	Y	Y	Y
Idaho	Y	Y	Y	Y	Pennsylvania	N	Y	Y	Y
Illinois	N	Y	N <sup>2</sup>	Y	Rhode Island	N	Y	Y	Y
Indiana	N	Y	Y	Y	South Carolina	N	Y	Y	Y
Iowa	N	Y	Y	Y	South Dakota	N <sup>1</sup>	Y	Y	Y
Kansas	N	Y	Y	Y	Tennessee	N	Y	Y	Y
Kentucky	N	Y	Y	Y	Texas	N	Y	Y	Y
Louisiana	N	Y	Y <sup>3</sup>	Y	Utah	Y	Y	Y	Y
Maine	N	Y	Y	Y	Vermont	Y	Y	Y	Y
Maryland	Y	Y	N <sup>2</sup>	Y	Virginia	N	Y	Y	Y
Massachusetts	N	Y	N	Y	Washington	Y	Y	Y	Y
Michigan	N	Y	Y <sup>3</sup>	Y	Washington D.C.	N	Y	Y	Y
Minnesota	N	Y	N <sup>2</sup>	Y	West Virginia	N	Y	Y	Y
Mississippi	N	Y	N	Y	Wisconsin	N	Y	N <sup>2</sup>	Y
Missouri	N	Y	Y	Y	Wyoming	Y	Y	Y	Y
Montana	Y	Y	Y	Y					

<sup>1</sup> Does not have chain control but can restrict traffic to only certain vehicles<sup>2</sup> There are some exceptions for use.<sup>3</sup> Rubber studs only

## CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

### 5.1 Conclusions

The Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center was tasked with performing an extensive study of traction devices, with an emphasis on quantifying the friction characteristics between the vehicle and the roadway. The specific tasks of this research work were:

1. The investigation of traction control products and availability
2. The investigation of testing methods for the measurement of the coefficient of friction in winter conditions
3. The development of an experimental approach and detailed experimental design
4. Data acquisition and processing
5. Engineering analysis
6. Documentation

This report is the primary deliverable for task 6 and documents the results of the research. The project was terminated at the end of tasks 1 and 2, and, thus, only the results of those two tasks are discussed herein. Accordingly, Chapter 2 has addressed the types of commercially available traction control devices. Chapter 3 discussed the results of a detailed literature search aimed at understanding the currently used methods for testing for the tire-road coefficient of friction in winter conditions. Chapter 4 presented the methods employed by the various transportation agencies for accepting tire traction control devices and summarizes the approved products.

Clearly, a wide range of products provide additional traction in winter road conditions. However, very few states have developed procedures for certifying existing products based on actual testing. Furthermore, no specific performance criteria have been established for assessing and ultimately certifying products. This research is in agreement with the results presented in the associated Caltrans Preliminary Investigation [33], which found “little research on the performance of tire chains and alternative traction devices.”

### 5.2 Recommendations

There are two areas recommended for additional work. First, it is necessary to develop very specific test procedures and associated performance criteria that can be used to assess and

ultimately accept any traction control device. Second, methods need to be developed to disseminate information on accepted devices to the travelling public, DOT employees, and law enforcement to ensure that proper use and enforcement takes place.

ÖNORM, Colorado DOT, and the Washington State Patrol have developed test procedures. Both Colorado and Washington require that traction devices perform at least as well as a reference chain. One challenge with this comparative approach is that the roadway's frictional properties are affected by environmental fluctuations. That is, the road coefficient of friction varies based on the depth of snow, the temperature of the road and snow, etc. Thus, the comparison between any device and chains needs to occur on the same road at the same time. In order to mitigate this issue, it would be ideal to perform a comparison in real time. However, none of the various friction measuring devices have this capability. Moreover, many of the commercially available friction measurement devices are not geometrically compatible with the variety of available and future traction devices. In order to streamline this comparative approach, a single device capable of comparing two products in real time could be developed. This approach could be supported through simple skid pad testing, consistent with that described herein.

In contrast to the direct comparison between any traction control device and a chain, another approach is to determine absolute performance minimums and associated test procedures for any product. The website [www.tirechain.com](http://www.tirechain.com) [58] discusses such an approach. For example, the minimum performance required of a vehicle is a lateral acceleration of at least 0.35g when tested on a circular track. In this approach, it is also necessary to describe the condition of the test road surface with certainty. Still, such an approach would establish performance values that can be used for certification. Accordingly, the acceptance or rejection of any future products would be determined by an accepted protocol based on quantifiable data.

The second recommendation concerns the dissemination of information regarding and the enforcement of the proper use of traction devices. This recommendation is highly dependent on the first recommendation. That is, once specific methods and/or criteria for product acceptance are established, these will be relatively easy to disseminate to traction control product manufacturers. Approved products would be certified by the state; in turn, lists of approved products would be made readily available. As such, the travelling public, Caltrans chain inspectors, and law enforcement would all have knowledge of the accepted products and their proper use.

In summary, using traction devices under winter conditions helps to maintain the safety of the motoring public when travel is required. This is accomplished due to the improved frictional characteristics at the vehicle-road interface when traction devices are implemented. Developing a detailed test method and associated approval process will lead to the proper use of devices, safer roadways, and fair enforcement, thus benefiting all.

## REFERENCES

1. Caltrans, *Maintenance Manual Chapter R*. Vol. 1, July 2014.
2. "Chain Requirements," <http://www.dot.ca.gov/hq/traffops/trucks/ops-guide/chains.htm>, [retrieved 4/15/2016].
3. "Winter Operations," <http://www.dot.ca.gov/dist3/departments/mtce/controlmp.htm>, [retrieved 4/15/2016].
4. "RMA Definition for Passenger and Light Truck Tires for Use in Severe Snow Conditions," <https://rma.org/sites/default/files/RMA%20Definition%20for%20Passenger%20and%20Light%20Truck%20Tires%20for%20Use%20in%20Severe%20Snow%20Conditions.pdf>, [retrieved 7/27/16].
5. "Trak - Home page," <http://www.trakonline.it/pages/trak-home-en.aspx>, [retrieved 4/15/2006].
6. "Q Tire testing Celsius retractable-stud snow tires," 4/15/2016].
7. Gene Petersen and Mike Quincy, "Innovative winter tire studs that deply when needed," *Consumer Reports*, 2014.
8. "FAQ - Autosock," <http://autosock.us/faq/>, [retrieved 4/15/2016].
9. G. Petersen, "Tested: Snobootz winter traction aid for car tires," *Consumer Reports*, 2009.
10. "Info|BLUMEC," <http://www.blumec.it/product/info.php>, [retrieved 4/15/2016].
11. "Proyecto Snowchains - Youtube," <https://www.youtube.com/watch?v=V1I9-MDKXNo>, [retrieved 4/15/2016].
12. "truck snow chains? - see TASAT invent, revolutionary new device!!! - YouTube," <https://www.youtube.com/watch?v=VKq0eCrutFM>, [retrieved 4/15/2016].
13. "Snow Monkey - Emergency Traction Device - YouTube," <https://www.youtube.com/watch?v=GaSqsbiqWn8>, [retrieved 4/15/16].
14. R. Brach and M. Brach, "The Tire-Force Ellipse (Friction Ellipse) and Tire Characteristics," *SAE International*, 2011.
15. M. Boulet, G. Descornet, and J. Wambold, "International Experiment to Compare and to Harmonize Pavement Texture and Skid Resistance Measurement Methods," *Routes/Roads*, (288), 1995.
16. J.W. Hall, K.L. Smith, L. Titus-Glover, J.C. Wambold, T.J. Yager, and Z. Rado, *Guide for pavement friction*, National Cooperative Highway Research Program, Transportation Research Board of the National Academies, 2009.
17. American Standard for Testing and Materials E2340, "Standard Test Method for Measuring the Skid Resistance of Pavements and Other Trafficked Surfaces Using a Continuous Reading, Fixed-Slip Technique," pp, 2015.
18. American Standard for Testing and Materials E501, "Standard Specification for Standard Rib Tire for Pavement Skid-Resistance Tests," pp, 2015.
19. American Standard for Testing and Materials E524, "Standard Specification for Standard Smooth Tire for Pavement Skid-Resistance Tests," pp, 2015.
20. "Skid Resistance - SCRIM," [http://www.pms.ie/download/i/mark\\_dl/u/4010955092/4575374913/scrim%20brochure.pdf](http://www.pms.ie/download/i/mark_dl/u/4010955092/4575374913/scrim%20brochure.pdf), [retrieved 4/18/2016].
21. American Standard for Testing and Materials E670, "Standard Test Method for Testing Side Force Friction on Paved Surfaces Using the Mu-Meter," pp, 2015.
22. "2008 January NORDICWAY Conference Halliday Presentation.pdf " [www.hallidaytech.com/reports/2008\\_January\\_NORDICWAY\\_Conference\\_Halliday\\_Presentation.pdf](http://www.hallidaytech.com/reports/2008_January_NORDICWAY_Conference_Halliday_Presentation.pdf) [retrieved 4/15/16].

23. ODOT Division of Highway Operations Office of Maintenance Administration Field Operations Section, "Analysis of Halliday Real-Time Traction Tool (RT3) Deployment & Potential Cost Savings for ODOT," pp, 2009.
24. American Standard for Testing and Materials E274, "Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire," pp, 2015.
25. American Standard for Testing and Materials E1337, "Standard Test Method for Determining Longitudinal Peak Braking Coefficient of Paved Surfaces Using Standard Reference Test Tire," pp, 2012.
26. B. Choubane, C. Holzschuher, and S. Gokhale, "Precision of locked-wheel testers for measurement of roadway surface friction characteristics," *Transportation Research Record: Journal of the Transportation Research Board*, (1869): pp. 145-151, 2004.
27. R. Zimmer and E. Fernando, "Evaluation of Skid Measurements Used by TxDOT," 2013.
28. American Standard for Testing and Materials E1859, "Standard Test Method for Friction Coefficient Measurements Between Tire and Pavement Using a Variable Slip Technique," pp, 2015.
29. G. Previati, M. Gobbi, and G. Mastinu, "Friction Coefficient on Snowy and Icy Surfaces of Pneumatic Tires Fitted with or without Anti-Skid Devices," SAE Technical Paper Rept. # 0148-7191, 2006.
30. "Data Collection for Determining Pavement Condition," [www.cee.mtu.edu](http://www.cee.mtu.edu); "Data Collection for Determining Pavement Condition", [retrieved 4/15/2016].
31. American Standard for Testing and Materials F1650, "Standard Practice for Evaluating Tire Traction Performance Data Under Varying Test Conditions," pp, 2014.
32. G. Hayhoe, *Evaluation of Winter-driving Traction Aids: An NCHRP Staff Digest of...* "Evaluation of Winter-driving Traction Aids", Transportation Research Board, National Research Council, 1982.
33. CTC & Associates LLC, "Preliminary Investigation: Performance and Regulation of Tire Chains and Alternative Traction Devices," CALTRANS DRISI, Editor, pp, 2014.
34. TÜV Automotive GMBH, "Testing of AutoSock on winter roads," 2001.
35. "Rules Regarding Travel Restrictions on State Highways 2 CCR 601-14," <https://www.sos.state.co.us/CCR/GenerateRulePdf.do?ruleVersionId=4616&fileName=2%20CCR%20601-14>, [retrieved 4/18/2016].
36. "AutoSock a Revolutionary Invention," <https://www.youtube.com/watch?v=WtBzXVbE3Rc>, [retrieved 4/18/2016].
37. "Washington Administrative Code Chapter 204-24 WAC," <http://apps.leg.wa.gov/wac/default.aspx?cite=204-24>, [retrieved 4/18/2016].
38. "State Chain Laws - March 2014.pdf," <http://www.trucking.org/ATA%20Docs/What%20We%20Do/Trucking%20Issues/Documents/Engineering/Chain%20Laws%20-March%202014.pdf>, [retrieved 4/15/2016].
39. "Tire Chain Laws By State | When to use tire chains," <http://www.tirechainsrus.com/tire-chains-laws.html>, [retrieved 4/15/2016].
40. National Association of Chain Manufacturers, "Tire Chain Specifications Number " *NACM 92805 (TC)*, pp, 2005.
41. "Wyoming Statutes: Title 31 Motor Vehicles," <http://legisweb.state.wy.us/statutes/compress/title31.doc>, [retrieved 4/18/2016].
42. "ChainReqdraft\_10-15 v5 - ChainRequire.pdf," <http://www.dot.ca.gov/hq/roadinfo/ChainRequire.pdf>, [retrieved 4/15/2016].
43. "Mechanical Device to Provide Traction," *NRS 484D.530*, <https://www.leg.state.nv.us/nrs/NRS-484D.html#NRS484DSec530>, pp
44. "Michelin 9800900 Easy Grip Composite Tire Snow Chain – Pair," <http://atire.net/michelin-9800900-easy-grip-composite-tire-snow-chain-pair/>, [retrieved 4/15/2016].

45. "Passenger and CMV Chain Law Requirements.pdf," <https://www.colorado.gov/pacific/sites/default/files/Passenger%20and%20CMV%20Chain%20Law%20Requirements.pdf>, [retrieved 4/15/2016].
46. "WSDOT - Tire Snow Socks: An alternative to chains," <http://www.wsdot.com/winter/TireSnowSocks.htm>, [retrieved 4/15/2016].
47. "CHPTraction.pdf," <http://autosock.us/wp-content/uploads/2016/02/CHPTraction.pdf>, [retrieved 4/15/2016].
48. "SNOWGRIPZ|Facebook," <https://www.facebook.com/snowgripz/posts/1526458127602503>, [retrieved 4/15/2016].
49. "Amazon.com: Carsun 2015 Anti Slip Chain/tire Chains of Car,SUV, Snow Tire Chains, Fully Enclosed Universal Emergency Pure Tendon Thickening Anti-skid Chains(set of 6),give Snow Shovel, Glove," <http://www.amazon.com/Enclosed-Universal-Emergency-Thickening-Anti-skid/dp/B015GXIC82>, [retrieved 4/15/2016].
50. "ChainTips.pdf," <https://www.codot.gov/travel/library/Brochures/ChainTips.pdf>, [retrieved 5/9/2016].
51. "Winter Road Chain Requirements - ChainRequirements.pdf," <http://www.wsdot.wa.gov/NR/rdonlyres/1BE3F4CB-6C4D-48DC-B954-F70CAC5EAA7D/0/ChainRequirements.pdf>, [retrieved 4/15/2016].
52. "Nevada Traction Device Requirements," [http://www.nevadadot.com/uploadedFiles/NDOT/Traveler\\_Info/Safety/2014%20Traction%20Devices%20Brochure.pdf](http://www.nevadadot.com/uploadedFiles/NDOT/Traveler_Info/Safety/2014%20Traction%20Devices%20Brochure.pdf), [retrieved 4/15/16].
53. "Tire Chain Requirements.pdf," <https://www.colorado.gov/pacific/sites/default/files/Tire%20Chain%20Requirements%20II.pdf>, [retrieved 4/15/2016].
54. "2015 chain law advisory: Land Line Magazine:," <http://www.landlinemag.com/Magazine/2015/Oct/story/chain-law-advisory.aspx>, [retrieved 4/20/2016].
55. "Tire Chains - AAA Digest of Motor Laws:," <http://drivinglaws.aaa.com/tag/tire-chains/>, [retrieved 4/20/2016].
56. "Studded Tires - AAA Digest of Motor Laws:," <http://drivinglaws.aaa.com/tag/studded-tires/>, [retrieved 4/20/2016].
57. "Regulations – AutoSock:," <http://autosock.us/products/regulations/>, [retrieved 4/20/2016].
58. "Tire Chains TUV Regulations," [http://www.tirechain.com/TUV\\_REGULATIONS.htm](http://www.tirechain.com/TUV_REGULATIONS.htm), [retrieved 4/15/2016].